Climate change
and agricultural land use in Sweden

A literature review

Henrik Eckersten, Stig Karlsson and Bengt Torssell

Swedish University of Agricultural Sciences (SLU)
Department of Crop Production Ecology (VPE)
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Preface

The purpose of this literature review is to create a base of information to identify gaps of knowledge in the assessment of the effects of climate change on agriculture in Sweden, and related effects of agricultural adaptation and mitigation measures. The review is a part of a project (FANAN, Fogelfors *et al*. 2008) at the Swedish University of Agricultural Sciences aiming at making a strategic analysis of future research needs for agriculture in Sweden, and should help in answering the following questions: What are the expected impacts of climate change on agricultural production and its effects on environment, which are the suggested methods for mitigation and adaptation, and what is the scientific base on which these assessments stands?

The work has been done in the following way: Literature has basically been searched for on the "Web of Science". The review has focused on scientific literature, although the literature has also been searched on the whole "Web", and several references have been found elsewhere in a non-systematic way. The limited number of researchers involved and time available for the study allowed only a few topics to be thoroughly examined. References within many topics are though cited, but the list is incomplete. Thus the reference list should not be regarded to be complete. Mainly abstracts have been read and analysed for results, conclusions and methods. The text has basically the character of citations using expressions close to those of the authors of the articles, although our own analyses were now and then unavoidable. All evaluations by us, the authors of this report, are intended to be concentrated to the summary. The citations are structured in relation to the questions they give answers to. The reader is recommended to use the questions to find the information of her/his interest.

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Förord

Syftet med denna litteraturstudie är att samla information till underlag för att identifiera kunskapsluckor vid bedömningar av klimatförändringars effekter på svenskt jordbruk och åtgärder för att anpassa jordbruket och lindra dess effekter på klimatet. Studien är en del av ett projekt (FANAN, Fogelfors m fl 2008) vid Sveriges lantbruksuniversitet (SLU) med syfte att göra en strategisk analys av framtida forskningsbehov för svenskt jordbruk för att svara på följande frågor: Vilka är de förväntade effekterna av klimatförändringar på jordbruksproduktion och där tillhörande effekter på miljön, vilka är metoderna för att anpassa jordbruket till dessa förändringar och mildra dess effekter, och på vilken vetenskaplig grund baserar sig dessa framtidsbedömningar?

Studien är utförd på följande sätt: Litteratursökning har främst skett på ”Web of Science”, och fokuserat främst på vetenskaplig litteratur. Men litteratursökning har också utförts på hela ”Nätet”, och ett antal referenser har hämtats från ej väldefinierade vetenskapliga källor på ett icke systematiskt sätt. Beroende på den begränsade arbetsinsatsen har endast ett färre antal ämnesområden kunnat behandlas utförligt, även om referenser från ett större antal ämnesområden citerats. Av det skälet gör referenslistan inte anspråk på att vara komplett. I de allra flesta fallen är det främst abstrakt som lästs och analyserats vad avser resultat, slutsatser och metoder. Citering av referenser har gjorts i form av referat där författarnas egna uttryck har använts i möjligaste mån. Vissa tolkningar har dock varit nödvändiga. Sammanfattningen är dock vår egen analys av innehållet i referenserna. Referenserna har strukturerats i relation till de frågor som studierna besvarar. Läsaren rekommenderas att utnyttja de uppställda frågorna för att styra uppmärksamheten till sitt eget intresse.

Studien har finansierats av Fakulteten för naturresurser och lantbruksvetenskap vid Sveriges lantbruksuniversitet och författarna vill tacka kolleger vid institutionerna för växtproduktionsekologi, ekologi, ekonomi, husdjurens utfodring och vård samt mark och miljö för bidrag och hjälpsamhet.

Contents

Introduction

Climate is an important factor regulating agriculture in Sweden. The seasonal variation in climate is large and during more than half of the year, and in some parts the whole year, crop production is limited by low temperature and low solar radiation, and in some areas growth is zero for almost half of the year. However, the climate of Sweden is by the meteorological scientists expected to change significantly the coming century, and we might anticipate a significant effect on agriculture. Atmospheric carbon dioxide (COB_{2B}) is expected to double in concentration, and temperature to increase and become more similar to that of central and southern Europe of today. However, the extreme seasonal variations in day length and low solar elevations at Nordic latitudes will remain the same, and also in the future give low radiation levels during autumn, winter and spring, and high levels during summer, compared to more southern latitudes. Water conditions are also expected to change compared to present. Although it is more difficult to generalise this change, and large spatial differences might occur, a general expectation is that precipitation will increase during the dark time of the year.

The relations between climate and crop production, cropping systems, grasslands and use of agricultural land are complicated and, although much research has been done on parts of these subject, general relations useful for climate change impact studies are a major weak point. Climate change (in the following mostly abbreviated: CC) will also influence other parts of the society than agriculture, as well as agriculture in other parts of the world, which will influence the use of agricultural land in Sweden by means of social, economical and political factors. During the last 5-10 years, methodology for making climate change impact studies on cropping systems has been developed (cf. Rounsevell et al., 2003; Ewert et al., 2005). For Sweden, only very few climate change impact studies for crop production and cropping systems have been made (Sigvald et al. 2001; Eckersten et al., 2007), and there is a strong need for further research. To plan this research there is a need to investigate research made elsewhere and to evaluate its relevance for Swedish agriculture.

The main objective of this study is to analyse and describe the present knowledge on how climatic change, in the range proposed by climate scenarios for Sweden, might influence the use and production of agriculture land in Sweden. The aim is to give a reasonably well covering list of scientific literature on studies of (i) principal relations between climate and agriculture of use for assessing impacts of a climatic change, and (ii) climatic change impacts assessments, of relevance for agriculture in Sweden.

The literature review is structured in six topics (Chapters 1-6): (1) The future climate scenarios that are the prime reason for, and superior driving factor behind this study; (2) The present relations between climate regions and agricultural production regions, of relevance for Sweden; (3) The current knowledge of the principal relations between climate and agricultural crop production and related environmental factors. These relations are the bases for extrapolation assessments of climate change scenarios; (4) Climate change impact assessments made until now, of relevance for Sweden; (5) Assessments of adaptation and mitigation of agriculture production to climate change, and (6) Climate change assessments that are linked to other expected changes in the society, due to for instance globalisation and to changed availability of natural resources. To give an overview of this literature review the report begins with a summary.

Summary

This summary is structured in a similar way of as the literature review presented below. No references are explicitly given in the summary and instead it is referred to the main review. The summary is then limited to reflect the content of this review and try to avoid including facts not found in the cited literature. This summary is synthezising the facts, and includes subjective evaluations, whereas the main review has the character of more or less direct citations of the publications referred to.

S1. Climate change scenarios

The climate change scenarios appearing during last decades are the underlying reason for climate impact studies on agriculture, and provides different sets of driving forces for these studies. Details in climate scenarios are uncertain and vary with the underlying assumptions, of notably the future use of energy, land use and other socio-economic factors. These uncertainties are formulated in a number of alternatives, in turn causing uncertainties in the impact assessments. It is of crucial importance to know these uncertainties, as well as the spatial and time resolution in predicted climate variables. This section aims at describing briefly methods and assumptions for making climate scenarios; which scenarios that are available on different geographical and time scales; which variables that are predicted on the different scales, and what the uncertainties are. In this context, the term *climate sensitivity*, meaning the change in the global mean temperature (ΔT_{2x}) due to a doubling of the atmospheric carbon dioxide concentration, is frequently used. Uncertainty in the ‘real’ climate sensitivity is one of the main sources of uncertainty in projections of future climate change.

Driving forces of agriculture (S1)

Meteorological variables like temperature and precipitation are known to influence agriculture, in terms of for instance average dates of first and last freezes, frequencies of heat spells, frequencies of heavy rains and drought periods, soil water availability etc. Some derived variables are frequently used as agroclimatic indices, e.g. *crop heat units* (CHU), *growing degree-days* (GDD) and *water deficit* (e.g. defined as the difference between potential evapotranspiration and precipitation).

Methods (S1)

Climate modelling and projections (climate *scenarios*) on the global scale are usually based on General Circulation Models, GCMs (GCM sometimes also meaning “Global Climate Model”), developed at a quite limited number of research centres and institutes around the world, e.g.: (i) Commonwealth Scientific and Industrial Research Organisation (CSIRO)/Australian Climate Change Science Program (ACCSP), Australia; (ii) European Centre for Medium Range Weather Forecasts (ECMWF)/Hadley Centre for Climate Prediction and Research, UK and Max Planck-Institute, Germany (Echam); (iii) Geophysical Fluid Dynamics Laboratory (GFDL), Princeton, US; (iv) National Centre of Atmospheric Research (NCAR), Boulder, US, to mention about half of them. Separate GCMs for the atmosphere/land –surface system (AGCMs) and for the ocean system (OGCMs), respectively, have been developed, but also models integrating the two systems in the same model, so called coupled models ((AOGCMs); often with the addition of other sub-models describing e.g. sea ice, biospheric processes or the carbon cycle. The Intergovernmental Panel on Climate Change (IPCC) compiles and assesses results/climate scenarios from dominating GCMs and presents the conclusions in the IPCC Assessment reports.

On the regional scale a higher spatial resolution is desired. This higher resolution may be achieved by either of the following approaches: (i) using an AGCM with a high resolution grid and boundary conditions from a coupled GCM; (ii) statistical downscaling to the regional/local scale from outputs of a driving AOGCM; (iii) dynamic Regional Climate Models (RCMs) – with a typical horizontal resolution of 50x50 km – with boundary conditions derived either from GCM simulations or from observations. In Europe RCMs have been developed both at Hadley Centre, UK, at Rossby Centre (SMHI), Sweden, DMI (Danmarks Meteorologiska Institut), Denmark, and in many other countries.

Scenarios, global (S1)

Future climate projections/climate scenarios based on GCM/RCM-simulations are (highly) dependent on underlying assumptions concerning future socio-economic development in terms of emission levels of greenhouse gases (GHG) – these mostly considered to be a key forcing factor for the climate change. A set of possible future scenarios (emission scenarios), widely used as external “driving forces” /background conditions in climate model simulations, are given and described in a report by IPCC (A1, A2, B1, B2).

Projections of future climate in Europe, based on different GCMs, indicate that annual temperatures may rise at a rate between 0.1 and 0.4 ˚C per decade, with the strongest warming over southern Europe and north-east Europe, and least along the Atlantic coastline. There are also indications that the occurrence of severe heat-waves over Europe (and North America) may be more frequent in the future. The general pattern of future change in precipitation indicates increases in northern Europe (of the order +1-2 % per decade) and smaller *decreases* across southern Europe (up to -1 % per decade) in the yearly amounts, but with a marked seasonal contrast; for instance, southern Europe in *summers* may have a decrease of up to -5 % per decade.

Some, but comparatively few studies, so far, have analysed the effects of a *rapid* or *abrupt* climatic change, for instance as a result of a collapsed or significantly weakened *thermohaline circulation* (THC, sometimes called the “[Thermohaline] Conveyor Belt”) in the North Atlantic, or as a result of strong positive feedback mechanisms in a warming climate, due to for instance further release of greenhouse gases from thawing tundra.

Scenarios, Nordic (S1)

According to climate scenarios from SWECLIM (SMHI, Swedish EPA) the yearly mean temperature in Sweden will rise more than the global average, with a possible ΔT ~ +3-6 ˚C during this century. Increases both in precipitation (P) and the difference between P and evaporation are projected to be largest during the winter (up to 30- 60 %), while during summers there may be a decrease by 20 – 40 % in the south of Sweden, similar to Denmark and southern Norway.

For the Nordic region the fate of the Atlantic meridional overturning circulation (AMOC or MOC) is of specific interest since the Gulf Stream and its extension into northly latitudes – the North Atlantic stream – is part of this circulation. This circulation is to a significant extent driven by the THC (see above) and a collapse or weakening of the THC would probably have a significant influence on the Nordic climate. At the same time, some analyses give no clear indications of a significant weakening of this circulation. However, many of the mechanisms involved remain so far poorly understood, and other studies of the THC argue that this oceanic circulation is quite sensitive to small disturbances, particularly in the form of changes in the freshwater influx into the system.

Uncertainties (S1)

Uncertainties in the climate scenarios are inevitable and are primarily due to: (i) uncertainties in the assumed future emission scenarios, (ii) uncertainty about the natural background climate variability, and (iii) model uncertainty. The model uncertainty may to some extent be reduced by using so called ensemble averages of the results from many different climate models, and thereby use *probabilistic*, instead of (single) deterministic, predictions. An illustrative example of model uncertainty is given in a simulation experiment with four different GCMs, projections for European climatic zones to the year ~2080, with a detailed analysis of southern Sweden. The four models gave markedly different results for the future climate zones over the south of Sweden.

Spatial patterns (S1)

In the environmental stratification of Europe (Metzger *et al.,* 2005a), climatic zones for Europe until ~2080 were projected. By using the Canadian model CGCM2 and emission scenario A1 as input conditions, they found the following climate zones for Sweden: Today south of Skåne is classified as Atlantic North, Öland and Gotland as Continental and the remaining parts of Götaland and Svealand, except Värmland and Dalarna, as Nemoral, whereas Norrland is Boreal. By ~2080 the zonal distribution is projected to become more complex: Skåne and Blekinge has now become Atlantic Central, the eastern part of Småland and Gotland is Continental. The remaining parts of Götaland, Värmland and the southern parts of Svealand have become Nemoral, whereas the northern parts of Svealand and the south of Norrland including Hälsingland are Atlantic North.

S2. Climate and agricultural patterns

There are relations, more or less clear, between agriculture and regional climate - in Sweden as well as in other parts of the world. The agricultural patterns, however, are only partly a consequence of climate. Therefore, these patterns can probably not be used straightforward for extrapolations of changes in climatic zones to give the corresponding changes in agricultural zones. However, to a certain extent these patterns might be useful. The aim of this section is to present information probably useful to evaluate to what extent present patterns, and changes of those in the past, are general, and possibly useful for assessments of climate change impacts on agricultural production and land use in Sweden in the future.

Climate patterns (S2)

Beside the well established and widely used system for climate classification by Köppen (with later modifications by e.g. Trewarta), Metzger et al.(2005a) have recently used Principal Component Analysis on a number of environmental factors, including both topographical and climatic such as altitude, oceanicity, temperature and precipitation, with a spatial resolution of 1 km^2, to establish an Environmental stratification scheme of Europe (EnS).Thus, 84 minor strata or classes were achieved which then are aggregated into 13 major "Environmental zones" (compared with about 10 subdivisions for Europe in the Köppen system).

Agricultural patterns (S2)

There are 8 basic agricultural production zones in Sweden used by the statistical authorities (SCB), basically representing gradients in south-north and lowland-highland. The first four (1-4) are lowland areas from south to north in Götaland and Svealand predominantly covered by good agricultural soils, 5 and 6 are highland areas in the same region with predominantly poor soils cultivated by forest, and 7 and 8 are the southern and northern parts of Norrland, respectively. The Regional Experimental Service of agriculture divides Sweden into 9 zones (i-ix). To a large extent they are similar to the SCB zones. Zones i and ii are almost similar to 1 and 2, zone iii and half iv is included in 3, and v is mainly 4. For Norrland the correspondence between zones are also high although less detailed, ix is the whole 8 and half 7. However for the central Sweden and especially the forest (highland) the zones vi - ix relation to the agricultural production zones 5 – 7 are more irregularly.

There are also classification zones for garden plants and forests. For garden plants the 8 zones should reflect growing zones also related to climate hardiness. The most southern zone is the SCB zones 1 and 2 together, possibly indicating that the separation of these zones in SCB might represent something else than differences in climate. Also, the coastal region of Norrland is separated in the classification of garden plants. This is also the case for the 8 forest zones, which also, in addition to the common south north gradient, have a separation into western and eastern zones for the northern part of Götaland and Svealand.

Agricultural and climatic patterns (S2)

Agricultural patterns are related to climatic patterns. The northern limit of agriculture in Finland is suggested to depend on low solar angle and temperature, short growing season and frost during the growing season, and deep snow cover. The limit of agriculture is suggested to be located where the accumulated sum of temperatures above 5^{o}C is lower than 600-1200 d^{o}C (degree days above the given base temperature), where the upper limit (1200 d^{o}C) is the limit for crop production, and 600 d^{o}C for animal production.

Different approaches have been tested for relating crop yields to climate. Pure correlations to climatic factors might give very different results. Spatially, high temperatures in Sweden correlate with high crop yields, whereas in Southern Europe high temperatures correlate with low yields. The strongest negative correlation has been found to high incident solar radiation, indicating a high evaporative demand and water shortage. In case of climate change we might expect that European climatic conditions are shifted northward, and an interesting question is how yield correlations to single climate variables holds in future. To overcome this problem more advanced approaches have started to be developed where simulated crop yields, considering integrated weather effects, are used to create climatic zones, for instance for Ireland. This approach is based on functional (ecophysiological) relationships between yield and climate.

It has also recently been developed advanced multivariable statistical methods (in the Netherlands), where so called "Environmental zones" are estimated using PCA-analysis of a large number of climate and site variables. As a first step the production levels of natural vegetation has been classified in zones by correlating altitude, slope, latitude, oceanicity, temperature, precipitation and sunshine. Sweden is basically divided into four classes: North Atlantic in south Skåne, continental in Öland and Gotland, Nemoral in the rest of Götaland and Svealand south of a line from Strömstad at the west coast to Gävle at the east coast, and boreal north of that. The second step is to relate the "Environmental zones" to crop yields. The advantage of the method is its applicability. The disadvantage is that it is based on statistically derived equations, instead of functionally derived equations, not allowing a functionally understandable evaluation of their generality under changing climate.

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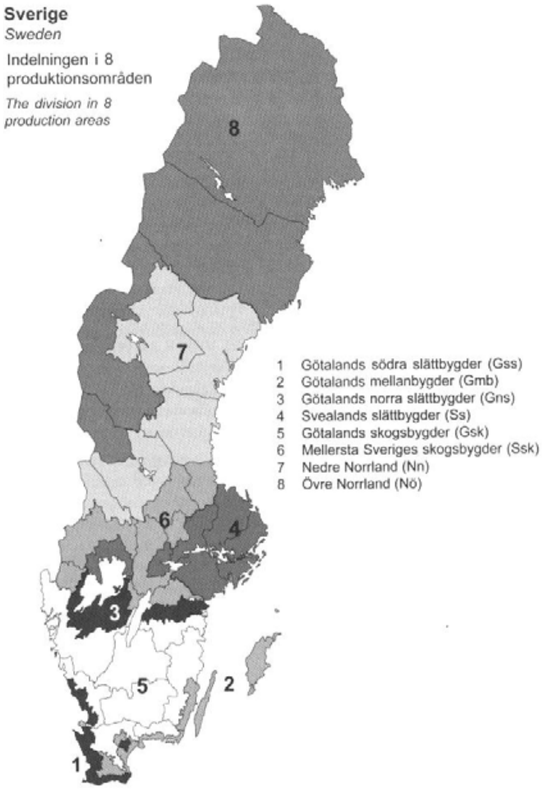


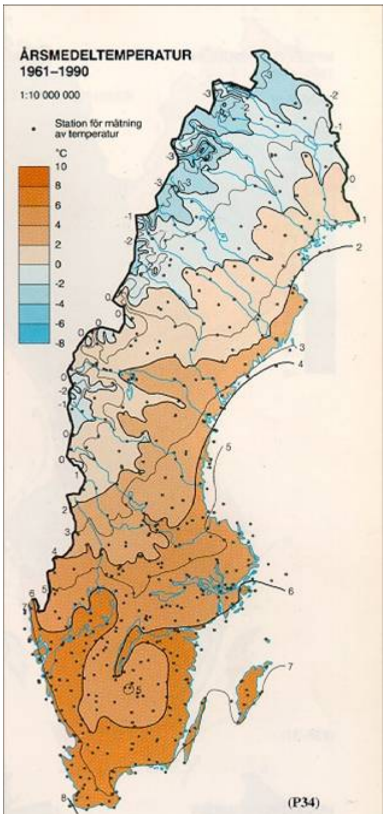


Fig. S1. Annual mean air temperature in Sweden 1961-90. The scale is from -8 to +10 ^{o}C. The warmest zone on the map is +7 ^{o}C in Skåne and along the south coast lines. The +1 ^{o}C isoterm pass through Haparanda. (source SNA (Sveriges Nationalatlas) 1995, SMHI-data (http://www.smhi.se/))

Fig. 2.1a. Agricultural production areas of Sweden used presenting regional yield statistics (source SCB).

There are systematic differences in climate between the agricultural production regions (SCB regions; Fig. S2), mainly as regards the temperature, that decreases from south to north (Fig. S1). For the reference period (1961-90) the annual mean temperature decreases, from about 8^{o}C in Skåne (in the far south), by 1^{o}C within Götaland, a further 1^{o}C in Svealand and the Götaland forest region, a further 2^{o}C in Svealand forest areas, and a further 2^{o}C in southern Norrland, and finally a further 2-4^{o}C in northern Norrland where the average temperature is below zero. There is a corresponding decrease in the temperature sum above the base temperature than 5°C from 1800 to 600 d°C (degree days). The suggested limit of crop production (1200 d°C for Finland, see above) is found in the Svealand forest area, whereas the limit for animal production (600 d°C) is satisfied in all regions. The length of the vegetation period decreases by about 3 weeks from region Götaland-Svealand, and another 4-5 weeks to southern Norrland. The forest areas have about 1.5 week shorter vegetation period than the lowlands. The start of the vegetation period differ only a little (a few days) in Götaland, another 1.5-2 weeks later in Svealand, and another 1.5-4 weeks later in Norrland.

The differences in precipitation between agricultural regions are not as pronounced and systematic as for temperature. The precipitation during the vegetation period is fairly similar for most regions 400-500 mm. There is a tendency of less precipitation (50-100 mm less) in the lowland regions 2 and 4 of Götaland and Svealand, and northern Norrland. The incident solar radiation sum during April to September is very similar for all regions. The variation within lowlands of Götaland and Svealand is only a few percent, and the variation within the whole Sweden except for mountain areas in the north is less than 10% (lower radiation in the north).

Changes over time (S2)

Climate change of Sweden has recently been evaluated as the difference in average temperature and precipitation between the period 2005-1991 and 1961-1990. This might be interpreted as the changes that have occurred from 1975 to 1998, a 23-year period. As an average over the whole year the increase is about 1°C. Within the year the largest changes have occurred for the winter (1.2–2.2 °C), with the largest increases in the north and especially in the eastern parts north of 62 °N (approx. the latitude of Hudiksvall). In summer the largest changes are found in the south and along the east coast (0.8 °C) and smallest in the north (0.4-0.5 °C). In spring the largest increase (1.0 °C) has occurred in Svealand and north-eastern parts of Götaland, and otherwise mostly 0.8 °C and no clear pattern within the country. In autumn the changes are comparatively small (0.2-0.4 °C).

Concerning precipitation the increases, for Sweden as a whole, are largest in summer followed by winter and spring. In autumn the changes are small. In summer it is mostly the eastern parts of Norrland (north of Sundsvall) except for the coast line that has experienced an increased precipitation by about 30%. Then there are inland areas in Götaland that have got a 20% higher precipitation during the 23-year period. Lowest or no increase is mainly along the coasts in southern Sweden, and north and eastern Svealand. In winter the regional differences are larger and there are two clear maxima of increase (about 30%) along the Swedish west coast, and in the northernmost mountain areas (Lappland), and an area of decrease (-10%) in central Norrland. In spring, the pattern is similar to the winter but not equally pronounced and the maximum over Lappland has shifted eastwards. In autumn, there are small changes and/or a slight decrease (-10%) all over Sweden.

S3. Climate impacts on agriculture

Crop productivity (S3)

Over long periods (25-85 years) crop yields of commercial cultivations are found to correlate with air temperature. For winter wheat the correlation is best to winter temperatures both in Sweden and Denmark. The correlation to precipitation was less clear, but high yields were related to low precipitation in March in Sweden (also for spring wheat), and July in Denmark. The correlations support the importance of winter survival for the regrowth in spring, dry conditions during regrowth in spring, alternatively sowing, and dry conditions during grain filling. A large problem in those types of correlations are that several other factors than climate influence the results, however. Regional yield have been found to correlate better with spatial variations in climate than to soil types and economic measures.

High temperatures during summer might be negative to crop growth as warming accelerates plant development and reduces grain filling, and might reduce nutrient and water use efficiency. At present conditions in Sweden, daily mean temperatures above 18 °C have found to be non-beneficial. This might reflect an optimisation of the whole cropping system for current Swedish climate. In other climates, with other varieties of wheat, daily mean temperatures of up to 25 °C has been reported not limiting growth, and for daily maximum temperature the limit has been reported to be 32 °C.

The effects of elevating atmospheric CO_2 on crop growth have been studied thoroughly during the last decades. These studies have revealed a large variability in response to CO_2 indicating the need of a process oriented research trying to find generalities on a functional basis. The results show that the CO_2 response is strongly related to water and nutrient conditions, and the responses have been expressed in terms of effects on functional parameters like radiation, nutrient and water use efficiencies, rather than effects on yields. The results indicate higher resource use efficiencies under elevated CO_2. Knowledge on a physiological level is high, whereas on a field (ecological) level the responses still are difficult to predict, possibly because the responses are so dependent on the availability of other resources, which are difficult to predict.

Climate variability influence crop production. Under CC climatic variability might change. The problem has been to evaluate the importance of changed variability compared to changes in mean climatic conditions. Studies of influences of climatic variability are few in comparison with studies of changes in the means. Effects of drought on crop production are evident and well documented, historically. Basically studies concern the effects on production, trying to estimate for instance the water use efficiency, rather than to relate the effect to when the drought occurs in relation to the development stage of the crop. Studies of drought effects on crop production for Swedish conditions are few. Concerning temperatures, controlled experiments, especially in Denmark, have exposed the crops to different temperature at different development stages. For winter wheat it has been shown that extreme high temperatures in the vegetative growth (around double ridge) might have no effect, whereas at anthesis it might have large detrimental effects on quality, and might cause a yield decrease higher than that caused by increased average temperatures. The response to different factors at different times reflects a non linear response of crop to climate, calling for a need to develop methodologies (models) that can evaluate non linear responses to temperature and droughts. Modelling applications have suggested that increases in variability of precipitation cause a larger yield variability and crop failures, than increases in temperature variability do.

Process based models are mostly used for climate applications. A large number of crop models exist and have different degree of complexity. Separate models, basically temperature driven, are used to estimate development stages. The growth models are dependent on development stages. Most growth models involve leaf area development and capturing of sun light, as a base for estimating potential growth. Then light is converted into biomass accumulation in accordance to radiation use efficiency. Allocation, respiration and litter fall (root turnover etc) are other important processes often included. The growth models are often linked to water and nutrient availability models that have a strong base in soil processes, often make the modelling complex, and input data demanding.

The number of input data needed is often substantial and the applicability to field conditions is difficult. This has asked for simplifications of the models in terms of reducing the number of needed inputs, which often is achieved on the expense of model structure representation of processes. Complicated models have not proven to better predict growth than models with simpler structure, rather the opposite. The validity of the models is of central importance for the reliance in climate impact scenarios in which they are used. There are several studies showing model applications not able to predict growth satisfactory. In many of these applications it is difficult to evaluate if miss predictions depend on the model structure or uncertainties in inputs. Nevertheless, it has been found more difficult to predict weather-induced variability on sandy soils than less sandy soils. It has also been suggested that process representations should be improved as regards leaf area development, morphologic development and sink. Several authors have found that the models reasonably well predict growth. A personal feeling is that the model predictability seems to at an unspecified degree, being dependent on the user, indicating the influence of a human factor. The scientific goal would be to minimize this influence, asking for further development of strict application methods and more applications to large field data sets.

Ozone in the lower troposhere is taken up by plants through stomata. Although dry conditions are expected to close stomata and to reduce ozone uptake, this is not always the case.

Grasslands (S3)

Effects of elevated CO_2 on grasslands are strongly related to site N conditions. Substantial amount of research has been made to clarify these complex relations, where experimental data has been analysed with help of process based dynamic modelling. The models seem able to fairly well explain the observed principal effects of elevated CO_2. For instance, increased C uptake of the grassland tightens the N cycle, and stimulates N fixation and the abundance of N fixating species. When considering also effects of increased temperature the models can give reasonable explanations of the observed outcomes, for instance that decomposition rates increase and thereby N mineralization, making more N available to growth and the CO_2 response becomes higher than without an accompanied temperature increase. However, if higher temperature results in dryer conditions the opposite response can be the case. This indicates that all major processes determining effects of CO_2 and climate on C and N dynamics in the grasslands are identified. The model simulations tell us that the experimental observations represent only a very small sample of all possible outcomes of a change in elevated CO_2 and climate. To apply the models under field conditions the process rates has to be quantified. Those rates are estimated from the driving variables (for instance water and temperature), and from the characterisation of the objects, in terms of parameter values of for instance, radiation and water use efficiency, decomposition rates etc. There is little information available about the variation of these parameters under field conditions.

Crop quality (S3)

Effects of climate on quality of crops have mainly been studied for protein and N concentrations (g N (g d.w.)$^{-1}$) of the harvested products. Most studies made indicate that increased atmospheric [CO_2] ([CO_2] = concentration of CO_2) decrease the N concentration of the plant. In a few cases there was no change, and in one case an increased N concentration was reported. Also at non-limiting N supply there is a reduction in N concentration ("critical N concentration for non N limited growth"). However, at limiting N supply the N concentrations more easily drop at elevated CO_2 and the ratio between actual N concentration and critical N concentration has been reported to decrease at high shoot biomass. For a doubling of [CO_2] (from about 350 to 700 ppm) the reported reductions, for different N conditions, range 5 to 20 %, including studies of spring wheat and natural grasslands in Sweden. When the effect of elevated CO_2 is combined with increased temperatures the N concentration decrease becomes higher. Reported decreases are 25-33 % for a 3 ^{o}C temperature increase. Water supply (irrigation) has both been found not to influence the N concentration reduction and to make the effect less pronounced. The plant N content (g/m^2) has been reported to increase under elevated [CO_2], however figures appears to be strongly related to site conditions.
During the last 40 years, air temperature in Sweden has increased by 0.6-0.8 ^{o}C. For Europe there are observations indicating an advanced beginning of the growing season by 9 days during this period (2.8 days/decade). It has been observed that a delayed sowing of Swedish malting barley have a negative effect on its protein concentration, suggesting that there might be a link between temperature, sowing date and protein worth to be investigated.

Studies for nutrients other than N, and other quality parameters are less well examined. The few results that exist should, rather than be regarded as generally valid, be looked upon as a few points of a large surface of response not well known. Reported single results of elevated [CO_2] are: decreased plant concentrations of K and Na, increase of Ca and unchanged P; decline in cell wall content; increased soluble carbohydrates and total non-structural carbohydrates before anthesis but a faster decline thereafter. Combined CO_2 and ozone effects are reported for 1000-grain weight. Increased ozone concentration decreased it but elevated [CO_2] counteracted the decrease.

Weeds (S3)

The following review of weeds is only fragmental. Climate change will alter the climatic limits that ultimately constrain the geographical range of a weed species. Weeds have a greater genetic diversity than most crops. Consequently, if a resource (water, nutrients, carbon dioxide, etc,) changes within the environment, it is more likely that weeds will show a greater growth and reproductive response and cope better with altered conditions such as higher temperatures, drought, very wet years, etc. Climate change might also be expected to favour invasive plants over established native vegetation, especially if accompanied by more variable conditions, as weeds are more adaptable to variable conditions and changes in selection pressure.

Pests (S3)

The following review of pests is only fragmental. The effect of climate on pest development involves firstly direct influences on insects and fungis. Second, climate influences crop development which in turn influences pest development. Finally there is also a more indirect effect of land use that to a certain degree depends on climate. Concerning the direct effects temperature affects development, survival, range and abundance. Increasing winter temperatures has been identified as a main factor increasing the abundance of some insects due to increasing winter survival. However, for more northerly latitudes also growth and reproduction are influenced by increasing temperature. While temperature seems to have a positive effect on aphid numbers, the correlation to rainfall has been found to be negative. As concerns the development of fungal diseases, it might become favoured in areas of Sweden where high temperatures will be combined with high humidity.

Increasing [CO_2] reduces crop N, which may retard many pests increased [CO_2] while in other cases enhances pest and decease resistance. Species with a large geographical range will tend to be less affected. Under field conditions climate, land use and geographical location all play a role in determining patterns of aphids, and using models it has been found that predictions of aphid distribution is improved by the inclusion of temporal land use data. Observations have shown that *M. persicae* annual numbers are positively correlated with area cultivated with oilseed rape. Statistical model approaches has been defended by difficulties in identification of the processes involved due to numerous of interactions between different factors.

Soil (S3)

Several soil processes like soil respiration is stimulated by increased temperature. Soil heating experiments has shown that N mineralisation might be more stimulated by higher temperatures than soil respiration and that the relation to moisture conditions might be complicated. For instance drought during summer might decrease mineralisation during summer and increase it during the following autumn and winter. Other experiments suggest, in line with this, that CO_2 fluxes are equally or more dependent on the variability of rainfall over time than the average change in the amounts, and that the two together can enhance the effect. Which qualities of soil organic matter that reacts most to increased temperatures seems unclear. Also allocation of carbon to mycorrhiza fungi is reported to increase with increased temperatures.

Increasing $[CO_2]$ is expected to increase root litter fall and increase the C/N ratio of the litter fall, suggesting that there will be a higher availability of dead organic matter to decompose but with reduced decomposability. In line with this it has been reported an increased soil C storage under elevated CO_2. But there are also FACE experiments suggesting very small effects, reporting increased soil respiration during first two weeks and increased mineralisation thereafter. Between-season effect was found for soil C and N contents, but not for CO_2 treatment effect. There is a debate of the role of N conditions for the sequestration of C into soil, and that it might be limited by progressing N limitation.

Environment (S3)

Agriculture emits greenhouse gases (GHG), and its contribution to the total GHG emissions of the European society is estimated to be significant. The N_2O emission is estimated to be the major (about 80%) contributor to GHG from agriculture, although not high in relation to other flows of nitrogen in the agricultural soils (about 0.5-3% of applied fertilizer N). The other two GHG emissions: CH_4 and CO_2 shear the rest of the agricultural emissions, although the variation in between them might be large. Especially CO_2 emissions might in some systems be large.

N_2O emission under current CO_2 levels predominately originates from the microbial processes of the nitrification, whereas under elevated $[CO_2]$ denitrification becomes more important and the N_2 emissions increase its importance in comparison to N_2O emission. The microbial activity depends on soil water and temperature conditions, and on available carbon used as energy source. Model calculations for Danish conditions have been used to evaluate the relative importance of increasing rainfall, temperature and CO_2 concentrations on N_2O emission. Largest increase was achieved with a 50% increase of CO_2, slightly smaller by a 4^oC increase of temperature, whereas the increase was essentially smaller in the case of an increase in rainfall by 20%. The effect depended on crop rotation and varied by a factor 4-5 in the case of increased rainfall and temperature, but much less in the case of elevated CO_2. In another study winter temperature and summer precipitation could explain 35% of the variation in N_2O emission from cropland, whereas for grassland only the influence of winter temperature was significant. N_2O emission from N fixing cropping systems has been estimated to be of similar magnitude to that of other crops (0.5-2 kg N ha^{-1} y^{-1}) and have been found insensitive to elevated $[CO_2]$. The effect of elevated $[CO_2]$ has also been found to depend on crop and fertilisation. In fertilised grass more CO_2 is allocated to below ground growth and turnover under elevated $[CO_2]$, resulting in more carbon access to the denitrification process. N_2O emissions are also found to vary considerably with soil type, being higher for clay than sandy soils.

The main N_2O emissions are often concentrated to short periods (2-20 days). The variation between years has been modelled to be small for grasslands but significant for cropland.

Main sources of N_2O emissions are fertilisers and manure and urine deposit from grazing animals. The main source of methane (CH_4) emissions is the rumen of the cattle, and substantial amounts originate also from manure (cattle, pig and poultry).

The IPCC method to estimate N_2O emissions from soils is simply a fraction (1.25%) of the applied N. More sophisticated methods have been proposed taking into consideration variations in climate, and soil organic and sand content. Model validity and/or applicability seems still to be a major problem.

Biodiversity (S3)

The following review of biodiversity is only fragmental. The influence of CC on biodiversity is often studied in terms of the effects of rising CO_2 levels. Elevated [CO_2] is expected to favour C3 plants over C4 plants, and this is expected to influence also the species distribution of grazers, referring to that such changes have in the past during glacial periods of decreasing CO_2 levels, been related to the expansion of C4 grasses. High temperature favours C4 plants. Therefore, both increasing temperature and [CO_2] both C3 and C4 are stimulated and in a competitive environment there is a need to estimate the relative stimulation. It has been proposed that at present CO_2 levels the C4 plants have advantage over C3 plants if the temperature of the warmest summer month is above 22 ^{o}C.

In agriculture it is mainly the composition of grasslands in terms of the abundance of forbs and legumes versus grasses that are studied. The abundance is often expressed in terms of above ground biomass. The effects of elevated [CO_2] are reported to be strongly influenced by especially the cutting frequency of the grassland. Low cutting frequency favours those plants that are strong competitors for light, that could be expressed as the absorption of light per unit leaf area and the rate of leaf area development, and forbs and grasses are favoured over legumes. The opposite is reported for high cutting frequencies. The competition is also related to the nutrient availability, and both observations and modelling studies suggest that legumes are favoured by their N fixation, but also that this improves soil N availability, which also grasses can benefit from.

In soil, an increased amount of labile organic content under climate change is suggested to increase the biodiversity.

Animal husbandry (S3)

The following review of animal husbandry is only fragmental. Twenty year old studies suggest that elevated [CO_2] does not have a significant impact on herbivore preferences or fitness. It is also suggested that plant biomass is not influenced; however, later research has proved that there is an effect but that it might be limited by for instance nutrient availability. Later studies suggest that elevated CO_2 levels will likely alter food quality to grazers both because of increasing C/N ratio and changes from C3 to C4 grasses. Under elevated [CO_2] a greater proportion of dietary N has been found to be partitioned to urine, probably because of the higher proportion of legume N in the diet, which might result in greater N loss through volatilization, compared to present CO_2 levels. Trials to assess climate effects on animal husbandry include considerations of fodder growth and quality, intake and grazing behaviour, and animal nutrient demand. Using a simulation model based on those processes grazing system was found to be most sensitive to stocking rate, milk output per cow and nitrogen fertilizer inputs.

Land use (S3)

Land use changes have been evaluated, using dynamic modelling, to be related to the idea that the farmer uses the land to maximise the economic net income of the farm. Before year 2000, land use models seem to have been largely single disciplinary, for instance trying to explain land use only from economical factors. Thereafter, socio-economic and biogeophysical processes have been combined in a number of models. One such model (ATEAM) is based on the mass balance, that all produced biomass is either used by the market (demand) or put into a category of oversupply. In case the market demand is higher than the production the oversupply is turned into an undersupply. The climate influences the production by means of the hectare yields being sensitive to atmospheric CO_2 and climate. It is unclear in what way climate influences the demand in the model. The main model seems to be quasi dynamic in that, for instance, a changed production due to a climate change of productivity not necessarily influences the prices of the demand submodel. The sub models are to a large extent dynamic. The model have been tested for Europe for the period 1960-2000, when the productivity increased by 140%, the demand increased by 50%, and the oversupply factor increased from a 10% undersupply to a 20% oversupply. The model predicted a 19% reduction in agricultural area. The observed value is a 15% reduction. The concept of the model has been extended to include also other ecosystem services than crop production produced on agricultural land.

Observed changes of land use that can be related to climate changes are difficult to find. In Denmark the area of maize production has increased from 0.4% in 1980 to 4.4% in 2003 of total agricultural land. The change might be related to changing climate, and a more careful analysis show a strong increase after year 2000 when the accumulated temperature sum of preceding 2 years became higher than about 2500 d^{o}C per vegetation period. For Scotland it has been proposed (in 1999) that increasing length of vegetation period would result in more areas cultivated with fodder maize, sugar beat and oil seed rape.

S4. Climate change impact assessments on agriculture

Crop productivity (S4)

The general pattern in predictions of future crop production is that C3 crops will increase their yield levels most (10-50%) and C4 crops less (0-10%). The increases are basically due to a doubling of the atmospheric CO_2 concentration. Increased average temperature climate will have both positive and negative effects. Positive effects are caused by earlier start of growing in spring, a potential for longer growing seasons and a greater N availability. For Western Europe some estimates suggest that earlier planting dates (up to 60 days) might increase yield with 15-22%, and the use of cultivars with longer vegetation duration might bring 1.5% yield increase per one extra day of vegetation period. A personal reflection: In Sweden the difference in harvest date between Skåne and Mälardalen, for the same variety of winter wheat, is estimated to be around 7 days. In reality different varieties are used and maturity occurs at about the same date.

Also less negative frost and over-wintering effects are expected, although not quantified. Concerning over-wintering it should be noted that damage might theoretically become more severe, due to increased respiration losses during warmer winters, still having low CO_2 assimilation rates because of low solar input. However, clarifying experiments are lacking.

Increased temperatures are also expected to have a negative effect on crop production, especially as concerns shortening the time between sowing and maturity. The effect is quite large but is expected to be overcome by the positive effect of increased CO_2. For Finland this was specifically evaluated for wheat and potato. Also, there is an unknown potential in having new varieties that mature less rapid. Comparison of regional differences in Sweden, show a clear pattern of higher yields in more warm regions. In southern Europe the opposite pattern is found; warm regions are those with the lowest yields. This is because high temperatures also increase evaporation losses and decreases water availability for plant growth. For Northern Europe the expectations are that high rain fall rates also under CC will compensate for the increased evaporation losses. However, this seems to be an average picture, and regionally large differences might occur. A question to be answered; Are there parts of Sweden that might get a relation to temperature similar to that of Southern Europe? A serious estimation of available water requires information of local soil properties. For Canada is estimated a ±50 mm change in available water.

At last, periods with extremely high temperatures are expected to have negative effects on crop production, both as concerns quality and yield. One year of this type has already occurred in 2003, when primary production in Europe was far below normal. In Sweden the commercial regional winter wheat yield reduction ranged 7-22% compared to normal (SCB-data). In France the wheat yield reduction was about 22%, whereas for fodder production the reduction was larger than 50% (J.Olesen, personal communication 2006).

Three climate factors influencing growth are usually discussed: Temperature, rain fall and CO_2. The factors act differently on different crops. C4 plants benefits from high temperature, whereas C3 plants benefit less. The opposite is true for CO_2. All crops suffer from water stress, but seldom is explored differences in sensitivity to CC between crops as concerns water. The evaluation of the net effect of these factors on crop productivity differs between studies. For UK for instance the effect is estimated to be positive for wheat, whereas for sunflower there might be a decrease during the first decades and thereafter an increase. For grasses the C3 species has been predicted to be favoured over C4 species. Looking to regional difference of current crop production in southern Sweden, it has been suggested that a $2^{o}C$ increase in temperature climate might result in an increased crop production ranging between 3-50% depending on crop type.

The net outcome of the three factors (temperature, rain fall and CO_2) most of all depends on the regional climate. For US (Kansas, Oklahoma bread basket regions) a large decrease (30-40%) is predicted for yields depending on a decrease in precipitation. A similar but smaller decrease has been predicted for Scotland for wheat and bean, but an increase for potato. For Scotland fodder maize has already become an important high energy crop and grain maize is expected to become important. Soybean is expected to become only a protein supplement crop. In Finland maize and winter crops are believed to increase. For Ireland an increased water deficit is expected in the eastern parts and that the crop production might shift towards the west, especially for non-irrigated potato. Nevertheless the increase in crop productivity due to climatic change is expected to be greater in northern parts of Europe than in southern parts more influenced by water stress. In Canada decreased yield are expected for especially grains and oilseed, but otherwise positive effects are expected.

In Denmark the maize production area has increased by a rate of about 25000 ha per year since 2000. The start of increase is related to the accumulated air temperature sum becoming larger than a certain value. Compared to climate conditions 1961-90, an increase of 1°C is estimated to make maize for grain yield suitable for Southern parts of Skåne and the Swedish west coast. Current climate statistics show that this would today (2006) already have happened. A 2°C increase is needed for major parts of Götaland and southern Svealand, and a 3°C would be needed for Småländska höglandet and other parts of Svealand. By 2080 whole Götaland and Svealand is suitable for grain maize production. However, the current trend is that earlier maturing varieties might make the northward propagation faster. The same scenarios do suggest that sunflower and sorghum will not be cultivated on a commercial level in Sweden by 2080.

Several studies have shown, especially for grasslands, that the expected response to CC can become absent because of nutrient deficiency. However, the N mineralization from soils has been estimated to increase as well as nutrient use efficiency, which would moderate this problem.

Irrigation needs are expected to increase for the majority of today irrigated areas. The variation between crops and region is high. In Ireland neither irrigation nor fertilisation need is expected to increase for spring barley under CC, whereas for potato a considerable increased irrigation need is expected. In the estimates current relations between fertilisation and yield have been used, although we might expect increased nutrient use efficiency.

Most climate impact assessments are made using simulation models driven by climate scenarios. Uncertainties in the impact assessments are related both to impact models and the climate models. The variation in wheat yield due to variations in GCM model used, given a certain emission scenario (SRES) have been estimated to range between 8-25%. The effect of if the GCM model assumes an accelerated change in climate instead of a gradual change is that the pattern of increased yields in Northern Europe and decreasing yields in Southern Europe is strengthen. Assuming a thermohaline circulation collapse (reduction of the "Gulf Stream") leads to reductions in suitability across large parts of Western Europe, as well as in southern Europe. The effects of emission scenarios (SRES: A1, A2, B1, B2) on global crop productivity is that regionalised world scenarios (A2, B2) give higher productivity than the globalised world scenarios. Most scenarios give a slight reduction in global productivity (0 to -5%).

Grassland (S4)

Effects of climate change on grassland is similar to that on crop productivity, except that these studies more focus the interaction with N conditions, and that increased temperature causes earlier maturation is not mentioned. The grassland productivity benefits from increased growing periods. So, basically there is a positive effect of CC on grassland yields that, however, is retarded by N availability and water availability that is related to soil conditions. Consequently effects of specific site conditions are often mentioned in the impact assessments. Up to 50 % increase in net primary production (+2°C and 2x CO_2) has been estimated for favourable conditions.

Few studies have looked on quality aspects of fodder due to CC. The effect of decreased N concentrations has been mentioned but regarded to be a minor effect.

Crop quality (S4)

Climate change assessments on crop quality are quite few, and quantitative results are rare also in an international perspective. For Swedish conditions simulations (only a few) for winter wheat N concentrations gave at most a 0.3%-units decrease. Threshold temperatures for crop processes have been identified as key parameters in those assessments.

Weeds (S4)

The following review of weeds is only fragmental. Nearly all weeds in Sweden are C3 plants and CO_2 concentrations are currently sub-optimal for photosynthesis in this type of plant. An increase in CO_2 concentration would increase net photosynthesis in C3 plants, whereas for C4 plants the effect would be small, and the competitive advantage of the C3 plants would increase. However, a situation with a warmer climate and drier conditions during the summer, especially in southern Sweden, might favour the C4 plants due to their possibility to grow also under water shortage. This might result in an increased frequency of C4 species, such as cockspur (*Echinochloa crus-galli*) and common amaranth (*Amaranthus retroflexus*) and a more permanent establishment of species that are very sporadic today, e.g. Johnston grass weed (*Sorghum halepense).* On the other hand, many C4 plants are short-day plants, which is a disadvantage under the Swedish long-day climate.

Increased temperatures give rise to faster development in plants which in combination with a longer vegetative period will create favourable conditions for more southerly species to invade and establish as weeds. This applies to a number of species, like wild oats (*Avena ludoviciana*) or littleseed canarygrass (*Phalaris minor*) that is a ‘super weed’ fairly recently observed in Ireland and orginates from Asia. In general, species with efficient dispersal mechanisms will be promoted. Frost-intolerant species can also be expected to shift their ranges further northwards due to milder winters. Increasing temperatures might also allow some native ‘sleeper weeds’ to become invasive and move into habitats (arable land, etc.) where they have not previously been found in modern agriculture. Such an invasion is also strongly linked to the design of future cultivation practices and cropping systems. A more frequent use of row sown crops like maize competes poorly against weeds early in the season. This would favour weed species with late development and poor competitive ability, e.g. millet species, common amaranth and black nightshade (*Solanum nigrum*). The expected increase in autumn-sown crops would favour winter annual weeds such as black-grass (*Alopecurus myosuroides)* and loose silky-bent (*Apera spica-venti*), and promoting the establishment of some new species such as *Avena ludoviciana.*

Pests (S4)

The following review of pests is only fragmental. Assessments of the role of pests in crop production under climate change has to predict both pest and crop development as function of climate change, as well as the interaction between them. Already in 1995 it was stated that there are methods available for modelling impact of changed pest pressure due to global climate change. But even recently it was argued that interactions are so complex that realistic predictions are very difficult, for instance genetic changes in the pest populations due to CC, and statistical approaches has been used. Long term records of climate impact on pest population changes are central to develop and test methods for predictions. However, those types of data are rare. A model based on such data has predicted that a fungus on grasses could extend its range. Another model also based on long term data suggested a slight increased ant colony growth by 2050 and by 20% in 2100, in Japan. Generally, different studies suggest an increase in pests, however, cereal aphids in southern Britain were predicted to decrease, mainly in response to increased temperature and changed precipitation, between -5 to -90% depend on degree of climate change. Qualitative predictions are often based on speculations of consequences of important mechanisms rather than assessments, like that short periods of hot temperatures may lead to the creation of novel vector species. In line with that higher winter temperatures increase winter survival pests are expected to shift northward in Finland

As a consequence of the changed pest development there is expected a change in the need of control measures. For wine Italy the control of downy mildew epidemics might require two more fungicide sprays. In USA the costs for pesticides are expected to increase in case of increased precipitation for corn, cotton, potatoes, wheat and soybeans, and also due to increased temperature except for wheat.

For Sweden insect and virus attacks on crops can probably be expected to generally increase under a warmer climate during the winter that will insects more numerous in the spring. Fungal diseases are favoured by both temperature and moisture. The moisture situation will be altered more irregularly in different parts of Sweden than the temperature. This means that we can expect large differences between regions. In line with these speculations, countries with a warmer climate than Sweden currently use considerably more herbicides than Sweden.

Soil (S4)

The effects of CC on soil dynamics have been investigated for more than a decade and there are several studies to review. The literature list in this review contains only occasionally found references when searching for other information. The topics concern the influence of CC on carbon sequestration to soil, often based on modelling studies, and assessments of the net effect of changed decomposition and changed litter fall under CC. Several studies suggest that the increased C input by litter fall will be larger than the increased losses by decomposition. Also regional soil C budgets have been assessed. Soil water assessments have suggested that the increased transpiration demand by rising temperatures is offset by a larger decrease due to rising CO_2

Environment (S4)

Runoff and drainage is estimated to change under CC, basically because of increasing precipitation but also due to limitations of transpiration due to increased stomatal resistance at higher CO_2 levels. In Sweden the pattern is complicated due to freezing temperatures, and changes in snow cover. Warmer climate and decreasing snow cover is expected to increase freezing and thawing cycles especially in the sandy soils with less water content. More frozen soils can result in increased surface runoff and less drainage. At larger temperature increases this phenomena would become rarer. Drainage of clay soils has been estimated to increase by up to 15-80% under moderate climate change (+1.7 °C, + 7-20% precipitation, 515 ppm).

Increased drainage is estimated to result in increased leaching of nitrate-N out of the soil profile. In addition mineralisation is also expected to increase resulting in higher soil nitrate-N. The increase of N leaching of different sites in southern Sweden has been estimated to range (+ 10-70%) similar to that of the drainage. The variability between 15 crops is estimated to range between 10-25 kg N ha^{-1} y^{-1} for pastures and leys to 85-95 kg N ha^{-1} y^{-1} for oat and potato, which is a variation as large as the variation related to uncertainties in precipitation predictions.

N_2O emissions are expected to increase under CC. For Scottish conditions a relative increase of 14% has been estimated if fertilisation levels remain the same. For Ireland larger increases (+50%) have been suggested, and that those increases are far larger than can be regulated by management.

Biodiversity (S4)

The following review of biodiversity is only fragmental. According to all cited references biodiversity seems to decrease under CC. Few studies refer to agricultural production. Some studies speculate in an increased demand for intensive agriculture under CC and that this would decrease the number of species. Studies of heathland in Denmark and the Netherlands suggest that nutrient availability will increase under CC leading to increases in grasses and a loss of biodiversity. Increased drought might though reduce grass invasion but also influence the heather vegetation negatively. Increased drought in southern Europe is expected to decrease biodiversity, possibly because of decreased soil carbon content. In model assessments of 15 different types of habitats, agricultural habitats were not among the three most sensitive (basically northern habitats) to loss of biodiversity. In another model assessment (using neural network) of 10 habitats (45 species) the most cloudberry (decreasing) and hairy green-weed (increasing) were most sensitive. There was a general shift in suitable climate from south-west towards north-east.

Animal husbandry (S4)

The following review of animal husbandry is only fragmental. Assessments of climate change effects on animal husbandry usually consider grassland production, livestock feeding, thermal balance of animals and buildings. Some predictions suggest that there is likely to be small increases in grass production in Britain. Others suggest considerable increases for Sweden. In Finland the length of the fresh fodder season is expected to increase. Integrated model assessments suggest that animal husbandry with sheep, beef calves and dairy cows in England should be able to adapt to the expected CC. For both pigs and chicken the frequency of severe heat stress is expected to increase substantially under CC, with a consequent risk of mortality and making it necessary to reduce the stocking densities considerably, or to invest in improved ventilation or cooling equipment. There will be an increased possibility of animal diseases.

Land use (S4)

Under climate change it has been suggested that the cereal crops have the potential to move northward in Finland by a rate of almost 150 km per one °C increase in annual mean temperature. In Sweden, the air temperatures have increased in the range of 1°C during the last 25 years, suggesting that we might expect an observable northward movement of crops in regional statistics, in case climate has dominated the changes. In line with this it has been stated that the current trend of agricultural production in Europe shifting towards west and North, will be accentuated under CC. For current Swedish conditions it has been estimated that the regional production is potentially equally much influenced by changes of choice of crop due to CC as increased productivity under CC.

For Europe model calculations at IIASA have predicted an increase of agricultural land area by 2080 by 16%. The increase is much larger (40%) for North America and Russia (64%) resulting in large potential increase of cereal production. At the same time developing countries is expected to decrease their potential cereal production. Other model predictions, though, result in opposite results for Europe. The estimates suggest that the production increases more than the demand and the agricultural area used for food production decreases by about 5-50% depending on model application. The reductions are estimated to be smaller in the North of Europe, and larger in the south with even as high reductions as 100%. Area used for bioenergy crops on agricultural land is estimated to increase by about 5% by 2080 for Europe as a whole, and by up to 15% for Northern Europe.

The large reduction (50%) of agricultural land area for crop production in Europe was predicted with the ATEAM model in which the assumptions about increased productivity due to technological development was the outstanding most important factor in the high emission scenarios. The technological development was assumed to go on in the same rate (kg per ha and year) as since 1960. This gave the highest relative increase for rye and triticale (2.5%/year) and lowest for oats (0.9%/year). According to this assumption (model) the relative increases decrease over time towards a similar value for different regions. In the low emission scenarios the climate change factors were about equally important as the technology factor.

The surplus area is suggested to be partly used for bio-energy crops, but will also lead to severe planning problems. The surplus area for such purposes is assumed to be even larger for former USSR, East Asia and South America. A more specific analysis of southern Sweden, using the ATEAM model suggests that the ultimate limit of how large area that can be used for agricultural production depends on soil properties, like acidity. The same analysis tested the effect of different climate change scenarios of the socio-economic scenario A1 on the land area used for a winter crop (winter wheat) and a spring crop (oat), for regions from Skåne in south to Västergötaland in the north. At current conditions the proportion of winter wheat decreases from 43% in the south to 29% in the north, and for oat the area increases from 5% to 35% of total cropped agricultural land. The predictions for 2080 gave a slightly larger decrease for the winter wheat area from 43 to 19-26%, and a similar increase of the oat area from 2 to 28-32%, from south to north. Three GCMs gave very similar results whereas a forth differed as concerns winter wheat area in Skåne (south) which became high (64%) in comparison to the prediction of the other three. In conclusion, almost no changes of relative area of the crops were achieved for year 2080.

S5. Adaptation and mitigation of agriculture to climate change

Crop production (S5)

Farmer's adaptive behaviour is expected to be governed by ambitions to minimise risks and to maximise profits. It is suggested that policy should support flexibility of for instance land use to encourage the farmer applying adaptation measures. Also there is a need of flexibility among farms. For instance, it has been estimated that the tax on crop production to reduce N leaching, should be different for a pig production than arable production systems. Tax on fertilisers favours pig production and tax on farm N surplus favours arable production.

Adaptation measures of crop production to CC except for using alternative management also include changes in the genetic material. It has been estimated that the current maize varieties in USA would get a decreased yield due to earlier maturity under a warmer climate. Introduction of later varieties would reverse this response to an increased yield. In case of warmer and drier climate in the future it is suggested that the wheat crop should be more efficient in exploring the soil water and that the crop has a slower leaf area development to reduce the transpiration losses. Methodologies for doing these evaluations are quantitative estimates with numerical models of the effects of differences in plant properties, on for instance plant water dynamics. In other cases qualitatively judgements are made from principal effects on different processes. For instance it is suggested that in the case of a thermohaline circulation collapse, resulting in a colder climate in Europe, a wheat crop not only has to be frost tolerant during winter, but also as it develops during summer.

Other measures to adapt crop production include timing and changes of cultivation practices, maintenance of soil properties and modified pest, as proposed for Finland. For African conditions windbreaks are used to reduce negative effects of drought.

Soil (S5)

The adaptation measures concerning soil mainly concerns carbon sequestration into the soil. About half of the C assimilated by plant is estimated to potentially be transferred into the soil. Already in the beginning of the 1990s global estimates were done for the potential of use land use and practices to enhance it. Suggested methods were agroforestry, fuel wood and fibre plantations, intercropping systems etc. In comparison with total CO_2 emissions the potential was regarded low. Globally, only one tenth of the emission from fossil fuel and industrial combustion could be stored and only one third of the emissions caused by deforestation and land use changes. For Europe the potential was about twice as high. Later estimates has suggested that in Europe cropland is the largest biospheric source for atmospheric carbon (about 80 MtC y^{-1}), but that the biological potential for carbon storage is about 25% higher. However, the actual storage in cropland is much lower, in Switzerland the stocks has been reduced by 16%, and instead it is forested areas that account for the increased C storage of European soils.

Conversion of arable land into grassland is an efficient way to increase soil C sequestration (about 1.5 tonnes C ha^{-1} y^{-1}) whereas several management operations have essentially less potential (10-20%), however, manure application is of the similar range. In a long term study for the past century the residual C added to the soil was estimated to have been most important. Gross C sequestration might is suggested to be four times higher under cool and humid climate compared to dry and warm climate and the soil C depletion has been suggested to be larger for tropical soils than for temperate soils.

Environment (S5)

The contribution from agriculture to total CO_2 emissions of the society is small (1%), and the ability of agricultural practices to reduce the emissions have been estimated to be only 10% of the 2010 commitment of the Kyoto-protocol, as concerns Belgium. The most efficient measure is the choice of crop or cropping system on the agricultural soil. Introduction of short rotation energy crops were most efficient, followed by manure application on grassland, new forest plantation, no till, and last organic farming, among the investigated types.

The fact that the alternative use of agricultural soil is the most efficient measure to regulate the CO_2-emissions argues for an intensified production of food and fodder crops, so that more land can be available for alternative use. Suggested intensification measures are conservation tillage and residue mulching, integrated nutrient management, crop rotations with cover crops, water use efficiency measures, and plant nutrient and energy use. Globally still there is a contribution of CO_2 to the atmosphere due to deforestation, mainly in the tropics. The last 300 years the contribution has been in total 170 Gt carbon, and still there is a contribution by 1.2 Gt carbon per year.

Carbon sequestration is argued to mainly be a short term (2020-30) measure to mitigate rising atmospheric CO_2 levels, whereas in long term (2100) it probably only has a minor role.

N surplus of a farm is suggested to be the best measure of N_2O emissions on a farm level, and reduction of the surplus is an efficient adaptation measure. Reduced fertilisation would then reduce the N_2O emissions, although exceptions with no beneficial effects are found. Optimised lifetime of dairy cows and frequent removal of manure are adaptation measures with significant effects whereas several other measures have almost no effect. Combining reduction of emission targets and economy it has been estimated with models that the most cost effective methods are to eliminate intensive beef production, reduce stored manure and increase frequency of manure spreading, substitute concentrate feed for grass and conserved grass in milk production, and to apply less mineral N to grassland.

For reducing methane emissions the most efficient adaptation measures have been found to optimise the reuse of methane gas for energy use, and to change the animal’s diet towards greater efficiency. For Denmark it is expected that there will be only a minor reduction in methane emissions from agriculture in future.

The reduction of ammonium emissions is expected to have a very small contribution to the total GHG emissions from agriculture in Denmark. The shortening of exposure time of spread manure is estimated to be the most efficient method to reduce ammonium losses. The total reduction of GHG emissions from Danish agriculture is estimated to be 12% by year 2030. Stopping the increasing trend in pig production would add another 5%, which also a 25% reduction in run off would do.

N leaching might be reduced by applying cover crop and spring ploughing, late termination of leys and fallow, and spring application of manure. For southern Sweden the estimated potential of management is a 20% reduction which is less than half of the suggested increase in N leaching due to CC. For French conditions it has been suggested a 40% decrease in fertilisation, and introduction of catch crops, to balance the estimated increased N leaching under CC.

On a global scale land use in terms of agricultural land or natural vegetation is estimated to be a very important measure for regulating the effect of agriculture on CO_2 air concentrations. Under high CO_2 emission scenarios the natural vegetation is the largest terrestrial sink of carbon. If agricultural land also in future expands on the expense of natural vegetation, the high CO_2 scenarios would be regarded as an underestimation of the high emission alternatives.

Biodiversity (S5)

Number of species is reported to be largely dependent on land use and management practices. Pastures and planted fallows are believed to result in higher diversity than cropping. Conservation tillage, mulching, integrated management systems, and mixed farming systems are supposed to promote biodiversity. As the effect of CC on biodiversity is not well expressed this might indicate a high potential of regulating biodiversity within agriculture with the choice of management practices and cropping systems. In a study in South Africa communal maize had double the number of species (7 species/m^2) compared to conventional maize which had similar numbers of species as ryegrass and pasture. The study also showed that protecting the grassland from grazing increased biodiversity; the number of species doubled during 50 years.

In the landscape agriculture and intensive land use are related to loss of habitats for endangered species. Nevertheless, protected areas in Canada were in 2004 found not to correlate with endangered species.

Policy (S5)

Concerning the need of adaptive measures to CC within agriculture there are different opinions found in the scientific related literature. In Scotland CAP (the Common Agricultural Policy) is believed to influence the farmer's actions more than CC that is believed to become a driver of little importance to Scottish agriculture. In line with this, by 2005 there have not been identified almost any ongoing or planned adaptations to CC within the agricultural sector in Sweden. The importance of socio-economic and environmental issues is often addressed as more important than CC issues. It is though unclear how CC is defined in this context, and how an action, that might be classified as an adaptation measure, is made because of CC or/and some other driving force of change.

Others have investigated how Europe could adapt to potential rapid CC. As alternative rapid climate changes are evaluated to still be possible, and climate might become both warmer and colder, it is difficult to see how organisations could adapt. And when you do not know what to do, you do what? Our simple logic would suggest the adaptation measures to focus the source creating the uncertainty.

Economical interests have proposed that more efforts should be put on decreasing the scientific uncertainties concerning the future projections, and that this could be done on the economical expense of trying to estimate the storage carbon by biological sinks. Sometimes it is difficult to evaluate to what extent this type of argumentation is a result of scientific knowledge or a demand of resources to certain research topics.

In several reports it is not evaluated how large CC is in comparison to other driving forces of change in agriculture. In Finland for instance it is listed a number of possible important policy measures to encourage adaptation: flexible use and allocation of land; relocation of zones having comparative advantages; compensation of loss of agricultural advantages; farm diversification grants; adjusting guidelines for water protection and N leaching; aid for the adaptation of new technology; plant breeding programmes and research on adaptation; developing new farming systems; developing new foods.

S6. Climate change impacts in relation to natural resources and globalisation

Natural resources (S6)

A current issue in European and Swedish agriculture is to investigate and evaluate the capacity of agriculture to produce biomass for energy use. Also globally this is a coming question reflected by estimated increased demand of biofuels by a factor of 5-11 by 2050, compared to a factor of about 1.5 for crops. An issue is to what extent agriculture can become self supported. For Ireland it has been estimated that 10% of the agricultural land is needed to support agricultural energy input needs. It is evaluated that already today it might be feasible to use this amount of land without disturbing the food production. Another way of closing the energy budget is to reduce the energy needs. Engine fuel is the largest direct energy input to agriculture. Mineral fertiliser is the largest indirect energy input. It has been estimated that a 20% reduction of mineral N fertilisation would be possible to compensate by higher precision in N management and application of slurry N.

For Ireland to produce bio-energy so as to cover the demand of the whole society, all present agricultural land would be cultivated with energy crops.

Effects of other drivers in relation to CC (S6)

Several studies has proposed that effects of climate change on cropping are of minor importance compared to possible changes in socio-economic conditions. For Europe as a whole and central Europe it has been suggested to be negligible, whereas for today marginal regions the effect might be significant. An important reason for this conclusion is that the dominating factor for changes is expected high yield increases due to technological development.

Land use (S6)

Sweden has a productive are of about 3.65 ha/person of which agriculture is 0.41 ha/person. This has been suggested to be enough to feed the population. In the future estimates have suggested that the need of area for food and fodder production will decrease in future, basically due to increased yields due to the technology development. However, this conclusion depends also on model assumptions concerning criteria for using the land for the food and fodder production. A model based on profitability suggest that only in the A1 scenario there will be a decrease, whereas in a model assuming that the overall demand for food and fodder would be determining, the total area would decrease. In another assessment with another model it suggested that the total area needed for food production globally will increase by 10-20% during the coming 50 years.

Land use in Sweden was by 2000 regarded not to try to set aside any land to reduce nutrient leakage. It was neither trying to get a net store of carbon in the forests, as a large part was harvested and exported from Sweden. In most European scenarios forested area is increased and there is some increase in the area for bioenergy crops. For Sweden the effect of increased price for oil to 100 dollars per “fat” would be that 34% of the agricultural land would be profitable for bioenergy crops.

Market (S6)

The global population is estimated to increase by about 50% and peak sometime during the current century. For certain regions the increase can become very high. Globally is expected an increased intensification of agriculture and for Europe is estimated a decrease in agricultural land. Some studies suggest reduced prices under climate change and others the opposite.

Vulnerability (S6)

Vulnerability of food security is assessed in different ways. First socio-economic factors are assessed, like demographic and economic development. This gives implications on which climatic scenarios to apply, and third what are the effects of climate change on factors of importance for the food security. These factors may be flooding, land use, water availability, fishing and pollution. In other cases the effects on wealth, connectivity (connections of the system) and diversity (financial risks) are assessed.

In other studies vulnerability is assessed by qualitatively evaluation of the comparison between potential effects of environmental changes and the adaptation capacity. The potential impact is assessed for ecosystem services represented by five indicators: food production, fibre production, energy production, farmer livelihood, and outdoor recreation. ES of these indicators are estimated as function of land use, which is divided into nine categories. The adaptation capacity was assumed to be driven by twelve indicators.

In other studies economic and ecosystem models are coupled and adaptation is represented as an endogenous process in terms of economic response to climate change. Vulnerability has been assessed to be higher for areas with the poorer resource endowments.

In a review it has been suggested that for Europe as a whole the vulnerability due to climate change impacts on agriculture is small, because the agricultural sector is only a small part of the society sector. However, for southern Europe it might be high, whereas agriculture in Western Europe is well prepared to cope with the changes. Pest, diseases and weeds are generally assumed to increase in abundance and the use of pesticides and fungicides may increase. Particular vulnerable regions are those where there is a reliance on traditional farming systems.

Assessments have suggested that vulnerability of agriculture and species are inversely related. Adaptation for reduced vulnerability of biodiversity, by for instance agricultural land abundant, increases the vulnerability of farmers. It is suggested that vulnerability assessments link these to two systems.

1. Climate change scenarios

The climate scenarios are the reason and driving forces for climate impact studies on agriculture. Details in climate scenarios are uncertain. This uncertainty causes uncertainties in impact assessments, and it is therefore of interest to know spatial and time resolution in predicted climate variables. This section aims at describing briefly methods and assumptions for making climate scenarios, which scenarios that are available on different geographic and time scales, which variables that are predicted on different scales, what the uncertainties in the predictions are, and which are the consequences for making impact assessments on agriculture.

1. Driving forces of agriculture

Which climatic factors are important?

-To asses the effect of global change it is important that future models describe shifts in average dates of first and last freezes, the frequency of heavy rain events and intensity of severe storms (in the USA), (Changnon and Kunkel, 1992).

-Long-term measurements of soil and meteorological parameters are necessary to test models for prediction of impacts of global change. A station for such measurements exists at Uppsala (Marsta), Sweden (Halldin *et al.,* 1999). Results from the first 5 years of operation have given valuable information about the microclimate of agricultural fields.

Which important agricultural relevant climate parameters are used in Canada?

-Impacts of potential climate change on three agroclimatic indices (crop heat units (CHU), effective growing degree-days (EGDD) and water deficit (DEFICIT)) in the Atlantic Canada are discussed in (Bootsma *et al*., 2005). The crop heat units is defined as: CHU = (Ymax + Ymin)/2, with Ymax = 3.33(Tmax-10.0) – 0.084$(\mathrm{Tmax}-10.0)^2$ (if Tmax <10, Ymax=0.0), and Ymin = 1.8(Tmin-4.44) if Tmin <4.44, Ymin=0.0, where Ymax and Ymin are the contributions to CHU from average daily maximum (Tmax) and minimum (Tmin) air temperature, respectively. Water deficit (DEFICIT) is defined as the difference between potential evapotranspiration and precipitation, accumulated over a specified time.

1. Methods

Which climate change models (GCMs, RCMs, EMICs and DGVMs) exist?

-See Appendix 1.

How can projections of a GCM model be related to that of a simple global model?

-Ruosteenoja *et al*. (2007) present seasonal GCM-based (Global Circulation Model) temperature and precipitation projections for the end of the 21st century for five European regions (one of which encompassing the Nordic region), and also compare these projections with corresponding estimates given by nine different RCMs (Regional Climate Model) within the EU project PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects; a review of this project is given by Christensen et al., 2007). Mostly, only results corresponding to the SRES A2 and B2 scenarios were available. To formulate projections also for the A1FI and B1 scenarios, a so-called 'super-ensemble pattern-scaling technique' was developed, that uses linear regression for the relationship between the local GCM-simulated response, and the global mean temperature change simulated by a simple climate model. (Among the GCMs included in the analysis were ECHAM4, HadCM3 and GFDL R30, and among the RCMs the Danish HIRHAM, the Swedish RCAO and the Hadley Centre HadRM3P. For estimates of temperature change from this study see "1. Scenarios" in this report.)

Who is making climate change assessments for Sweden?

-Intergovernmental Panel on Climate Change (IPCC, 2002, 2007), Climatic Impact Research Centre (CIRC, Umeå universitet; http://www.emg.umu.se/circ/), Rossby Centre (SMHI, 2007).

Does regional climate modelling improve climate simulations?

-The latest progress in regional climate modelling studies is reviewed, including RCM (Regional Climate Model) development and applications of RCMs to dynamical downscaling for climate change assessment and seasonal climate predictions, in a paper by Wang *et al.* (2004). It is stated, that regional climate modelling has proven to be able to improve climate simulation at the regional scales, and especially in regions where forcing due to complex orographic effects, land-sea contrast, and land use patterns regulate the regional distribution of climate variables and the variations. (The paper includes several references to RCMs.)

In which ways can high-resolution climate change scenarios be obtained?
-Jones *et al.* (2004a) describe the regional modelling system "PRECIS" in a "handbook". PRECIS is a personal computer (PC)-based modelling system to provide regional climate information for impact studies, which can be run over any area of the globe. It is based on the third-generation Hadley Centre regional climate model (HadRM3P), with implicit maximum resolution of 25 km. Techniques for obtaining regional, fine scale climate change information from GCM outputs such as statistical and dynamical downscaling, are discussed.

What is the effect of assumed increased variability to the predictions of heat waves?
-Schar *et al.* (2004) found that an event like that of summer 2003 is statistically extremely unlikely. They propose that a regime with an increased variability of temperatures (in addition to increases in mean temperature) may be able to account for summer 2003. To test this proposal, possible future European climate was simulated with a regional climate model in a scenario with increased atmospheric greenhouse- gas concentrations, with the result that temperature variability might increase by up to 100%, with maximum changes in central and Eastern Europe.

1. Scenarios, global

Which greenhouse gas emission scenarios are formulated by IPCC in SRES?
-The emission scenarios given by IPCC (2000b), which are commonly used in many climate models as (external) forcing factor, are fully described by Nakicenovic *et al.* (2000): the 'Special Report on Emission Scenarios' (SRES). These scenarios comprise 4 scenario "families" (A1, A2, B1, B2) with the A1 family containing three different groups (A1FI, A1T, A1B). The A1 family assumes a future world of rapid economic growth, a global population that reaches its maximum in the mid-century, and a rapid introduction of more efficient technologies. The A2 family assumes a heterogeneous world, where economic growth and technological achievements are slower than for the other scenarios. The B1 family assumes a world with the same population development as for A1, but with a rapid change in economic structures, and with the introduction of clean and resource efficient technologies, while the B2 scenario family describes a world with an intermediate rate of economic growth, and a less rapid technological change than in A1 and B1, oriented towards environmental protection and social equity on the local and regional levels. In fact, for each scenario family several different scenarios are developed so as to encompass the current range of uncertainties of future greenhouse gas (GHG) emissions, resulting in a total of 40 scenarios (for instance A1FI refers to fossil-fuel intensive use, A1T predominantly non-fossil fuel, and A1B 'balanced' use). Normally, however, only four illustrative "marker scenarios" are used as "driving scenarios" in e.g. climate model studies.

Which socio-economic and emission scenarios were formulated by IPCC 1992?
-Six alternative scenarios – IS92a to f – were published in the 1992 Supplementary Report to the IPCC second Assessment (Leggett, Pepper *et al.*, 1992). These scenarios, like the above-mentioned SRES scenarios, encompass a wide spectrum of assumptions on how future greenhouse gas emissions might evolve. Especially IS92a has been widely used previously as the emission scenario in many impact assessments or future climate change simulations. In brief, IS92a (sometimes referred to as a "business-as-usual"- scenario) assumes a 1 % per year increase in CO_2-equivalents (from 1990 onwards), implying a more rapid rise in atmospheric GHG concentrations than for example the A2 or B2-scenarios

What climate change projections are given for central agricultural regions?
-In a study of the impact of global warming on soil moisture, based on predictions of 15 global climate models, Wang (2005) compared the after-stabilization climate in response to the emission scenario SRES A1B with the pre-industrial climate. The models were consistent in predicting summer dryness and winter wetness in only part of the northern middle and high latitudes. The models were especially consistent in predicting drier soils over south-western North America, Central America, the Mediterranean, Australia, and South Africa during all seasons. Over some of these regions, the dryness will be due to both a decrease in precipitation and an increase in evaporation, while in others, however, precipitation is predicted to increase slightly and the drought will primarily be due to enhanced evaporation. The author suggests that the anticipated future warming will cause a worldwide agricultural drought, because the only major areas of future wetness predicted with a high level of model consistency are parts of the northern, middle and high latitudes, and then for the non-growing season.

What climate changes are expected in Europe?

-In a survey by Maracchi *et al.* (2005) a set of future climate scenarios for Europe (mainly derived from modelling by GCMs; see Hulme and Carter, 2000) are quoted: Annual temperatures over Europe warm at a rate of between 0.1 and 0.4 K per decade. This warming is greatest over southern Europe and northeast Europe (Finland, western Russia), and least along the Atlantic coastline. Seasonal patterns indicate that in winter, the continental interior of Eastern Europe and western Russia warm more rapidly than elsewhere.

-The general pattern of future change in precipitation is for widespread increases in northern Europe (between +1 and +2% per decade) and rather smaller decreases across southern Europe (maximum: -1% per decade), but it appears to be a marked contrast in the patterns between winter and summer: Most of Europe gets wetter in the winter season (by +1 to +4% per decade), whereas in summer, there is a strong gradient between northern Europe (with an increase of up to +2% per decade) and southern Europe (with drying of up to –5% per decade).

-Contrasting climate change scenarios were studied for different sectors in society, including a *rapid* or *abrupt* climate change in Europe (Report from Tyndall Centre for Climate Change Research; Arnell *et al.,* 2005). Whereas many studies concern a future *gradual* climate change, there have been no published quantitative studies of the effect of an *accelerated* climate change or thermohaline circulation collapse in the North Atlantic on agricultural productivity. An initial assessment of the implications of three different types of abrupt climatic change (i) a thermohaline collapse, (ii) an accelerated climatic change, due to a positive feedback by the additional release of greenhouse gases from thawing permafrost areas and the oceans, and (iii) a rapid rise in sea level resulting from disintegration of the West Antarctic ice sheet) was therefore made (for impact results of this study see "4. Crop productivity" in this report).

What will happen to climate variability? Will heat waves become more frequent in the future?

-Meehl and Tebaldi (2004) reports that present-day heat waves over Europe and North America coincide with a specific atmospheric circulation pattern that is intensified by ongoing increases in greenhouse gases, indicating that it will produce more severe heat waves in those regions in the future. Global coupled climate model shows that there is a distinct geographic pattern of future changes in heat waves. Model results associated with the severe heat waves in Chicago in 1995 and Paris in 2003, show that future heat waves in these areas will become more intense, more frequent, and longer lasting in the second half of the 21st century.

- Vidale *et al.* 2006 (see also Schär et al. (2004) and the PRUDENCE project) studied European summer climate variability in the time period 2071-2100 compared with the control period 1961-1990 as simulated by a number of different GCMs and RCMs in a multi-model ensemble experiment. The experiment analyses results from the PRUDENCE project and includes simulation results from 3 GCMs and 9 RCMs – mostly using Hadley Centre data and the SRES A2 scenario – over a large-scale Central European area also including most of Scandinavia. For the summer, there was a rather dramatic shift to warmer and drier conditions, especially in the southern parts of Europe. In winter, there was an increase in precipitation in Central Europe, and a pronounced warming in the continental north-eastern parts of the continent. There was also indication of an increase in the variability in summer mean temperatures (between 20 and 80 % increase of the standard deviation) for Central Europe. While all models agreed in such an increase in variability, there was a disagreement regarding the amplitude and the geographical distribution. One of the key results was that the soil moisture reservoirs by 2071-2100 are accessed earlier during the spring, resulting in peak summer water deficit.

-Barnett *et al.* (2006) used a large ensemble of GCM simulations to study, primarily, the uncertainty (see also under 'Uncertainties') in the occurrence of extreme temperature and precipitation events in response to a doubling of atmospheric carbon dioxide concentration [CO_2]. Changes in extremes are quantified by calculating the frequency of exceeding of a fixed threshold. Large increases in the frequency of extremely warm days are simulated in the 2 x [CO_2] case. For example, the global ensemble-mean of the relative frequency of extremely warm days (when the extreme threshold was defined as the 99th percentile of the "present" (1x [CO_2]) distribution) was found to be 20 in January and 28 in July (i.e. extreme events would become 20 and 28 times more frequent, respectively). In July, the largest increases were found over the western parts of US, much of southern Europe, northern Africa and in some other regions. They also found that simulated increases in the frequency of extremely warm or wet seasons under 2 x [CO_2] are almost everywhere greater than the corresponding increase in daily extremes.

-Ruosteenoja *et al.* (2007) present seasonal GCM-based temperature and precipitation projections for the end of the 21st century for five European regions, one of which encompassing the Nordic region, and also compare these projections with corresponding estimates given by nine different RCMs within the EU project PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects). 95 % probability intervals were calculated for regional temperature and precipitation change to 2070-2099 from 1961-1990 for four forcing scenarios: A1FI, A2, B2 and B1. For the high-end of the A1FI uncertainty interval, temperature increases up to more than 6 ^{o}C in summer and close to 10 ^{o}C in winter are projected for the northern European region, whereas at the low-end of the B1 interval, the corresponding values are ~1 °C in summer and ~ 2.5 °C in winter. For the southern European summer, the high-end value of A1FI is close to 10 °C, and the low-end B1 value close to 1.5 °C. The uncertainty intervals of precipitation change were quite broad, but the mean projection show a marked increase during winter in the north, and a drastic decrease during summer in the south.

What changes in frost, snow and ice conditions for Europe might be expected?
- Jylhä *et al.* (2007) analysed changes in frost and snow in Europe by the period 2071-2100 from simulation experiments performed with seven regional climate models (RCMs) within the PRUDENCE project, but mostly run with the same driving GCM (HadAM3H) and emission scenario SRES A2. There was a distinct tendency towards fewer frost days and shorter frost seasons throughout Europe. The proportion of those frost days for which the diurnal temperature range crosses the freezing point will increase. The number of days with snow covers, and the average equivalent water content of the snow pack, will be notably smaller by the end of the century, the largest absolute changes occurring around the northern Baltic Sea. For the Baltic Sea-ice, a drastic decrease in annual maximum ice extent was projected. These results were consistent across all model simulations considered.

What might happen to the Atlantic meridional overturning circulation (MOC, Gulf Stream)?
-The Atlantic meridional overturning circulation (AMOC or MOC) is often also mentioned as the "Thermohaline circulation" (THC) or the "Conveyor belt". Rahmstorf (2000) gave a brief elucidative description of this circulation system, and its potential sensitivity to external disturbances in connection with anthropogenic climate change, in the review article: "The Thermohaline Ocean Circulation: A system with dangerous thresholds?"
- Broecker, W. (1997) gives an initiated description of how the today's ocean circulation functions, especially regarding the Atlantic MOC. He also discusses how the Earth's climate during the last glacial period underwent frequent large and abrupt global changes, and argues that this behaviour appears to reflect the ability of the ocean's thermohaline circulation to assume more than one mode of operation. The trigger mechanism for these reorganizations may have been associated with the orbital cycles of the Earth. Finally he discusses the possibility of future reorganizations of the THC as a consequence of the ongoing build-up of greenhouse gases in the atmosphere, and warns for the possible severe impacts on e.g. food production of such an event.
-Dickson *et al.* (2003) provides no convincing evidence of any significant, concerted slowdown in the Atlantic overturning circulation. However, the mechanisms remain poorly understood and our ability to detect these changes remains incomplete. They mention four main types of ocean change with greenhouse-gas forcing. These are: (i) a slowing of MOC overturning rate; (ii) changes in northern seas which might affect a change in Atlantic overturning, including changes in the freshwater flux from the Arctic, and changes in the transport and/or hydro-graphic character of the northern overflows which ventilate the deep Atlantic; (iii) a change in the trans-ocean gradients of steric height (both zonal and meridional) which might accompany a change in the MOC; and (iv) an intensification of the global water cycle.
-According to Latif *et al.* (2006) analyses of ocean observations and model simulations suggest that there have been considerable changes in the THC during the last century. These changes are likely to be the result of natural multi-decade climate variability and are driven by low-frequency variations of the North Atlantic Oscillation (NAO). According to the authors, no indications of a sustained weakening of the THC are seen during the last few decades. Instead, a strengthening since the 1980s has been observed. They claim that combined assessment of ocean hydro-graphic data and model results indicates that the expected anthropogenic weakening of the THC will remain within the range of natural variability during the next several decades.

Which factors might cause a sudden global cooling?
-Engvild (2003) listed a number of possible causes for a sudden global cooling: changes in the solar output, volcano eruptions, impacts of comet or asteroid collisions with the earth and changes in ocean currents. The present interglacial climate is probably maintained by the so-called "Thermohaline Conveyor" (TC, or "thermohaline circulation",THC) (Rahmstorf, 2002, Broecker, 1995, 1997, Stocker, 2000). One branch of this "conveyor belt" is the Gulf Stream; the other is a dense cold, high-salt water deep-ocean return flow. This total system of ocean currents seems to be quite sensitive to small disturbances, especially of fresh water influx (causing some climatologists to talk about "chaotic climate"). The review gives no quantitative estimates, however, of the risk for a collapse of the THC.
-In a paper by Stouffer *et al.* (2006) the simulated response of the THC to freshwater perturbations (and the associated climate changes) as simulated by a large number of models, ranging from earth system models of intermediate complexity (EMICs) to fully coupled general circulation models (AOGCMs), are inter-compared (within the frame of the World Climate Research Program (WCRP) Coupled Model Intercomparison Project

(CMIP)). In response to a 0.1-Sv (1 Sv = 106 m^3 s^{-1}) freshwater input in the northern North Atlantic (by comparison, the present-day strength of the THC, expressed in terms of the southward flow of North Atlantic deep water at latitude 30 °N, is estimated to be about 14-18 Sv) the multimodel ensemble mean THC weakens by 30 % after 100 years. All models simulated some weakening, but no model simulated a complete shutdown of the THC at this assumed external input. In response to 1.0-Sv freshwater input, however, the THC switches off rapidly in all model simulations, is resulting in a large cooling over the North Atlantic area. The models disagreed in terms of the reversibility of the THC after its shutdown.

What might be the effects of a collapse of the North Atlantic THC on vegetation and soil?
-Köhler *et al.* (2005) discuss results from simulations with the Lund-Potsdam-Jena dynamic global vegetation model (LPJ) forced with climate perturbations from glacial freshwater simulations with the ECBILT-CLIO (modules of the Earth system model LOVECLIM is discussed under “1. Methods” /EMICs in this report). The simulated North Atlantic THC collapses in response to a freshwater discharge linearly increasing to 0.5 Sv during a period of 500 years, then decreasing back to zero in the following 500 years, at which time the THC recovers again (1 Sv = 106 m^3 s^{-1}). The resulting initial cooling of several degrees C over Eurasia causes a reduction of boreal and temperate forests, and a decrease in carbon storage in high northern latitudes, whereas improved growing conditions and slower soil decomposition led to enhanced storage in mid-latitudes according to the simulations. However, the magnitude and evolution of the carbon storage changes were quite sensitive to the initial climate conditions, and varied between –67 and +50 PgC for a range of conditions during the past 21 thousand years simulated with the HadSM3 coupled model.

1. Scenarios, Nordic

How might temperature and precipitation change in Sweden?
-In a report from Swedish EPA and STEM (Naturvårdsverket/Energimyndigheten, 2004a, b) it is stated that according to the scenarios from SWECLIM from 2002 (SMHI, 2003b) the yearly mean temperature in Sweden will rise somewhat more than the average for the globe as a whole (with possible $\Delta T \approx +3\text{-}6$ °C during the next 100 years). This warming would imply a lengthening of the vegetation period in Sweden with 1-2 months. The calculated regional changes in precipitation and evaporation show considerable variations, both within the region and between the seasons. The increases both in precipitation (P) and in net precipitation (difference between precipitation and evaporation) are largest during the winter (with a calculated possible increase in precipitation by 30-60%). During the summer the precipitation may, on the other hand, decrease by 20-40% in the south of Sweden (as well as in Denmark and the south of Norway).

How will regional climate in Scandinavia change under a 2 ºC global warming?
- Christensen (2006) made a regional downscaling of a GCM-simulation corresponding to a 2 degrees warming relative to pre-industrial conditions. The background to this simulation experiment is the decision of the European Union to work towards limiting the anthropogenic induced global warming to just 2 °C. In the experiment, GCM transient simulations (with ECHAM5/MPI-OM; horizontal resolution 150 km) for the two time periods 1961-1990 (control) and 2071-2100, respectively, were downscaled to 50 km resolution – over an area enclosing Europe and the North Atlantic – with the regional climate model (RCM) HIRHAM. The simulation used the SRES A1B emission scenario until 2020, and thereafter kept the year 2020 concentrations of greenhouse gases constant (labelled the “EU2C” experiment). In winter, the largest warming – around 2-3 degrees – was found over Scandinavia and northern Russia, whereas southern Europe warms around 1 °C and the North Atlantic mostly below 1 degree. In summer, Southern Europe shows the largest heating of around 2-2.5 °C, whereas Northern Europe warms about 1-1.5 °C. The amplitude of the changes between the period 1961-1990 and 2071-2100 for the EU2C scenario was lower than for corresponding downscaling results for the A2 and B2 scenarios used for comparison. The precipitation and related indices appear to be much more uncertain, and did not scale with the choice of scenario to the same extent as in the case of temperature.

1. Uncertainties

How well can climate sensitivity be modelled based on paleo-climate data?
-Uncertainty in climate sensitivity is a main source of uncertainty in projections of future climate change according to Schneider von Deimling *et al.* (2006). They present a new approach for constraining this uncertainty by combining ensemble simulations of the last glacial maximum (LGM) with paleo-data. For this purpose the CLIMBER-2 climate model (cf. Appendix 1) was used to perform a large set of equilibrium runs for (1) pre-industrial boundary conditions, (2) doubled CO_2 concentration, and (3) a “complete set” of glacial forcing. Using proxy-data from the LGM the authors constrained the set of realistic model versions. They found,

that irrespective of model-parameter and feedback uncertainties, there was a close link, within the model, between the simulated warming due to doubled CO_2, and the cooling obtained for the LGM. Based on this close relationship regarding past and future temperature evolution, they argue that paleo-climatic data can help to reduce uncertainty in future projections. Their inferred range for climate sensitivity is 1.2-4.3 ºC, almost identical to the IPCC-2001 estimate (1.5-4.5 ºC).

What is the relative importance of different sources to uncertainty in CC scenarios?

-In an inter-comparison of a number of regional climate simulations for Europe (Déqué *et al.*, 2007) the PRUDENCE (the Prediction of Regional scenario and Uncertaities for Defining European Climate change risks and Effects project) database was used for estimating the relative importance of different sources to uncertainty in regional climate projections. Ten regional climate models (RCMs) have been run with the SRES A2 radiative forcing scenario, and some of these RCMs also with the SRES B2 scenario. Three different GCMs were used to provide the RCMs with lateral boundary conditions. The RCMs have been used to simulate the winter and summer mean seasonal temperature and precipitation, expressed as the difference between the periods 2071-2100 and1961-1990. The results are averaged over eight sub-domains of Europe. The uncertainties in the projected mean values are measured by the variance in each of the sub-domains. The total variances were decomposed into: V(R)- variance due to RCM, V(S) – due to scenario, V(G) – due to driving GCM, and V(M) – variance due to sampling of a finite number of years (30) from a climate system with a natural variability. Some conclusions: The uncertainty introduced due to the choice of GCM is in general the largest of the four sources considered, except for summer precipitation, where the choice of RCM (including inputs) is the major source for the European domain as a whole, and also for some of the sub-domains. The uncertainty due to choice of scenario is at maximum for summer temperature in the southern regions of Europe.

-Fowler *et al*. (2007b) used six RCM integrations from the PRUDENCE ensemble together with extreme value analysis to assess changes in extreme precipitation over Europe by 2070-2100 under the SRES A2 scenario, and for investigation of the uncertainties in the climate scenarios introduced by the driving GCM and the choice of RCM respectively. A key finding is, that all the RCMs project increases in the magnitude of short- and long-duration extreme precipitation, but that the individual model projections vary considerably. The magnitude of the changes is strongly influenced by the driving GCM but moderated by the RCM, which also influences spatial pattern. The authors therefore recommend, that when designating (model) ensemble experiments 1) the number of GCMs should at least equal the number of RCMs, and 2) if spatial pattern is important, then integrations from different RCMs should be incorporated (see also Fowler *et al*., 2007a).

How large are the uncertainties in the projections of future extreme weather events?

-Uncertainties in simulations of the occurrence of extreme events under a doubling of atmospheric CO_2 are explored by Barnett *et al*. (2006). In this paper, equilibrium changes in daily extreme near surface air temperatures and precipitation events were simulated in an ensemble of 53 versions of HadSM3 (HadAM3 coupled to an ocean model), are examined. Changes in extremes are quantified by calculating the frequency of exceeding a fixed threshold in the 2 x CO_2 simulation relative to the 1 x CO_2 simulation. The ensemble-mean of this relative frequency is considered as the best estimate of the expected change, while the range of values across the ensemble provides a measure of the associated uncertainty. Due to its design, the resulting uncertainty arises both from model uncertainty, and from inherent, natural, climate variability. For example, the global ensemble-mean of the relative frequency of extremely warm days (when the extreme threshold is defined as the 99th percentile of the "present" distribution) was found to be 28 in July (i.e. such extreme events would become ~28 times more frequent than today), but with considerable uncertainty in the magnitude of the increase. The ensemble range of changes in precipitation extremes was typically larger than in the case of temperature, indicating a greater uncertainty in the simulated precipitation changes.

-Fowler *et al*. (2007) assessed changes in precipitation extremes over Europe by 2070-2100 under the A2 emission scenario for investigating the contribution of the formulations of global (GCM) and regional (RCM) climate models to scenario uncertainty. A key result was that all RCMs projected increases in the magnitude of short- and long-duration extreme precipitation for most of Europe. However, individual model projections varied considerably, and the magnitude of change was strongly influenced by the driving GCM, but moderated by the RCM, which also influenced the spatial pattern.

What is the uncertainty of statistically downscaled precipitation projections in Sweden?

-When statistical downscaling is used to obtain regional climate change scenarios, the uncertainty originate from uncertainties in the global climate models (GCMs) used, the skill of the statistical model, which forcing scenario is used, and from the natural (internal) variability in the climate. The uncertainty associated with the GCMs used can be evaluated by examining the differences in the predictors and in the downscaled climate change scenarios with standardized simulations with a set of different GCMs. Chen *et al.*, (2006) applies this method to the estimation of GCM-related uncertainty in regional precipitation change scenarios for Sweden, using results from downscaling based on 17 GCMs. The results show an overall increase in annual precipitation over Sweden, although with a considerable spread in the simulated changes. The estimated uncertainty was nearly independent of region. However, there was a seasonal dependence, where the estimates for winter show the highest confidence, while the estimates for the summer season show the least.

Which factors might explain projected future summer drying over Europe?

-A common feature of many regional climate change scenarios is their anticipation of drier summers in large parts of Europe (see e.g. Giorgi *et al*, 2001). Rowell and Jones, (2006) propose a methodology that partitions some of the mechanisms of regional climate change, and apply it to the problem of the causes of this summer drying. They claim that a plausible partitioning of the working mechanisms of future mid-latitude continental summer drying might comprise the following parts: (a) an earlier and more rapid decline in soil moisture (SM) during spring ('Spring SM'), (b) conditions in the lower tropospheric warming leading to reduced relative humidity in the air, and hence reduced rainfall ('Warming'), (c) other large- scale atmospheric changes ('Large-scale'), and (d) a positive feedback due to the beginning dryness of soils, reducing the convective activity further ('Summer SM Feedback'). The authors attempt to assess their relative importance by using an appropriate mix of inputs to the model (HadAM3P). For continental and south-eastern Europe, it was found that both the 'Warming' and 'Spring SM' mechanisms are the primary drivers of the projected summer dryness, and 'Summer SM Feedback' played an important secondary role. The authors claim, that we have reasonable confidence in the processes of the two dominant mechanisms, and therefore also a high confidence in the sign of the anticipated summer drying over these regions. Over Great Britain and southern Scandinavia, however, their experiments indicated that the rainfall anomaly is dominated by opposing effects from the 'Warming' and 'Large-scale' mechanisms in this area. Due to this rivalry, even the sign of the projected change in this region is uncertain.

How well do precipitation predictions fit empirical data?

-Uncertainties in projected future European drought characteristics are also discussed by Blenkinsop and Fowler (2007). The skill of six regional climate models (or, rather, 4 different RCMs: HIRHAM, RCAO, HadRM3P and Arpège, which in combination with different GCMs providing the driving data makes a total of six) in reproducing the mean precipitation for the 1961-1990 period for six European catchment areas are compared. Some of the conclusions are: Considerable variation in model skill in reproducing monthly mean precipitation and drought statistics was observed (many model estimates falling significantly outside the 95 % confidence interval for the observed (grid-interpolated) 30-year means for smaller or greater parts of the year). In broad terms, the models indicate decreases in summer and increases in winter precipitation across Europe. On the regional scales required for impact analysis, however, considerable model uncertainty was demonstrated for future projections. For shorter-duration droughts, projections of future changes even "encompass the direction of change". It is suggested that probabilistic scenarios for specific hydrological impacts have a considerable potential to incorporate this uncertainty in climate change projections as to make them more informative for decision-makers.

Which are the expert evaluations of a future decrease of the "Gulf stream"?

-In a paper by Zickfeld *et al.* (2007) the results from detailed interviews with 12 climate scientists about the possible effects of global climate change on the Atlantic meridional overturning circulation (AMOC), which encompass the Gulf stream, are presented. The inquiery sought to examine the range of opinions within the climate research community about which physical processes that are determining the current strength of the AMOC, its future evolution under a CC and the potential consequences of possible changes in the AMOC. All experts anticipated a weakening of the AMOC under scenarios of increasing greenhouse gas concentrations. Assuming a global mean temperature increase to the year 2100 of 4 °C, eight experts assessed the probability of an AMOC collapse as significantly different from zero, three of them considered this risk as larger than 40 %. Their estimates of a weakening of the AMOC to the year 2100 in response to a 2x [CO_2] and a 4x [CO_2] of the atmospheric [CO_2], respectively, ranged from ~2 % to 55 % for the doubling, and from 10 to 90 % for the quadrupling scenario. This latter is much larger than the range of responses simulated by present climate models (10 to 50 %, see e.g. Gregory et al., 2005). Concerning the ability of these models to represent the physical processes relevant to the state of the AMOC, most experts considered some of these processes to be relatively well represented in the models, while some other, also relatively important, are less well understood and simulated.

How might the timing of a sudden reorganization of the North-Atlantic circulation depend on emission scenario?
-Schaeffer *et al.* (2002) used an ensemble climate-model experiment to explore the timing and nature of an abrupt regional climate change within the 21st century. In response to global warming a North-Atlantic climate transition occurs, which affects climate in north-western Europe. For a high IPCC emission scenario (SRES A1b) the transition was found to have a high probability to occur before 2100 (in fact, for the A1b scenario the transition occurs between 2040 and 2080 for all of the ten 'runs' in the ensemble), whereas in a lower emission scenario (SRES B1) the probability was lower and the transition threshold is approached more gradually. The authors found that close to the transition threshold the evolution of the system becomes sensitive to small perturbations. As a consequence, natural climate fluctuations limit the predictability of the timing of a threshold crossing, and thus of an abrupt climate change. This limited predictability of North-Atlantic climate change adds to the uncertainty in projections of ice-sheet melting and other impacts of global warming in this region. (The ocean general circulation model CLIO coupled with the ECBilt atmosphere model of 'intermediate complexity' was used for the simulations.)

What are the effects of uncertainties in GCM scenarios on climatic zones in southern Sweden?
-Metzger *et al.* (2005) made projections for European climatic zone classes, and a more detailed analysis of southern Sweden. In the baseline (1990) Skåne is Atlantic North, Halland south west Småland is Nemoral6, and north of that Nemoral3. In 2080, four different GCM models (for A1 emission scenario) gave quite different climate patterns. (i) NCAR PCM ('Parallel Climate Model') gave similar pattern of today except that Atlantic North moved north along the Halland and Blekinge coasts, moving Nemoral6 and Nemoral3 north accordingly. (ii) HAdCM3 gave Skåne similar of today and north of that almost only Nemoral6 (high temperature increase and increased winter but decreased summer precipitation). (iii) CSIRO2 gave Atlantic North moving north to a line Göteborg-Kalmar, north of that Boreal (related to increased spring precipitation). But there were also patches of Nemoral6 and 5, and Continental in Småland. (iv) CGCM2 gave Atlantic Central in Skåne and Blekinge and patches of east Småland, Continental in east Småland, Nemoral6 in west Småland and Halland.

How important is it to have high resolution CC information?
-A spatial resolution of 1° x 1° of soils and climatic data was found optimal for simulation of wheat and maize production on the Great Plains of America (Easterling *et al.,* 1998).
-Easterling *et al.* (2001) have studied the effect of resolution of climatic input data used in simulating global change impacts on yield. They simulated "adaptation" in terms of using earlier planting date and late maturing varieties of various crops in USA. They conclude that more decisive results are obtained with high-resolution data. However, they are not convinced "that the use of high resolution climatic change information provides insight into the direct effects of higher atmospheric CO_2 levels on crops beyond what can be obtained with low resolution".

1. Physical parameters

What determines predictions of frost days?
-Meehl *et al.* (2004) found that the numbers of frost days are most consistently related to sea level pressure, with more frost days occurring when high pressure dominates on the monthly time scale in association with clearer skies and lower night time minimum temperatures. They pointed out that the regional changes of frost days are generally most influenced by changes in regional atmospheric circulation. There is a general decrease in the number of frost days with global warming. Soil moisture, clouds, sea level pressure, and diurnal temperature range have effects that were quantified by a statistical multiple regression model. Coefficients for present and future climate are similar among the predictors, indicating that the physical processes that affect frost days in present and future climates do not appreciably change. Only the intercept changes, in association with the significant warming of the mean climate state.

1. Spatial patterns

How will the climatic zones of Sweden be changed by 2080?
-Metzger *et al.* (2005) made projections for Europe climatic zone classes (Environmental stratification of Europe, EnS) until 2080. For Sweden today (1990) south Skåne is classified as Atlantic North, Öland and Gotland as continental, and the rest of Götaland and Sveland (except Värmland and Dalarna) as Nemoral, and north of that Boreal. By 2020 (CGCM2 –A1 models and inputs) the only change is that Blekinge and Kalmar region partly has become Continental. By 2050 Skåne and most of Småland also have become Continental (no Atlantic North zones are available). The Nemoral zone has moved northward accordingly to include also

Värmland, Dalarna and parts of Hälsingland. By 2080 the picture has become complex. Skåne and Blekinge has become Atlantic Central. East Småland and Gotland Continental. The rest of Götaland, Värmland and south Svealand Nemoral. Uppland, Västmanland, Dalarna, Gästrikland, Hälsingland Atlantic North. North of that, Boreal.

2. Climate and agricultural patterns

There are relations between regional agriculture and climate, in Sweden. Regional agriculture, however, is only partly a consequence of climate. Of this reason the patterns can probably not been used straightforward to extrapolate changes in climatic zones to give corresponding changes in agricultural zones. However, to a certain extent these patterns might be useful. The aim of this section is to present information likely to be useful to evaluate to what extent present patterns and changes in the past are general, and possibly useful for assessments of climate change impact on agricultural production and land use in Sweden in the future.

2. Climate patterns

Which climate region classification methods exist for Europe?

-Metzger *et al.* (2005) classified the whole of Europe into climatic zone classes (Environmental stratification of Europe, EnS) by comparing combinations of a number of climate variables for different regions (1 km^2 resolution). They used a PCA ('principal component analysis') model based on altitude, slope, latitude, oceanicity, temperature, precipitation and sunshine to assign a certain climatic zone class to each region. Outputs of the first principal component of the PCA model correlated best with annual mean temperature and length of vegetation period, R^2 being 0.95 and 0.83, respectively, taken from another European dataset (MARS). Altogether, the three principal components accounted for 88% of the variability in the total data set. They used ISODATA (Iterative Self-Organizing Data Analysis Technique) to assign an environmental classification to the continent according to the outputs of the PCA model. 84 environmental strata ('classes') were achieved and aggregated to 13 'Environmental zones'.

2. Agricultural patterns

Along which principles may an agroclimatic zonation of the Nordic countries be done?

-A principal discussion of possible methods to be used in agroclimatic mapping for the Nordic countries is presented in a 'working-group report' by Skjelvåg *et al.*(1992). The report also gives a comprehensive summary of the prevailing climatic conditions in the Nordic countries regarding the most relevant climate parameters in this context (e.g. solar radiation, temperature climate (incl. temperature-sum indices) and water supply) but also concerning questions like weather imposed pests and diseases, over-wintering, phenological development etc., and the praxis utilized in climate mapping at that time.

Which are the vegetation zones of Sweden?

-On a continental scale Sweden covers six vegetation zones, classified according to the dominant tree species: Alpine-, Northern boreal-, Middle boreal-, Southern boreal-, Boreonemoral- and Nemoral zone (National atlas of Sweden, Geography of plants, 1996, p 27.(Limes Norrlandicus). These zones have been predicted not to shift significantly in response to climate change (Bengtsson, 1994).

- As a finer pattern within this broader scale and as a base for the Regional Experimental Service in the agricultural sector, Sweden has in the past been divided into 9 regions (Fig, Larsson, 2004).

Which cultivation region classifications exist in Sweden?

Which are the regions of the Swedish regional yield statistics (SCB)?

-SCB (Statistics of Sweden) divides Swedish agricultural area into 8 production areas for the yearly yield statistics of different crops (Fig. 2.1). These eight areas are based on 18 minor production areas, which in turn originally were formed from 61 "natural agricultural areas" (jordbruksområden) (SCB/Jordbruksverket 2005). The borders of these areas have changed several times during the past century, but the numbers of different areas have remained unchanged (i.e. 8, 18, and 61) until year 2000.

On which criteria are borders of SCB regions established?

-The criteria used when establishing the SCB regions are a combination of natural growing conditions (including e.g. climate) and practical - administrative reasons (Larsson, 2004). In comparison with another regional classification system used by the Regional Experimental Service in Sweden (data published in "Sortval") it seems that the SCB regions are somewhat more adapted to the natural conditions than to administrative regions (Larsson, 2004).

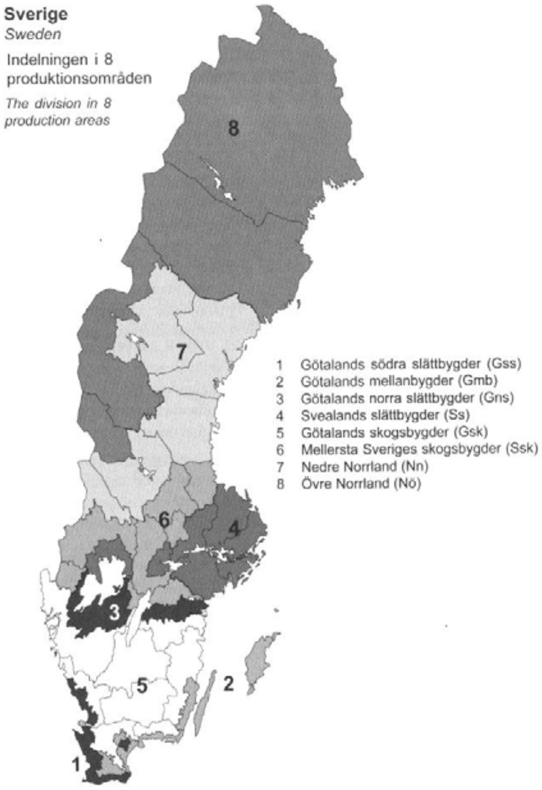


Fig. 2.1a. Agricultural production areas of Sweden used presenting regional yield statistics (source SCB).

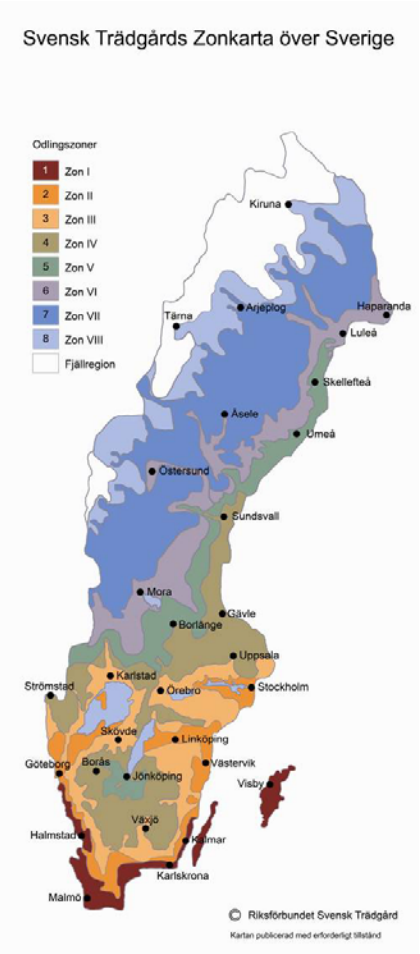


Fig. 2.1b. Growing zones for garden plants published by Riksförbundet Svensk Trädgård (source: http://www.tradgard.org/)

Which are the regions of Regional Experimental Service in Sweden?

-The Regional Experimental Service divides Sweden into 9 major crop production zones (A- I), described (including a map) in Lantbrukshögskolan, 1967: "Planer för Hushållningssällskapens…" (see also Larsson, 2004). These 9 show a rather high correspondence with the 8 SCB regions (see HSF-67 in Table 2.1)

Which are the regions of gardening in Sweden?

-For garden plants, especially lignified plants like fruit trees and bushes, Sweden is divided into 8 growing zones ("odlingszoner" or "växtzoner"), widely used, and published by Riksförbundet Svensk Trädgård, originally established by "Sveriges Pomologiska Förening" (http://www.tradgard.org/). This zonal division is based on climatic data and knowledge about the climatic hardiness by, primarily, ligneous garden plants. These 8 zones correspond to a certain extent, and sometimes coincide with the 8 production areas used by SCB (see Fig. 2.1b and RST in Table 2.1)

How are the different Swedish cultivation regions related?

Table 2.1. *Cultivation regions for agricultural production, agricultural experimental service, garden plans and forest in Sweden. In the table is given the parts of other classifications that fit into the SCB areas.*

Agricultural production area: **SCB ("produktionsområden”)**	Regional Experim. Service HSF-67 ("jordbruksområden")	Garden plants RST (”växtzoner”)	Forest regions SNA:"Skogen" ("klimatzoner")
1: Götalands södra slättbygder (Gss)	A	I	8
2: Götalands mellan-bygder (Gmb)	B (mainly) + A (small part)	I	7 (mainly), 8
3: Götalands norra slättbygder (Gns)	D (~50% of prod.area 3) + E (~50%)	II (~50%) + III (~50%)	6 (western part of Gns), 5 (eastern part of Gns)
4: Svealands slättbygder (Ss)	mainly F + E (smaller area)	III (60-65%) + IV (35-40%)	5 (mainly), 6 (N Vänern)
5: Götalands skogsbygder (Gsk)	C (~80-85%), small areas in zone D and E (<10% each)	IV + V (~60%), II + III (~40%)	8 + 7 + 5 (approx. equal parts)
6: Mellersta Sveriges skogsbygder (Ssk)	G (80-85%), F (15-20%)	IV + V	3 (the major, nothern, part) minor areas in 4, 6, 7
7: Nedre Norrland (Nn)	I (~50%) + G (~30%) + H (~20%)	VI + VII (major part), IV (along the coast)	3 (major part), 4 (along the coast), 2 (area in NW)
8: Övre Norrland (Nö)	I	VII (major part), V, VIII	1 (major part in W and NW), 2 (central part of area), 4 (along the coast)

2. Agricultural and climate patterns

Which climate factors limit production?

Which climate factors limit production in Northern Sweden and Finland?

-Low solar angle, low temperature, short growing season, frosts in the growing season, long winters and thick snow cover are the main constraints to crop production in Finland (and Northern Sweden) between the 600 and 1200 degrees sum C isopleths above +5 ^{o}C. In Finland the growing season varies from 180 days (60 ^{o}N) to 120 days (70 ^{o}N). The most advanced agriculture in northern areas has more than 1200 degreessum (ºC) above +5 ^{o}C. North of that limit animal production becomes more common than grain production (Mela 1996).

-Reilly *et al.* (2003) found that non-climatic forces have likely dominated the north and westward movement of crops in US.

How important is water as a production-limiting factor?

-A model was developed and tested to describe in particular the water and radiation-use efficiency relations in production (Richter *et al.*, 2001). This model was then applied to analyse sugar beet production 1961-95 in Europe, where irrigation is uncommon. Drought losses were greatest in the east (Ukraine, southern Russia, 40% of potential yield), intermediate (15-30%) in central Ukraine, Poland, East Germany and sandy soils in England, and lowest in NW Europe and west Ukraine (Pidgeon *et al.*, 2001). Model output was used to examine the efficiency of beet production: NW European farmers deliver 80% of potential production, Polish farmers only 40%.

How could climate and agricultural patterns be related?

Which techniques are used to spatially relate agriculture to climate?

-Using a clustering technique and hydrothermal and simulated crop yield data on a 10 km x 10 km grid, three to seven agricultural regions were defined in Ireland (Holden and Brereton, 2004).

-Xiao and Moody (2004) correlated a normalized vegetation index, integrated over the growing season, (gNDVI) with mean precipitation, maximum temperature (T-max) and minimum temperature (T-min) over 11 years for six biomes in the US. Within- and across- biome variance of means of gNDVI was correlated with spatial gradients in long-term average seasonal climate. This gave relations between seasonal precipitation and temperature regimes and productivity.

Which climate factors correlate with regional production?

-Bakker *et al.* (2005) found that wheat yield in central and southern Europe correlated strongly with several climatic factors separately. There was strong negative correlation to solar radiation (-0.92 to –0.88; Pearsson coefficient), air temperature (-0.79 to –0.53), potential evapotranspiration (-0.87 to –0.72), respectively. There was a positive correlation to soil water available to plants (0.64 to 0.74), and also to soil depth (0.71 to 0.83).

May the classification of climatic regions be better adapted to agriculture?
-A more process oriented analyses of climatic production conditions has been done with various growth indices, e.g. Fitzpatric and Nix (1970).
-Apart from the preliminary reports of Torssell (1984) and Kornher and Torssell (1983) this technique has been little used in Sweden. It was shown that the high summer growth index for Lund in the south and Vojakalla above the Artic Circle were equal, and that the difference between these sites was the length of the growing season.
-There is for Sweden empirical knowledge of the relations between climate, weather and crop production (Osvald, 1959).

Which are the climatic characteristics of the SCB regions?
-In Table 2.2a an attempt is made to characterise the climatic conditions of the 8 major production areas used by SCB (Data sources: (a): SNA, 1990, (b): SNA, 1991, (c): SNA, 1995, (d): Ångström, A., 1974).

Table 2.2a: *Ranges of climate variables within agricultural production regions in Sweden*

SCB production area	**Global radiation April- Sept. [MJ/m^2] (d)**	**Sunshine hours/year (b,c)**	**Yearly average temp. [°C] (b)**	**T-sum during vegetation period [ddgr[1]>5 °C] (b)**
1 Götalands södra slättbygder	2930 -3145	1800 – 2000	+7 - +8	1600 – 1800
2 Götalands mellanbygder	2930 -3350	1800 – 2000 (Gotland>2000)	+7 - +8 (south) +6 - +7(Gotland)	1400 – 1600
3 Götalands norra slättbygder	2930 –3145	1800 – 2000 (minor area <1800)	+6 - +7 (domin) +5 - +6 (minor area)	1400 – 1600
4 Svealands slättbygder	2930 –3150	1800 – 2000 (minor area >2000)	+5 - +7 (+5-6 dominates)	1400 –1600 (~70%) 1200 –1400 (~30%)
5 Götalands skogsbygder	2720 –3140	1600 – 1800 (perif. area >1800)	+5 - +7 (+4 – 5 minor area)	1200 –1400 (1400-1600 minor area along coast)
6 Svealands skogsbygder	2850 –3140	1800 – 2000	+3 - +5	1200 –1400 1000-1200 (≤25%)
7 Nedre Norrland	2725 –3140	1600-1800(~40%)[2], 1800-2000(~40%)[2]	+1 - +4,	1000 –1200 (~50% of area)
	(typically ~2930)	>2000 (coastal area)	+4 - +5 (minor coastal area)	800 –1000 (~50% of area)
8 Övre Norrland	2510 –3145 (dom. 2725-2975)	<1600 - >2000	-3 - +2, (+2 - +3 minor coastal area)	600 – 1000, 1000 – 1200 (minor coastal zone)

[1] ddgr = daydegrees

[2] % of actual SCB prod. area given in left column

How does radiation differ between SCB regions?
-One striking pattern in Table 2.2a is that the differences in solar radiation (April to September) and sunshine hours (all year) are very small. Thus, average solar radiation sum of SCB area 8 (upper Norrland), excluding the most mountainous regions in the eastern part, is about 91-95% of southern areas 1, 2, 3 or 4. The total number of sunshine hours is similar (1800-2000) in the dominating parts of SCB areas 1-4, 6 and for about 40% of areas 7 and 8. Area 5, the hilly forest districts in Götaland (Götalands skogsbygder), has about the same conditions in this respect as area 7, the southern parts of Norrland (nedre Norrland).
How does temperature differ between SCB regions?
-The *yearly average temperature* of the three production areas 1-3 in the south are fairly similar (+6 to +8 °C; [SNA, 1991]). The areas 4 and 5 are also fairly similar but about 1 °C colder (i.e. +5 - +7 °C), than regions 1-3. For the remaining three areas, 6,7 and 8, temperature decreases gradually from +3 - +5 °C to about –3 - +2 °C going from south (area 6) to north (area8).
-There is a pronounced decrease in *temperature sum* of about 800 – 1000 day-degrees (Tbase +5 °C) from production area 1 in the south to area 8 in the north. However, the production areas 2 and 3 and most of 4 have about the same T-sum (1400 – 1600 ddgr), and T-sum of regions 5 and 6 and a minor part of region 4 is also similar (1200 – 1400 ddgr). Finally, a minor coastal zone of area 8 has an equally high T-sum as those parts of area 6 with lowest values (1000 – 1200 ddgr).

How does length of vegetation period differ between SCB regions?

-The length of the vegetation period is often defined as the (continuous) period of the year when the daily average temperature exceeds +5 ºC (SNA, 1995, p.57). However, some authors, i.e. Ångström, 1974, use the temperature threshold +3 º. Thus, the length of vegetation period, roughly, shows the same pattern as for the temperature. Some parts of area 8 in the upper parts of Norrland thus have a vegetation period almost three months shorter than region 1, whereas it is similar for temperature areas 2 and 3, and regions 4 and 5, respectively. However, areas 5 and 6 are not so similar, as in the case of the T-sum.

Table 2.2b. *Ranges of climate variables within agricultural production regions in Sweden*

SCB production area	**Beginning of vegetation period [date] (a)**	**Length of veget. period [days] (c)**	**Precipitation during veget. period [mm] (b)**	**Average number of days with snow cover (d,c)**
1: Götalands södra slättbygder (Gss)	31/3 – 10/4	200 – 220	Appr. range: 400 – 650, typ. 450/500	<40 – 60
2: Götalands mellan-bygder (Gmb)	31/3 – 20/4	190 – 210	Range: ~300 – 450, typical: 350/400	40 – 80
3: Götalands norra slättbygder (Gns)	5/4 – 15/4	190 – 200	Range: 400 – 550, typical: 450/500	60 – 100, typical: 80-100
4: Svealands slättbygder (Ss)	10/4 – 20/4	180 – 195	Range: 350 – 450	60 – 140, typical: 100-110
5: Götalands skogsbygder (Gsk)	5/4 – 20/4	≤190 – 200	Range: 400 – 750, typical: 450/500	40 – 120, typical: ~80-100
6: Mellersta Sveriges skogsbygder (Ssk)	10/4 – 25/4	~170 – 190	Range: 350 – 550, typical: 400/450	80 – 160, typical: 120-140
7: Nedre Norrland (Nn)	~20/4 – 10/5	140 – 175	Range: 350 – 500, typical: 400/450	120 – 200, typical: ~150-170
8: Övre Norrland (Nö)	30/4 – 20/5	<120 – 160	Range: 250 – 400, typical: 300/350	160 – 240, 140 – 180 in coastal reg.

(Data sources: a) – d) as for the table above)

How does snow cover differ between SCB regions?

-The average number of days per year with snow-cover increase from less than 40 days in area 1 to 6 to 8 months per year, in area 8.

How does precipitation differ between SCB regions?

-The average seasonal (vegetation) precipitation ranges from about 750 mm as most in parts of area 5, down to 250 – 400 mm in area 8. However, comparing typical values for different regions some of the areas are similar. Typical seasonal precipitation within areas 1, 3 and 5 are similar (450-500 mm). For areas 6 and 7 the typical values are 50 mm less (400-450 mm), and for areas 2 and 4, a further 50 mm less (350-400/450).

How are agricultural and forest regions of Sweden related to climate regions?

Which are the regions of forest climatic zones in Sweden?

-SNA (1990, Skogen, B28, p.49) divides Sweden into 8 forest zones as concerns effects of climate on forests. The characteristic of a region is mainly based on accumulated temperature sum (base temperature 5°C), and humidity (Table 2.3; see also Table 2.1 in (Zonjämförelse – SNA/Skogen).

Table 2.3. *Climate characteristica of forest regions in Sweden.*

Zone	**Region**	**Character**	**Criteria Tsum in day-degrees**
8	Western part of Götaland	Favourable to very favourable temp. climate. Mainly high to very high humidity	T-sum >1300
7	Central parts of the highlands of southern Sweden	Medium good to favourable temp. climate. Weak to normal humidity	T-sum 1100 – 1500
6	A zone around lake Vänern	Favourable to very favourable temperature climate. weakly humid climate	T-sum >1300
5	Eastern parts of Götaland and Svealand	Favourable to very favourable temperature climate. Summer dry and weakly humid climate	T-sum >1300
4	40-60 km broad zone along the coast of Norrland	Summer dry and weakly humid climate	T-sum >900
3	Central parts of southern Norrland and the part of Svealand north of *Limes Norrlandicus*	Relatively cold – medium good temp.	T-sum 900- ca 1300
2	Inner parts of Norrland and north-western parts of Svealand	Cold temperature	T-sum 750 – 900
1	Western half of upper Norrland	Extremely cold	T-sum <750

How do climatic zones correlate with land use?

-Metzger *et al.* (2005) classified Europe into environmental classes using a PCA model based on altitude, slope, latitude, oceanicity, temperature, precipitation and sunshine to assign a certain climatic zone class to each region (1 km^2). Outputs of the first principal component of the PCA model correlated fairly well with production of "potential" natural vegetation (R^2=0.85 Pearsson coefficient=0.92) but less good with land use patterns zones (R^2 = 0.23-0.34, P=0.45; data from PELCOM (Mücher *et al.* 2001) and CORINE databases), indicating a strong influence of the human factor in land use.

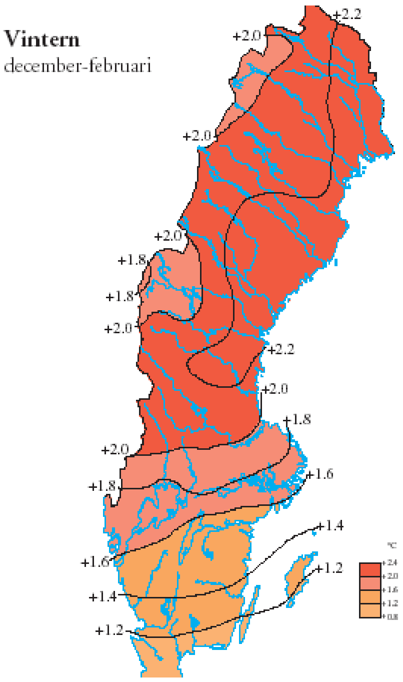
2. Changes over time

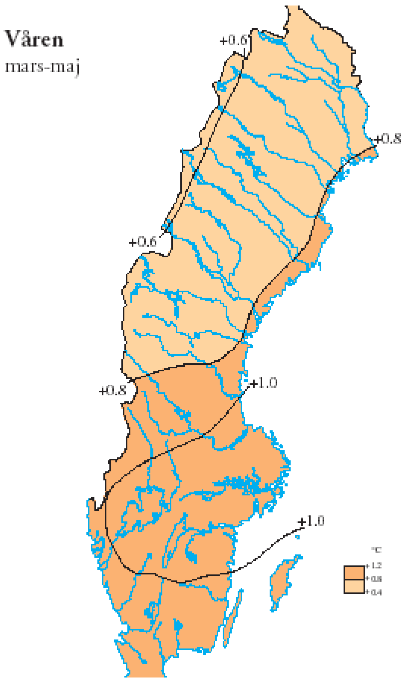
How has climate changed over a recent decade in US?

-Xiao and Moody (2004) correlated a normalized vegetation index, integrated over the growing season (gNDVI) with mean precipitation, maximum temperature (T-max) and minimum temperature (T-min) over 11 years for six biomes in US. According to IPCC increases in temperature minima and fall precipitation have been dominant contributing components of US increases in temperature and precipitation, respectively.

How has climate changed in Sweden since the reference period 1961-90?

-SMHI, 2006, has presented changes in temperature and precipitation for the last 15-year period (1991-2005) compared to the reference 30-year period (1961-90). Temperature has generally increased, from most in winter and along the coast of Norrland, to least in southern Sweden during autumn (Figs. 2.2a-b). Corresponding comparison for precipitation shows also a general increase except for autumn which show small changes. During winter precipitation has increased most in south-west and north-west parts of Sweden. During summer there has been a pronounced increase inland in Norrland, but also in Götaland (Figs 2.3 a-b).





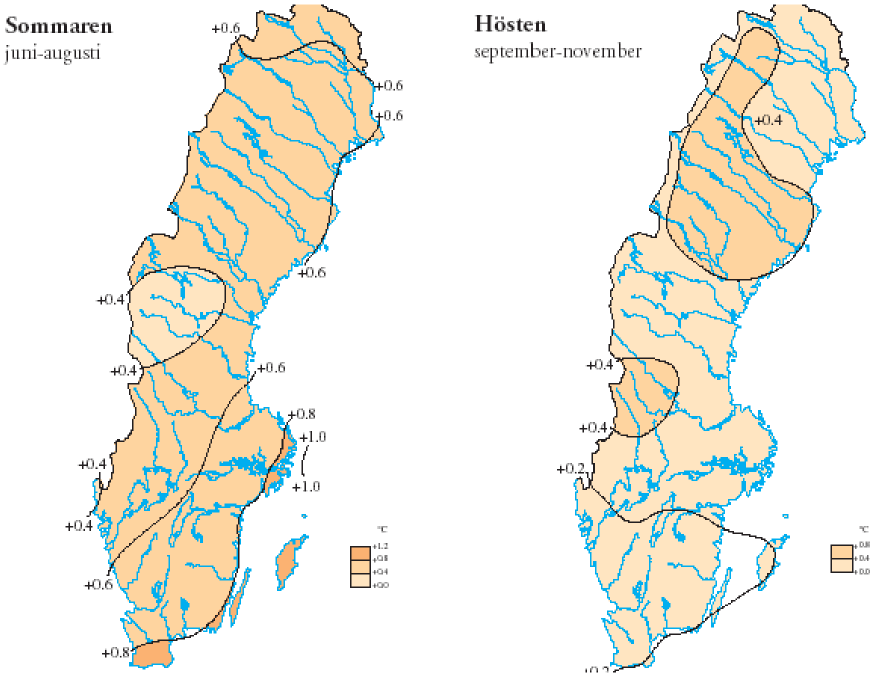
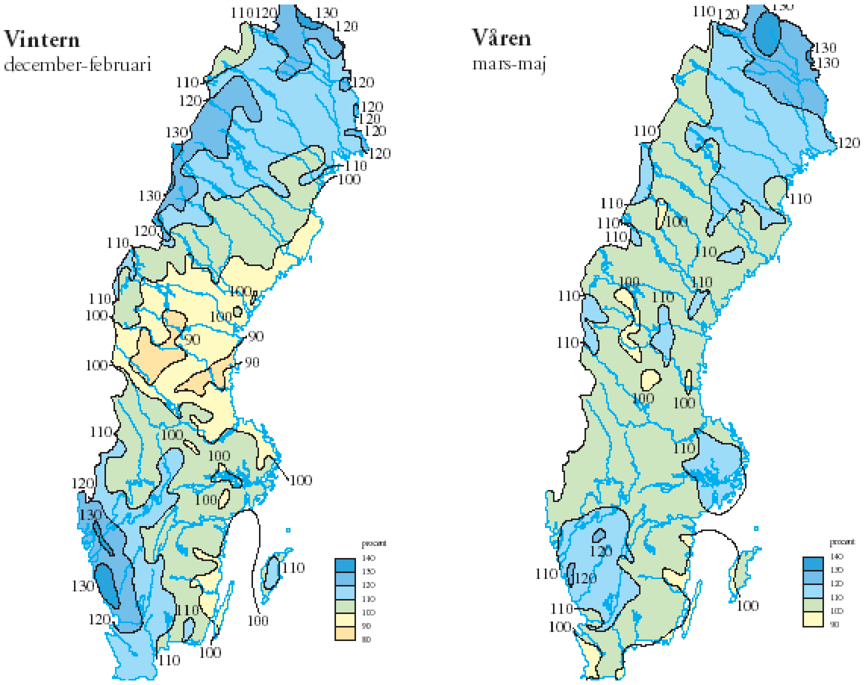


Fig. 2.2a and b. Changes in seasonal temperature for the last 15-year period (1991-2005) compared to the reference 30-year period (1961-90) for periods winter (December to February), spring (March to May), summer (June to August), and autumn (September to November), respectively (source SMHI, 2006; http://www.smhi.se/).



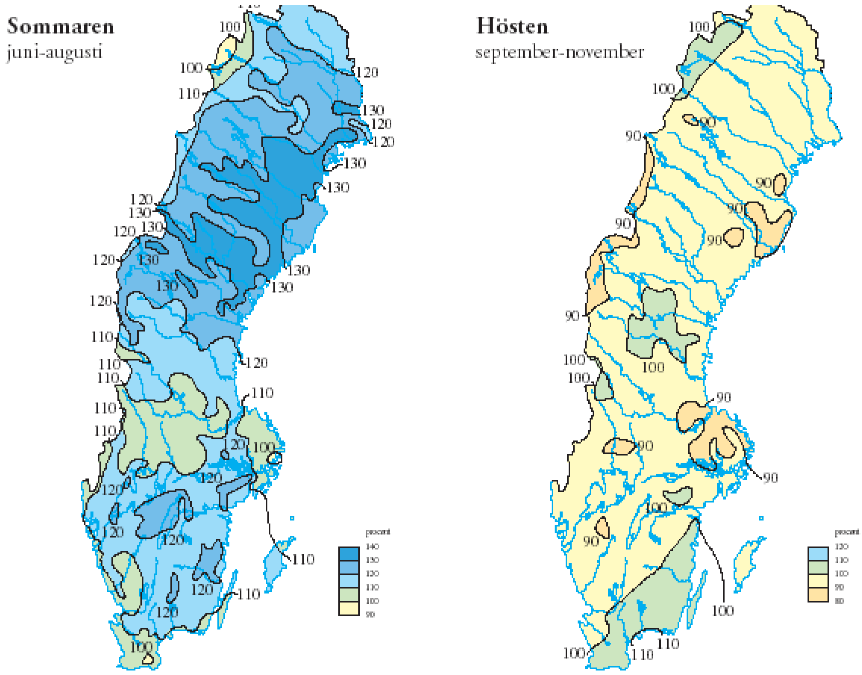


Fig. 2.3a and b. Changes in seasonal precipitation for the last 15-year period (1991-2005) compared to the reference 30-year period (1961-90) for periods winter (December to February), spring (March to May), summer (June to August), and autumn (September to November), respectively (source SMHI, 2006; http://www.smhi.se/).

Which crop yield data are available for Sweden?

-There are basically three sources of data for studies of time series in Swedish crop production: SCB, the variety trials in the plant breeding institutions and long-term field trials conducted by the Regional experimental Program. The SCB data describes time series of commercial crop production including the combined effects of several management and genetic factors at a time. The possibilities for analysing climate effects are limited. In the variety trials, long time series may be found, where only the weather and pest damages are the external factors that are varying over time. There are few Swedish studies of such data sets. One such is Torssell (1953) where the genotypic and phenotypic plasticity of different varieties were examined and discussed in relation to the growing value of the varieties.

How have yield levels developed in Sweden?

How have hectare yields developed since 1960 in Sweden?

-Hectare yield of cereals in Swedish agriculture (SCB) have shown a linear increase since 1950. There has been stagnation during the last 5-10 years. This trend is more pronounced in Svealand than in Götaland. Annual increases of winter wheat are 83-86 kg/ha (Fogelfors ed., 2001; see also Figs. 2.4-7).

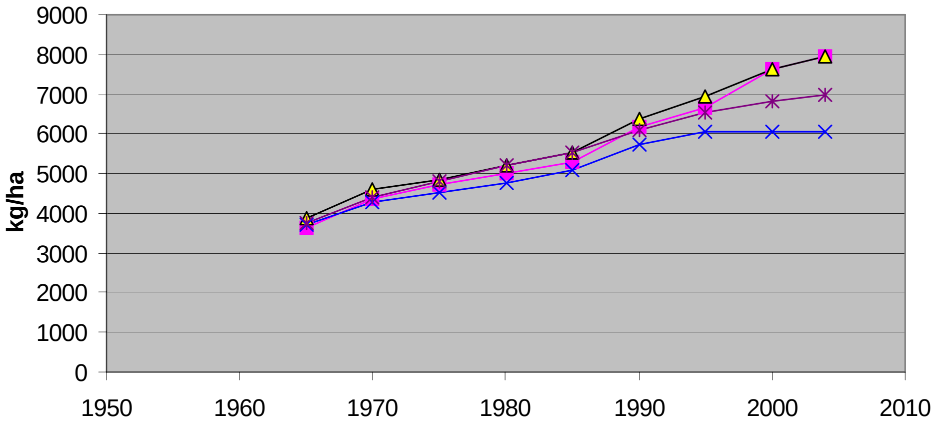


Fig. 2.4. Regional “standard yields” of winter wheat for every fifth year, as calculated by SCB. Squares are Kristianstad county,

triangles are Malmöhus county, crosses are Halland county, and rhombs are average of "Götaland södra slättbygder".

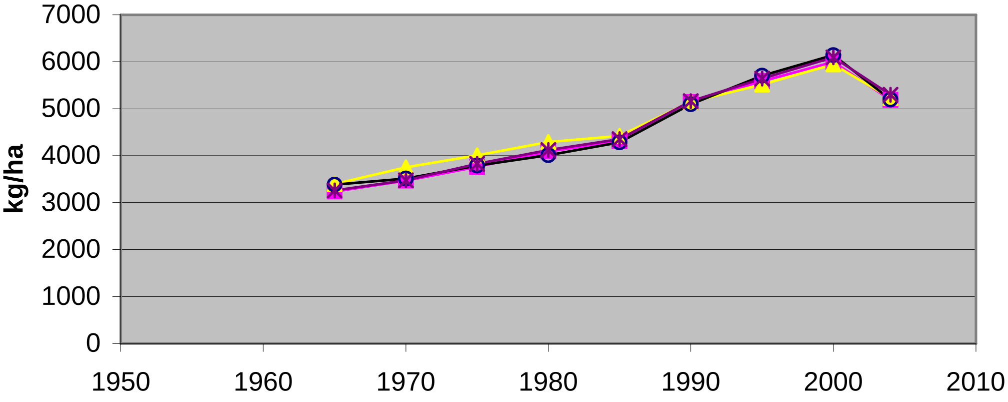


Fig. 2.5. Regional "standard yields" of winter wheat for every fifth year, as calculated by SCB. Squares are Stockholm county, triangles are Uppsala county, and rhombs are Södermanland county. Average values of "Svealands slättbygder" are similar to those of Stockholm county.

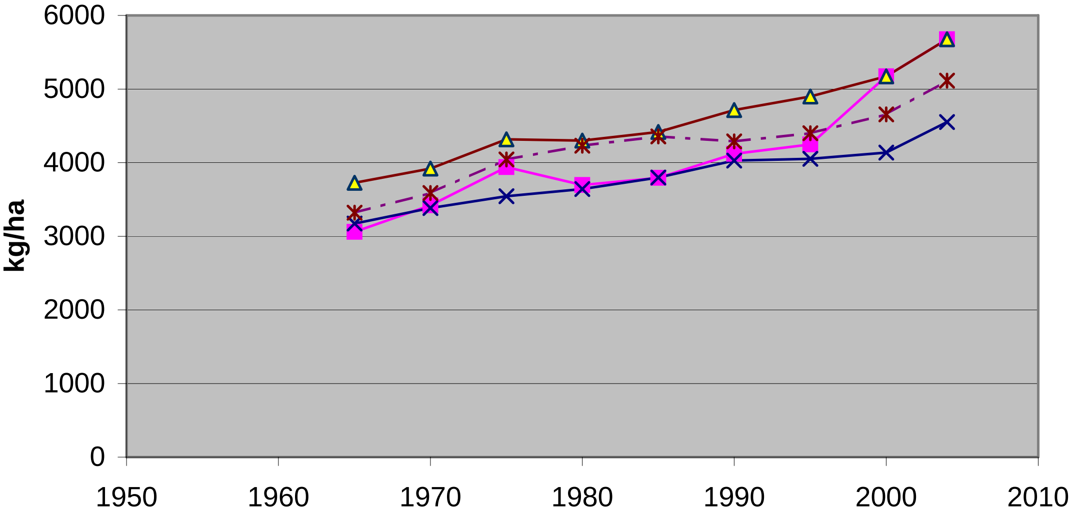


Fig. 2.6. Regional "standard yields" of spring barley for every fifth year, as calculated by SCB. Squares are Kristianstad county, triangles are Malmöhus county, crosses are Halland county, and dotted lines are average of "Götaland södra slättbygder".

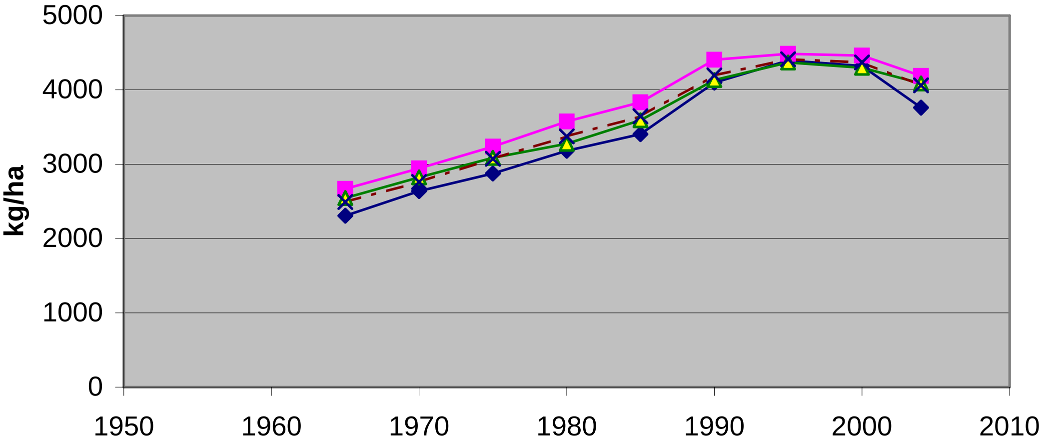


Fig. 2.7. Regional "standard yields" of spring barley for every fifth year, as calculated by SCB. Squares are Stockholm county, triangles are Uppsala county, and rhombs are Södermanland county. Dotted line is average values of "Svealands slättbygder".

How have yields developed on Gotland since 1913?
-Michael (2002) showed a pronounced increasing trend in yields per hectare, of both winter and spring wheat in Gotland county during the period 1913-1999, at least from 1940 and onwards.

How have yields developed in Sweden since 1866?
-In a report from Jordbruksverket (Jordbruksverket 2005) the actual yields of different grain crops and potatoes for 1866-2004 and of oilseed crops for the period 1961-2004, given as 5-year averages, are presented. The yields per hectare of grain increased gradually but slowly during the period 1866/70 to 1931/35. Then, after a minor decrease between 1936 and 1945, they increased very markedly until present years (e.g. for winter wheat from an average of 2240 kg/ha in 1946-50 to an average of 6100 kg/ha for the period 2001-04; for barley from 2060 kg/ha to 4270 kg/ha; and oats from 1390 kg/ha in 1941-45 to 3960 kg/ha in 2001-04). The yields from oilseed crops have also increased over the (shorter) time period 1961 to 2004: for winter rape with 38%, spring rape 48%, spring turnip rape 67%, but for winter turnip rape only with 4%.

Which methods exist to consider the influence of weather variations on SCB yield statistics?

How is the weather influence on SCB yields estimated?
-Actual yield data are, since 1961, recalculated by SCB to compensate for influence of the current year weather on yield. This *standard yield* ("normskörd") is defined as the expected yield during "normal" weather conditions in the production area (or county) concerned. Such standard yield calculations are performed both for 420 "minor harvesting areas" ("skördeområde") and on the county scale; SCB 1986). Crops included are those considered in the "*objective crop yield surveys*", i.e. winter wheat, spring wheat, rye, barley, oats, grass on arable land for hay or silage, potatoes, oilseed crops and sugar beets. Standard yields are published yearly in SCB/ *Statistiska meddelanden (*Statistical reports)*, SM, serie J* (from year 2000 on in "*serie JO"*). During the period 1961 to 1987 the method used for these calculations may be summarized as follows (SCB/Statistiska meddelanden, 1986): The standard yields refer to yield values which have been standardized with respect to changes over time, and are estimated on a county scale. First an average county value is calculated as the mean of all hectare yields for all years from 1958 until present. Then yearly values are calculated by adding the average linear increase from 1922 to present. Yearly values during 1922-1957 are using the average value for this period as a base, and then adding the same linear increase rate, i.e. from 1922 to present. In summary, the time scaling method split the trend line into two parts – one for the "subjective" and one for the "objective" period. This procedure is used because the two periods are not fully comparable since the yields were underestimated, in general, during the period with subjective estimates (1922-1958) (see Fig. 2.8). This method has been used for the period 1961-87. The estimates of "standard yield" form 1988 to1997 used a similar procedure as above, except that only data for the latest 25 years were considered. From 1998 only the latest 15-year period data are used. The standard yield of the minor harvesting areas is obtained by multiplying the county

standard yield by a value representing the average relation between the yield of the minor harvesting area and that of the county during 15 years. The difference between the standard yield and the actual yield of the minor harvesting areas has been used as a measure for economical compensation to farmers in that area.

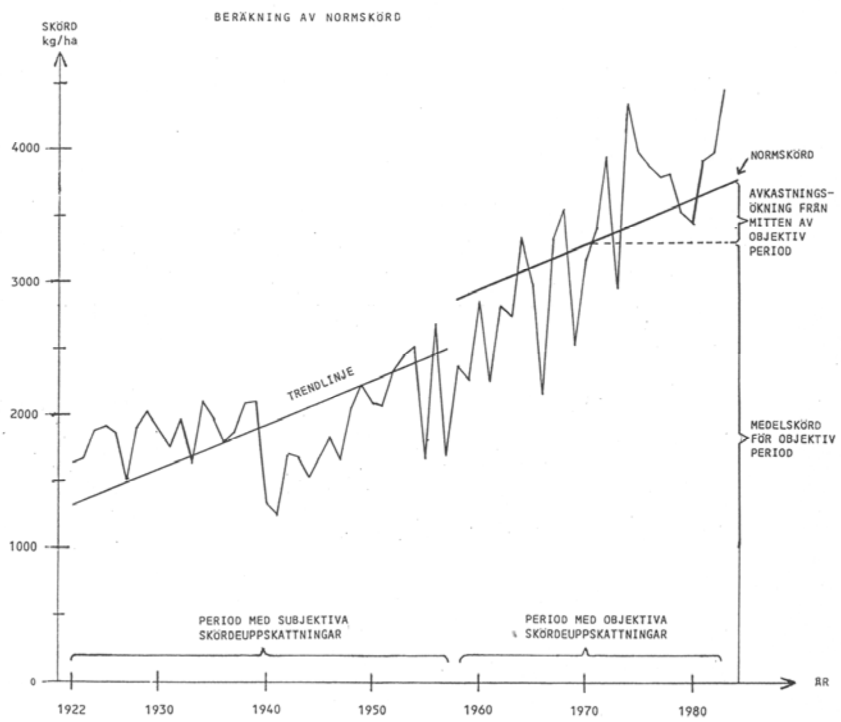


Fig. 2.8. Schematic description of the calculation procedure of the “standard yield” (source SCB, 1986).

How has land use of agricultural area changed in Sweden?

How has the area of cultivated land changed since 1960 in Sweden?

-In 2005 the areas cultivated with winter wheat and barley were about similar due to mainly decreasing barley area but also increasing winter wheat area. Barley has decreased more in “Svealands slättbygder” than in “Götalands södra slättbygder”. The area of winter wheat has fluctuated strongly in “Svealands slättbygder”, but no obvious trend, whereas in “Götalands södra slättbygder” it has increased (Figs 2.9-10).

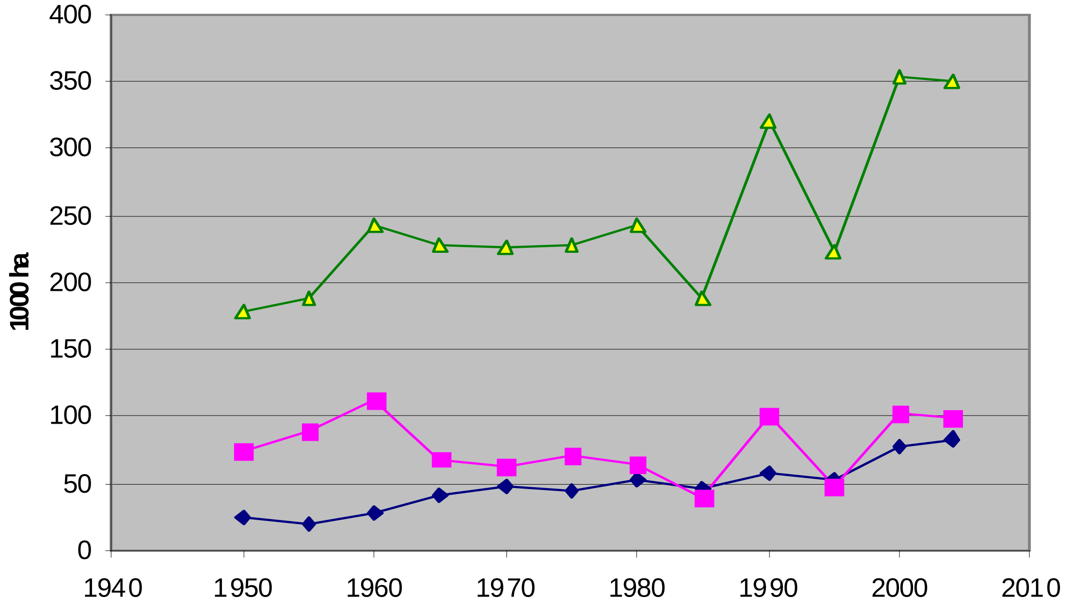


Fig. 2.9. Area cultivated with winter wheat given for every fifth year. Triangles are for whole Sweden, rectangulars are "Svealands slättbygder" and rhombs are "Götalands södra slättbygder".

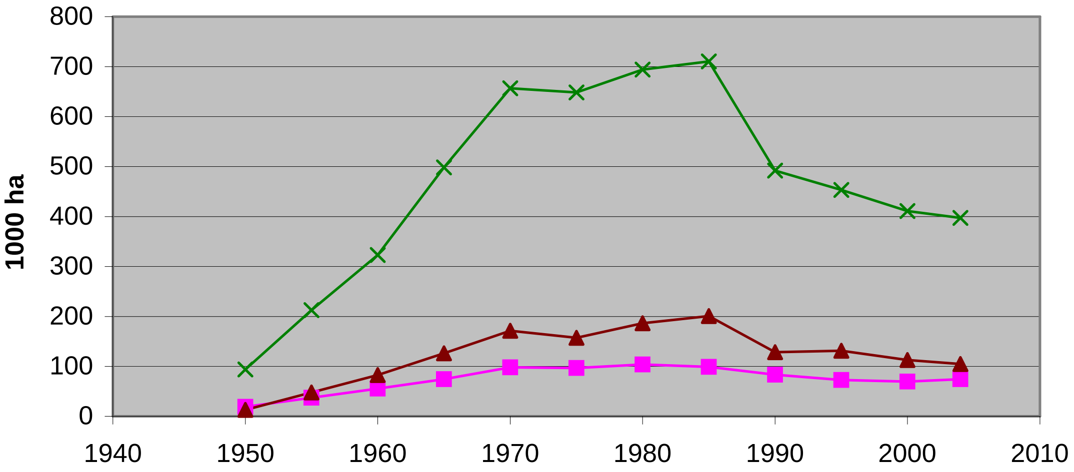


Fig. 2.10. Area cultivated with spring and winter barley given for every fifth year. Crosses are for whole Sweden, triangles are "Svealands slättbygder" and rectangulars are "Götalands södra slättbygder".

Which other databases than SCB exist for agricultural land use in Sweden?
-Naturvårdsverket /The Swedish Environmental Agency, SNV/ (Naturvårdsverket 1997, 1998, 2004) reported changes in agricultural land use, primarily during the period 1991-2001 but also for 50 years backwards (basically due to environmental and biodiversity issues, and as part of projects Livsmedelspolitikens Miljöeffekter and later the CAP-project, CAP= Common Agricultural Policy). The cultivated landscape is classified, using GIS, in three geographical scales: national, regional and local, with the emphasis on the regional scale. The data includes agricultural statistics from SCB from 1951, 1981, 1991, 1995 and 2000 (data aggregated to parish-level). Secondly there are data on land use, vegetation etc. (focus on grassland) from interpretations of aerial photographs from twenty parishes spread over large parts of Sweden from 1992, 1996 and 2001 (see, "NILS: Nationell Inventering av Landskapet i Sverige www-nils.slu.se, Esseen, P-A. *et al*., 2003).

How has the use of Swedish agricultural land changed over time?
-Jordbruksverket (Jordbruksverket 1999; a study focused on environmental influences) reported statistics showing the changes of the areas of certain crops, like cereals, oil-plants and leys, and total area of arable land

during the period 1961-1998 for Sweden as a whole. For 1985-1998 the average yearly changes are given for each of the eight major production areas (Ch. 2.1-2.4, pp.30-33). For 1994-1998 some groups of crops are presented in greater detail (Ch. 2.3-2.4, pp.33-40 and Bilaga 3). Some conclusions for recent years (after Sweden joining to EU) are: The area of managed pasture has increased; abandonment of arable land is greater in Norrland and in the wooded districts of southern Sweden than elsewhere; the area of arable land increased in the middle of Sweden, promoted by CAP.

-Jordbruksverket (Jordbruksverket 2003a; in principle similar to Jordbruksverket 1999) reported that during 1998-2002 the total area of arable land in Sweden decreased, and since 1995 (the beginning of CAP) it has decreased with about 85000 ha or 3%. Regarding the distribution on different crops it is more difficult to see any clear trends, explained by the authors to be partly due to weather-conditioned differences between years and varying market prices. On the national level, the relative share of land used for leys and green crops has decreased marginally since 1998, whereas cereals has decreased with 12% (152 000 hectares) over the period 1998-2002. The area used for oleiferous plants show a marked variation between years but has decreased significantly from 160 000 ha in the 1980´s to 67 700 ha in 2002.

- Jordbruksverket (2003b) gives (in Ch.2, pp.9-12) a historical résumé of the development of the Swedish agricultural land use. They also discuss the most probable influencing factors, and also expected future changes. Of about 4 600 000 ha total agricultural land (including pastures and also semi-natural grasslands (“naturbetesmarker”)) in 1945, about 2/3 remains today (2002). About 800 000 ha of arable land, and a very large part of the meadow land have been lost during this time. They present a chart showing the changes over time of the total area of pasture between 1989 and 2002. Before 1994 there was a slow but steady increase in pasture area from about 330 000 ha in 1989 to about 350 000 ha 1994. Thereafter the increase has been larger until last record in 2002. In 1999 the pasture area was about 450 000 ha.

-In a publication from Jordbruksverket (2005): “Swedish Agriculture in figures 1800 – 2004”, the development of both animal stocks and crop husbandry – during roughly the last 200 years are described in detail, including a discussion of the reliability of the statistical material. The area of *leys and pasture* peaked around 1940-1950 and has since then decreased rather steadily until 1990, but has since then showed an irregular increase. The total area of *grain* shows a bimodal distribution over the period 1866 to 1990 (Diagr.1.5, p.9) with two maxima: one around 1910/20 (just below 1 700 000 ha) and a second in the beginning of the 1990´s (about 1 650 000 ha), and a minimum around the early 1950´s (about 1 300 000 ha). Since the last maximum in the 1990´s this area has decreased markedly to become the lowest in 200 years (less than 1.2 million ha in the early 21st century). The acreage of *wheat* has undergone a ´steady´ but rather irregular increase during the whole period 1866 – 2004 (from about 50 000 ha 1866/70 to just below 400 000 ha 2001/04), the most marked increase occurring between 1926/30 and 1956/60 and after 1996. The area of *barley* decreased steadily from 1876/80 until the early 1950’s (down to about 100 000 ha). Between that time and to the beginning of the 1990´s a very large increase occurred (up to more than 700 000 ha), but the area has since then again showed a rapid decrease (down to 400 000 ha) (Diagr.1.6, p.9, ibid).

Which factors have influenced yield per unit area over time?

-Non-climatic factors have dominated the trends in yield variability in the US (Reilly *et al.* 2003)

-It was concluded that those crops exhibiting the highest increase in yield in the Czech Republic over the 75 years were also the most adaptable to inter-annual variability in weather, cultivars grown and to cultivation techniques used. The least adapted crop in the 10 European countries was sugar beet. Fertilization was an important factor in the adaptability (Chloupek *et al.* 2004).

How have European crop yields evolved over time?

Which crops have had the strongest yearly increase?

-Officially published yield data for the Czech Republic (1920-2000) and for Europe (1960-2000) was analysed by Chloupek *et al.* (2004). The fastest yield growth was found for flax (2.15% per yr), maize and wheat (1.61 and 1.53% per yr), while growth was slower for hops and root crops and slowest for grassland hay (0.22% per yr).

Which crops show highest yield variations between years?

-The highest yield variation between individual years was for wine grapes (32%), poppy (“valmo” in Swedish), edible legumes and flax (18.5-18.3%), while the lowest level of variation was for cereals (oats, barley, wheat, rye) and hay from arable land (9.7-12%). For many crops yield variation decreased with time (Chloupek *et al.* 2004).

-Torssell (1953) reported on coefficients of variation for grain yields over the periods 1915 – 1947 for wheat, 1929-1949 (oats) and 1925-1950 (peas). They were for winter wheat 27,0 - 27,7 %, for white oats 17,4 - 24,7 %, for black oats 15,5 - 22,1 %, and for peas 23,3 - 42,2 %, respectively.

Which crops responded best to favourable conditions?
-The most adaptable crops, whose yield increased most in favourable years, were flax, wheat, edible legumes, maize, rape and barley, while the lowest level of adaptability was shown by hops, sugar beet, hay and poppy. The higher the level of adaptability, the higher the yield growth over the 75 years analysed (Chloupek *et al.* 2004).

How large area is used for cropping?
-The decrease in agricultural land use in Sweden, arable land and pasture together, over the last four decades (1961 – 2004) is ~ -623 000 ha (or about 16 %), or, for arable land alone, ~ -635 000 ha, corresponding to almost 19 % (SJV, 2005).
-The decrease in agricultural land use in Europe over the last four decades is 13% (Rounsevell *et al.,* 2003).
-The decrease in agricultural land use in Denmark over the last four decades is 14%, and for Greenland there is an increase by 89% since 1990 due to fodder production (Danish EPA, 2005).

2. Current trends in agriculture

Which are the current trends in live-stock?
-From 1970 to 2003, in Denmark, cattle population decreased by 39%, pig increased by 55%, sheep increased by 100%, and poultry was roughly unchanged (Danish EPA, 2005).

Which are the current trends in greenhouse gas emissions due to agriculture?
-From 1990 to 2003 agriculture in Denmark has reduced its greenhouse gas emissions by 24%, the reason being initiatives in nutrient management (Danish EPA, 2005). It accounted in 2003 for 17-19% of Denmark's total emissions. Today CH_4 annual emissions are 3.7 M tonnes CO_2 equivalents, and for N gas emissions 6.2 M tonnes CO_2 equivalents (43% from manure, 31% from run-off (Olesen *et al.*, 2004), 6% from ammonium (mainly manure handling in animal housing (Mikkelsen *et al*., 2005)). Of the reduction of about 2.4 M tonnes CO_2 equivalents per year almost all (2.2) are due to reduction in N-gas emissions (Danish EPA, 2005).

Which are the current trends in N leaching?
-In 2003 the N leaching was reduced by 1 k tonnes N per year for whole Denmark (Olesen, 2005, Grant *et al*., 2000).

3. Climate impacts on agriculture

Principal relations between climate and agricultural crop production are the bases for making climate change impact assessments. The assessments concern different scales, ranging from the yield/quality changes of a specific crop in a s specific field, to changes in crop types and crop sequences on farm level and regional scales. The evaluation also concerns different factors like crop production and its impacts on the environment in terms of pollution and sequestration, as well as spread of diseases. General principles for how such factors react on a change in climate exist for some factors but not for others, and have different generality. The principles are derived from observations and application of models. The aim of this section is to describe available principals and methods, already used or potentially useful for assessments of agricultural production and land use in Sweden under climate change, as well as observed data on relations to climate confirming or falsifying these principles.

3. Soil

How do soil processes respond to climate?

How does the microbial respiration react on temperature?
-Rustad *et al.* (2001) found that increased temperature (0.3 – 6 ºC) increased soil respiration by 18-22%, for different types of biomes: grassland, forest and low tundra. The effect was highest in the forest. They used physical heating methods including electrical ground cables, greenhouses, field chambers, infrared lamps and passive night time warming.
-An increase of 5 ^{o}C in atmospheric temperature could have the potential to produce a significant increase in enchytraeid ("små varelser" in Swedish) activity resulting in a near twofold increase in soil CO_2 release from the soil. The interaction between temperature and soil biology will clearly be an important determinant of soil respiration responses to global warming (Briones *et al.*, 2004).

How does the microbial respiration react on drought?
-Sowerby *et al.* (2005) investigated the effect of periodic drought and increased temperature on microbial activity in four heathland ecosystems along a geographical and climatic gradient across Europe. The effect of drought on microbial activity and soil physic-chemical properties was more pronounced in the northern European sites than in the southern European. This suggests that the effect of temperature increases may be observed across all regions; however, the soils of northern Europe may be more sensitive to changes in rainfall patterns than more moisture limited Southern European soils. The study was within the large pan-European projects, CLIMOOR and VULCAN. Fluorogenically labelled substrates for four enzymes (glucosidase, sulphatase, phosphatase, leucine amino peptidase) were used to measure extra-cellular enzyme activity in soil samples from each of the CLIMOOR sites.

How does nitrogen mineralisation react on temperature?
-Rustad *et al.* (2001) found that increased temperature (0.3 – 6 ºC) increased N mineralisation by soil respiration by 30-64%, for different types of biomes: grassland, forest and low tundra. (For method see the same section above).

How do mycorrhiza fungi react on temperature?
-Rillig *et al.* (2002) indicated that ecosystem warming may stimulate carbon allocation to AMF (abuscular mycorrhiza fungi), using infrared heaters in a field experiment in an annual grassland, USA. AMF soil hyphal length was increased by over 40% in the warmed plots, accompanied by a strong trend for AMF root colonization increase. In the second year, AMF root colonization increased significantly in the warmed plots. Concentration of the soil protein glomalin, a glycoprotein produced by AMF hyphae with importance for soil aggregation and soil aggregate water stability, was decreased in the warmed plots. There were no effects on measured weight, length and average diameter of roots. They observed small changes in soil aggregation, and if widespread among terrestrial ecosystems, they suggest that this could have important consequences for soil carbon storage and erosion in a warmed climate, especially if there are cumulative effects of warming.

How does the temporal distribution of precipitation influence soil moisture and growth?
-In a field experiment in a Kansas tall grass prairie, Fay *et al.* (2002) studied the effect of reduced rainfall quantity (30 % smaller rain events, no change in rainfall pattern) and an altered more extreme distribution of rainfall (no reduction in quantity, 50 % increased inter –rainfall pattern). It was concluded that, (1) temporal

variability in rainfall inputs can have as much impact on soil moisture as simple reductions in rainfall quantities with no change in temporal distribution and (2) that altered rainfall patterns may have the potential to offset elevated CO_2 impacts on grassland vegetation (same experiment as Harper *et al*., 2005).
-Fang *et al.* (2005) found that more frequent precipitation significantly increase growth of grasslands and broadleaved deciduous trees in China.

How does temperature influence soil C stocks?
-Knorr *et al.* (2005) concluded that soil organic carbon pools with longer turnover times are more sensitive to temperature.
-Reichstein *et al*. (2005) concluded that it is premature to conclude that stable soil carbon is more sensitive to temperature than labile carbon. They showed that the conclusion by Knorr *et al.* (2005) is equivocal, largely dependent on the specific selection of data and does not persist when the data set of Kätterer *et al*. (1998) is analysed.

How do soil processes respond to CO_2?

How does the root- microbial system react on elevated CO_2?
-Net primary productivity below ground and CO_2-C production in the soil was stimulated by elevated CO_2, consistent with increased input of root biomass and readily decomposable material, evaluated in controlled environment experiments (Newton *et al*., 1995). Microbial biomass was unchanged, but enchytraeids were more abundant.

How does the soil fauna react on elevated CO_2?
-There was in general an increase in soil fauna community of grasslands (1-2 years) under elevated CO_2, from reviewed literature (90 references) (Tate and Ross, 1997).

How does N mineralisation react on elevated CO_2?
-No effect on N mineralisation was observed under elevated CO_2 in controlled environment experiments (Newton *et al*., 1995).

How does decomposition rate change under elevated CO_2?
-Sindhöj *et al*. (2006) measured that the C loss from root of a semi-grassland, under doubled CO_2 increased from 53 % to 57 % during a 160 day period. A six-year experiment with open top chambers was used.

Is C and N storage influenced by elevated CO_2?
-There was in general no increase of soil C of grasslands (1-2 years) under elevated CO_2, from reviewed literature (90 references) (Tate and Ross, 1997).
-Ross *et al*. (2004) concluded for grasslands in New Zealand that rising concentrations of atmospheric [CO_2] in a multi-species ecosystem had a significant increasing effect on microbial N, CO_2-C production (0-14 days) in field-moist soil, and net mineral-N production (14-56 days) in soil at 60 % of water-holding capacity. It had a small predictable effect on soil C storage and nutrient availability. After 5 years' CO_2 exposure soil metabolic activity tended to increase, with little changes in soil C pools. They used a free-air [CO_2]-enriched (FACE) system (475 µL/L) and seasonal sampling over a 5-year period, the influence of elevated atmospheric [CO_2] on soil C and N pools and mineralization in a fertilized (P, K, S), sheep-grazed pasture of mixed grass, clover, and forb species on a seasonally dry sand (Mollic Psammaquent) in New Zealand. Most properties in 0-50 mm-depth soil differed significantly with year of sampling, but [CO_2]-treatment effects were non-significant for moisture, pH, total C and N, extractable C and organic N, microbial C, and mineral-N. However, increased availability of N is suggested, probably because of increased inputs from N-fixing clovers.

How is below ground allocation influenced by elevated CO_2?
-In general below ground net primary productivity and C cycling rate increased of grasslands (1-2 years) under elevated CO_2, from reviewed literature (90 references) on global C budget (Tate and Ross, 1997).

How does increased CO_2 influence drainage?
-In a series of experiments with perennial ryegrass Casella *et al*. (1996) found for elevated CO_2 (700 ppm) slightly reduced evapotranspiration during the growing season and increased drainage by 9 % during winter.

How is CO_2 and temperature influencing C-N relations in soil?

-The effect of elevated CO_2 and +3 degrees temperature increase on C accumulation in a grassland soil (Rye grass) was investigated in a long-term experiment (2.5 yr) (Loiseau and Soussana, 1999). Elevated CO_2 increased the C/N ratios of the below ground phyto-mass and of the macro organic matter. A supplementary fertilizer N or a 3 degrees temperature increase in elevated CO_2 reduced it. At the last sampling date elevated CO_2 did not affect C/N ratio of the soil organic matter, but increased significantly the accumulation of roots and macro organic matter.

How is CO_2 and soil moisture influencing C-N relations in soil?

-Ross *et al*. (2004) found in a FACE-experiment in New Zealand that relationships with soil moisture were mainly non-significant for microbial C and N, but mainly significant for net mineral-N production in field-moist soil, and highly significant for CO_2-C production.

How is exchange of CO_2 between soil and atmosphere related to climate?

-Seasonal mean soil CO_2 flux decreased by 8 % under reduced rainfall amounts, by 13 % by altered rainfall timing and by 20 % when both were combined in a tall-grass American prairie (Harper *et al*., 2005; same experiment as Fay *et al.,* 2002). The effect of timing highlights the complexity of the grass ecosystem.

How large are the C fluxes to the soil?

-A net carbon sink between 135 – 205 Tg [1)] per year in Europe's terrestrial biosphere is estimated, which is equivalent to 7 – 12 % of the 1995 anthropogenic carbon emissions (Janssens *et al*., 2003).

How much does C transfer into soil vary between fields?

- A comparison (162 references) between eight studies showed that 0.1 –2.8 t C /ha was transferred to the soil during one growing season (Ress *et al*., 2005).

How is C sequestration dependent on soil N availability?

-Daily net C assimilation was increased in elevated CO_2 by 29 % and 36 % at low and high N supplies respectively in ryegrass swards in a 2-year experiment (France) (Casella and Soussana, 1997). On average a 35% increase in below ground respiration was measured in elevated CO_2. The below ground C storage was increased by 32 % and 96 % at the high and low N respectively, with no significant effect of 3 degrees temperature rise.

-Lou *et al*. (2004) formulated the term "progressive N limitation" (PNL). A highly discussed issue in global biochemistry is the regulation of terrestrial C sequestration by soil N availability. This causes a great uncertainty in predicting future global terrestrial C sequestration. In PNL, available soil N becomes increasingly limiting as C and N are sequestrated in long-lived plant biomass and soil organic matter. Testing and validation of the PNL hypothesis remains to be done.

What is the contribution of agricultural land to the total potential European C storage?

-Recent studies have suggested that although the overall quantity of C stored in European soils is increasing, this increase is confined to forested areas, and that many cropped soils are loosing organic matter. The biological potential for C storage in European cropland lies between 9 –120 Mt C /year. Better process understanding is needed to take advantage of this large potential (Ress *et al*., 2005).

-Leifeld *et al*. (2005) estimated that about 16 % of the national SOC (soil organic carbon) stock in Swiss agricultural soils has been lost historically due to peat land cultivation, urbanisation, and deforestation. It seems unlikely that future changes in agricultural practices could compensate for this historical SOC loss in Swiss agricultural soils.

Which methods exist to predict soil C?

-Evrendilek and Wali (2001) developed a simple dynamic model to quantify long-term C dynamics in cropland. (for results see "4. Soil" and "5. Soil").

-In order to account for changes in net CO_2 emission a method for full carbon cycle analysis of agricultural systems was developed. (West and Marland, 2002a,b).

-A model was developed to calculate carbon fluxes from agricultural soils. (Vleeshouwers and Verhagen, 2002).

[1)] 1 Tg = 10^{12} g = 1 million metric ton

-Also, based on long-term observations, a conceptual model of the dynamics of soil carbon in Swedish soils has been developed (Andrén *et al.*, 2004). The model is intended to be used for estimates of soil carbon in a climate change perspective.

Which methods exist to observe soil C?

-The natural abundance tracer technique can provide a rapid new clue to the fate of slurry in agricultural C and N budgets, which is important for environmental impacts, farm waste management and climate change studies (Glaser *et al.*, 2001)

3. Crop productivity

How does climate influence crop production in Nordic countries?

How does Swedish crop production relate to climatic variations over time?

-Michael (2002) studied the climatic influences, on the hectare yields of both winter and spring wheat in Gotland county during the period 1913-1999. The pattern of covariance between yields during "bad" and "good" years respectively were related to the monthly temperature and precipitation conditions at Visby. It was concluded that temperature conditions seems to be more decisive for the yields of winter wheat than for spring wheat, and for winter wheat it is primarily the temperature during the winter (January-March) which seems to be most important. The co-variance between yields and precipitation appeared more erratic and difficult to interpret, but small precipitation amounts in March seem to be favourable both for winter and spring wheat. For spring wheat it was favourable with an early sowing date.

Which climatic factors correlate with observed winter wheat yields in Denmark?

-Observed winter wheat grain yield for 7 sites in Denmark during 1971-97, were positively correlated with temperatures in October, November and January, and radiation in April, but strongly negatively correlated with precipitation in July (Olesen *et al.*, 2000b).

How large part of observed crop variability is explained by variation in weather?

-Only 0-20 % of variations in observed (de-trended) winter wheat yield for 7 sites in Denmark during 1971-97, could be explained by a weather driven model for crop growth (Olesen *et al.,* 2000b). The predictability depended on soil type. The observed yield was correlated with 5 climate factors (temperatures in October, November and January, radiation in April, and precipitation in July), whereas the simulated yield was correlated only with radiation in April.

Is water shortage to plant a problem in Scotland?

-Kerr *et al.* (1999) stated that water stress is not a problem in Scotland except for the south east, and specific water demanding crops like potatoes.

Is water logging a problem in agriculture in Scotland?

-Kerr *et al.* (1999) reported that in 1998 many potatoes fields could not be harvested because of water logging. They conclude that water logging is a larger problem to the Scottish farmer than water stress.

How does crop production in other countries respond to climate?

-Variations between years in growth in response to CO_2 can be largely explained by differences in weather conditions (especially temperature) between growing seasons (Grashoff *et al.,* 1995).

-In C_3 crops increased CO_2 stimulates yield, improves resource use efficiency and reduces O_3 toxicity (Fuhrer, 2003). Many of these advantages may be lost to some extent in higher temperatures.

-Warming accelerates plant development and reduces grain-fill, reduces nutrient use efficiency and increases water use (Fuhrer, 2003)

-Xiao and Moody (2004) correlated a normalized vegetation index with mean precipitation and temperature over 11 years for six biomes in US. Within and across biome variance of means of gNDVI (normalized vegetation index, integrated over the growing season) was correlated with spatial gradients in long-term average seasonal climate. This gave relations between seasonal precipitation and temperature regimes and productivity, indicating that these variations have particularly significant consequences for above ground plant productivity, especially for grassland, shrub land and evergreen needle forest. Further increases in productivity can be expected with associated consequences in C budgets.

-Bakker *et al.* (2005) found that wheat yield in central and southern Europe was strongly correlated also to gross domestic product, on both national and local scale. In conclusion, climatic variables showed highest correlation

to regional yield levels (0.83-0.88), whereas these yields were less correlated to economic as well as to soil variables (0.51-0.73).
-Ciais *et al.* (2005) estimated for the dry year 2003 a 30 % reduction in gross primary productivity over Europe, which resulted in a strong anomalous net source of CO_2 (0.5 Pg C/yr) to the atmosphere and reversed the effect of 4 years of net ecosystem C sequestration. Productivity reduction in Eastern and Western Europe can be explained by rainfall deficit and extreme summer heat. Ecosystem respiration also decreased, together with gross primary productivity, with the temperature rise. For this evaluation they used measurements of ecosystem CO_2 fluxes, remotely sensed radiation absorbed by plants, and country- level crop yields taken during the European heat wave in 2003, together with a terrestrial biosphere simulation model that assessed continental scale changes in primary productivity during 2003, and their consequences for the net C balance.

How is grain yield influenced by temperature?

-Pettersson *et al.* (2006) reviewed temperature effect on barley grain yield. Daily mean temperatures above 18 ºC decrease grain yield of wheat by 5 % per ºC. For rice, though, the decrease does not start until above 27 ºC, at a similar rate 4.4 % per ºC (Tashiro and Wardlaw, 1989). Wardlaw and Wrigley (1994) defined daily mean temperature between 15-25 ºC and maximum temperatures below 32 ºC during grain filling as moderate temperature not negatively affecting wheat. Higher temperatures were regarded as heat shock conditions. Several other studies have used 32 ºC or higher values as lower limit for injurious conditions (Mac Nicol *et al.,* 1993; Savin and Nicolas, 1996; Savin *et al*, 1996; Wallwork *et al*., 1998). However, other studies have observed dramatic effects on wheat and barley also under moderate temperature conditions (Triboi and Triboi-Blondel, 2002; Passarella *et al*., 2002).

How has phenology been influenced by climate trends since 1970?

-Chmielewski, F.-M. (2003) reports the importance and use of phenological observations in agricultural practise, and particularly the already observed effects of climatic change are discussed. It is stated that between 1969 and 2000, the average beginning of the growing season in Europe has advanced by 9 days, corresponding to a significant trend ($p<0.05$) of -2.8 days/decade, and a relatively smaller shift of the end of the growing period (by about 1 day/decade). Such changes in the length of the growing season can influence crop management in areas, for example, such as cultivar selection, catch cropping and crop rotation.

How does crop production respond to El Niño?

-Amissah-Arthur *et al.* (2002): The 1987-88 El Niño had a significant effect on the growing season rainfall with consequent positive influence on national maize yield in Kenya. However, it was found that the spatial and seasonal variations in El Niño influence on rainfall are highly inconclusive, except for some highland high rainfall sites and seasons, in Kenya. Significant event-to-event variability was observed during the October-January (OJ) crop-growing season. Furthermore, 'super El Niño's may give rise to larger rainfall responses than normal El Niño's at some sites: the magnitude varies from site to site and the effect is not obvious at some sites. They concluded that all El Niño's are not equal in terms of their regional manifestation, indicating that the ability to predict rainfall variability a season in advance could have a major impact on the fragile Kenyan (African) economy

How does elevated CO_2 affect growth?

-Yield (regrowth over 3 week interval) of temperate grassland species increased only slightly when subjected to elevated CO_2 in controlled environment experiments (Newton *et al*., 1995). Net primary productivity below ground was stimulated by elevated CO_2.
-In contrast to the Newton *et al.* (1995, 1996) experiments, above ground production of two limestone grassland communities was not stimulated by elevated CO_2 (enriched with 250 ppm CO_2) at any time during two seasons (Wolfenden and Diggle, 1995). However, rate of photosynthesis was increased, but also respiration. The results suggest that increasing atmospheric CO_2 concentration is unlikely to cause large changes in net primary production in these grasslands.
-In a controlled environment experiment with native short-grass steppe swards, elevated CO_2 (700 µL /L) increased total biomass after two seasons with 19 %, with no significant differences between C3 and C4 grasses, (Hunt *et al.,* 1996).
-In field experiments with ryegrass at a doubled atmospheric [CO_2] (Jones *et al.,* 1996), harvestable annual yield increased with 20%, but the effect differed during the season and between years. Other effects were decrease in LAI and canopy conductance.

-Harvest index of spring wheat was not affected by a doubling of CO_2-concentration in an open top chamber experiment, over three seasons (1994-96) close to the Swedish west coast (Pleijel *et al*., 2000). In two seasons the straw yield increased (+21% in 1996). Grain yield increased significantly in one year (+21% in 1994). There was a positive chamber effect on grain yield.

-Pearson *et al.* (1997) also found production in lettuce to increase 32% with an increase in CO_2 from 350 to 700 ppm.

- Batts *et al.* (1998) observed a 7-35 % increase in production after 500 degree-days, at elevated CO_2.

-Tuber yield of potato was not significantly affected by a doubling of CO_2-concentration in an open top chamber experiment in 1998, north of Gothenburg (Persson *et al*., 2003). Number of tubers with lower size increased, though. Haulm dry weight decreased (15 %) as did haulm/tuber ratio. They conclude that potato growth response to CO_2 and a (potential) effect of ozone are not simply additative.

-The production of soybean increased by 18-15% when grown in open-air experiments (USA), where the concentration of CO_2 had been raised to 550 ppm (Morgan *et al*., 2005). This yield increase is smaller than predicted from growth chamber studies. The findings are important since soybean is planted on more land on the globe than any other dicotelydonous plant.

How do elevated concentrations of CO_2 influence effects of water conditions on growth?

-In grassland experiments under controlled conditions Newton *et al.* (1996) observed different strategies in response to soil moisture stress, depending on CO_2 concentration. At ambient CO_2 concentration, growth stopped, but plants were able to respond strongly on rewatering. At elevated CO_2 growth continued (particularly below ground), but no additional growth was evident on rewatering. After 428 days the total amount CO_2 fixed was 33% higher in the elevated CO_2 atmosphere. Thus interactions with water availability and elevated CO_2 have the potential to be important factors in determining future forage supply from temperate pastures.

-Soil moisture increased in spring wheat at a doubling of CO_2 concentration in one (1996) out of three seasons (1994-96), in an open top chambers experiment, close to the Swedish west coast (Pleijel *et al.,* 2000).

-Raising the atmospheric CO_2 concentration from 363 to 484 µmol /mol reduced midday latent heat fluxes by 50 W m^{-2} for wheat fertilised with 35 g N m^{-2}, and by 100 W m^{-2} for wheat fertilised with only 7 g N m^{-2}, when N deficits developed later in the season (Grant *et al*., 2001). These reductions were dependent on wind speed. At a seasonal time scale the above raise in CO_2 reduced simulated and measured evapotranspiration of wheat by 7-9% at high N and by 16-19% at low N. Models of changes in atmospheric CO_2 concentration in mass and energy exchange studies should therefore reflect N availability and wind.

How does elevated CO_2 influence temperature effects on growth?

-In a controlled environment experiment with native short-grass steppe swards Hunt *et al.* (1996) found that the positive effect of CO_2 was greater at normal temperatures in the C4 grass, and greater at elevated temperatures in the C3 grass. Intermediate watering regime gave best response. There was no effect on root/shoot ratio or production of seed heads.

What do we know, and not, so far, concerning CO_2 effects on growth?

-In a report from "Australian Greenhouse Office" in the Department of the Environment and Heritage, Australia (Steffen, W. and Canadell, P., 2005) the current knowledge on "Carbon Dioxide Fertilisation and Climate Change Policy", also outside Australia, are discussed. There is an agreement that different water balance processes operate at different scales from the leaf to the plant to the ecosystem. Any attempt to extrapolate the effects of elevated CO_2 on plant water use efficiencies from micro-level studies to macro-level understanding must be undertaken with extreme care. The knowledge based on the effects of *step-wise* increases in atmospheric CO_2 on fundamental physiological effects at leaf level appears quite robust. There is, however, an increasing uncertainty concerning the effects of elevated CO_2 on growth, yield and water use when scaling up to monoculture cropping systems, perennial pasture/rangelands systems and short-rotation plantation forests. Uncertainty increases further when the effects are scaled up to mature forests over long timescales. In addition, little is known about the effects at the system level when other effects of elevated CO_2 (e.g. carbon allocation, nutrient interactions, inter-species competition) are considered concurrently.

How is ozon affecting plants under waterstress?

-Jaggi *et al.* (2005) concluded that in species such as T. pratense stomatal O_3 uptake can be maintained during dry periods when roots can reach deeper soil layers where water is not a limiting factor. The strongest effect of O_3 on $\delta^{13}C$ occurred in the absence of irrigation, suggesting that under field conditions lack of moisture in the topsoil does not always lead to protection from O_3 uptake. They measured stable carbon isotope ratios ($\delta^{13}C$) and leaf conductance (2002, 2003) in four dicotyledon plant species at two levels of ozone (O_3) with or without irrigation.

How does climate variability influence crop production?

-Mearns *et al.* (1992) performed sensitivity analyses of how crop-climate models respond to changes in climate variability. Wheat yields were simulated for two regions in Kansas. Increases in variability of both temperature and precipitation resulted in significant increases in yield variability and crop failures, but precipitation changes had a more pronounced effect. It is concluded that not only mean but also variability changes of climate variables must be considered in estimates of the impact of climate change on production.

-Semenov and Porter (1995) question the rationale in formulating average climatic change scenarios when used in combination with the many non-linear responses of crops to their environment. Accordingly, they coupled a wheat model, AFRCWHEAT2, with a stochastic weather generator and found that modelled changes in temperature variability may have more profound effect on simulated grain yield than changes in mean values.

-Mitchell *et al.* (1995) observed wheat growth in a controlled environment facility at two CO_2 concentrations (350 and 700 ppm) and two temperature regimes (tracking ambient and ambient +4 ºC). Dry matter production and grain yield increased 27 % and 39 % respectively for CO_2 and decreased by -16 % and –35 % for increased temperatures. The results were analysed with AFRCWHEAT1. It was found that the model could be improved in the earlier vegetative phase of the growth.

-Ferris *et al.* (1998) suggested that crop responses to increased temperature must be considered in terms of not only mean temperature but also in terms of variability. The frequency of episodes of brief hot temperatures can be detrimental to annual crop seed or grain production.

-Wheeler *et al.* (2000): Evidence is presented for the importance of variability in temperature, independent of any substantial changes in mean seasonal temperature. Seed yields are particularly sensitive to brief episodes of hot temperatures if these coincide with critical stages of crop development. Hot temperatures at the time of flowering can reduce the potential number of seeds or grains that subsequently contribute to the crop yield.

-Richter *et al.* (2001) and Pidgeon *et al.* (2001) developed a model for sugar beet and tested it to describe the water and radiation use efficiency relations in production. European sugar beet crops suffer from drought stress and climatic change is likely to increase the frequency of drought situations.

-Wollenweber *et al.* (2003) found that biomass accumulation of winter wheat plants experiencing high temperatures during the double-ridge stage was not affected, but reduced by 40 % when plants were subjected to a heat event at anthesis. Grain number on the main and side tillers declined by 41 %, and individual grain weight declined by 45 % with heat stress applied at the double-ridge stage and anthesis or at anthesis alone. The harvest index was reduced from 0.53 to 0.33. The maximum rates of CO_2 assimilation increased with heat stress at the double-ridge stage and higher rates were maintained throughout the growing season.

-Wollenweber *et al.* (2003) stated that increased climatic variability and more frequent episodes of extreme conditions may result in crops being exposed to more than one extreme temperature event in a single growing season and could decrease crop yields to the same extent as changes in mean temperature. The developmental stage will determine the severity of plant damage. It was not known if the damaging effects of heat episodes at different phenological stages are additive, but results of this study (Denmark) clearly indicate that an extreme heat event at the double-ridge stage does not affect subsequent growth or the response of wheat to heat stress at anthesis.

-Porter and Semenov (2005) pointed out that crops can respond nonlinearly to changes in growing conditions, exhibit threshold responses and are subject to combinations of stress factors that affect growth, development and yield. Increasing temperature and precipitation variability increases the risks to yield, (computer simulation, experimental studies). Thus, climate variability and changes in the frequency of extreme events are important for yield stability and quality.

-Porter and Semenov (2005): Using models of wheat, the concentration of grain protein is shown to respond to changes in the mean and variability of temperature and precipitation events.

What further research is needed for predicting effects of climate variability?

-Wheeler *et al.* (2000) review evidence for the importance of variability in temperature for annual crop yields, and consider how the impacts of these events may be predicted. Three research needs are identified: reliable seasonal weather forecasts, robust predictions of crop development, and crop simulation models which are able to quantify the effects of brief episodes of hot temperatures on seed yield.

How does scale influence climate effects on crop production?

How do regional effects differ from those on the field scale?

-Simulation of the spatial crop yield variability (on a regional scale) requires data from more than one weather station and a spatial resolution of soil data of 10 x 10 km^2 or finer in Denmark (Olesen *et al.,* 2000).

How are climate effects on crop production modelled?

Which methods could be used for predicting effects of variation in climate?

-Bakker *et al.* (2005) found that wheat yield in central and southern Europe correlated strongly with several climatic factors, separately, concluding that there is a high risk of confounding results using empirical regression models on the regional scale.

Which factors are modelled and how do they respond to climate?

-In the beginning of 1990 the EPIC model was modified so it would account for the combined effect of increase in CO_2 and the CO_2 induced climatic change (Stockle *et al*., 1992a, b).

-Version GEM2 of the grassland ecosystem model links biochemical, ecophysiological and ecosystem processes in a hierarchical approach (Chen *et al.,* 1996). The model includes biochemical level mechanisms of C3 and C4 photosynthetic pathways to represent direct effects of CO_2 on plant growth, mechanistically simulated biophysical processes which control interactions between the ecosystem and the atmosphere, and linked with detailed biogeochemical process submodels. The model has been satisfactorily validated and can therefore represent the interactions between several levels: photosynthesis and stomatal movements at the leaf level, energy and gas exchanges at the canopy level, and water budget and nitrogen cycling at the ecosystem level. (For model predictions, see below)

-Kleemola and Karvonen (1996) developed a model for snow dynamics and soil temperature in Finland. The model was used in relation to barley production.

-Riedo *et al*. (1998) have developed a detailed pasture dynamics model for dry matter production, and fluxes of carbon, nitrogen, water and energy. The model was validated and found suitable for global change assessments in mid-European conditions between 500-1000 m above sea level. Similar work in lettuce by Pearson *et al.* (1997), but this model was restricted to growth in relation to environmental changes.

- CO_2 effects on simulated wheat growth acted through effects on light use efficiency in three crop growth models (AFRCWHEAT2, FASSET and Sirius; Jamieson *et al.,* 2000).

-Curd initiation and harvest of cauliflower was modelled by Olesen and Grevesen (2000) basically as a function of temperature and solar radiation influencing development, LAI and intercepted radiation.

-Models that predict radiation penetration in a plant stand on the bases of canopy architecture have been developed (Birch *et al*., 2003). Such models can generate virtual plants and could be useful for studying details in canopy responses to a changing climate. In this context the role of LAI in relation to increased CO_2 has been pointed out by Ewert (2004). The modelling of LAI must be improved, which requires better understanding of substrate allocation, leaf area development and senescence, and the role of LAI in controlling plant adaptation to environmental changes.

-Detailed process models and simple parametric models for primary production and transpiration can be effectively combined to scale leaf photosynthesis and transpiration up to large spatial scale (Chen and Coughenour, 2004). Simulation with the GEMTM process model showed that net carbon assimilation was proportional to intercepted PAR (photosynthetic active radiation), but RUE (radiation use efficiency) changed with leaf N concentration, temperature and CO_2 concentration. Transpiration was linearly correlated with the product of net primary production (NPP) and atmospheric water vapour deficit, and the slope varied with leaf N concentration. RUE increased with leaf-N content asymptotically, and responded to temperature in an asymptotic bell shaped pattern with a 22 ºC and 26 ºC optimal temperature at current ambient and doubled CO_2 concentration, respectively. A simple parametric NPP model and a regional transpiration model were developed from these relationships.

How well do models mimic observations?

-CENTURY is a general grassland model of the plant-soil ecosystem (Hall *et al.* 1995). It has been validated at 11 sites of tropical and temperate grasslands and then been used to model climatic change effects at 31 other such sites. Predictions of plant and soil organic matter C and N requires knowledge of climate, soil texture, N inputs and fire and grazing patterns. (Simulation results are shown below)

-A larger part of the yield variation between years was captured by the model on loamy soils than compared to sandy soils. (Olesen *et al*., 2000).

-Models for describing the impact of climate and climate change on production have performed erratically when tested against field measurements (Monteith, 2000).

-Observed values on green area index, and shoot and grain biomass of wheat were reasonably well predicted by three crop growth models (AFRCWHEAT2, FASSET and Sirius; Jamieson *et al*., 2000).
-The interpretation and synthesizing of experiments with increased CO_2 and temperature in wheat has been difficult because of the large variation in the experimental results (Wolf *et al*., 2002). Simulation of data from a large number of wheat experiments in Europe and USA has shown poor agreement between observed and calculated responses. A model improvement in terms of morphologic development and sink size is suggested for improving the consistency and interpretability.
-Chen and Coughenour (2004) derived from the more detailed GEMTM process model a simple parametric net primary production (NPP) model and a regional transpiration model. This model simulated well the seasonal and inter-annual variation in regional NPP in the Central Grassland Region in USA.

3. Grassland

How does plant production react on temperature?
-Rustad *et al.* (2001) found that increased temperature (0.3 – 6 ºC) increased plant production by 15-23 %, for different types of biomes: grassland, forest and low tundra; most for tundra. Above ground production increased most for cold regions. No correlations were found to geographic, climatic or environmental variables. (For method see section 3. Soil)

How fast do grassland systems respond to a combination of CC and grazing?
-From Hurley Pasture Model simulations (Thornley and Cannell, 1997) it was concluded that: (1) initial ecosystem responses to step wise (or gradual) changes can be different in both magnitude and sign compared to the response to a new equilibrium state, and this can continue for many years; (2) grazing can drastically alter the magnitude and sign of the response of grassland to climate change, and be highly site specific; (3) experiments should try to lessen uncertainties about processes within models rather than try to predict ecosystem responses directly. (For results, see section 4. Soil)

How does CO_2 influence growth?
How does increased CO_2 influence yield?
-Swards of monocultures of white clover and perennial rye grass and a mixture of the two were exposed season long to ambient (380 ppm) and elevated (670 ppm) CO_2 concentrations (Schenk *et al*., 1997). Swards were harvested four times at monthly intervals. The CO_2 related increase in seasonal yield was 16-38 % in white clover monocultures, 12-29 % for mixed swards and 5-9 % for ryegrass monocultures.

How are radiation use, allocation and water use efficiency influenced by elevated CO_2?
-In experiments with perennial ryegrass in the Wageningen Ritzolab (Schapendonk *et al*., 1997) light use efficiency ranged between 1.5 g CO_2/MJ for high light and ambient CO_2 to 2.8 g CO_2 /MJ for low light and doubled CO_2. The above ground NPP was greater by 29 % in 1994 and by 43 % in 1995 in the doubled CO_2 treatment, but only 20 % and 25 % respectively was recovered in the periodical cuts. Thus there was a preferential allocation of extra C to the root and soil. Elevated CO_2 decreased the specific respiration rate of the shoots but total canopy respiration was not affected, due to higher amount of standing biomass. Allocation of C to the roots was highest in the spring, low in the early summer and increasing again in late summer and autumn. The total amount of C partitioned to roots and soil during the two years was 57% more in doubled CO_2. The average water use efficiency of the swards was increased by a factor of 1.5 in doubled CO_2.

Does the initial growth stimulating CO_2 effect disappear in the long-term perspective?
-The initial stimulation of photosynthesis observed at elevated atmospheric CO_2 concentration in grasslands has been predicted to be a transient phenomenon that will be constrained by the loss of photosynthetic capacity due to other limitations, notably nutrients and sinks for carbohydrates (Ainsworth *et al*., 2003a). Legumes might be expected to escape these feedbacks by N_2 fixation. This was tested for years 8-10 of a 10-year experiment at FACE in Switzerland with white clover and high and low N supply. Elevated CO_2 increased both vegetative and reproductive growth at both N-treatments. There was a strong effect of season on photosynthesis. The results show that acclimation of photosynthetic capacity can occur in a N_2-fixing species, in the field where there is no restriction on sink capacity. However, even with acclimation there was a highly significant increase in photosynthesis at elevated CO_2.
-In an experiment parallel to that of Ainsworth *et al.* (2003a), the response of 10 years of exposure of perennial rye grass to elevated CO_2 at two nitrogen levels was studied by Ainsworth *et al.* (2003b). Over the 10 years as a whole, growth at elevated CO_2 resulted in 43 % higher rate of light saturated leaf photosynthesis and a 36 %

increase in daily integral of leaf CO_2 uptake. Photosynthetic stimulation was maintained despite a 30 % decrease in stomatal conductance. In contrast with theoretical expectations and the results of shorter duration experiments, the present results provide no significant change in photosynthetic stimulation across a 10- year period, or greater acclimation in maximum carboxylation velocity or maximum rate of electron transport in the later years of either nitrogen treatment.

How is root- shoot partitioning influenced by increased CO_2?
-Sindhøj *et al.* (2004) measured root shoot partitioning of semi-natural grasslands in Uppsala (Sweden) in open top chambers with elevated CO_2 (ambient +350 ppm). Root biomass of elevated CO_2 was 25 % higher than ambient treatment in the first year, and 80 % higher in the 5:th year. The shoot biomass increased more in the beginning (+50 %) but less in the end (+5%). This resulted in a clear shift in root to shoot ratio due to elevated CO_2, being 15 % less than that of ambient treatment in the first year and 70% larger in the 5:th year.

How are effects of elevated CO_2-concentrations related to the N conditions?

How do effects of CO_2 depend on N conditions?

-Daepp *et al.* (2001) concluded from a 2-yr field experiment with swards of Lolium perenne that plant response to elevated concentrations of atmospheric CO_2 may depend on the carbon sink strength, determined by the availability of resources other than CO_2, and the developmental stage. Biomass allocation and the height of the plants, clearly depended on N fertilization and developmental stage. During vegetative growth, the greatest increase in DM yield occurred in high N treatment; with no change in DM allocation. At low N, residual biomass, but not yield, increased, and the tillers were shorter. During reproductive growth, DM yield increased similarly across all N treatments; no change in DM and N partitioning. Mean weight and height of the reproductive tillers increased. At high N availability, or during reproductive growth, carbon-sink limitation were overcome and showed a strong yield response.

Will N use increase at higher CO_2 -concentrations, and how is this related to N uptake?
-Soussana *et al.* (1996) studied swards at two sub-optimal (160 and 530 kg N ha^{-1} yr^{-1} and one non-limiting (1000 kg N ha^{-1} yr^{-1} N fertilizer supplies. At elevated CO_2 leaf N concentration per unit mass at cutting was reduced by 25 to 33 %. Under non-limiting N conditions, the leaf N concentration (% N) declined significantly with shoot dry-matter (DM); in ambient CO_2: $\%N = 4.9DM^{-0.38}$, and in elevated CO_2: $\%N = 5.3DM^{-0.52}$. The results indicated a lower critical leaf N concentration in elevated than in ambient [CO_2] for high, but not for low values of shoot biomass. Under sub-optimal N conditions the ratio of the actual to the critical leaf N concentration, was significantly lower in elevated CO_2. This indicated a lower inorganic N availability for the grass plants in elevated CO_2, which was also apparent from the significant declines in the annual N yield, and the N leaching during winter. For most cuts the harvested fraction of the plant dry-matter decreased in elevated N, due to a 25-41% increase in the N contents of the roots. The annual means of the DM and N harvest indices were highly correlated to the ratio between actual N and critical N concentration.

Which questions arise concerning N availability to plants?
-Riedo *et al.* (1998) made simulations that revealed the importance of a parameter for the nitrogen concentration of the structural plant dry matter.
-The impact of elevated CO_2 on terrestrial ecosystems C balance is not clear because the resulting alterations in C input, plant nutrient demand and water use efficiency often have contrasting impacts on microbiological decomposition processes (Hu *et al.*, 2005). One major source of uncertainty stems from the impact of elevated CO_2 on N availability to plants and microbes (Hu *et al.*, 2005). In a controlled environment experiment with Avena, elevated CO_2 increased the plant N acquisition from the soil. The results suggest that elevated CO_2 may tighten N cycling through facilitating N acquisition. It is uncertain if these results can be extrapolated to the field. Long- term field experiments are needed to determine whether the effect of CO_2-enhancement on plant N acquisition can significantly increase N availability for plant growth in an elevated CO_2 environment.

In what way is CO_2 influencing plant uptake of N from soil and fertilizer?
-In a rye grass sward elevated CO_2 reduced the total amount of N harvested in the clipped parts of the sward (Loiseau and Soussana, 2000). The harvested N derived from soil was reduced to a greater extent than that derived from fertilizer. At two N-levels, elevated CO_2 modified the allocation of fertilizer N in the sward in favour of the stubble and the roots and significantly increased the recovery of fertilizer N in the soil macro-organic matter. This increase was associated with a decline in fertilizer N uptake, which supported the hypothesis of a negative feed back of elevated CO_2 on the sward N yield and uptake. A 3-ºC temperature increase alleviated the CO_2 effect throughout much of the N cycle, increasing soil N mineralization, N derived

from the soil in the harvests and the partitioning of the fertilizer N to the roots. Thus, at ambient temperature the N cycle was slowed down under elevated CO_2, which restricted the increase in above ground production, and apparently contributed to the sequestration of carbon below ground. In contrast, a temperature increase under elevated CO_2 stimulated the soil N cycle, improving the N nutrition of the sward, and restricted the soil C sequestration.

Will N use increase at higher CO_2, and how is this related to N uptake?
-Growth at elevated CO_2 resulted in reductions in apparent Rubisco activity in Agrostis sp., perennial rye grass and white clover at two nutrient regimes (Davey *et al.,* 1999), associated with reductions in total leaf nitrogen content on a unit area bases. The photosynthetic nitrogen use efficiency (the rate of carbon assimilation per unit leaf nitrogen) increased at elevated CO_2, both owing to higher values of photosynthesis at elevated CO_2, and as a result of lower leaf nitrogen contents. Contrary to previous studies, this investigation indicates that elevated CO_2 can stimulate photosynthesis under a severely limited nutrient supply. Changes in photosynthetic nitrogen use efficiency may be a critical determinant of competition within low nutrient ecosystems and low input agricultural systems.
-(Soussana *et al*., 2005) found in mixtures of Lolium perenne with *Holcus lanatus* or *Festuca arundenacia* that N-use efficiency and N-uptake were negatively correlated. A high N-use efficiency, and conversely low N uptake, appeared to favour the grasses in response to elevated CO_2.

Will N fixation change at higher CO_2 and how does that influence C fixation?
-Soussana and Hartwig (1996) in a literature review (94 references), states that the responses of plants to elevated CO_2 is dependent on the availability of nutrients, especially nitrogen. Elevated CO_2 generally increases the C-N ratio in plant residues and exudates, which promotes temporary N-immobilization. In addition, both a CO_2 stimulated increase in growth (= more N requiring) and an increase in N demand for the decomposition of soil residues with a large C-N ratio will result under elevated CO_2 in a larger N-sink of the whole grassland ecosystem. To balance the high C-N ratio in an elevated CO_2 grassland environment the import of N by symbiotic N_2 fixation is one possibility. To explore this, the following hypothesis has been tested: (1) symbiotic N_2 fixation in legumes will be enhanced under elevated CO_2, (2) this enhancement will result in greater input of N in the grassland system, and (3) larger N input will allow the sequestration of additional C above or below ground. Long-term experimental data support the first two hypotheses, since (i) both the percentage and the amount of fixed N increases in white clover grown under elevated CO_2, and (ii) the contribution of fixed N to the nitrogen nutrition of the mixed grass also increases in elevated CO_2. Concerning the third hypothesis an increased N input to the grassland from N_2 fixation usually promotes shoot growth (above ground C storage) in elevated CO_2. However, the consequences of this larger N input under elevated CO_2, on the below ground carbon fluxes is not fully understood. On the one hand, the increased quantity of plant residues might result in a long-term C storage under ground; on the other hand the increased N may favour decomposition and reduce the C storage.
-The concept of increased legume development and symbiotic N_2- fixation triggered by an increased ecosystem scale demand of N under elevated CO_2, is confirmed by experiments in south England (Picon-Cochard *et al.,* 2004). DM yields were increased by 26% and N-yields by 30%. Elevated concentrations of CO_2 also affected plant competition in favour of the legumes.

How fast do grasslands react on elevated CO_2?
-Cannell and Thornley (1998) used the Hurley Pasture Model to examine the short and long term responses of British upland grasslands to elevated CO_2 under low N (5 kg N ha^{-1} yr^{-1}) and high N (100 kg N ha^{-1} yr^{-1}). In high N, elevated CO_2 quickly increased NPP, total carbon and plant biomass by 30%. In low N treatment there was a prolonged transient period when there was little response, but eventually, NPP, total carbon and plant biomass more than doubled. The delay in response was due to an N immobilization and severe depletion of the soil mineral N pool. The large response in the long term was due to an accumulation of N, as a result of decreased leaching, decreased gaseous N losses and increased N_2- fixation. This amplified the CO_2 response much more in the N poor, than in the N rich grassland. It was concluded that (1) ecosystems use larger amounts of fixed carbon at high CO_2 to acquire and retain nutrients, (2) in the long term and in the real timescale of increasing CO_2 the response of nutrient poor ecosystems may be proportionally greater than that of nutrient rich ones, (3) short term experiments on nutrient poor ecosystems may observe only the transient response, (4) the speed of ecosystems response may be limited by the rate of nutrient accumulation, and (5) ecosystems models must represent processes affecting nutrient acquisition and retention to be able to simulate the real world CO_2 responses.
-The Hurley Pasture model has been used to assess the effect of elevated CO_2 on the nitrogen cycle in grasslands (Thornley and Cannell, 2000). Elevated CO_2 enriches the organic matter in plant and soils with C, which leads to

removal of N from the soil mineral N pools into plant biomass, soil biomass and soil organic matter. Immobilization then exceeds mineralization, and the ecosystem gradually increases in N. At the same time elevated CO_2 increases N-fixation. The extra C fixed in elevated CO_2 atmosphere is used to capture and retain more N and so the N cycle follows the C cycle. However, the amount of extra N fixed and retained by the ecosystem each year is small (5-10 kg N ha^{-1} yr^{-1}) compared with the N in the immobilization -mineralization cycle (ca. 1000 kg N ha^{-1} yr^{-1}). Therefore it can take decades to centuries to gear up to higher N levels. The consequences of these relations are so complex that they probably need to be explored by modelling, and are practically impossible to explore fully by experimentation.
-Thornley (2001) used a submodel of the Hurley Pasture Model (Cannell and Thornley, 1998) for a simple approach to model the grass-legume dynamics. A target legume content of the sward was assumed to depend on the C-N ratio of the easily mobilized C and N pools of the plant. Test of the model indicates that some important aspects of grass legume competition could operate primarily through the C-N substrate ratio. This ratio may determine those characteristics of morphology, growth and function that largely determine the relative aboundance of C an N in a grass legume sward. The approach may be useful for climate change (CC) investigations.

Will the fraction of N fixating species in grassland increase at high CO_2?
-The stimulatory effect of doubled ambient CO_2 on grassland production averages about +17 % in ecosystem based experiments (Campbell and Smith, 2000). Species composition change is likely to be an important mechanism altering grassland production and its value for grazing live-stock, on average the legume content of productive grass-legume swards is increased by +10% due to CO_2 enrichment. Leaf nitrogen reductions due to elevated CO_2 are often observed, but are generally modest compared with other management factors.
-Ross *et al.* (2004) concluded that rising concentrations of atmospheric CO_2 in a multi-species ecosystem can influence species composition and increase plant productivity. Total yields did not increase significantly, but the proportions of clovers and forbs increased markedly.

What are the combined effects of CO_2 and other factors (other than N)?

Does a positive CO_2 effect on production overcome a negative drought effect?
-In a series of experiments with perennial ryegrass Casella *et al.* (1996) studied the effect of elevated CO_2 (700 ppm) at two N-levels (N+ and N-, respectively) and two water levels (field capacity (W+) or summer water deficit and drainage in winter (W-)). During both years elevated CO_2 increased the annual above ground dry matter yield of the W- swards by19% at N- and by 14% at N+, with the strongest effect in summer and smaller in spring and fall. Elevated CO_2 slightly reduced evapotranspiration during the growing season and increased drainage by 9 % during winter. There were strong interactions between temperature and CO_2 in soil moisture. Therefore the altered climatic conditions acted both directly on the productivity and the water use of the sward, and indirectly, through changes in the soil moisture content.

How large is the CO_2 effect on yield in comparison with temperature and cutting effects?
-In Australian experiments Volder *et al.* (2004) studied the grass *Phalaris aquatica* at ambient and elevated CO_2 (750 ppm) and three temperature treatments: no warming, constant warming at +3 ºC and a daytime warming of 2.2 ºC combined with a night time warming of 4.0 ºC, and two cutting frequencies. Averaged across 20 months of growth there was an 11% yield (?) increase at elevated CO_2, no effect of the temperature treatments and a negative (-19%) of defoliation. All responses were strongly seasonal with positive CO_2 response only in the spring.

How is growth influenced by CO_2 and temperature?
Pure and mixed swards of subterranean clover and phalaris grass were subjected to ambient and +3.4 degrees C and ambient and elevated CO_2 in eastern Australia (Lilley *et al.,* 2001). After more than one year under elevated CO_2, foliage clover growth in the monoculture increased by 19 % and in the mixture by 31 %. Warming reduced clover monoculture herbage production at ambient CO_2 by 28 % and reduced the growth enhancement in elevated CO_2 by +8 %. Grass was not affected by either factor. Foliage growth in the mixture was increased by 34 % in response to higher CO_2, but unaffected by warming. The two factors combined increased mixture growth by 23 %. Long term effects on species composition and persistence are not clear from these experiments.
-Marissink *et al.* (2002) measured a 30-60% higher leaf photosynthesis, an 20-40 % lower stomatal conductance, but no change in specific leaf area in shoots in semi-natural grasslands in Uppsala (Sweden) in open top chambers with elevated CO_2 (ambient +350 ppm).

How is growth influenced by CO_2, temperature, precipitation and N?

-Dukes *et al.*(2005): A California grassland was exposed to elevated CO_2, temperature, precipitation, and nitrogen deposition for five years. Root and shoot production did not respond to elevated CO_2 or modest warming. Supplemental precipitation led to increases in shoot production and offsetting decreases in root production. Supplemental nitrate deposition increased total production by an average of 26%, primarily by stimulating shoot growth. Interactions among the main treatments were rare. They suggest that this grassland will respond minimally to changes in CO_2 concentration, winter precipitation and warming. Increased nitrate deposition would have stronger effects on the grassland.

How is plant response to CO_2 enrichment related to cutting?

-Picon-Cochard *et al.* (2004) subjected monoliths of a fertile (although N limited) C_3 grassland community to an atmospheric CO_2 enrichment (600 µmol /mol), from August 1998 to June 2001, at two contrasting cutting frequencies (3 and 6 cuts per year). Elevated CO_2 affected dry matter (DM) yield of the swards (+26%) only in the second year (2000), and the nitrogen yields (+30%). With the frequent cutting, the DM of the legume was strongly increased by elevated CO_2. This effect became also significant in the second year for the low cutting frequency, where the DM of the forbs was strongly increased in elevated compared with ambient CO_2. This increased development of the forbs apparently led to a competitive decline of the grasses. The results agree with the concept of an increased legume development and symbiotic N_2 fixation triggered by an increased ecosystem scale demand of N under elevated CO_2.

Which models simulate grassland dynamics?

-Hunt *et al.* (1991) have designed a grassland ecosystems model which simulates seasonal dynamics of shoots, roots, soil water, mycorrhiza fungi, saprophytic microbes, soil fauna, inorganic nitrogen, plant residues and soil organic matter (for results, see '4. Soil').

-The Hurley Pasture Model (Thornley and Cannell, 1997) is process-based and copies the carbon, nitrogen and water cycles in the soil-grass-animal system.

-Riedo *et al.* (1998) developed a mechanistically based ecosystem model for managed productive pastures. The model simulates the annual production of plant biomass and the nitrogen balance, and seasonal patterns of growth, and of fluxes of latent, sensible and soil heat. One hour time step is used. A soil biology submodel is included. The model is designed for analysis of climatic change effects.

3. Crop quality

How does climate and CO_2 influence plant N?

How does increased CO_2-levels influence plant N or protein content?

-In field experiments with ryegrass in double CO_2 concentration (Jones *et al.,* 1996), increased C/N ratio in the tissues (lower protein content) was found.

-Schenk *et al.* (1997) studied the effect of increased CO_2 in grass and clover swards: The crude protein content was reduced at the beginning of the season only, and was increased by CO_2 in the coarse of the experiment. The yield of N was significantly enhanced by CO_2.

-Grain protein concentration decreased in spring wheat at a doubling of CO_2-concentration in two (1994 by -13 % and 1995 by -11 %) out of three seasons (1994-96), in an open top chamber experiment, close to the Swedish west coast (Pleijel *et al.,* 2000). For irrigation treatment only, there was a decrease in protein concentration (-6%).

-Protein concentration of spring wheat was negatively (linearly) related to grain yield. This relation holds when grain yield was either increased by doubling CO_2 or decreased by increased ozone levels in an open top chamber experiment, close to the Swedish west coast (Pleijel *et al*., 2000). Effects of water treatments had a minor effect.

-Marissink *et al.* (2002) measured a 5-20 % decrease in shoot N concentration in semi-natural grasslands in Uppsala (Sweden) in open top chambers with elevated CO_2 (ambient +350 ppm).

-Picon-Cochard *et al.* (2004) found in legume experiments in south England that DM yields were increased by 26 % and N-yields by 30 % at elevated CO_2. Digestibility was improved by decline in cell wall constituents and stem to leaf ratio.

How is N concentration influenced by CO_2 and temperature?

-Perennial rye grass swards were subjected to ambient and elevated CO_2 at ambient and ambient +3 degrees C at two sub-optimal and one non- limiting N-level (Soussana *et al*., 1998). At cutting date elevated CO_2 reduced the leaf N concentration per unit mass by 25 % to 33 % on average. With the non-limiting N supply the leaf N concentration (%N) declined with the shoot DM in both ambient and elevated CO_2. The regressions were significantly different between CO_2 levels and indicated a lower critical leaf N concentration in elevated than in ambient CO_2, but not for low values of shoot biomass. With the sub-optimal N supplies the ratio of actual to the critical leaf N concentration was significantly lowered in elevated CO_2. This indicated a lower inorganic N availability for the grass plants in elevated CO_2. For most cuts the harvested fraction of the plant DM decreased in elevated CO_2, due to a 45-52 % increase in the root phytomass. In the same way, a smaller share of the plant total N was harvested by cutting, due to a 25-41 % increase in the N content of roots.

How does high temperature episodes influence leaf N?
-Wollenweber *et al*. (2003) found that winter wheat plants experiencing high temperatures during the double-ridge stage reduced leaf N content by 10 %, and a heat event at anthesis reduced it by 25 %.

How does increased CO_2 -concentrations influence plant nutrient content (other than N)?
-Schenk *et al.* (1997) studied the effects of increased atmospheric CO_2 in grass and clover swards: K and Na decreased, Ca increased and P was unchanged by CO_2 enrichment. The yield of P, S, Mg and Ca was significantly enhanced by CO_2. Besides the positive effects of CO_2 quality should also be considered in response to expected global changes.
-Picon-Cochard *et al* (2004) observed for a fertile C_3- grassland community an increase in the water soluble sugar content of the bulk forage under elevated CO_2 and a corresponding decline in cell wall contents (NDF), correlated with an increased in-vitro DM digestibility. The forage quality was also indirectly affected by elevated CO_2 through changes in leaf/stem ratio and in botanical composition. At a low cutting frequency, the increased forbs content favoured the herbage quality because of a higher digestibility of the forbs shoots and, indirectly, through the reduction in the mass of the grass stems. The results emphasize the role of species dynamics for elevated CO_2 impacts on semi-natural grassland productivity and herbage quality.

How does increased CO_2 influence other plant quality parameters?
-In field experiments with ryegrass in double CO_2 concentration (Jones *et al*., 1996) there was no effect on digestibility.
-Schenk *et al.* (1997) studied the effects of increased CO_2 in grass and clover swards: Crude fibre content decreased throughout the season.
-Soluble carbohydrates (WSC), fructans, starch and total non-structural carbohydrates (TNC) in leaves of spring wheat was higher under doubled CO_2 concentration than at ambient before anthesis, indicating sink limitation. After anthesis leaf WSC and TNC decreased faster under elevated CO_2, possibly due to earlier senescence. At harvest there was no effect of elevated CO_2 left. The effect was larger due to an increase from 360 to 520 ppm than from 520 to 680 ppm. The experiment was conducted in open top chambers (Sild *et al.,* 1999).

How does elevated concentrations of ozone influence effects of elevated CO_2?
-1000-grain weight of spring wheat decreased at elevated ozone at present CO_2 levels, but remained unchanged at a doubling of CO_2-concentration, in an open top chamber experiment, close to Swedish west coast (Pleijel *et al.,* 2000).

How does a delayed sowing date influence protein concentration of barley?
-Pettersson and Eckersten (2007) found for malting barley in central Sweden a strong correlation between delayed sowing date and decreasing protein concentration.

3. Weeds

How may increased temperature promote invasion of weeds?
-Increased temperatures give rise to faster development in plants (e.g. seeding, several generations/year), which in combination with a longer vegetative period will create the conditions for more southerly species to invade and establish themselves as weeds (Glemitz *et al*., 2000).

How does increased CO_2 concentration influence C3 and C4 weed species?
-An increase in CO_2 concentration would increase net photosynthesis in C3 plants through decreased losses as regards photorespiration. In C4 plants on the other hand, an increase in CO_2 concentrations would have little effect on net photosynthesis, which would therefore increase the competitive advantage of the C3 plants (Patterson, 1995).
-In C3 crops increased CO_2 improves competition with C4 weeds (Fuhrer, 2003).
-Warming accelerates favours of C4 weeds over C3 crops (Fuhrer, 2003).

How does decreased frost influence weed development?
-Frost-intolerant species can also be expected to shift their ranges further northwards with milder winters. Examples of these are black-grass (*Alopecurus myosuroides)*, green nightshade (*Solanum physalifolium*) and common fiddleneck (*Amsinckia micrantha)* (Millberg and Andersson, 2006). At present, these species only occur in the most southerly parts of Sweden. Increasing temperatures might also allow some native ‘sleeper weeds’ to become invasive and move into habitats (arable land, etc.) where they have not previously been found in modern agriculture. Such an invasion is also strongly linked to the design of future cultivation practices and cropping systems (Fogelfors, 1979).

Which weed species might be favoured in new cropping systems?
-Maize, competes poorly against weeds, and weed species with late development and poor competitive ability, e.g. millet species, common amaranth and black nightshade (*Solanum nigrum*) are favoured. (Håkansson, 2003).
-An increase in the proportion of autumn-sown crops (e.g. wheat, oilseed rape and possibly oats), favour winter annual weeds such as black-grass and loose silky-bent (*Apera spica-venti*) while also opening the way for establishment of new species such as *Avena ludoviciana* etc. (Fogelfors, 2001; Håkansson, 2003).

3. Pests

What is known about climate influence on pests?
-Most published work on responses to weather and microclimate has dealt with crops. Less intention has been paid to pests (Monteith, 2000).

How does number of insect pest species depend on temperature?
-Yamamura *et al.* (2006) found for paddy fields in Japan that the number of rice stem borer and green rice leafhopper in summer increases with increasing winter temperatures, but the effect was not carried over to the next summer. They also studied small brown planthopper. They used a state-space model selected by Akaike’s information criterion to analyse 50 year annual light-trap data.

How are herbivorous insects influenced by temperature, CO_2, UVB and precipitation?
-Bale *et al.* (2002) found in a review that temperature is the dominant abiotic factor directly affecting herbivorous insects. There is little evidence of any direct effects of CO_2, UVB or precipitation. Temperature directly affects development, survival, range and abundance. The main effect in temperate regions is to influence winter survival; at more northerly latitudes, higher temperatures extend the summer season, increasing the available thermal budget for growth and reproduction. Photoperiod is the dominant cue for the seasonal synchrony of temperate insects, but their thermal requirements may differ at different times of year. Interactions between photoperiod and temperature determine phenology. Species with a large geographical range will tend to be less affected. They conclude that insect herbivores show a number of distinct life-history strategies to exploit plants with different growth forms and strategies, which will be differentially affected by climate warming. Future research needs to consider insect phenotypic and genotypic flexibility, their responses to global change parameters operating in concert, and awareness that some patterns may only become apparent in the longer term.

How does elevated CO_2 influence the effects of herbivores on growth?
-In a work by Diaz *et al.* (1988) aphids and garden snails were used as herbivores. Elevated concentrations of CO_2 did not have a significant impact on (1) the combined biomass of fast growing and slow growing plants, (2) herbivore feeding preferences or (3) herbivore fitness.

How does plant quality for insects change under elevated CO_2?
-Drake *et al.* (1997) concluded that reduced plant nutrient quality for insects is a possibility under CC that has been observed in field studies of the effects of elevated CO_2

How does land use influence number of aphids?
-Cocu *et al.* (2005) found that land use variables, the area of agricultural crops, in particular oilseed rape, were positively correlated with M. persicae annual numbers. Rainfall is negatively and temperature positively correlated with aphid numbers. The geographical components also explain a significant part of aphid annual numbers. However, the variance partitioning procedure indicates that while each group has an effect, none is dominant. The study was focused on the aphid *Myzus persicae*, and aspects of its environment. They concluded

that climate, land use and geographical location play a role in determining patterns of aphid annual numbers and phenology. The study also includes Sweden.

How do different methods for predicting number of aphids perform?

-Cocu *et al*. (2005) found that the variance accounted for by the ANN models ("artificial neural networks") was 6 – 44 % higher than that of the MLR (multiple linear regression) models. They conclude that the ability of ANN models to predict aphid distribution is improved by the inclusion of temporal land use data. However, identification of the processes involved in such relationships is difficult due to numerous interactions between the environmental factors. The study was on the aphid *Myzus persicae*, and aspects of its environment based on four spatial scales in Europe, including Sweden. MLR was used to identify the variables in the Geographic location, Climate and Land use groups, that explained significant proportions of the variance in *M. persicae* total annual numbers and Julian date of first capture. A variance partitioning procedure was used to measure the fraction of the variation that can be explained by each environmental factor and of shared variation between the different factors. ANNs were employed as an alternative modelling approach to determine whether the relationship between aphid and environmental variables was better described by more complex functions as well as their ability to generalize to new data.

3. Animal husbandry

What is known about climate influence on live stock?

-Most published work on responses to weather and microclimate has dealt with crops. Less intention has been paid to live stock (Monteith, 2000).

How will elevated CO_2 influence food quality to grazers?

-Surprisingly little has been published on the response to elevated CO_2 at the community level, where herbivores can select their preferred food. In this work by Diaz *et al*. (1988) aphids and garden snails were used as herbivores. Elevated CO_2 did not have a significant impact on (1) the combined biomass of fast growing and slow growing plants, (2) herbivore feeding preferences or (3) herbivore fitness.

-Drake *et al*. (1997) concluded that reduced plant nutrient quality for animal grazers is a possibility that has been observed in field studies of the effects of elevated CO_2.

-Ehleringer *et al*. (2002) pointed out in a review paper that elevated CO_2 levels will likely alter food quality to grazers both in terms of fine-scale (protein content, C/N ratio) and coarse-scale (C_3 versus C_4) changes. To herbivores, the decreased leaf protein contents and increased C/N ratios common to all leaves under elevated CO_2 imply a reduction in food quality. C_4 grasses are a less nutritious food resource than C_3 grasses both in terms of reduced protein content and increased C/N ratios. Today there is evidence that mammalian herbivores differ in their preference for C_3 versus C_4 food resources, although the factors contributing to these patterns are not clear.

How are grazing animal returns to soil influenced by elevated CO_2?

-Allard *et al*. (2003) compared nitrogen (N) returns from sheep grazing a temperate pasture exposed to ambient or elevated CO_2 (475 umol mol^{-1}). A greater proportion of dietary N was partitioned to urine at elevated CO_2, probably because of the higher proportion of legume N in the diet, with possible differences in protein quality. A potentially significant consequence of this change in partitioning is greater N loss through volatilization at higher CO_2 levels.

How may the grazing season be simulated?

-Fitzgerald *et al*. (2005) developed a dairy system simulator, 'Dairy-sim', which was found useful for evaluating the interaction of climate and management. Simulation results indicated that herbage production might vary by a proportionality factor of 0.10 between regions. The length of the grazing season may vary by 0.25. The simulator comprises three main components: a grass herbage growth model, an intake and grazing behaviour model, and a nutrient demand model that was parameterized using the Irish National Dairy Blueprint. The simulator was most sensitive to stocking rate, milk output per cow and nitrogen fertilizer inputs, but less sensitive to other variables. Field data from four grazing systems were used to test the simulator.

3. Biodiversity

How does increased CO_2 influence species composition?

-In controlled environment experiments with elevated CO_2 (Newton *et al.,* 1995), species composition changed: The grasses *Paspalium* and *Lolium* declined and the legume white clover increased, due to CO_2 induced differences in axillary bud activity.

-Schenk *et al.* (1997): The white clover content of all swards was significantly enhanced by elevated CO_2

-Marrisink and Hansson (2002) found that elevated CO_2 (ambient + 350ppm) influenced species composition in a semi-natural grassland in Uppsala (Sweden). However, the effect was weak and difficult to distinguish from time related effects due to changing weather conditions and changes in management (from being grazed by horses to seasonal cutting). Diversity (Shannon index) increased during summer but decreased during spring. The experiment was conducted in small open-top chambers over a six-year period.

-Ehleringer *et al.* (2002) point out in a review paper that elevated CO_2 levels will likely alter food quality to grazers both in terms of fine-scale (protein content, C/N ratio) and coarse-scale (C3 versus C4) changes. The abundance of C3 and C4 plants (particularly grasses) are affected by CO_2. C4 grasses currently predominate over C3 grasses in warmer climates and their distributions expand as atmospheric carbon dioxide levels decreased during glacial periods. There is an indication that as C4-dominated ecosystems expanded 6-8 Ma B.P., there were significant species-level changes in mammalian grazers.

-Teyssonneyre *et al.* (2002a) found that elevated concentrations of atmospheric CO_2 significantly increased the proportion of dicotyledons (forbs + legumes) and reduced that of the monocotyledons (grasses). Management differentiated the response. At infrequent defoliation elevated CO_2 increased the proportion of forbs, whereas at frequent defoliation the proportion of legumes increased. They concluded that the botanical composition of temperate C3 grasslands is likely to be affected by the current rise in the atmospheric CO_2 concentration (+ 0.5% per year), and that grassland management guidelines may need to be adapted to a future high CO_2 world. The experiment was monoliths of a fertile, N limited, grassland subjected to atmospheric CO_2 enrichment (600 µmol/mol) using a Mini-FACE system, from August 1998 to June 2001 in two contrasting cutting frequencies (3 and 6 cuts per year). Between the two dominant forbs species, only one was significantly enhanced by elevated concentrations of CO_2. Not all grass species responded negatively to high levels of CO_2. At a low cutting frequency, the observed decline in species diversity (Shannon-Weaver index) and in forbs species number under ambient [CO_2], was partly alleviated by elevated CO_2.

-Ross *et al.* (2004) concluded that rising concentrations of atmospheric CO_2 in a multi-species ecosystem can influence species composition and increase plant productivity After 5 years of elevated [CO_2]-exposure increased availability of N is suggested, probably because of increased inputs from N-fixing clovers.

How does increased CO_2 influence seed production and dispersal?

-Edwards *et al.* (2001) measured seed production and seedling recruitment over 2 years under ambient (360 ppm) and elevated (475 ppm) atmospheric CO_2, in a sheep-grazed pasture on dry, sandy soil in New Zealand. In both years elevated CO_2 led to more dispersed seeds of the three European grass species, two legumes and two herb species. The increased seed dispersal reflected both more inflorescences per unit area and more seeds per inflorescence under elevated CO_2. They concluded that elevated concentrations of CO_2 influenced plant species composition in the pasture through changes in the pattern of seedling recruitment.

How does temperature influence competitiveness between C3 and C4 plants?

-C4 plants are favoured over the photosynthetically more primitive C3 plants by warm humid climates and conversely C3 plants by cold climates. Model calculations and analyses of current plant distribution suggest a mean temperature of 22 degrees for the warmest month to be the cross over temperature at present CO_2 concentration. C4 plants can be competitively excluded by trees regardless of photosynthetic superiority of the C4 pathway (Collatz *et al*., 1998).

What can transects of plant diversity tell?

-A method based on multi-scale vegetation plots established across forest ecotones, which provide baseline data on patterns of plant diversity, invasions of exotic plants species and plant migrations at landscape scales (Colorado, USA) is proposed by Stohlgren *et al.* (2000). Replicate transects along several environmental gradients may provide the means to monitor plant diversity and species migrations at the landscape scale.

-Lal (2005) mention that there is a strong relation between soil biodiversity and the increased labile fraction of SOC.

How to model species composition from resource use?

-Teyssonneyre *et al*. (2002b) hypothesized that species response to elevated CO_2 in mixtures can be explained by taking into account resource partitioning between species. The dry matter yield response to CO_2 in a mixture may be predicted from both the species response in monoculture and the light capture per unit leaf area in ambient CO_2 of the mixed compared with the pure grasses. The hypothesis was tested experimentally on three perennial C3 grass species (*Lolium perenne*, *Festuca arundinacea* and *Holcus lanatus*) grown in monocultures and in binary mixtures (Lolium-Festuca and Lolium-Holcus) under mild competition (frequent cuts) or severe competition (infrequent cuts) for light. N supply was high (40 g N /m^2). Under mild competition for light, the dry matter yield response to elevated CO_2 of the mixed grass species was similar to that observed in monocultures. By contrast, under severe light competition, the grass species that absorbed more light per unit leaf area (Holcus and Festuca), also had a greater response to elevated CO_2 in mixture compared with monoculture.

How to address local-scale effects on biodiversity in CC modelling studies?

-del Barrio *et al*. (2006) made a modelling study using integrated approaches to analyse fine-scale impacts of CC on species distributions within two contrasting regions (UK and Spain). They concluded: (i) CC involves the development of transient conditions and fragmentation within the core of species distributions; (ii) CC would favour the opening of gaps within the current vegetation zones, rather than a simple zonal shift of them. In the study four models were integrated (a continental scale bioclimatic envelope model, a regional scale bio-climate and land use suitability model, a dispersal model, and a connectivity model). Eight and six species respectively were used to test the approach under three climate change scenarios. They conclude that dynamic and integrated conservation policies are required, that take account of the current and potential future spatial arrangement of species and their habitats, to assist species to respond to future environmental change.

3. Environment

How does climate influence emissions from agriculture?

How does climate influence C emissions?

-A model was developed to calculate carbon fluxes from agricultural soils. (Vleeshouwers and Verhagen, 2002). Carbon emission from arable land and grassland was estimated to vary considerably in response to crop x soil x climate interactions. Rise in temperature by 1 degree decreased carbon emission with 0.05 t C ha^{-1} $year^{-1}$, whereas rising CO_2 concentrations gave an increase of 0.01 t C ha^{-1} yr^{-1}.

How does climate influence N emissions?

-The IPCC estimates that over 50 % of the total N_2O emission in New Zeeland derives from animal excreta during grazing. In this work of de Klein *et al.* (2003) the N_2O emission factor was refined. For cow urine it was found for the first four months after urine application to vary greatly depending on rainfall and soil drainage class, and ranged from 0.3 to 2.5 % of the urine N applied, suggesting that adopting a single emission factor for New Zeeland might be wrong. The largest emission factor was found in a poorly drained soil, and the lowest on a well drained soil. To characterise urine induced N_2O emissions it was recommended to continue measurements more than 4 months allowing the soil to return to background emission levels.

-Increased rainfall by 20 % was modelled (DAISY-model) to increase GHG emissions with 11-53 kg CO_2-eq ha^{-1} yr^{-1}, for three types of crop rotations in Denmark (Olesen *et al*., 2004). Increased temperature by 4 ºC increased GHG emissions by 66-234 kg CO_2-eq ha^{-1} yr^{-1}.

May considerations of crop type and climate improve N_2O emission estimates?

-Flynn *et al.* (2005) used a method to calculate N_2O emissions that takes into account crop type or climatic conditions, not considered in IPCC guidelines, and the trampling effects from grazing animals, for Scotland. The new method produces significantly higher estimates of annual N_2O emissions than the IPCC default method. On a spatial basis, emission levels are closer to those calculated using field observations and detailed soil modelling than to IPCC estimates.

How does CO_2 influence N emissions?

How does high levels of CO_2 influence N_2O emissions in crops?

-The N_2O emissions from spring wheat decreased at doubling CO_2, from anthesis until harvest. After harvest the N_2O emissions increased, but was the same for elevated and ambient CO_2. The results were from an open top chamber experiment north of Gothenburg in Sweden (Pleijel *et al.,* 1998). The protein content of spring wheat was higher at elevated CO_2 suggesting that microbes competed harder with plant for N, than at ambient CO_2.

-Increased atmospheric CO2 by 50% was modelled (DAISY-model) to increase GHG emissions with 180-269 kg CO2-eq ha^{-1} yr^{-1}, for three types of crop rotations in Denmark (Olesen *et al*., 2004).

How do high levels of CO_2 influence N_2O emissions in swards?
-Elevated CO2 increased N_2O emission from high-fertilized swards of ryegrass, and a mixture of ryegrass and white clover in an experiment in Switzerland (Baggs *et al.,* 2003). The emission from monoculture white clover was not affected by elevated CO_2. The greater emissions from high fertilized ryegrass at elevated CO_2 were attributed to greater below ground allocation under elevated CO_2 providing the energy for denitrification in the presence of excess mineral N. An annual emission of 959 mg N_2O m^{-2} yr^{-1} (= 1.7 % of fertilizer N applied) was measured from the high fertilized ryegrass under elevated CO_2. Emission varies with rainfall and caution is therefore required when extrapolating from short- term measurements. Thus elevated CO_2 may, depending on sward composition and fertilizer management, increase green house gas emission of N_2O. When applying high rates of N fertilizer to grassland systems, pure white clover stands, or mixed swards with a greater proportion of white clover, may minimize the negative effect on global warming of increasing atmospheric CO_2.
-Swiss experiments with ryegrass (Baggs *et al.,* 2003) supported the hypothesis that increased below ground C allocation under elevated CO_2 provides energy for denitrification. Nitrification was the dominant N_2O producing process under ambient CO_2 whereas denitrification was predominant under elevated CO_2. The N_2:N_2O ratio was often higher under elevated CO_2 suggesting that previous estimates of gaseous N losses based only on N_2O emission have greatly underestimated the loss of N by denitrification.

How large are emissions?

How large are N_2O emissions?
-N_2O emission from fertilized humid grassland in Ireland was continuously measured during 2003 using an eddy covariance system (Heleh *et al*., 2005). For most of the year emission was close to zero, and 60% of the emission occurred at eight major events of 2 to 20 days duration. 207 kg N /ha of synthetic N and 130 kg N /ha of organic N was applied over the year.

How large are GHG emissions from agriculture of different European countries?
-An alternative and compatible method to the IPCC guidelines for estimates of gaseous emissions has been developed by Fribauer (2002). It relies on emission factors and regression equations derived from all long term measurements in Europe available by the end of 2001. As a result in 1995 European agriculture emitted 0.84 ± 0.19 Tg N_2O 8.1 ± 2.0 Tg CH_4 9 ± 25 Tg CO_2, which adds up to 470 ±80 Tg CO_2-equivalents, 11% of the overall GHG emissions. These figures are surprisingly close to UNFCCC inventory, but compared to the overall EU figures, the approach taken here leads to higher agricultural CH_4-emission in Austria and the Netherlands, at least 20% lower CH_4-emission in Denmark, Germany, Greece, Spain and Sweden, and higher N_2O emissions in most EU states. It is concluded that the calculations given here are better than the IPCC guidelines.

How does cropping system influence emissions?

Do organic soils significantly contribute to overall N_2O emissions?
-Fribauer (2002) estimated that in countries with even small areas of farmed organic soils, CO_2 emitted from peat oxidation can significantly contribute to the overall GHG emissions.

How much do cropping systems influence emissions?
-Frank *et al.* (2001) used the Bowen ratio/energy balance (BREB) technique to measure CO_2 fluxes over a mixed-grass prairie at Mandan, ND, in 1996-1999. Results suggest that the C budget of Northern Great Plains mixed-grass prairie grasslands may be near equilibrium.
-Greenhouse gas (GHG) emission reduction of multi-product cropping systems is 3-4 times larger in the Netherlands than in Poland (0.2-2.4 versus 0.9-7.8 CO_2 eq per ha and year. Greenhouse gas (GHG) emission reduction is not lowered by multi-product cropping systems. Further research on large scale multi-product systems and their impact on land is desirable (Dornburg *et al*., 2005).
-Two models for N_2O emission from crops and grasslands were developed. The models demonstrated inter annual variation in N_2O emission from cropland but not from grasslands. The models can be used for estimation of inter annual variation in N_2O emission at the regional scale (Roelandt *et al*., 2005).

How much do N fixing crops influence emissions?
-Rochette and Janzen (2005) have reviewed the literature on N_2O emissions from agricultural soils (73 references), and found no evidence for specific N_2O emissions related to the biological N- fixation. The average emissions from legumes are 1.0 kg N ha^{-1} for annual crops, 1.8 kg N ha^{-1} for pure forage crops and 0.4 kg N ha^{-1}

for grass-legume mixtures. The N_2O emissions from legumes are therefore a result of root and shoot decomposition and not a direct result of the N-fixation process.

Which factors in animal husbandry influence greenhouse gas emissions?
-Gas abatement strategies for animal husbandry is reviewed by Monteny *et al.* (2006); (55 references). The rumen is the main source for methane production, especially in cattle husbandry. Less, but still substantial amounts originates from cattle, pig and poultry manure. The main sources for nitrous oxide are: nitrogen fertilizers, land applied animal manure and urine deposit from grazing animals.
-The main uncertainties in estimating GHG emissions in milk production are lack of understanding of the biological systems, poor validation of results and weather-induced variability (Gibbons *et al.*, 2006).

How do N_2O emissions respond to fertilization?
-For fertilized humid grassland in Ireland (Heleh *et al.*, 2005) a reduction of fertilization from 207 to 170 kgN/ha (there was organic fertilization of 130 kg N/ha, not changed) reduced annual modelled N_2O emission from 22.4 kg N /ha, to 21.2 kg N /ha (to comply with recent EU water supply legislation).

How does land use and CO_2 influence uptake of atmospheric CO_2?
-Berry and Roderick (2006) estimate an averaged rate of increase in living vegetation (roots, stems and leaves; 'C-living'; CSI) of about 50 TgC /year over the last 200 years for the continent, due to increased CO_2 and changed land use. Where wooded areas have been extensively cleared for agriculture, the CSI is negative (down to -4g C m^{-2} /year. Elsewhere, the CSI over the last 200 years ranges from similar to 55 g C m^{-2} /year in the tropical and subtropical forests to similar to 0 g C m^{-2} /year in the most arid regions. The change resulting from CO_2 alone is the difference between the nveg280[2]) and nveg350[5]) scenarios. The estimated 'C-living' for the continent is 21 Gt for pveg350[5]) for the present vegetation (i.e. 1988); 23 Gt for nveg350 a hypothetical natural vegetation (in 1988); and 10 Gt for 350 µmol /mol, the natural vegetation (in 1788). They used a tractable and transparent approach (the TMSC model) to estimate the total stock of carbon (roots, stems and leaves) in (C-living), based on gross primary productivity (GPP) estimates. The TMSC model utilises the TMS scheme of canopy functional types and a generic allometric scheme to derive these estimates. Model estimates are presented for the Australian continent under the following three vegetation-[CO_2] scenarios: (1) the present (1988) vegetation (pveg350) and (2) a hypothetical natural (1988) vegetation cover with atmospheric CO_2 concentration ([CO_2]) of 350 µmol /mol (nveg350), and (3) the natural vegetation (1788) having [CO_2] of 280 µmol /mol (nveg280). The change between the nveg280 and pveg350 scenarios represents the combined effects of changes in land use and CO_2.

How may emissions be predicted?
Which are the important feedback mechanisms between cropping systems and their emissions?
-In a general survey Smith and Almaraz (2004) states that crop production and climate change affect each other because crop production (1) produces greenhouse gases, (2) is affected by climatic change, (3) will have to adapt to changed climatic regimes and (4) has a potential role in mitigating the production of greenhouse gases. Agriculture is a major producer of methane and nitrous oxide, but a minor producer of CO_2.

Which methods exit to predict emissions?
-The IMAGE 2.0 and TVM are important models for calculation of the greenhouse gas fluxes between the terrestrial biosphere and the atmosphere and global vegetation characteristics respectively (Leemans and Vandenborn, 1994).
-A standard method from IPCC estimates direct N_2O emissions from soils as a constant fraction (1.25%) of the nitrogen input (Roelandt *et al.,* 2005). This is not good enough, and therefore two empirical models (for croplands and grasslands, respectively) were developed to calculate N_2O emissions as a function of spatial and temporal variation in environmental conditions. In the cropland model spring temperature and summer precipitation explained 35 % of the variation. In the grassland model fertilizer rate and winter temperature explained 48 % of the variation. The models can be used to estimate the effects of inter-annual variation in climate and climate change on direct N_2O emission from soils at the regional scale.
-Schills *et al.* 2006, using detailed farm data, concluded that the N surplus at the farm level is a useful indicator of GHG emissions.
-Two multiple regression models were developed for the N_2O emission as driven by fertilizer, topsoil, organic carbon and sand content (Freibauer and Kaltschmitt, 2003). One model was derived for soils in the oceanic,

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[2] For explanation, see end of this summary.

temperate west of Europe and one for sub-boreal Europe. In the first area the average emission rate was below 2 kg N_2O ha^{-1} yr^{-1} and rarely exceeded 5 kg N_2O ha^{-1} yr^{-1}. In the second area the variation was larger, between 0 and 27 kg N_2O ha^{-1} yr^{-1}, dependent on available N. Compared to existing methods for large scale inventories, the present regression models allow a better regional fit to measured values, since they integrate additional driving forces for N_2O emissions.

How well do models reproduce measured N_2O emissions?
-For fertilized humid grassland in Ireland Heleh *et al.* (2005) compared measured N_2O emission with model predictions, resulting in a 32 % overestimation by the models.

3. Land use

Are components of agricultural systems sensitive?
-Kerr *et al.* (1999) suggested from preliminary results of a Scottish study that individual components of the agricultural system appear to be inherently robust and adaptable.

In what ways does climate influence land use?
-Rounsevell *et al.* (2003) simulated the use of agricultural land using a whole farm model (SFARMOD; Audsley, 1993) based on both socio-economic and biogeophysical factors, and with the main assumption that land use is ultimately determined by the farmer trying to maximise the profit. They tested the model for two regions in UK and concluded that it well explains the spatial variation in land use. An important part of the model was to simulate the timeliness and crop rotational penalties on costs for workable hours (Audsley, 1981) and crop growth (simulated with the ACCESS model; Mayer *et al.*, 1996).

How does choice of crop depend on climate?
-Danish EPA (2005) states that the maize area in Denmark has increased from 0.4% of total agricultural land in 1980 to 4.4% in 2003, in part as a consequence of a warmer climate.

How might a longer growing season influence the choice of crops?
-Kerr *et al.* (1999) stated that a longer growing season in Scotland would increase the diversity of crops, with the potential of higher value crops, such as fodder maize, sugar beet and increased areas of oil seed rape.

How is land use modelled?
-Veldkamp and Lambin (2001) discuss different aspects of modelling land use. Most often models are either considering a single process or a single discipline, like economy. Two new approaches for considering scales have evolved, one with fixed spatial units combined with spatial regression analysis, and one with flexible spatial units, like farms. Most models deal with impact of land use on biophysical processes. A new approach is needed which should consider feedbacks between biophysical processes and land use, for instance, the influence of C sequestration goals on land use.
-Ewert *et al.* (2005) described the ATEAM model used to estimate land use changes. The model is based on the assumption that the productivity per region (P*L) is equal to the demand of that region (D) times a surplus fraction (O) (i.e. $P_0*L_0 = D_0*O_0$). The land use in the future (L) can then be estimated assuming a value for overproduction in future (O) and using models to estimate productivity per ha (P) and demand (D). The variables depend on each other and an optimisation is needed.

How well is land use modelled?
-Ewert *et al.* (2005) applied the ATEAM model for historical data (1960-2000) and found, as an average for Europe, that demand (D) increased by 50 %, the oversupply fraction (O) increased from 0.9 to 1.2, and the technology factor increased ha yield (P) by 140% ($P/P_0 = 2.4$). This gave a change in land use area (L) of –19 % ($L/L_0 = 0.81$). The observed change in land use area was –15%.

4. Climate change impact assessments on agriculture

Climate change impact assessments on crop production have been done for many countries in the world. Studies directly aiming for Swedish conditions are comparable few, and therefore a question is to what extent studies made elsewhere can be useful for assessing impacts on Swedish agriculture. The assessments have been made on different scales ranging from controlled laboratory experiments, fields up to region and national and even global levels. Depending on scale, different mechanisms of the agricultural system are significant. The aim of this section is to present climate change (CC) impact assessment studies on crop production, and related effects on the environment and the use of the agricultural land. The assumptions they are based on are presented in those cases they are found in the abstracts concerned.

4. Methods

Which model approaches exist, to make CC assessments?

-There is insufficient information to predict the response to climate change of primary production of forests and grasslands. However, predicting production from light interception and conversion efficiency is a promising approach (Long and Hutchin 1991)

-The IPCC has developed a simple approach for calculating soil C sequestration and new parameters have been determined by Ogle and Paustian (2004). The procedure provides a methodological framework for countries to derive region specific coefficients.

-The current knowledge of carbon cycling and sequestration is discussed by Soussana *et al*. (2004) (58 references). They fitted a two parameter model to literature data. Temperate grasslands account for about 20% of the land area in Europe and carbon accumulation in these systems occur mostly below ground. They also discuss carbon fluxes within the context of farming systems, including crop – grass rotations and farm manure applications.

-Changes in climate modify crop yield and variance in a way that is specific for the crop (Chen and Schimmelpfennig, 2004). This variance can be estimated from observed variance projected into a climatic change scenario.

Which climate factors are considered in CC assessments?

-Climate warming concerns based on daily temperature may be less important than rising night temperatures on crop growth (Krupa, 2003).

-For estimation of the effect of climate change on national productivity of wheat it is not necessary to apply detailed climatic information for Denmark (Olesen *et al*., 2000).

Which factors have been modelled, and which need further modelling?

-Our present knowledge of the *joint* effects on crops of increased [CO_2], ultraviolet B-radiation and ozone is virtually zero according to Krupa (1997).

-In a comprehensive literature survey Tubiello and Ewert (2002) conclude that about 20% of all crop modelling studies since 1995 have focused on climatic impact studies. Half of these explicitly concerned the effect of increased CO_2 on production. To improve confidence in predictions the authors recommend: (i) continued model evaluation with existing field experiment data; (ii) increased focus on limiting factors such as pests, weeds and diseases; and (iii) attention to temporal and spatial scaling issues.

-Effects of changing climate on crops are often based on univariate studies (Krupa 2003). Limited bivariate studies may suggest that the effects of increased CO_2 and O_3 may offset each other.

-To predict global change impact on agriculture much work has been devoted to models for plant production. Some of these models concern whole cropping systems and the most comprehensive model in that respect appears to be the work of Jones *et al.* (2003). This package incorporates models of 16 different crops with modules for weather, soil (water, carbon, nitrogen, and temperature), soil-plant-atmosphere, crop growth, management and pests. The model has capabilities to deal with the plant-soil- pest interactions in various cropping systems under a specified sequence of years. This work is published by 10 American scientists in European Journal of Agronomy with more than 150 references.

Are global effects of CC possible to assess from global mean temperature rise alone?

-Hitz and Smith (2004) surveyed the literature to assess the state of knowledge with regard to the presumed benefits of reducing GHG emissions to lower levels. They reviewed published studies addressing global impacts of climate change. The criterion they used for quantifying the degree of climate change was increase in global mean temperature (GMT), and their analysis focused on determining the general shape of the “damage curve” expressed as a function of GMT. The studies examined covered a wide variety of sectors, e.g. sea level rise, agriculture, water resources, human health, terrestrial and marine ecosystems productivity, and more. They found that some sectors exhibit increasing adverse impacts with increasing GMT, e.g. biodiversity and possibly marine ecosystem productivity. Other sectors are characterized by a parabolic response to temperature (i.e., benefits at lower GMT increases; damages at higher GMT increases), in particular agriculture, terrestrial ecosystem productivity, and possibly forestry. One consistent pattern seemed to be that beyond approximately a 3-4 ºC increase in GMT, all the studied sectors, possibly except for forestry, show increasing adverse impacts. However, the authors found important uncertainties in the studies surveyed which prevented them from a precise identification of this critical ‘threshold’.

4. Soils

How do CC influence soil organic matter?

-Soil organic C pool was predicted, using SOIL/SOILN models, to decrease by 5-10 gC m-2 y^{-1} (10-15%) more under CC (ΔT =+1.7 to +2.1 ºC, ΔP =+4 to +22% and CO_2 =515 ppm*)* than at present climate for a mono crop sequence of winter wheat in Sweden (Eckersten *et al.*, 2001). Soil organic N storage was predicted to change in similar relative terms.

-The rate of residual C addition to the soil is the primary factor that controls simulated soil organic matter for Ohio cropland under continuous corn, wheat and oats for the period 1866-1996 (Evrendilek and Wali, 2001). Also, the interaction of CO_2 fertilisation and a temperature increase of 0.5 °C decreased mean soil organic matter under the same conditions and time period. Calculations show that long-term change in soil organic matter is a measure of change in atmospheric CO_2.

-Sindhöj *et al.* (2006) projected a reduced loss of soil C under doubled CO_2. Semi-natural grassland under doubled CO_2 in Uppsala region lost 70 g C/m^2 during a 30- year period compared to 90 g C/m^2 at current CO_2 levels. The main reason of a lower decrease under elevated CO_2 was due to increased litter input, which overcomes increased decomposition rates. They used the ICBM model calibrated to a six-year open top chamber experiment.

-In a surveying paper by Maracchi *et al.* (2005) on the impacts of present and future climate variability on agriculture and forestry in Europe (ACACIA project) they quoted that agriculture may be negatively affected with (increased) risk for nutrient leaching and accelerated breakdown of soil organic matter. Adaptation management strategies should be introduced to reduce the negative impacts on the agricultural and forestry sectors.

How will soil microbial community change under CC?

-Experimental results of Kandeler *et al.* (1998) suggest that on soils with low nutrient availability the effects of CC on the soil microbial community and processes are likely to be small and largely unpredictable.

How will the soils C stock change under CC?

How might the European soil C stocks change under CC?

-Increased soil temperature and moisture will tend to speed-up decomposition and cause soil carbon stocks to decrease, whereas increases in carbon input with increasing NPP will slow the loss. Technical improvement will further increase C input. Changes in crop- and grassland areas will further affect the total carbon stock in Europe. Considering all factors, crop- and grassland soils show a small increase in soil C under future climate: 1-7 t C /ha for cropland and 3-6 t C /ha for grassland, but when the decreasing areas is considered the total European C pool will decrease. (Some data on variation and uncertainties are also given). These results were achieved in a pan European survey by Smith *et al.* (2005b) (45 references; similar to Ress *et al.*, 2005), estimating soil carbon on a European 10 x 10′ grid using climate data from four global climate models.

-Schröter *et al.* (2005) estimated the soil organic C storage of Europe to decrease by 0.1 (IPCC scenario B1) to 4.8 (scenario A2) Pg C (0-30 cm depth) by 2080 depending on driving socio-economic scenarios. Main contributor was a decrease in cropland C storage by 4.8 to 5.9 Pg C. C storage of grassland decreased for all scenarios except for one (B2). Forest soil C increased by 0.7-3.6 Pg C.

How might the soil C stocks change under CC, world-wide or generally?

-A warming of ecosystems world wide caused soil carbon to decrease overall, especially in cold desert and temperate steps. Increased production due to elevated CO_2 tended to make tropical savannas to soil carbon sinks actually. The estimates were done using the model CENTURY (Hall *et al.* 1995) to assess effects of climate change.

Will the biosphere act as a C sink or a C source in the future?
-The terrestrial biosphere is predicted to be a net sink for carbon over practically all of the 21st century (Levy *et al.* 2004). This sink peaks around 2050 and then diminishes rapidly towards the end of the century as a result of climate change.

How does CC influence soil organic matter?

-Hunt *et al.* (1991) found by simulation that doubling CO_2 (1) caused persistent increase in primary production, in despite of greater nitrogen limitation, and (2) led to greater storage of carbon in plant residues and soil organic matter. The increased carbon storage was not great enough to keep pace with the present rate of increase in atmospheric CO_2.
-Using the Hurley Pasture Model Thornley and Cannell (1997) draw three conclusions about the operation of grasslands as carbon sinks: (1) increasing CO_2 alone will produce a carbon sink, as long as it continues to accelerate photosynthesis and increase NPP; (2) by contrast, increasing temperatures alone are likely to produce a carbon source, because soil respiration is accelerated more than NPP, even when assuming the same temperature function for most soil and plant biochemical processes; (3) the net effect of projected increases in CO_2 and temperature is likely to be a carbon sink of 5-15 g C m^{-2} yr^{-1} in humid temperate grasslands for several decades, which is consistent with the magnitude of the hypothesised current global terrestrial carbon sink.
-CENTURY is a model of terrestrial biogeochemistry based on relationships between climate, management, soil properties, plant productivity and decomposition (Parton *et al.* 1993). The grassland version of the model was tested on data from 11 grasslands around the world. Soil C and N and plant biomass could be simulated within +/- 25% of observed values. Results indicate that prediction of plant and soil organic matter (C and N) dynamics requires knowledge of climate, soil texture and N inputs. Using the model, (Parton *et al.* 1995) simulated climatic change to increase net primary production in 31 temperate and tropical grassland sites, except in cold dessert steppe, and elevated CO_2 to increase production everywhere. Climate change caused soil C to decrease overall, with a loss of 4 Pg from global grasslands after 50 years. Combined climate change and elevated CO_2 increased production and reduced global grassland C losses to 2 Pg.
-Using the Terrestrial Ecosystems Model (TEM), a series of empirical regression equations were developed to describe changes in global SOC (soil organic carbon) (McGuire *et al.* 1995). The study suggested that the maximum loss of SOC to the atmosphere per °C warming is less than 2 % of the terrestrial soil carbon inventory. Because the NPP response to elevated CO_2 has the potential to compensate for this loss, a scenario of an accelerated greenhouse warming due to an enhanced CO_2 emission from SOC (i.e. due to a positive feedback mechanism) is unlikely, unless a land use change or changes in vegetation distribution takes place.

How is C sequestration influenced by changes in water conditions under CC?
-In a semi-arid natural grassland in Alberta, Canada, long-term rate of C accumulation under current climate was 26 g C m^{-2} yr^{-1} (Li *et al.*, 2004). Under CC increases in transpiration caused by rising temperatures were fully offset by decreases in transpiration caused by rising CO_2, thereby alleviating water deficits and lengthening growing seasons. The consequent rise in grassland net primary production was largely offset by a rise in heterotrophic respiration so that C sequestration rose by less than 2 g C m^{-2} yr^{-1} under CC.

How is the carbon cycle in grasslands influenced by CC?
-Rising temperatures are supposed to increase decomposition of soil organic C leading to increased CO_2 production and this extra CO_2 implies a positive feedback, which will raise the temperature further (van Ginkel *et al.*, 1999). Negative feedbacks also exist: more primary production is allocated to roots at elevated CO_2, and these roots decompose more slowly than roots grown at ambient CO_2 levels. Experimental data and modelling showed that increased below-ground C storage will be more than sufficient to balance the increased decomposition of soil organic matter in perennial ryegrass. Once a doubling of the present atmospheric CO_2 has been reached, C equivalent to 55% of the annual CO_2 increase above a 1 ha ryegrass can be withdrawn from the atmosphere. Thus, grassland soils represent a significant sink for rising atmospheric CO_2.

How are run off and soil erosion influenced by CC and crop?

- A simulation study by Brown *et al.* (2000) showed that precipitation increases under CC resulted in greater runoff from the traditional crops but not from switchgrass due to the crop's increased growth and longer growing season. Simulated soil erosion rates under switchgrass were less severe than under corn management. However, simulated erosion under switchgrass was considerable in eastern Iowa during the period of crop establishment because of strong winds at that time. (For the experimental description, see "4. Crop productivity" in this report.)

How will N mineralization change under CC?

-Net N mineralization rate of the grassland was modelled to decrease under doubled CO_2 (Chen *et al.*, 1996). For C3 grass the decrease was 3% and 2% at normal and high temperatures, respectively. Corresponding figures for the C4 grass were 5% and 6%. N mineralization increased with precipitation in both C3 and C4 species. Elevated CO_2 decreased N mineralization in the C4 system. The effect of elevated CO_2 on N mineralization varied with precipitation and temperature. Elevated temperature decreased N mineralization under dry conditions, but increased it under wet conditions. Thus, there were strong interactions among the effects of CO_2 enrichment, precipitation, temperature and species on NPP and N mineralization. The predictions were made with the Version GEM2 ecosystem model.

-Burke *et al.* (1997) used field observations, the Century simulation model and regression analyses to simulate net N mineralisation in the central Grassland region of USA. The analysis indicates that NPP and net N mineralisation both increase with annual precipitation; thus it is not possible to separate the extent to which annual NPP is controlled by water or N availability. Nitrogen use efficiency increases with increasing precipitation across the region. Above ground NPP decreased with increasing temperature across the region, while N mineralisation increased slightly, leading to decreasing nitrogen use efficiency with increasing temperature.

-Using soil warming cables and devices to control rainfall and irrigation, Jamieson *et al.* (1998) studied soil N mineralisation in semi-natural calcareous grassland in southern England. Results from control plots showed a strong seasonality of N mineralisation with highest rates in autumn and winter and lowest rates in summer. Water availability appears to be the main constraint on microbiological activity and plant growth. Summer drought significantly increased N mineralisation rates in autumn and winter. Winter warming had no direct effect on N mineralisation in winter but decreased rates in spring. It is postulated that the observed treatment effects result from changes in organic C and N input in plant litter, resulting from the direct impact of climatic manipulation on perennial plant growth, death and senescence.

-Net N mineralisation was predicted, using SOIL/SOILN models, to increase by 14-26% under CC ($\Delta T = +1.7$ to $+2.1\ ^{o}C$, $\Delta P = +4$ to $+22\%$ and $CO_2 = 515$ ppm*)* than at present climate for a mono crop sequence of winter wheat in Sweden (Eckersten *et al.*, 2001).

4. Crop productivity

How are hectare yields and quality influenced by CC?

-Wheeler *et al.* (2000): Within temperate regions, CC will cause current cultivars of determinate annual seed crops to mature earlier, and hence yields will decline. This negative effect of warmer temperatures should be countered by increased rate of crop growth at elevated CO_2, if water is sufficient.

-The possible impacts of climatic change on European agriculture was summarised by M. L. Parry in the *1998 Bawden Lecture* (Parry, 1998). The evaluation is based on works by Parry (1990); Harrison *et al.*, (1995); IPCC (1997), and mostly concerns effects at c.2050 under the IPCC IS92a scenario ("business-as-usual"). (i) A doubling of atmospheric CO_2 concentration from 330 to 660 ppmv can be expected to cause a 10-50% increase in growth and yield of C3 crops and a 0-10% increase for C4 crops (such as maize and sugarcane) according to Warrick *et al.* (1986), much depending, however, on the prevailing growing conditions (confer the statements by Steffen and Canadell (2005), referred to above). (ii) Concerning the overall effects on crop yields and changes in location of zones suitable for different crops, due to the anticipated climate change: "Increased rates of maturation, and reduced risk of early and late frosts, are likely to lead to a northward shift of crop potential throughout Europe. There is a strong likelihood that zones of suitability for grain maize will extend into southern Sweden, southern Finland and the Baltic states…" (iii) "Accounting for the enhancement of growth resulting from increasing CO_2 concentrations, the yield of winter cereals (largely C3 crops) increases across most of Europe. In the case of winter wheat, the rate of increase in yields across Europe could be 0.20-0.13 t/ha/decade. The largest increase per country might occur in northern Europe, because of increased possibilities of converting from spring to winter cereals."

-Trnka *et al.* (2004) found in a simulation study that the effect of climatic change on barley yield in central and Western Europe was mostly negative: -19% to +5%. The effect of doubled CO_2 concentration was 13-52 % increase. Earlier planting dates (up to 60 days) would increase yield with 15-22% in 2 x CO_2 conditions. Use of cultivars with longer vegetation duration would bring 1.5% yield increase per one extra day of vegetation period. Initial soil water increased yields by 50-100 kg ha^{-1} per 1% increase in available soil water.

-Crop production and yield in Finland under CC will be influenced by lengthening of potential growing season, accelerated development of plant, on average increased plant productivity, changed risk of frost and winter damage and that over-wintering of plants can deteriorate (Carter and Kankaanpää, 2003).
-In Finland wheat yields will increase and become less variable, and potato yields will increase especially in central and northern Finland (Carter and Kankaanpää, 2003).
-Impacts of potential climate change on some agroclimatic indices in Atlantic Canada are discussed in (Bootsma *et al.,* 2005). The anticipated changes in heat and moisture are likely to have a significant impact on the potential yields of crops grown in the region. The additional crop heat units (CHU), from 500 to 700, will likely promote higher yields in heat-loving crops such as corn. The impact of increased heat is likely to be small for spring cereals due to shifts to earlier dates for both planting and maturity. Both water deficits and surpluses (the anticipated changes in the DEFICIT-index typically were in the range from +50 to –50 mm for both periods used in the projections, 2010- 2039 and 2040-2069, respectively), might happen resulting in either negative or positive effects on crop. The range of outcomes was larger when results from different GCMs were included.
-In a surveying paper by Maracchi *et al.* (2005) on the impacts of present and future climate variability on agriculture and forestry in Europe (some results from the ACACIA project are quoted), it is proposed that agriculture may be positively affected by climate change in northern areas (through the introduction of new crop species and varieties, higher crop productivity and expansion of suitable areas for cultivation). In northern Europe, the increased precipitation is expected to be large enough to compensate for the increased evapotranspiration.
-Ciais *et al.* (2005) state that future climate warming is expected to enhance plant growth in temperate ecosystems and to increase C sequestration. Severe regional heat waves may become more frequent in a changing climate; their impact on terrestrial C cycling is unclear. The observed reduction in Europe's primary productivity 2003 is unprecedented during the last century. An increase in future drought events could turn temperate ecosystems into C sources, contributing to positive C- climate feedbacks already anticipated in the tropics and at high latitudes.

How is yield of bioenergy crops influenced by CC?
-Brown *et al.* (2000) simulated biomass of switchgrass at CO_2 concentration of 365 and 560 ppm. It increased at all sites with a mean yield increase of 5.0 Mg /ha under the used climate change scenario provided by the NCAR-RegCM2 model 'nested' to a GCM from CSIRO. Yields benefited from temperature increases of 3.0-8.0 degrees C, which extended the growing season and reduced the incidence of cold stress. The study aimed at exploring the feasibility for the Missouri-Iowa-Nebraska-Kansas (MINK) region of the US to convert some agricultural land to the energy crop production of switchgrass (Panicum virgatum L.), a perennial warm season grass.

How might yield responses to CC differ between crops?

-In climatized crop enclosures the increase in yield due to increased CO_2 to 700 µmol /mol was 58% for faba bean, 35% for spring wheat and 19% for winter wheat in Wageningen (Grashoff *et al.* 1995). Harvest index was not changed. Model simulations indicated that the differences between the crops may not be due to fundamental physiological differences between the crops, but may be at least partly due to differences in the daily air temperature during comparable stages of growth.
-Kleemola and Karvonen (1996) predicted that barley cultivars adapted to the longer vegetation period in Finland due to climate change would increase production by 23% under low N and by 56% under high N.
-By 1996 Harrison and Butterfield (1996) predicted that wheat yields would increase throughout Europe for all regions and climatic scenarios, and water-limited sunflower yields to decrease in most regions and scenarios. For UK wheat yield increase would be 0.2 t /ha per decade up to 2020 and 0.36 t /ha per decade thereafter. For sunflower a decrease of 0.05 t /ha per decade up to 2020 followed by an increase of 0.05 t /ha per decade.
-Peiris *et al.* (1996) simulated three crops of contrasting development type: field bean, potato and winter and spring wheat in Scotland (4 sites, 5 soils) using a weather generator for 100 years. Eight scenarios (increasing temp and rainfall) but non with CO_2 increase were simulated. Increased temperature increased crop development rate, which shortens the growing season for beans and wheat, but, given a fixed harvest date, lengthens the season for potato. Potato yield increased by up to 33% over all sites and scenarios, whereas wheat yield decreased by 5-15% and bean yield by 11-41%. Increased rainfall reduced variability in all crops.
-In Quebec, C4 cereals (corn, sorghum) would benefit more from climatic change than other prevailing C3-crops but would be least favoured by CO_2 fertilisation (ElMaayar *et al.* 1997)
-Collatz *et al.* (1998) constructed global maps of the distribution of C3 and C4 grasses and for mixed stands, for current, past and future climates. Published floristic studies were used to test the accuracy of these predictions, with reasonably good results. The analyses predict a substantial reduction in the area of the C4 grasses under

future CO_2 conditions. These predictions are based on the assumption of greater stimulation of C3 photosynthetic efficiency at higher CO_2, than inhibition by higher temperatures.

-Tubiello *et al.* (2002) showed that regional distribution of the simulated yields, largely depended on the projected precipitation increases. In some important rainfed production areas where precipitation was projected to decrease, (the Kansas and Oklahoma Bread Basket regions, Canadian Centre Climate Model scenario), CC resulted in 30 to 40% reductions of grain yield and increased year-to-year variability. Response to additional factors affecting the simulated US crop production, such as higher temperature and elevated CO_2 was discussed. Two scenarios of CC, developed with the Hadley Centre Model and the Canadian Centre Climate Model were used together with the DSSAT (Decision Support Systems for Agro-technology Transfer) dynamic crop-growth models

-There will under CC in Finland be an improved potential for cultivation of new crops (like maize), a greater variety in suitable crop species and cultivation of higher yielding winter crops (Carter and Kankaanpää, 2003).

-Holden *et al.* (2005): Using the Decision Support System for Agrotechnology Transfer (DSSAT) and a simplification of the General Soil Map of Ireland, it was concluded that maize could become a major crop in Ireland but may suffer water stress in summer, and that soybean may become a specialist, marginal crop. The future possibilities of maize growing was investigated because it was until recently a semi-marginal crop that is now regarded as a good source of high energy forage in Ireland. Soybean was investigated because it is not currently suitable for commercial production in Ireland but is used as a protein supplement by livestock producers.

-Crop yield changes for Sweden under changing temperature conditions were estimated by comparing regional differences at present conditions (Sigvald *et al.*, 2001 and Eckersten *et al.*, 2007). The results suggested that cereals increase for the region of Mälardalen would range between +15 and +30%, for leys +20%. Extremes were found for spring rape (+3%) and potato (+109%), the latter probably strongly dependent on non-climatic factors.

How does the combined effect of CC influence growth?

How large are the sole effects of temperature and CO_2 on crop yield?

-Brown *et al.* (2000) found that the sole effect of the higher temperatures of CC scenario in Iowa had a decreasing effect on simulated crop yields due to increased heat stress and a speeding of crop maturity. Without the CO_2-fertilization effect in CC scenarios, simulated maximum yields were lower than for baseline, by 1.5 Mg /ha for corn, 1.0 Mg /ha for sorghum, 0.8 Mg /ha for soybean and 0.5 Mg /ha for winter wheat. Including the CO_2-fertilization effect (560 ppm) in CC scenarios, simulated yields increased for all crops compared to baseline, by 34% of the soybean and 37% of the winter wheat farms. Water use increased for all crops under the higher temperatures of the CSIRO scenario. The erosion productivity impact calculator (EPIC) crop growth model was used at 302 sites within the MINK (see above) region. The analysis was done for both current climatic conditions and a regional climate model-based scenario of possible climate change. Daily climate records from 1983 to 1993 served as baseline and the NCAR-RegCM2 model (RegCM hereafter) nested within the CSIRO general circulation model (GCM) provided the climate change scenario.

How does the combined effect of CO_2, climate and N influence growth?

-Shaw *et al.* (2002) found an increased net primary production (NPP) in the third year of ecosystem-scale manipulations in a California annual grassland due to simulated warming, increased precipitation, and nitrogen deposition, alone and in concert. Elevated CO_2 also increased NPP, but only as a single-factor. Across all multifactor manipulations, elevated CO_2 suppressed root allocation, decreasing the positive effects of increased temperature, precipitation, and nitrogen deposition on NPP. The NPP responses to interacting factors differed greatly from those to single-factor responses, indicating the importance of a multifactor experimental approach to understand the ecosystem responses to global change.

How are the management and CC effects related?

How are the fertilisation and/or irrigation needs changed under CC?

-Doll (2002) found that two-thirds of the global area equipped for irrigation in 1995 will possibly suffer from increased water requirements, and on up to half of the total area, the negative impact of CC is more significant than that of climate variability. He concluded that anthropogenic CC does affect water resources and water demand, particularly for irrigation. He used a recently developed irrigation model, (spatial resolution of 0.5degrees by 0.5degrees) for a global analysis of the impact of CC and climate variability on irrigation water requirements.

-Holden and Brereton (2006) concluded that there will be little impact of changes in water and nitrogen management for spring barley, arising from possible climate change in Ireland, but in central and western parts of Ireland it might be possible to reduce nitrogen application rates by half. The impact on potato production will be stronger: without irrigation yield will only remain viable in areas where rainfall remains high, elsewhere between 150 and 300 mm of irrigation will be required each year, but this might be offset by the possibility of reducing nitrogen inputs by up to half. Production on less suitable (heavier) soils would be less desirable if irrigation is required because of possible run-off losses. For the investigation, the locations with the highest proportion of barley and potato production were identified, and 1961-1990 monthly climate data were used to drive mechanistic crop models. Nitrogen and water response curves were created using current recommended management guidelines. A series of step-wise manual irrigation simulations were then undertaken to estimate the minimum future (2041-2070) irrigation demand.

Which regional changes in crop production can we expect?

-Global change will have both good and bad production effects in areas under 5 °C mean annual temperature in Finland (Mela, 1996).

-Methods for deriving response surface diagrams to evaluate climate change impacts on crop production have been developed. A method that accounts for spatial and seasonal variability of climate is reported by Van Minnen (2000). The method was applied to crop production in Germany and Kongo. It was demonstrated how the production in Germany was more sensitive to changes in temperature, whereas in Kongo it was more sensitive to changes in precipitation.

-A study on the potential cultivation of grapevine in Europe under future climate scenarios (using a HadCM2 scenario for 2050) showed that there is a potential for expansion of the wine-growing area in Europe and an increase in yield. However, detailed projections for the main viticultural areas have also shown an increase in yield variability (Harrison and Butterfield, 1999).

-Another large-scale global change simulation study, but limited to maize in the USA corn and wheat belt (5 states) was made by Southworth *et al.* (2000). With future CO_2 concentrations of 555 ppm, wheat yields increased up to 60-100% above current yields in the central and northern areas when modelled for the 2050-59 scenarios. In the southern areas small increases or decreases were simulated. CO_2 fertilisation effects are found to be significant for wheat, representing a 20% yield increase under future climate scenarios.

-Predictions of global change impacts do not always agree. Weber and Hauer (2003) states that, contradictory to many predictions, for Canada the effect of global change would be positively beneficial for agriculture. The pessimistic predictions are regionally specific and focus on particular crops, particularly grains and oilseed.

-Impacts of climate change in Ireland were predicted by Holden and Brereton (2002) and Holden *et al.* (2003) using elaborate statistic- and simulation techniques. The first work concerns grassland agriculture, where effects on the whole forage-meat-milk production change are anticipated. Grass yields were predicted to decrease in the east of Ireland due to water stress, causing grassland agriculture to shift to the west of the country. In the second work barley and potatoes are considered. The change in climate is predicted to cause little change in the geographical distribution of barley yield, but grain yield in all areas is expected to increase, possibly more in the west. Potato yield in 2055 and 2075 is expected to fall for non-irrigated tubers. The impact is likely to be a severe loss in potato yield over most of the country.

-Increase in crop productivity due to climatic change will be greater in northern parts of Europe than in the southern (Ewert *et al.*, 2005), which might increase their competitive advantage towards the rest of Europe.

-In an extensive simulation of ecosystems services supply Schröter *et al.* (2005) predicted no change in water stress in Northern Europe but severe stresses in Southern Europe.

How might changed frequency of extreme climate events affect food production and water availability in Russia?

-In a study by Alcamo *et al.* (2007) the impact of a changing frequency and spatial in-homogeneity of extreme climate events, and the reliance of most of Russia on a few food-producing regions, is investigated. They analyzed impacts of the SRES A2 and B2 scenarios with the use of the Global Assessment of Security (GLASS) model, containing the Global Agro-Ecological Zones (GAEZ) crop production model. They find, as in previous studies, that decreased crop production in some Russian regions can be compensated by increases in others, resulting in relatively small *average* changes (when focusing mainly on *average* climate change). However, taking projected changes in the frequency of extreme climate events into account gives a different perspective: Under ‘normal’ climate conditions it is estimated that “food production shortfalls” (i.e. a year in which potential production of the most important crops in a region is below 50 % of its average normal production) occur roughly 1-3 years per decade. This frequency will double in many of the main crop growing areas in the 2020s, and triple in the 2070s. The effects of these shortfalls are likely to hit all over Russia because of the high likelihood of shortfalls occurring in many crop export regions in the same year.

How certain are crop yield impact assessments?

-Tubiello *et al.* (2002) criticize previous optimistic US yield simulations. US agricultural production in 2030 and 2090 simulated at 45 sites have previously been aggregated nationally (using economic models) to show an increase in overall US agricultural output under CC. They showed that regional distribution of the simulated yields largely depended on the projected precipitation, which in some important rainfed production areas was projected to decrease.

-Spatial resolution of climate change scenarios can be an important uncertainty in climate change impact assessments, depending on crop and management conditions (Tsvetsinskaya *et al.* 2003).

-To study the uncertainties in predicting effects of the climatic change, Trnka *et al* (2004) compared seven global simulation models applied with a stochastic weather generator to seven European experimental sites with high quality yield data. The CERES wheat model was used to generate yield data for three time periods: 2025, 2050 and 2100. The results were: Wheat yields tended to increase 8-25% for 40 of 42 scenarios. For the CCSR scenario, predicting the highest temperature increase, yields were reduced by 10% in 2050 and by 25% in 2100. Temperature variability was important. Changes in temperature variability by more than 25% resulted in statistically increased yield distribution. The effect of changes in temperature variability increased with mean temperature.

-A rather similar approach as used by Trnka *et al.* (2004) in Europe is followed in a large USA-study. Twelve GCM -scenarios were used, resulting in general statements about the predicted climate change in America (Smith, *et al.*, 2005a). Crop production- and water resource models, EPIC and HUMUS, were validated against historical data, and were found to work satisfactorily (Thomson *et al.*, 2005a). Simulated future yields of corn, soybean, winter wheat, alfalfa and clover hay decreased in general with higher temperatures, but increased with CO_2. Regional variation was large: ± 25%. Future agronomic potential will be significantly affected, mostly dependent on the change in precipitation pattern (Thomson *et al.,* 2005b). Water resources are predicted to vary regionally (Thomson *et al.*, 2005c). Areas, in which crop production is dependent on irrigation, will have reduced water resources in the future (Thomson *et al.*, 2005d).

-Ewert *et al.* (2005) estimated an increase in crop productivity by 2020 to 2080 between 25% and 163% in Europe depending on time slice and socio-economic scenario used as input. Technology development was identified as the most important driver for this increase, essentially more important than CC. The relative crop yield increases were 11-32% for CO_2 increase, based on experimental data, whereas the corresponding factor for technology development was 20-140% assuming a country specific constant absolute change over time (kg ha^{-1} y^{-1}).

-Rounsevell *et al.* (2005a, b), based on the same study, estimated that increases in productivity beyond 2020 were consistent with predicted world wide increase in food demand. However, estimated increases in productivity exceeded expected demand changes in Europe, which is consistent with the present oversupply in Europe.

-Effects of a *rapid* or *abrupt* climate change in Europe are treated in a report from Tyndall Centre for Climate Change Research (Arnell *et al.*, 2005). Potential effects of future *gradual* climate change on agricultural productivity etc. were compared with the effects of an *accelerated* climate change or thermohaline circulation collapse in the North Atlantic. An initial assessment of the implications of three different types of abrupt climatic change (i) a thermohaline collapse, (ii) an accelerated climatic change, due to a positive feedback by the additional release of greenhouse gases from thawing permafrost areas and the oceans, and (iii) a rapid rise in sea level resulting from disintegration of the West Antarctic ice sheet was made, using a combination of model simulations, reviews of published studies of the effects of gradual climate change, and “expert judgements”. (I) Under gradual change suitability for crop production increases in northern Europe and decreases in parts of southern Europe. (II) Accelerated climate change enhances this pattern, whereas (III) a thermohaline circulation collapse leads to reductions in suitability across large parts of Western Europe, as well as in Southern Europe.

What are the effects on global crop yields of uncertainties in emission and climate scenarios?

-The magnitude of change in global food production, and the rate of change were assessed for different socio-economic development scenarios derived from the IPCC SRES (IPCC Special Report on Emissions Scenarios) (Arnell, 2004). The results are discussed in Parry et al. (2004). The climate change scenarios have been taken from SRES-driven experiments using the UK Hadley Centre´s third generation coupled atmosphere-ocean global climate model (HadCM3). Using this model for simulation of transient climate change, some conclusions are made: (i) in most cases the SRES scenarios exerted a slight to moderate negative (0 to –5%) impact on simulated world crop yields, even with beneficial direct effects of COB2B and farm-level adaptations taken into account. The only scenarios that increase global crop yields are derived from the SRES A2 ensemble; (ii) the SRES scenarios of a more globalised world (A1FI and B1) experience greater reduction in yield than the scenarios of a more regionalised world (A2 and B2); (iii) the use of ensemble realizations of the SRES scenarios highlights the regional uncertainties inherent even under similar greenhouse gas emissions pathways. Members of the A2 and B2 ensemble scenarios produce moderate differences in the crop yield results in some regions and time slices.

4. Grasslands

How are yields and legume fraction influenced by CC?

-The model CENTURY (Hall *et al.*, 1995) was used to predict world- wide effects of climate change. Climate change alone increased NNP in all regions except in cold desert steppe regions and CO_2 increased NPP everywhere.

-As an example of the views on the effect of CO_2 enrichment in grasslands held 10 years ago, Jones and Jongen (1996) is quoted. They stated that elevated CO_2 affected plants in two ways: directly by increased CO_2, and indirectly by changes in temperature and rainfall. At high latitudes, where growth is largely temperature limited, it is probable that the direct effect of enhanced CO_2 on production will be less than at low latitudes. However, interactions with increasing temperature and water stress are complex. Different grassland species react differently to elevated CO_2. This will probably result in major alterations in the community structure of temperate grasslands in the future. A long- term effect of elevated CO_2 will likely be a significant increase in soil carbon storage. However, this may be counteracted by increases in temperature.

-From field experiments with ryegrass Jones *et al.* (1996) concluded that the climate change will significantly increase the grassland production in northern Europe. Production will be stimulated by the direct fertilizer effect due to elevated CO_2.

-Version GEM2 of the grassland ecosystem model (Chen *et al.*, 1996) predicted for doubled CO_2 in a C3 grass (Colorado, USA) a NPP increase of 36% and 43% under normal and elevated temperature, and a corresponding increase of 29% and 24% in a C4 grass. The responses of NPP to elevated CO_2 in the C4 species were positive under all temperature and precipitation treatments (simulations). Thus, there were strong interactions among the effects of CO_2 enrichment, precipitation, temperature and species on NPP.

-Pasture production in Scotland was predicted with a mathematical model by Topp and Doyle (1996). It was projected that the global warming might increase the length of the growing season by 12 to 37 days for every 1degree temperature rise in mean annual temperature. The indications are that global warming will have little effect of annual production of grass either from pure grass or grass-white clover mixtures. On the other hand, white clover percentage in the mixture is likely to increase from 32% to 45% for a 2 degree temperature rise. Increasing CO_2 concentration is predicted to increase the yields of grass and white clover under both current climatic conditions and the global warming scenario.

-A synthesis of progress made between 1994 and 1999 in the Global Change and Terrestrial Ecosystems (GCTE) and Pasture and Rangelands Core Research Project 1 (CRP1) is presented by Campbell and Smith (2000). The network has resulted in a considerable reduction in the uncertainties about the effect of elevated CO_2 on growth, and to a lesser extent composition and forage quality, of intensive pastures in cool, wet climatic zones. The stimulatory effect of doubled ambient CO_2 on grassland production averages about +17% in ecosystem-based experiments. Species composition changes are likely to be an important mechanism altering grassland production and its value for grazing live-stock: on average the legume content of productive grass-legume swards is increased by +10% due to CO_2 enrichment. Leaf nitrogen reductions due to elevated CO_2 are often observed, but are generally modest compared with other management factors. This synthesis indicates that greater focus is required on the linkage between the biophysical, social and economic factors that will influence future changes in pasture and rangeland ecosystems and their implications for food security.

-Grasslands occupy more than 25 % of the earths land area (Newman *et al.* 2001), but grassland species have received limited attention from global change research. A 3-year field experiment with a C3 legume (Rhizoma peanut) and a C4 grass (Paspalium) with increased temperature and CO_2 was conducted. Analysed over the years there was a 25% yield increase in the legume for near doubled CO_2. This response was larger for the legume than for the C4 grass. Both species responded to increased temperature, on average 11% in 1996, 12% in 1997, 26% in 1998.

-Local effects of CC and elevated CO_2 (=2 x CO_2) were simulated for two Swiss grassland sites: one low, relatively dry and one high and more humid (Riedo *et al.*, 1999). At both sites shoot DM increased in response to elevated CO_2, the low site being more sensitive. The effect of assumed CC was negative at the low, but positive at the high site. Shoot DM was more sensitive to the effects of elevated CO_2 than of CC. Both effects combined increased DM 20%. This was attributed to the direct effects of CC and CO_2, and indirect stimulation via increased soil N availability. DM partitioning to roots increase with elevated CO_2 but decreased with CC, while an intermediate response resulted from the combination of the two. Under elevated CO_2 evapotranspiration (ET) decreased, but increased under CC. The seasonal water use efficiency was improved under elevated CO_2, and reduced under CC. With the combination of both factors the change was small but still positive, especially at the high site with more favourable soil water conditions. This reflects the stronger positive yield response in combination with a smaller increase in ET under cooler, more humid conditions. The results highlight the importance of site-specific analyses of ecosystems responses.

-Climate impact (CO_2 and temperature) on a complex alpine landscape (Switzerland) was assessed by Riedo *et al.*, (2001) using a simulation model (PaSim), statistical interpolation of climate parameters and stochastic weather generation, A seasonally uniform temperature increase by 2 °C raised the mean evapotranspiration (ET) from 200 to 300 mm yr^{-1}, and the net primary production (NPP) from 0.2 to 0.3 kg C m^{-2} yr^{-1}. Doubling CO_2 to 700 ppm partially offset the increase in ET but caused an additional increase in NPP. Largest absolute changes in ET were obtained for sites with ample precipitation, and largest absolute changes in NPP for the most productive sites.

-Dukes *et al.* (2005) suggested from a California grassland experiment that under CC reactive nitrogen is entering natural systems at unprecedented rates. These global environmental changes have consequences for the functioning of natural ecosystems, and responses of these systems may feed back to affect climate and atmospheric composition. Expectations that CC would promote carbon storage by increasing plant growth appear unlikely in this system. However, the response of a particular system may be unique and dependent on its environment.

-Lloveras *et al.* (2006) presented results of the LEGISIL grassland model (see also Topp and Doyle, 1996; Hopkins, 2003; Harmens *et al.*, 2004; Hopkins, 2004; Scholefield *et al.*, 2005) under climate change in UK, suggesting an increased herbage growth due to elevated temperature by 30%, due to elevated CO_2 by 46%, and due to both by 56%. However, greater incidence of summer drought might at its most serious offset those increases.

-Eckersten *et al.* (2007) estimated, with a simulation model, fertilised swards of pure grass to have a large potential of increased growth under climate change, mainly because of increased length in growing period and increased atmospheric CO_2 concentration. To fully cover the increased growth potential would require an increased fertilisation rate by up to 100 kg N ha^{-1} y^{-1}, strongly dependent on site conditions.

How is grassland botanical composition influenced by CC?

-Variation between populations and species must be considered when predicting grassland community responses to CO_2. It is inappropriate to ignore compositional changes in communities when modelling CO_2 effects on pasture production. Given the importance of temperature in determining CO_2 responsiveness, phenology may prove to be a useful attribute in plant functional analyses of community responses to CO_2 (Campbell *et al.*, 1995).

-Photosynthesis by cool temperature pasture species can respond to elevated CO_2, especially at low temperatures. This will have consequences for predicting the potential effects of CC, accompanied by rising CO_2, on pasture ecosystems (Greer *et al.*, 1995).

-Lloveras *et al.* (2006) presented suggested based on the LEGISIL grassland model that legumes will be favoured under CC in UK, and especially red clover and lucerne.

4. Crop quality

Are there many studies on CC and food quality?

-Porter and Semenov (2005) stated that food quality has not been given sufficient attention when assessing the impact of climate change for food.

What is important when predicting the influence of temperature changes on crop quality?

-Porter and Semenov (2005) pointed out that threshold temperatures for crop processes are rather similar for different crops. The threshold temperatures are important to define for the major food crops, to assist climate modellers in predicting the occurrence of crop critical temperatures and their temporal resolution.

How will increased CO_2 and heat affect wheat quality?

-Production of high quality hard wheat in some areas may be at risk if exposed to high CO_2 and “heat shock”. This is the case for wheat in Queensland, Australia (Reyenga *et al.*, 1999).

How will crop quality be affected by CC in the Nordic countries?

-Eckersten *et al.* (2001) simulated for winter wheat under CC an increased harvested biomass by 6 to 16%. The corresponding increase in harvested N was less, -3 to +7%. N/C ratios ranged from 0.036-0.042 under current climate and from 0.033-0.036 under CC.

-Quality of crops can deteriorate under CC in Finland, and there might also be an increased risk of heat or cold stress to plants in Finland according to Carter and Kankaanpää (2003)

4. Weeds

How will weed occurrence be influenced by climate change?

-Risk of weeds increases in Finland (Carter and Kankaanpää, 2003).

-Eckersten *et al.* (2007) suggested increased occurrence and changed flora of weeds in Sweden under climate change due to longer vegetation period, more winter cropping, and new crops on the expense of area cultivated with leys.

How might warmer climate favour C4 plants?

-A warmer climate and drier conditions during the summer could favour the C4 plants because as they can continue photosynthesis also when stomata have to be closed due to shortage of water. This could, therefore mean an increased frequency of C4 species such as cockspur (*Echinochloa crus-galli*) and common amaranth (*Amaranthus retroflexus*), plus a more permanent establishment of species that are very sporadic today, e.g. Johnston grass weed (*Sorghum halepense).* On the other hand, many C_4 plants are short-day plants, which have a disadvantage for phenological development in long-day climate (Huang *et al*., 2000; Swanton *et al*., 2000).

Which new severe weed species may occur?

-The autumn-germinating form of wild oats (*Avena ludoviciana*) might become more common, as well as little-seed canarygrass (*Phalaris minor*), a fairly recently observed ‘super weed’ in Ireland that originates from Asia (Anonymous, 2004).

4. Pests

Which methods are available to predict climate change impact on pests?

-Although the science to predict climate change impact on agriculture has developed significantly over last years, there is still a lack of consideration of how CC will affect the occurrence of pests and plant pathogens (Scherm, 2004). There are two important sources of information: one is “fingerprints” in terms of long-term records of climate impact on pest population changes, the other is the use of predictive models. Information in terms of long-term records is unfortunately rare. The success of model predictions is limited because of the large likelihood of genetic changes in the pest populations in response to CC.

How can pest models be parameterised against spatial distribution?

-CLIMEX is a pest risk assessment model, that can be applied to weeds, pathogens and anthropod pests (Yonow *et al.* 2004). In the present application the model is parameterised on geographical distribution data, and departs in that respect from most previous applications in plant pathology, where physiological data have been used to derive model parameters. In the present application of the model, it is predicted that a fungus, ‘leaf spot’, in grasses (Pyrenophora semeniperda), could extend its range through out Europe, and the temperate regions of Asia, Africa and South America.

How will codling moth and Colorado potato beetle be influenced by CC?

-The model CLIMEX (Yonow *et al.*, 2004) was used in combination with agrometeorological data in Norway to predict the future distribution of the codling moth (Cydia pomonella) and the Colorado potato beetle (Rafoss and Saethre, 2003). CC scenarios (0.1 degree increase in daily maximum and minimum temperature per degree in latitude) indicated an extension in the potential geographical range of the codling moth, and 23 new locations were found suitable for long-term survival. Where the moth already exists, it was predicted to increase dramatically in response to CC. The Colorado beetle could only temporarily find suitable locations in Norway, but in case of CC the beetle could establish as far north as 64 degrees N. Also in USA, in the Great Lakes Region, the codling moth will increase in response to CC, particularly in the number of generation per season (Winkler *et al*., 2002).

How will pest occurrence be influenced by CC?

-Goudriaan and Zadoks (1995): CO_2 and UV radiation are not likely to have major effects on insects and pests.

-Wittmann *et al.* (2000) suggest a number of likely insects under CC: the Culicoides biting midges, the vectors of several arboviruses, including those that cause bluetongue (BT) and African horse sickness (AHS). The major old-world vector of BT and AHS viruses, C. imicola, occurs in southern Europe and will spread further north as global temperatures increase. As the distribution of C. imicola moves north, it may bring BT and AHS viruses

into the range of other Culicoides species that are known to be competent vectors and which occur much further north. Once infected via this 'baton effect', these species may be able to spread the viruses over much of Europe, including the UK. They point out that changes in the distribution and abundance of insects are likely to be amongst the most important and immediate effects of CC. CC may also increase their vector competence further and also the likelihood of viruses surviving from one year to the next. The predicted increase in the frequency of short periods of hot temperatures may lead to the creation of novel vector species, by removing the barriers that in colder conditions make them refractory to viral infection.
-Warmer winters favours pest winter survival (Fuhrer, 2003)
-Risk of pests and diseases increases in Finland and there will be a northward shift in pest distribution and increased numbers of reproductive cycles (Carter and Kankaanpää, 2003).

How might number of insect pest species change under CC?
-Yamamura *et al*. (2006) used a state-space model selected by Akaike's information criterion, derived from 50 year annual light-trap data in Japan, to predict impact of global warming on the number of rice stem borer, green rice leafhopper and small planthopper.
-Eckersten *et al*. (2007) suggested that insect and virus attacks on crops can probably be expected to generally increase in Sweden under CC due to that insects will presumably be favoured by a warmer climate during the winter and will therefore be more numerous in the spring.

How are periods of favourable development and number of generations of onion thrips influenced by CC?
-Bergant *et al.* (2005) used a simple degree-day model to relate the development of onion thrips to temperature. Potential changes of favourable development and number of generations were assessed for CC. Changes were sensitive to magnitude of increased temperature, to asymmetry within the year and to present climate conditions. The authors suggest that further research is needed to evaluate the plausibility of such simplified projections.

How might new species of beetles in Canada develop under CC?
-Three new species of beetles on cabbage has recently been introduced into Canada (Olfert and Weiss, 2006). CC will likely increase the risk for these species to become intense both in terms of severity in regions where they presently occur and in terms of their ability to become established in areas where they presently do not occur.

How are cereal aphids predicted to respond to CC?
-Cereal aphids in southern Britain are predicted to decrease in response to elevated CO_2: at low emissions by –5%, at medium low emissions by –12%, at medium high emissions by –61%, and at high emissions by –92% (Newman, 2005). Of the six variables used in the model, changes in temperature and rainfall were the most important over all emissions scenarios. The results suggest that the pest status of cereal aphids may significantly decline by the end of the century.

How is ant predicted to increase in US under CC?
-A dynamic ecophysiological model of the ant colony growth coupled with models simulating climatic change was used to predict the future expansion to the north of a South American ant species (*Solenopsis invicta*). Presently the ant occupies south-eastern USA. Its area is predicted to increase by 5% to the north over the next 50 years, and by 2100 this area is predicted to be more than 21% greater than the present area (Morrison *et al*., 2005).

How might downy mildew influence grape in Italy under CC?
-Salinari *et al.* (2007) predicted an increase of the fungicide pressure on grape for 2030, 2050 and 2080 in Italy. Severe downy mildew epidemics might occur during May and June as a consequence of rising temperature and two more fungicide sprays are needed. Increased precipitation had an opposite effect, although small in comparison with temperature effect. They used simulation models and GCM scenarios based on SRES-A2 emission scenario.

How might pest effects on crop be influenced by CC?

-Methods for modelling impact of changed pest pressure due to global climate change are available according to Goudriaan and Zadoks (1995). They argue that increasing CO_2 reduces crop N, which may retard many pests and diseases and change the weed flora.

-The interactions between the climatic factors on development and growth of crops, weeds and pests are so complex that realistic predictions are very difficult (Fuhrer, 2003). Southern, poorly developed areas are likely to suffer from global change.

-In C_3 crops increased CO_2 in some cases improves pest and decease resistance (Fuhrer, 2003).

-In a surveying paper by Maracchi *et al.* (2005) on the impacts of present and future climate variability on agriculture and forestry in Europe (the ACACIA project) it is proposed that agriculture may be negatively affected by increased need for plant protection. Adaptation management strategies should be introduced to reduce the negative impacts on the agricultural and forestry sectors.

-Eckersten *et al.* (2007) suggested that spring sown crops might become more vulnerable to infections during spring due to possible delayed sowing in relation to the start of the vegetation period.

How might fungi infections in Sweden be influenced by CC?

-Eckersten *et al.* (2007) pointed out that fungal diseases are favoured by both temperature and moisture. The moisture situation will be altered more irregularly in different parts of Sweden than the temperature. This means that we can expect large differences between regions. In northern Sweden fungi will probably be of increased importance due to the generally wetter and warmer climate.

How might need of pesticides change under CC?

-CC will affect the cost of pesticide use (Chen and McCarl, 2001). In USA it was found that increases in rainfall increases the cost of pesticides for corn, cotton, potatoes, wheat and soybeans. Increased temperature increases it for corn, cotton, potatoes, and soybeans but decreases it for wheat. Also the variability in cost was affected.

4. Animal husbandry

How might food supply to animals be influenced by CC?

-The length of fresh fodder season will increase in Finland (Carter and Kankaanpää, 2003).

- The potential impact of CC by the year 2050 is assessed by simulation models of farming systems (Parsons *et al.*, 2001). The model includes grassland production, livestock feeding, thermal balance of animals (sheep, beef calves and dairy cows) and buildings and a stochastic weather generator. It is concluded that eastern dry lowlands, western wet lowlands and uplands in England should be able to adapt to the expected CC. There is likely to be a small increase in grass production, possibly allowing an increase in total production in some areas.

-Lloveras *et al.* (2006) presented results of the LEGISIL grassland model under climate change in UK, suggesting reduced opportunities for grazing and harvesting on wetter soils.

How might grazing animal returns to soil be influenced by elevated CO_2?

-Allard *et al.* (2003) compared nitrogen (N) returns from sheep grazing a temperate pasture exposed to ambient or elevated CO_2 (475 μmol/mol). A greater proportion of dietary N was partitioned to urine at elevated CO_2, probably because of the higher proportion of legume N in the diet, with possible differences in protein quality. A potentially significant consequence of this change in partitioning is greater N loss through volatilization at higher CO_2 levels.

How might management be influenced by CC?

-Turnpenny *et al.* (2001) found for both pigs and chicken that the frequency of severe heat stress is substantially increased under CC, with a consequent risk of mortality. They concluded that the effect of CC by the year 2050 on intensive livestock systems in Britain would make it necessary to reduce stocking densities considerably, or to invest in improved ventilation or cooling equipment. This was assessed through the use of simulation models of farming systems. The submodels comprise livestock feeding, livestock thermal balance and the thermal balance of controlled environment buildings and a stochastic weather generator. These are integrated to form system models for growing pigs and broiler chickens. They are applied to scenarios typical of SE England, which is the warmest region of the country and represents the worst case.

-Parsons *et al.* (2001) concluded that the effect of CC by the year 2050 on British grazing livestock systems is, that they should be able to adapt to the expected CC. This was assessed through the use of simulation models of farming systems (see further above under: *How will food supply to animals be influenced by CC?).*

How might occurrence of animal diseases be influenced by CC?

-There will be an increased risk of animal diseases (vector borne, water and feed related) in Finland (Carter and Kankaanpää, 2003).

4. Management

How are the management and CC effects related?

-Riedo *et al.* (2000) found in a simulation study that elevated CO_2 alone, or in combination with increased temperature, stimulated NPP at all sites. The stimulation was positively related to increasing precipitation at dry sites, but negatively at cool sites. Climate change in combination with elevated CO_2 increased C stocks. The sensitivity of C stocks to changes in temperature and precipitation was similar, and much larger than to management. Grazing led to higher C stocks compared with cutting, depending mainly on the difference in NPP between grazing and cutting. Grazing had a positive effect on C stocks under cool conditions, but the effect tended to become negative with increasing temperature. They concluded that the combination of elevated CO_2 and climate change affects NPP and C stocks, and that the influence of management is site-specific. The mechanistic pasture simulation model (PaSim) was used to quantify effects on net NPP and C stocks at three locations (Switzerland) differing in climate and soil type, under either cutting or grazing (lactating cows).

How might management and CC influence soil carbon storage from 1850-2100 in US?

-Grace, Colunga-Garcia *et al.* (2006) linked net primary production algorithms, where the effects of enhanced [CO_2] on plant growth were included, to the 'Soil Organic Carbon Resources And Transformations in EcoSystems' (SOCRATES) model to develop a soil organic carbon (SOC) map for the North Central Region (NCR) of US between the years 1850 and 2100 in response to agricultural activity and a climate change scenario generated by a global climate model (CSIRO Mk2) under the IPCC IS92a [3] emission scenario. In this study, with an average temperature increase of 3.9 ºC and a precipitation increase of ~80 mm across the region, by the year 2100 the model projected the SOC stores of North Central Region to decline by 11.5 % (in relation to 1990 values) for conventional tillage, and by 2 % for conservation tillage scenarios.

How might land use changes and grassland management affect carbon cycling and sequestration?

-Soussana *et al.* (2004) fitted a two parameter model to literature data and assessed (1) soil organic carbon fluxes resulting from shift between arable land and grassland and from various grassland managements, (2) carbon fluxes in cropping systems, (3) using a grassland ecosystems model estimated the greenhouse gas balance in pastures for a range of stocking rates and N applications and (4) carbon sequestration opportunities for France resulting in restoration of grasslands and reduced live stock breeding systems. The uncertainties in the calculations are pointed out.

4. Biodiversity

How will biodiversity be influenced by CC?

-Loss of biodiversity is enhanced under CC. The larger CC the larger area affected and the higher the number of species influenced (Carter and Kankaanpää, 2003).

-Harrison *et al.* (2006) simulated (with the SPECIES neural network model) the present European distribution satisfactorily for 45 species (from 10 habitats, including plants, insects, birds and mammals). The predicted responses to CC demonstrate that the distribution of many species in Europe may be affected by CC, but that the effects are likely to differ between species. The general pattern is of a southwest to northeast shift in suitable climate space. Species most sensitive to CC were *Rubus chamaemorus* (Cloudberry; decreasing) and *Genista acanthoclada* (Hairy greenweed; increasing). They pointed out that the disparity in species' response to CC has important implications for EU biodiversity policy as the significance of different countries changes in terms of their future contribution to the conservation of habitats and species.

What might the effect of CC on heathlands and shrublands be?

-Using results from field manipulation experiments, changes in goods and services in terms of bio diversity, various forms of recreation, landscape preservation, drinking water supply and carbon sequestration of west European shrublands was predicted by Wessel *et al* (2004). Some of their conclusions, drawn from these field experiments, are*:* (i) Warming of dry lowland heathlands in the Netherlands and Denmark increases nutrient availability, which may lead to increases in grasses, decreasing biodiversity and recreational value? Warming of the upland heather vegetation in UK increases its productivity, leading to increased animal productivity. (ii) Drought may reduce grass invasion, but degrade heather vegetation. Complex interactions with invading species may occur. (iii) In the shrublands of Spain both warming and drought leads to a shift in species composition of seedlings and recruitments, which may change plant communities and reduce biodiversity. In the drought

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[3] For explanation, see under 'Scenarios'

treatment, decreasing soil carbon content may lead to loss of biodiversity, recreational possibilities and an increased threat of wildfires and erosion.

Which habitats are most sensitive to CC?
-The future effect of CC on fifty-four species representing 15 habitats in Britain and Ireland was modelled (Berry *et al.*, 2002) using SPECIES (Spatial Estimator of Climate Impacts on the Envelope of Species). This model (Pearson *et al.*, 2002) integrates five bioclimatic variables for predicting the distribution of species through the characterization of bioclimatic envelopes. The modelled species could be placed in 3 categories: those loosing suitable climatic space, those gaining it and those showing little or no change. The most sensitive habitat to CC was Arctic-Alpine/montane heath communities, followed by pine woodland and beach woodland in southern England. The other habitats showed little or mixed responses. The species respond differently to CC and thus their current habitat associations may alter. Some species have uncertain future. Conservation policy and practice will need to be revised in the face of CC.

Which topics of biodiversity are of interest under CC?
-Watkinson and Ormerod (2001) found that in the face of CC and growing demands for agricultural productivity, future pressure on grassland ecosystems will intensify. In this system, where productivity and conservation are closely bound, there is a need both to raise the profile of the issues involved, and to improve our understanding of the applied ecology required for successful management. In the cited special issue of Journal of Applied Ecology, three topics on global issues of biodiversity in grasslands were considered: plant responses to grazing, plant invasions and the responses to management of valued grassland biota.

How will the weed flora be influenced by CC in southern Sweden?
-Metzger *et al.* (2005) expected expansion of weed species with current southern distributions (e.g. *Picris echioides*) for southern Sweden under CC.

4. Environment

How can the SOCRATES model predict long-term changes in soil organic carbon?
-Grace *et al.* (2006) describes the SOCRATES (Soil Organic Carbon Reserves And Transformations in Ecosystems) model. This is a simple, processed based model for soil organic carbon (SOC) dynamics in terrestrial ecosystems, which requires minimal input data, and which is specifically designed to examine the impact of land use and land use changes on the soil carbon storage. It is claimed, that the model has been successful in predicting SOC change at eighteen long-term crop, pasture and forestry trials from North America, Europe and Australia, ranging from 8 to 86 years in duration, over a wide range of climates and soil types.

Is land projected to become a carbon sink or a carbon source in the future?
-Scholze *et al.* (2006) used outputs from 52 combinations of 16 different coupled general circulation models (GCMs) and different emission scenarios (including runs where atmospheric composition were held constant) as input to the Lund-Potsdam-Jena (LPJ) dynamic global vegetation model in an attempt to get a more quantitative, spatially resolved, global assessment of climate-change-driven risks for world ecosystems. The 52 scenario simulation outputs were divided into three groups according to the simulated increase in global mean surface temperature between the standard period 1961-1990 and 2071-2100: < 2 °C, 2-3 °C, and >3 °C. Among their results: A land carbon sink of ≈1 Pg of C (1 Pg = 1015 g) per year was simulated for 'present-day' conditions (the late 20th century), but for the output group >3 °C this sink converts to a carbon source during the 21st century (2071-2100) in 44 % of the cases, and in 13 % of the cases from the scenario group < 2 °C.

How might water conditions be influenced by CC?
How might water losses be influenced by CC?
-Eckersten *et al.* (2001) estimated for winter wheat drainage to increase by 1-17% for sandy and clayey sites in Uppsala and Halmstad under CC. The change in surface runoff ranged from –37 to +23% showing a complicated relation to soil temperature conditions. The unchanged drainage of sandy soil was due to increased surface runoff. Evapotranspiration increased by 5-8%. For definition of simulated CC conditions, see below.

How do CO_2-effects on plant influence soil water storage and transfer to the atmosphere?
-A scenario with doubled CO_2 over the Canadian prairies may result in a doubled canopy resistance according to experimental observations (Raddatz, 2003). This will result in: increased soil moisture levels, and weakening of

the regional contribution of water vapour from the prairies to the atmosphere. Therefore, this physiological effect should be included in climate change models for Canada.

How might N leaching be influenced by CC?

-Eckersten *et al*. (2001) estimated for winter wheat N leaching to increase by 17-18% for a sandy and clayey site in Uppsala but remained unchanged for Halmstad climate. They used the SOIL/SOILN models with a dynamic plant growth and N model and CC was defined with the GCM delta method ($\Delta T = +1.7$ to $+2.1\ ^{o}C$, $\Delta P = +4$ to $+22\%$ and $CO_2 = 515$ ppm). The estimated N leaching increase was +64% when the simulated precipitation increased from +7% to +22% related to spatial variation in GCM predictions of precipitation. Fertilization rates were not changed.

-Arheimer *et al.* (2005) used SOIL/SOILN database version (database of parameter inputs) without a plant growth model but with a simplified plant N uptake model to simulate N leaching of 15 different crops, several of which were in crop rotation, from the Rönnå catchment basin in Skåne under a climate change of +2.5 to +4.5 °C (six RCM models; delta method). N fertilisation rates were not changed but N leaching increased by 32-70% depending on crop and RCM. N leaching was well related to simulated annual mean soil mineral N concentration. N leaching varied between 10 for pasture and 25 for leys up to 85 for oats and 95 kg N ha^{-1} yr^{-1} for potato.

-Eckersten *et al.* (2007) summarised evaluations of changed N leaching in Sweden due to climate change, and found scenarios ranging between 10 and 70% depending on site and climate scenario. They found several expected reasons for increased N leaching, like increased mineralization, increased winter rainfall in place of snowfall, increased spring rainfall, increased fertilisation and altered land use towards for instance more maize in place of leys.

How are N_2O emission influenced by CC?

-Flynn *et al.* (2005) used a method to calculate N_2O emissions that takes into account crop type or climatic conditions and the trampling effects from grazing animals. Applying the method to climate change by ~2080, Scottish N_2O emission may increase by 14%, if fertilizer regimes and management remain unchanged. Reduction in agricultural land use have the potential to mitigate this increase, and dependent on the replacement land use, may even reduce emissions to below current levels.

-For fertilized humid grassland in Ireland (Heleh *et al.* 2005) climatic shifts will increase annual modelled N_2O emission from 15.4 kg N /ha to 22.4 kg N /ha if current levels of N fertilization are maintained. The projected increase in N_2O emission due to climate change is far larger than the decrease expected from reduced N application (-37 kg N fertilized resulted in 1.2 kg N reduction in N_2O emission.

4. Land use

What are the consequences of CC for agriculture?

-Hulse (1993) mentioned that the United Nations Conference on Environment and Development stressed two urgent research priorities; global climate change and genetic diversity. He suggested that the consequences of CC to agriculture are highly unpredictable, and that more is known on agronomic characters than food processing.

How will the northern limit of crops develop under CC?

-A northward expansion in suitability for cereal production in Finland. Cropping zones will shift at a rate of 130-150 km/°C according to Carter and Kankaanpää (2003).

Will new crops be cultivated because of CC?

-Farmers attitude towards global warming has been little investigated. Studies by Holloway and Ilbery (1996) indicate a willingness to adopt new crops such as vining peas and navy beans in UK.

How will the extent of good agricultural land develop in the future?

-Fisher *et al.* (2002) suggested that in 2080 the total extent of potentially good agricultural land has systematically decreased in Northern Europe by 1.5 – 9.6%, in particular in the UK and Ireland; in Southern Europe by 0.7 – 7.7%, particularly in Spain, and in Eastern Europe by 0.2 – 5.9%, particularly in Ukraine. The results were based on a study on climate change and agricultural vulnerability.

How will the cereal cropping area develop globally in the future?

-Fisher *et al.* (2002) also estimated that the total cropping area will increase in northern Europe (16% increase over reference climate estimate of 45 million ha), and in North America (40% increase over reference climate estimate of 358 million ha), and in the Russian Federation (64% increase over reference climate estimate of 244 million ha). This will result in increased production of cereals of great concern for the developed nations. Developing countries consistently face a substantial decrease of wheat production potential, according to all scenarios for the 2080s (in the order of 15 – 45%). The underlying bases for the conclusions in this report were the use of FAO/IIASA Agro-ecological Zones (AEZ) model, IIASA´s global linked model of the world food system (BLS – Basic Linked System) and the climate scenario-outputs of four different Global Circulation Models (the HadCM3, CSIRO, CGCM2 and NCAR).

In what way may CC influence regional land use patterns?

-A model was validated and used to assess the spatial distribution of grassland in England and Wales, considering soil, climate and topography (Rounsevell *et al.* 1996). The simulations indicate that grassland production is sensitive to changes in temperature and precipitation. The effect of increasing temperature by 1 degree C is almost completely offset by precipitation increases of 10 % resulting in small changes in distribution of grassland suitability. However, greater temperature changes (+4 °C) have a major influence on the ability of land to support intensively managed grassland, because of increased drought stress. Results indicate that a change in the climate, comparable with current best estimates for the future world, would be beneficial for grassland on good quality land at higher altitudes.

-Climate change will increase the current trend to move agriculture production to Western and Northern Europe (Olesen and Bindi, 2002).

-Levy *et al.* (2004) predicted that land use change results in a loss of carbon to the atmosphere in a scenario where the increase in cropland areas continues. In other scenarios there is a decrease in cropland and grassland with a corresponding increase in natural vegetation, resulting in a net sink to the biosphere. The credibility of these scenarios depends on the accuracy in the predictions of the land use change. These are highly uncertain. As CO_2 is the dominating influence on the vegetation, the scenarios with highest CO_2 concentrations generate the largest net terrestrial sink for carbon. This conclusion would change if scenarios assumed continued deforestation and cropland expansion. Without the beneficial effects of elevated CO_2, the effects of climate change are much more severe. This is a concern, as the long-term and large-scale effects of elevated CO_2 are still open to question.

-In an extensive simulation of ecosystems services supply, Schröter *et al* (2005) predicted reduction in cropland area for most of Europe with the smallest reduction (0-20%) in Northern areas and largest (20-100%) in the Mediterranean regions.

-Land use for food production was expected to decrease by 7-11 % for Europe as a whole, depending on socio-economic scenario, but quite insensitive to climate scenarios (Schröter *et al*., 2005).

-Land use for grassland (livestock) was expected to decrease by 1-10 % for Europe as a whole, depending on socio-economic scenario, but quite insensitive to climate scenarios (Schröter *et al*., 2005).

-Schröter *et al.* (2005) considered 26 potential bioenergy crops from spring crops to trees like eucalyptus. On average for Europe the area increase will be 1-7% by 2080 depending on socio/climate scenario. For latitudes 55-65^{o}N the variation was less and most sensitive to climate scenario, but the increase in area was much larger, 11-15%.

-Crop yield changes on a regional basis for Sweden under changing temperature conditions were estimated by comparing regional differences at present conditions (Sigvald *et al*., 2001 and Eckersten *et al*., 2007). The relative increase in crop yields per hectare, for a 2-3 ^{o}C temperature increase, ranged approximately between 15% in the south and more than 70% in the north, however, strongly dependent on crop type. Changes of land use were found to be potentially equally significant for predicting total regional production as changes in hectare yields.

What changes in the extension of northern boreal forests do climate models simulate?

-Scholze *et al.* (2006) used outputs from 52 combinations of 16 different coupled general circulation models (GCMs) and different emission scenarios (including runs where atmospheric composition were held constant) as input to the Lund-Potsdam-Jena (LPJ) dynamic global vegetation model in an attempt to get a more quantitative, spatially resolved, global assessment of climate-change-driven risks for world ecosystems. The 52 scenario simulation outputs were divided into three groups according to the simulated increase in global mean surface temperature between the standard period 1961-1990 and 2071-2100: < 2 ^{o}C, 2-3 ^{o}C, and >3 ^{o}C. Among the results: A high risk of forest loss was shown for Eurasia, eastern China and Canada, but with forest extensions into the Arctic (and semiarid savannas). The fraction of scenario runs showing a shift from forest to non-forest vegetation (or vice versa) - affecting an area of minimum 10 % - was 44 % in the T < 2 ^{o}C scenario group, and 88 % in the group with T >3 ^{o}C. The corresponding percentages of runs showing a shift affecting an area of at least 20 % was 0 and 31 %, respectively.

What do land use assessments tell us?

How can land use assessments be done?

-Verburg *et al*. (2004) concluded that substantial progress have been made, but that there is a need for development as concerns: address of multi-scale characteristics, new technique to quantify neighbourhood effects, temporal dynamics, and integration between disciplinary approaches, and between urban and rural land models. They reviewed a number of land use models concerning six basic concepts: level of analysis, cross-scale dynamics, driving forces, spatial interaction and neighbourhood effects, temporal dynamic, and level of integration.

-Ewert *et al*. (2005) applied the ATEAM model for the future. Land use (L) was estimated from estimates of changes in the productivity per ha (P) and the demand (D) and assumptions on overproduction (O) that depended on IPCC scenario. D was estimated with the IMAGE 2.2 model (IMAGE-team, 2001; Strengers, 2001). P was calculated by multiplying current yield levels with the sum of relative changes in P due to increased CO_2, climate, and technology, respectively. The CO_2 effect was taken from literature on physical and modelling experiments to range +11 to +32% by 2080 depending on IPCC scenario, which gave a value on CO_2 concentration. The climate effect was taken from a PCA analysis of current relations between yields and climate in Europe (Metzger *et al.,* 2005), and technical effects were taken from historical yield statistics of major European crops giving annual yield increases ranging between 0.84%/year for oats, 1.74% for wheat, 1.89% for maize to 2.05 to 2.56%/year for rye and triticale ("rågvete" in Swedish), respectively.

-Total agricultural area of Europe is assessed using the Integrated Assessment Model (IMAGE 2.2) that simulated commodity demand on the European scale as function of the global conditions (Schröter *et al*., 2005). A second method was used to allocate this demand to regions within Europe (Rounsvell *et al*., 2005; 2006). Stakeholders were consulted to identify land use change drivers. Thirdly, an assumption of maintaining a constant land use was introduced (Schröter *et al*., 2005).

Is CC an important factor in assessments for future land use?

-Rounsevell *et al*. (2005b) estimated, by simulation method, that crop land and grassland area might decrease by up to 50%, depending on socio-economic scenario, due to an oversupply of agricultural land, which have to be met with reduction of area of agricultural land. The use of this surplus land will involve severe planning problems.

-The surplus land has by far the greatest potential for energy crops, and geographically Former USSR, East Asia and South America has the greatest advantage (Hoogwijk *et al*. 2005).

How is flooding of agricultural land influenced by CC?

-Holman *et al*. (2005) evaluated interactions between four major sectors driving landscape change (agriculture, biodiversity, coasts and floodplains, and water resources) using the Drivers-Pressure-State-Impact-Response (DPSIR) approach. For UK it was found that severe flood impacts might be expected in East Anglia if no policy adaptive measures are undertaken.

How will uncertainties in GCM scenarios influence crop production in southern Sweden?

-Metzger (2005) made projections for Europe climatic zone classes and its consequences on agricultural land use, using ATEAM model. They made a more detailed analysis of southern Sweden. In 2050, four different GCM models (for A1 emission scenario) gave quite different climate patterns and therefore different land use. (i) CGCM2 gave from Skåne in south to Västergötland in north a growing season (>10°C) decreasing from 213 to 190 days. Grain yields decreased from 6.1 to 5.3 t/ha. Percentage of cropland used for winter wheat was 22% in Västergötland (2005 SCB-value is about 29%, and for oat 32% (2005-value is about 35%). For the east coast of Sweden, the same conditions are projected to prevail from Skåne up to about the level of Västervik.

What constrains land use in southern Sweden?

-Metzger *et al*. (2005) expected from their detailed analysis of southern Sweden that the total arable land (at present 40% of total land; source Eurostat NewCronos) will not increase because the forest soils are too acid for cropping. Land use is strongly constrained by soil properties. As there is expected an increased overproduction in Europe, they concluded that the area will not increase further. It is unclear what are speculations and what results are. Production levels will increase.

Which strategic factors are important to think of in land use?

-Christersson, L. (1994) argue that European agriculture must progress towards a more multi-faceted utilization of different types of land in order to conserve arable land and thereby food production. The simultaneous production of food, energy and fibres appears economically viable. This also provides a solution to environmental problems of the community. The utilization of waste products as fertilizer when cultivating biomass is argued to be done in such a way that it is possible to return rapidly to full-scale food production if unexpected developments occur. Thus chosen crops should be able to be replaced rapidly by grain or pasture on land, which has not experienced a loss of fertility or pollution by heavy metals.

5. Adaptation and mitigation of agriculture to climate change

Having knowledge, or thoughts, about possible changes in climate and their effects on agricultural production, the farmer and the society are expected to do something, either to adapt to the changes or to mitigate the effects of the changes. The measures can range from changing the fertilisation regime on the field level to changing crops or whole cropping systems or changing land use to improve agricultural production including environmental concerns and available resources. In this section we aim at describing both scenarios and methods used for assessing adaptation/mitigation strategies for agricultural production. We have tried to structure the text in terms of the response variables on which the measures will act.

Which types of adaptation measures exist?

-In a general survey Smith and Almaraz (2004) states that agricultural adaptations to climatic change are (1) management and genetic alterations of crops, (2) legislative changes, (3) policy and economic changes and (4) adoption of mitigation practices. Mitigation of greenhouse effects can be: new cropping systems and crops that reduce greenhouse gas production by emitting less nitrous oxide, increasing soil organic matter, and allowing production of bio-products such as bio-fuels.

-Carter and Kankaanpää (2003) listed a number of adaptation measures that might be expected under CC in Finland: Changes in crop species and varieties, timing of cultivation practices, changes in cultivation practices and use of fertilisers, maintenance and improvements of soil properties, plant breeding and modified pest and animal disease control.

5. Soil

What are the potentials to increase soil C sequestration in agriculture?

-In a report from GCSI (Global Change Strategies International Inc., 1999; *Soil Carbon Sinks Potential in Key Countries*) the focus is on the function of soils as a carbon sink by increasing soil organic matter (SOM) or carbon (SOC) through the use of different management practises in agriculture. The report estimates for potentials to increase soil sinks. On a global basis, the estimates show that a major world-wide initiative could result in sequestering 0.45-0.61 Pg (= Giga tonne = 1000 Mt) C/year (1640-2240 Mt CO_2) in the next 20-30 years (this is equivalent to about 1/10 of annual CO_2 emissions from fossil fuel combustion and industrial sources, or 1/3 of global emissions due to deforestation and land use changes). For industrialized countries with small areas, soil C sinks were only 1-2 % of industrial emissions. However, for EU as a whole, including potential for set-aside of "surplus" agricultural lands, it was much higher (19-25 % of industrial emissions).

-Smith (2004) found in a review that European croplands are estimated to be the largest biospheric source of carbon lost to the atmosphere in Europe each year, but the cropland estimate is the most uncertain among all land-use types. The mean loss for EU is estimated to be 78 (1 st. dev. is 37) MtC per year. The biological potential for carbon storage in European (EU15) cropland is of the order of 90-120 MtC per year with a range of options available including reduced and zero tillage, set-aside, perennial crops and deep rooting crops, more efficient use of organic amendments, improved rotations, organic farming, and conversion of arable land to grassland or woodland, etc. The sequestration potential, considering only constraints on land-use, amounts of raw materials and available land, is up to 45 MtC per year. It is concluded that there is significant potential within Europe to decrease the flux of carbon to the atmosphere from cropland, and for cropland management to sequester soil carbon, relative to the amount of carbon stored in cropland soils at present. The realistic potential and the conservative achievable potentials may be considerably lower than the biological potential due to socioeconomic and other constraints (15-20% vs. 80-85%).

What is the role of soil carbon sequestration in the long and short term?

-Smith (2004) argued that carbon sequestration in soil has a finite potential and is non-permanent and can probably play only a minor role in closing carbon emission gaps by 2100. However, carbon sequestration forms a central role amongst the measures to reduce atmospheric CO_2 concentrations in the short/medium-term perspective over the next 20-30 years.

How does management influence C sequestration?

-In a report from GCSI (1999) it is concluded that ´conservation tillage´, maintaining crop residues on the soil surface, the use of crop rotations with three or more years of perennial forages (leys) within the rotation and combination of practices are considered to have positive effects.

-The rate of residual C addition to the soil was the primary factor that controlled simulated soil organic matter for Ohio cropland under continuous corn, wheat and oats for the period 1866-1996 (Evrendilek and Wali, 2001).
-Average carbon fluxes into agricultural soils under business as usual scenario in the 2008-2012 commitment period were estimated at 0.52 t C ha^{-1} $year^{-1}$ in grassland and -0.84 t C ha^{-1} $year^{-1}$ in arable land (Vleeshouwers and Verhagen 2002). Conversion of arable land to grassland yielded a flux of 1.44 t C ha^{-1} $year^{-1}$. Farm management related activities aiming at carbon sequestration ranged from 0.15 t C ha^{-1} $year^{-1}$ for the incorporation of straw, to 1.5 t C ha^{-1} $year^{-1}$ for the application of farm manure. Reduced tillage resulted in a positive flux of 0.25 ha^{-1} $year^{-1}$. The calculations were made using a model developed for carbon fluxes from agricultural soils.
-Using US national averages values for agricultural inputs, calculation indicate that the net carbon flux from atmosphere to soil, averaged over all crops, under no tillage, is 189 kg C ha^{-1} $year^{-1}$. For conventional tillage the net flux is from soil to atmosphere by 182 kg C ha^{-1} $year^{-1}$. The difference (371 kg C ha^{-1} $year^{-1}$) represents the total atmospheric CO_2 reduction caused by changing tillage practices, (West and Marland, 2002 a, b).
-Agricultural ecosystems have the potential to sequester carbon in soils by altering agricultural management practices (West and Wali, 2002). In order to account for changes in net CO_2 emission a method for full carbon cycle analysis of agricultural systems was developed. -Soil and crop management is important in determining C sequestration by soils. A comparison between 11 field studies showed that soil respiration varies between 4–26 t C ha^{-1} $year^{-1}$ dependent on management such as tillage, drainage, grazing and manure application. Net exchange of C has been shown to be an order of magnitude lower than respiratory losses (Ress *et al.*, 2005).
-Approximately 50 % of C assimilated by young plants can be transferred into the soil (Ress *et al.* 2005).
-Ogle and Paustian (2004) found for US conditions that over a 20 year period changing management could sequester from 5 to 142 Tg C per year or 0.1 to 0.9 Mg C ha^{-1} $year^{-1}$. They applied the IPCC simple carbon accounting approach.
-Lal (2005) estimated the effect on soil C sequestration of adaptation to Recommended Management Practice (RMP). Gross rates of soil C sequestration could range from 400 to 800 kg/ha/yr for cool and humid areas, and 100-200 kg/ha/yr in dry and warm climates. In total for Brazil this gives about 50 Tg C/yr. Effective erosion control measures could add 60 Tg C/yr to this value.
-Smith (2004) argued that carbon sequestration in soil has a finite potential and is non-permanent and can probably play only a minor role in closing carbon emission gaps by 2100. However, carbon sequestration forms a central role amongst the measures to reduce atmospheric CO_2 concentrations in the short/medium-term perspective over the next 20-30 years.

What is the effect of no tillage on soil C sequestration?
-In a report from GCSI (1999) is presented studies (cited in Paustian *et al.*, 1997, based on 39 studies) founding that the average soil C level was 285 g/m² more (8% higher) under no-till compared to conventional tillage. For temperate agro-ecosystems, experiments in Europe with three or more years of leys within annual crop rotations had up to 25% more soil C compared to rotations with only annual crops.

How does the use of land for agriculture influence global storage of carbon?
-In order to assess the role of agriculture within the global climate-vegetation system, Bondeau *et al.* (2007) present model results for the managed planetary land surface, using the 'Lund-Potsdam-Jena managed Land (LPJmL)' model. The model simulates the transient changes in water and carbon cycles due to land use, the specific phenology and seasonal CO_2 fluxes of agricultural-dominated areas, and the production of crops and grazing land. Based on the concept of crop functional types (CFTs), it uses 13 CFTs (11 arable crops and two managed grass types). Carbon is allocated daily towards four different carbon pools, one being the yield-bearing storage organs. For transient simulations for the 20th century, a global historical land-use data set was developed, providing the annual cover fraction of the 13 CFTs within 0.5 ° grid cells for the period 1901-2000, using published data on land use, crop distributions and irrigated areas. Monthly carbon fluxes measured at three agricultural sites compared well with simulations. Globally, the simulations indicated a ~24 % reduction in global vegetation carbon, and a ~10 % reduction in soil carbon, due to agriculture. In contrast to simulations of the potential *natural* vegetation, showing the land biosphere to be an increasing carbon sink during the 20th century, the LPJ-managed-land model simulated a net carbon source until the 1970s (due to land use), and a small sink (mostly due to changing climate) after 1970.

How do changes of cropping system influence soil C?

-Foereid and Hogh-Jensen (2004) predicted an increase in soil organic matter for the first 50 years of 10-40 g C m^{-2} $year^{-1}$ and a stable level after about 100 years, after conversion to organic farming on sandy and loamy soils in Denmark. The use of grass covers in the rotation was important for the increase in organic matter. The model CENTURY was used for the predictions.

Are windbreaks efficient for mitigation of drought effects on soil?
Seck *et al.* (2005) found less soil erosion and benefits in carbon sequestration due to plantations of dense perennial hedges as windbreaks during a period of increased frequency of drought. The results came from evaluation of changes since 1970 in Senegal. Methodology is not indicated in abstract.

Which measures are used to reduce wind erosion?
-In Denmark 1300 km wind shelters have been planted to reduce wind erosion (Danish EPA, 2005).

How may land use be used to sequester more soil C?
-Degraded or sub-standard soils and marginal lands occupy a significant proportion of boreal, temperate and tropical biomes (Dixon *et al.* 1994). These represent a significant global opportunity to reduce the accumulation of greenhouse gases in the atmosphere. It could sequester 0.82-2.2 Pg C per year globally over a 50-year time frame. Slowing soil degradation by alternative grassland management could conserve up to 0.5-1.5 Pg C per year. Promising land use systems and practices identified to conserve and temporarily store C include agroforestry systems, fuelwood and fibre plantations, bioreserves, intercropping systems, and shelterbelts/windbreakes. For example, successful establishment of low-intensity agroforestry systems can store up to 70 Mg C/ha in boreal, temperate and tropical ecoregions.

What makes stakeholder interested in soil organic matter?
-"Stakeholders were interested in soil organic matter content as a key factor in the carbon cycle and as an indicator of soil fertility (Schröter *et al.*, 2005)."

5. Crop production

How should cultivars be changed to adapt to climate change?
-Engvild (2003) suggested that that it would be necessary with seed supplies of appropriate frost/cold-resistant crops, in case of a sudden climate cooling. There will be a need for stress tolerant crops, and the ordinary definitions may have to be extended. For example, it is not enough that a wheat cultivar is cold tolerant during winter, it must also be cold tolerant during growth and grain filling.
-Porter and Semenov (2005) argued that characters that enable better exploration of the soil and slower leaf canopy expansion could lead to higher crop transpiration efficiency and adaptation possibilities for crops in response to drought.

How can cultivars be used in adaptation?
-Another large-scale global change simulation study, but limited to maize in the USA corn and wheat belt (5 states) was made by Southworth *et al.* (2000). With existing varieties warming would in general decrease yield, especially in the south. The introduction of late varieties in northern areas would increase yields. The work illustrates the principal relationship between temperature, maturity type and yield. Future corn production in US would require heat resistant and/or late varieties.

How can cropping systems be used in adaptation?
-The production of two different cropping systems at two locations in Italy was simulated. Simulated climatic change reduced yields, but this could be counteracted by irrigation and new varieties. The cost of irrigation must be considered (Tubiello *et al.* 2000)

How can we predict farmer's adaptive measures?
-Farmers are risk adverse and profit maximisers – this is one of the outcomes of a model for land use in England (Rounsevell *et al.*, 2003). The approach is based on the simulation of farm-scale decision making processes and the response of crops to their physical environment. Climate change impacts on land use can thus be predicted by the model.
-Policy will have to support the flexibility of land use, crop production, farming systems etc. considering also the multifunctional role of agriculture (Olesen and Bindi, 2002).

Are windbreaks efficient for mitigating effects of drought on crop production?
-Seck *et al.* (2005) evaluated changes since 1970 in Senegal due to plantations of dense perennial hedges as windbreaks during a period of increased frequency of drought. They found an increased production of fruit and vegetables. (Methodology is not indicated in the abstract.)

How can N supply be taxed to be cost efficient?
-Tax on mineral fertilizers favours pig production, whereas tax on N surplus favours arable farms, was a conclusion of a whole farm model study (FASSET 1.0) by Berntsen *et al.* (2003). The social abatement cost of reducing N leaching was 1 – 9 Euro per kg N. Taxation schemes to reduce N leaching should differentiate between farm types.

5. Animal husbandry

How might food supply to animals be adopted under CC?
-The grazing period could become longer in Finland under CC (Carter and Kankaanpää, 2003).
-Lloveras *et al.* (2006) presented results of the LEGISIL grassland model under climate change in UK, suggesting that farm-scale adaptive responses might include increased need of conserved food for housed livestock, and increased use of maize and legumes in place of N-fertilised grass. The results also suggested increased need for manure storage and improved applications, and that dry seasons would require alternative forage species or mixtures adapted to drought.

How can buildings be adopted under CC?
-Lighter animal shelters would be needed in Finland (Carter and Kankaanpää, 2003).

5. Biodiversity

Which measures may be used to increase biodiversity?
-In Denmark wind shelters are planted to ensure biodiversity (Danish EPA, 2005).
-Lal (2005) mention that soil biodiversity is usually higher under pastures an planted fallow systems than under crops, and is likely to increase with adoption of conservation tillage, and mulch farming, integrated nutrient management and manuring, mixed farming systems and integrated pest management techniques.

How does plant biodiversity depend on land use?
-O'Connor (2005) found for an experiment in South Africa that the number of species depended on plant cover types: kikuyu (1.4 species /m2), ryegrass (2.9), pasture (3.1), commercial maize (3.2), and communal maize (7.8). Abandoned communal cropland reverted to indigenous grassland almost free from exotic species in 20 years. It was predicted that frequently cultivated sites would support less diversity than long-lived pastures. This prediction was contradicted by the high diversity of communal maize, which was attributed to the lack of herbicides. The number of species of indigenous grassland was not influenced by grazing, only the composition. Protecting grassland from grazing in 50 year corresponded to a double amount of species (100 instead of 50 per plot).

A balance between agricultural production and biodiversity – what might it depend on?
-Firbank (2005) suggests that there can be no "theoretical" optimum balance between agricultural production and biodiversity, as environmental goals depend greatly on scales and the viewpoint of stakeholders. He concludes that the social challenge is larger than the scientific challenge, as concerns delivering sustainable agricultural landscapes. No methodology is mentioned.

How is biodiversity related to land use and spatial scales?
-Gall and Orians (1992) consider two spatial scales, micro (field and farm) and regional. At the micro scale, they state that agricultural options influencing biological conservation are tillage methods, water availability, fertilizers, and harvest methods. On a regional scale the options are: level of efforts to increase habitat diversity and patchiness, interests of urban peoples in recreation and nature, and pest management control.

How is species distribution related to land use and spatial scales?
-Kerr and Cihlar (2004) found for Canada that endangered species density is strongly related to land use, being a measure of habitat loss to agriculture and intensity of land use. They found that protected areas were unrelated to

endangered species. They used remote sensing and species distribution data sets on regional and national scales, respectively, and a spatial resolution of 1 km.

5. Environment

How does land use influence greenhouse gas emissions?

-The dynamics of greenhouse gases is very much related to soil processes, where soil science will have to play a leading roll in the mitigation of negative effects (Smith, 1999). The global increase in atmospheric CO_2 comes mainly from fossil fuels (6.5Gt C/yr) together with 1.6 Gt C/yr from deforestation. However, the atmospheric increase is only 3.4 Gt C/yr due to a net sink in terrestrial ecosystems of about 2.0 Gt C/yr and another in the oceans. Reforestation and changed forestry and agricultural land management practices can contribute to C sequestration. However, growth of biomass crops may increase N_2O, and drainage of wetlands may increase CH_4.

-Integrated combination of land-management strategies show considerable potential for carbon mitigation. The most important resource for carbon mitigation in Europe is the surplus arable land. To use this potential resource, policies must allow long-term land use (Smith *et al.*, 2000b). In UK the greatest potential in using surplus land for carbon mitigation purpose is bioenergy crops (Smith. *et al.*, 2000c)

-In an overview paper, Sauerbeck (2001) discusses the CO_2 sources in agriculture and the possibilities to minimise their respective emissions. Agriculture is expected to help slow down the CO_2 increase in the atmosphere by sequestering part of it in soil organic matter, and by producing suitable biomass as a substitute for fossil fuels. Agricultural biofuels, shelterbelts, agroforestry and 25% crop residues can replace fossil fuels by up to 0.5-1.5 Gt C/yr, corresponding to a potential saving of fossil fuels by 10-25%. The combined losses from the earth's biomass and from soils due to cultivation between the year 1700 and today amount to 170 Gt carbon, which is now largely in the atmosphere. A further CO_2 release of 1.2 Gt C per year is still going on due to land clearing for agriculture in the tropics. The only way out is escape from this forest clearing, more sustainable land use and improved productivity on existing farmland. Soil organic matter of farmland is increased only if additions can be enhanced or decomposition reduced. There are opportunities by which such improvements can be achieved.

-Agricultural intensification (conservation tillage and residue mulching, integrated nutrient management, crop rotations with cover crops, water-use-efficiency measures, plant nutrient and energy use) is a means for soil organic carbon sequestration, the potential for Europe being 0.1-0.3 Pg C per year (Lal, 2003).

-Dendoncker *et al.* (2004) estimated that for Belgium less than 1% reduction of total national C losses might be achieved by adjusting agricultural practice by means of increasing soil C sequestration. It is about 5-9% of total emission from the agricultural sector. This is only one tenth of the Belgium commitment by 2010, according to the "Kyoto-protocol". Highest increase in oil C sequestration was achieved by the introduction of short rotation energy crops (about 100 Gg C per year for Belgium), spreading farmyard manure on grassland (~85), new forest plantations (~30), no-till farming (~15), improved farming practice on peat soils (~15), and organic farming (~2).

-The expansion of crops and pastures to the detriment of forests results in an increase in atmospheric CO_2 (Gitz and Ciais, 2004) due to loss of forest biomass and soil carbon during and after conversion. An additional cause is the reduction of the residence time of carbon in the biosphere, when forest or grasslands are converted into cultivated land. This may add 61 ppm extra CO_2 in the atmosphere by 2100. Analyses of the carbon dynamics show that there is an additional atmospheric benefit of preserving pristine ecosystems with high turnover time.

-In Denmark, the plantation of 1300 km of wind shelters are estimated to have resulted in a CO_2 sequestration into woody biomass by 130 000 tonnes CO_2 per year (Danish EPA, 2005; Gyldenkærne *et al*, 2005).

-Lloveras *et al.* (2006) presented results of the $\mathrm{SIMS}_{\mathrm{DAIRY}}$ model (Prado *et al*, 2006) giving that a short term sward (2-3 years) emitted 7% less N_2O per unit of milk produced than long term swards (> 11 years).

Are management practices important for regulating gas emissions?

-Gas fluxes may change the mitigation potential of agricultural management options significantly and should always be considered alongside CO_2-C mitigation potentials. Also, agricultural management options show considerable potential for carbon mitigation even after accounting for trace gas fluxes (Smith *et al.* 2000a, 2001).

How do GHG emissions due to fertilization depend on crop rotation?

-Increased fertilization rate was modelled (DAISY-model) to increase greenhouse gas (GHG) emissions for winter wheat cereals, but remained unchanged for crop rotations with spring cereals and catch crops (Olesen *et al.*, 2004).

How efficient are different management measures in reducing GHG emissions?

-Weiske *et al.* (2006) modelled that an optimised lifetime of dairy cows might reduce GHG emission (CH_4 and N_2O) by 13%, compared to baseline model farm. Frequent removal of manure reduced emissions by 7%, scraping of fouled surfaces gave almost no effect, and manure application by trail hose and injection, instead of broadcasting, reduced emissions by 1-3%. The largest reduction of GHG emissions depended on how much of the thermal energy produced that is exploited (96%), and combining all methods, the reduction range between – 25% (i.e. higher emissions) and 1a full reduction compared to the model farm.

How much do GHG emissions increase in relation to farm net input of N?

-Olesen *et al.* (2006) showed that GHG emissions (CH_4 and N_2O) of a farm could be related either to farm N surplus by using a whole-farm model (FarmGHG) for five European agro-ecological zones for both organic and conventional systems. An increase of N surplus from 56 to 319 kg N ha^{-1} y^{-1} resulted in a GHG emission from 3 to 16 Mg CO_2-eq ha^{-1} y^{-1}. They also examined effects of farm-N efficiency and fount it to be important.

How can management be adopted to reduce emissions from animal husbandry?

-Gas abatement strategies for animal husbandry are reviewed by Monteny *et al.* (2006), (55 references). The most effective mitigation strategies for methane are changing the animals diet towards greater energy-use efficiency. Methane emission can be reduced by optimal use of the gas for energy purpose. Some further mitigation practices are discussed in the paper.

-Dairy systems in Europe contribute to the greenhouse emissions with N_2O, CH_4 and CO_2 gases. These emissions were calculated for Holland using a panel of climate change (IPCC) methodology, an updated and refined IPCC methodology and a full IPCC accounting approach. Schills *et al.* (2006) using detailed farm data showed that changes in N management have reduced GHG emissions. A reduction of the N-surplus per kg milk with 1 g N reduced the GHG emissions with approximately 29 g CO_2 equivalents. This was achieved by reduced fertilizer use and reduced grazing time. Conclusion: the N surplus at the farm level is a useful indicator of GHG emissions. A full accounting system, as used here, may effectively enable farmers to address the issue of GHG emissions in their operational management decisions.

-Gibbons *et al.* (2006): Following a Monte-Carlo simulation and modelling approach it was concluded that the most cost effective adaptations were: (i) eliminate intensive beef production, (ii) reduce stored manure and increase frequency of manure spreading, substitute concentrate feed for grass and conserved grass in milk production (= use more concentrate), and (iv) apply less mineral N to grassland. The cost effective adaptations were the most certain in the simulations.

How can management be adopted to reduce N leaching?

-Larsson *et al.* (2005) simulated N leaching from arable land in Skåne. Single cultivation measures, i.e. cover crop and spring ploughing, late termination of leys and fallow, and spring application of manure, reduced N leaching with 5 – 8%. Combining all three measures and replacing winter crops by spring crops resulted in a simulated reduction of 21%.

How can N leaching remain at present levels?

-Simulation of nitrogen leakage in a French catchment area showed increased leakage for a number of global change scenarios (Durand, 2004). A reduction of 40% in fertilisation and introduction of catch crops was required to keep pollution at the present level.

-Lloveras *et al.* (2006) presented results of the $SIMS_{DAIRY}$ model (Prado *et al*, 2006) giving that a short term sward (2-3 years) leached 24% less N per unit of milk produced than long term swards (> 11 years).

-Eckersten *et al.* (2007) summarised evaluations of changed N leaching in Sweden due to climate change and found scenarios ranging between 10 and 70% depending on site and climate scenario. Considering the national environmental objective of a 30 % reduction of N leaching by 2015, and that the potential to decrease the N leaching with current cropping methods under current climate has been estimated to maximum 20-25 %, the problem of achieving environmental targets will be accentuated under climate change.

How are CH_4 emissions expected to change in future?

-In Denmark only a minor reduction of methane emissions are expected: 0.1 M tonnes CO_2- equivalents per year (about 1% of total agricultural emissions) from 2003 to 2012, due to improved efficiency in cattle farming (Danish EPA, 2005).

How are N gas emissions expected to change in future?

-In Denmark, N gas emissions are expected to decrease to 3 M tonnes CO_2-equivalents (CO_2-eq.) per year by 2008-2012, from 6.2 M tonnes CO_2-eq. per year in 2003, due to special action planes (Danish EPA, 2005; Olesen *et al*., 2004; Olesen, JE, 2005). In the same report (Danish EPA, 2005) a 12 % decrease in annual emission rates (including methane) by 2030, is reported, i.e. from 9.9 to 8.69 M tonnes CO_2-eq. per year, mainly as a consequence of reduced N leaching, commercial fertiliser application, and spread manure. A sensitivity analyses suggest that the inclusion of CAP plus stop in increased pig production, would lead to a further decrease by about 5%. A 25 % reduction in run off would result in another 5%, as well as extra initiatives for aforestation. Values are not consistent within the report.

-In Denmark, ammonium emissions are expected to decrease by 0.034 M tonnes CO_2-eq. per year by 2010 due to optimisation of manure handling, covering storage, ban on surface spreading, and ban on ammonia treatment of straw. The shortening of the exposure time of spread manure is expected to contribute most, about 30 % (Danish EPA, 2005).

How are CO_2 emissions expected to change in future?

-In Denmark ban on burning straw is expected to increase the use a straw as fuel. No quantitative measures of the expected reduction in CO_2 emission are available (Danish EPA, 2005).

-In Denmark the replacement of fossil fuels with biogas (to an amount corresponding to approx. 2 PJ up to 2010) from manure and organic waste is expected to reduce CO_2 plus N and CH_4 emissions by 0.25 M tonnes CO_2-eq. per year by 2010 (Danish EPA, 2005). Half of this reduction is due to reduced CO_2.

Which methods exist to define and assess land use impacts?

-Brentrup *et al.* (2002) discuss the assessment of the environmental impacts of land use within LCA (Life Cycle Assessment) studies. They put forward, that the impact category 'land use' in the LCA methodology describes the environmental impacts of occupying, reshaping and managing land for human purposes. The impact category 'land use' comprises those environmental consequences, which impact the environment due to the land use itself, e.g. through the reduction of landscape elements, the planting of monocultures or artificial vegetation, etc. Land use leads to a degradation of the naturalness of the area. To determine the remaining naturalness of land under use, the study suggests applying the 'Hemeroby' concept. The Hemeroby level of an area describes the intensity of land use and can therefore be used to characterise different types of land use. Characterization factors, allowing estimation of the degradation of naturalness due to a specific type of land use, are proposed.

What is the effect of deforestation on climate?

-Six Earth system models of intermediate complexity (EMICs) that are able to simulate the interaction between atmosphere, ocean, and the land surface, were forced with a scenario of land cover changes during the last millennium (Brovkin *et al.*, 2006). In this experiment it was found, that in response to a historical deforestation of about 18 million km^2, the models simulated a *decrease* in global mean temperature in the range 0.13-0.25 ºC. The rate of this cooling accelerated during the 19th century, and reached a maximum in the first half of the 20th century. This trend was explained by temporal and spatial dynamics of land cover changes, as the effect of deforestation on temperature was less pronounced in tropical than in temperate regions, and reforestation in northern temperate areas during the second part of the 20th century partly offset this cooling trend. As reforestation might be used as an option in the future for enhancement of terrestrial carbon sequestration, the authors argue, that this study indicates that biogeophysical mechanisms need to be accounted for in assessments of land management options.

5. Policy

What is the current status of adaptation policy in Sweden?

-In a report from Swedish EPA and STEM (Naturvårdsverket/Energimyndigheten, 2004a, b) it is stated that vulnerability and risks in Sweden (relating to effects of climate change) have been focused in a few analyses (see e.g. Miljödepartementet, 2001), but so far no co-ordinated society program has evaluated the needs, the possibilities and costs for adaptive measures.

-In a survey through inquires to different Swedish stakeholders about ongoing or planned adaptation measures, relating to climate change (SMHI 2005, RMK No.106), the agricultural sector reported that no such adaptive measures, neither already taken nor planned, were taken. They concluded (i) there is a number of analyses concerning the effects of climate change, though rather few analyses of vulnerability, or needs for adaptation measures, are actually performed; (ii) with a few exceptions, no actual adaptive measures to a changed climate have been identified in the survey.

Which policy measures could be taken to adapt agriculture to CC?
-Carter and Kankaanpää (2003) listed a number of policy measures that might be appropriate for Finland: Encouraging flexible land use and changes in land allocation; relocation of zones having comparative advantages; compensation of loss of agricultural advantages; farm diversification grants; adjusting the guidelines for water protection and especially N leaching; aid for the adaptation of new technology; plant breeding programmes and research on adaptation; developing new farming systems; developing new foods.

Will Scottish agriculture be influenced by CC?
-Kerr *et al.* (1999) concluded from preliminary results, that the CC has to be essentially larger than proposed for the coming century, to become a major driver in modifying Scottish agriculture. The temperature rise by 2085 for the Scotland grid box ranged 0.9 – 2.6 ºC, and rain fall rise ranged between 5% in summer to 30% in winter. For the period until 2050 there was a decrease in spring rainfall.

Will Scottish agriculture adapt to CC?
-Kerr *et al.* (1999) concluded that the agricultural sector will adapt to the Common Agricultural Policy, rather than to CC.

How prepared is society to alternative CC scenarios?
-The vulnerability of different sectors in society, including agriculture and forestry, to a *rapid* or *abrupt* climate change in Europe is treated in a report from Tyndall Centre for Climate Change Research (Arnell *et al*., 2005). An initial assessment of the implications of three different types of abrupt climatic change (i) a thermohaline collapse, (ii) an accelerated climatic change, due to a positive feedback by the additional release of greenhouse gases from thawing permafrost areas and the oceans, and (iii) a rapid rise in sea level resulting from disintegration of the West Antarctic ice sheet) was made. It is concluded, that due to the uncertainties (cooling or rapid warming, and maybe also low probability for such changes), it is difficult to see how organizations can plan to adapt to abrupt climate change.

What might be the role of social processes in adaptation?
-Adger (2003) argues that adaptation to CC is a dynamic social process: the ability of societies to adapt is determined, in part, by the ability to act collectively. Specifically, social capital is increasingly understood within economics to have public and private elements, both of which are based on trust, reputation, and reciprocal action. The public-good aspects of particular forms of social capital are pertinent elements of adaptive capacity in interacting with natural capital and in relation to the performance of institutions that cope with the risks of changes in climate. They review emerging perspectives on collective action and social capital and it is pointed out that insights from these areas inform the nature of adaptive capacity and normative prescriptions of policies of adaptation.

What are the needs to develop adaptation strategies in Indo-Gangetic plain?
-Aggarwal *et al.* (2004) argue that further information is needed to develop a range of adaptation strategies of food systems in IGP to GEC (Global Environmental Change). (IGP is Indo-Gangetic plain; including regions of Pakistan, India, Nepal, and Bangladesh). The strategies include augmenting production and its sustainability, increasing income from agricultural enterprises, diversification from rice-wheat systems, improving land use and natural resource management, and instigating more flexible policies and institutions. Strategies to reduce the vulnerability of the region's food systems to GEC need to be based on a combination of technical and policy options, and developed in recognition of the concurrent changes in socioeconomic stresses. Adaptation options need to be assessed with regard to their socioeconomic and environmental efficacy, but a greater understanding of the interactions of food systems with GEC is needed to be able to do this with confidence.

Which methods are needed to estimate effects of adaptation measures?
-In a report from GCSI (1999, see “5. Soil” in this report) is stated that a general acceptance internationally in the Kyoto protocol of agricultural soil sinks requires reliable and verifiable methods for determining changes in soil carbon stock. While such methods have been proposed, further assessment and evaluation is required.

How can projects on C sequestration influence greenhouse gas emissions in the future?
-CAN Europe (Climate Action Network Europe; 2006) conclude in a “Briefing Paper” that proposals to allow sink projects in the EU ETS, do not address the serious issues such as scientific uncertainty and lack of long-

term contribution to avoiding climate change. It continues to be difficult and expensive to estimate the uptake and storage of carbon by biological sinks with any degree of accuracy. They argue that including sinks projects will delay action required to reduce the threat of climate change. It may also increase the cost of compliance as it may be more expensive in the future to mitigate climate change and mitigate the re-emissions from the temporarily sequestered C.

How will, in summary, climate change influence agriculture in Denmark?

-Danish EPA (2005): "For Danish agriculture, the overall effects are estimated to be advantageous. Changes in cultivation practice can be implemented at short notice, and production is expected to grow with rising temperature and CO_2 concentrations. EU regulation is currently causing a development leading to less dairy production and increasing production of pig meat. The projected climate changes could reinforce this trend because market constraints in the dairy sector would limit production. In this context, the forthcoming EU CAP will play a greater role than climate change. Despite the extreme summer heat in Germany, France and Spain in 2003, where the harvest in several places fell by up to 30%, there was no overall drop in farmers' incomes because higher prices meant better profits in the countries that were not affected. In the longer term – in a climate under change – Denmark is favourably placed in the EU internal market. However, higher temperatures and humidity could increase the risk of pests and plant diseases, resulting in an increased demand for pesticides. At the same time, increased production would require more nutrients for plants, which, together with more precipitation and higher soil temperatures in winter, as well as irrigation in summer, would increase the risk of nutrient leaching and run-off. Implementation of the EU Water Framework Directive will help ensure both cost-effective agriculture and long-term protection of water resources in a future changed climate."

How will, in summary, climate change influence agriculture in Scotland?

-Kerr *et al.* (1999) made an investigation of possible influences of climate change on Scotland. They conclude that for the agricultural sector the land use will play a key role under climate change as it influences the greenhouse gas emissions. Set-aside land and aforestation is especially mentioned.

Which are the research needs?

-Research priorities are: the effect of secondary factors on production, quality of crop and animal production, changes in frequency of isolated and extreme weather events and interactions with the surrounding natural ecosystems (Olesen and Bindi, 2002).

Concerning crop production?

-Ewert *et al.* (2005):" The importance of advances in technology for future productivity as evident from our results draws particular attention to relationships that determine technology development. Our assumptions about technology effects on potential yield and yield gap were based on qualitative judgments and there is a clear scope for model improvement. Consideration of dynamic feedback mechanisms between crop productivity and demand for food, agricultural land use and socio-economic conditions are likely to provide further insights into the complex relationships determining productivity change."

What are the options for future climate change research of interest for Scotland?

-Kerr *et al.* (1999), as a first priority, identified the needs of: (i) higher resolution of climate data (especially precipitation and snowfall); (ii) more impact studies for Scotland, where regional differences are identified; (iii) CC indicators developed for UK should be evaluated for Scotland specifically; (iv) creation of a 'meta-data' depository including key indicators of climate that are of interest and useful by users; (v) maps of exposure areas within Scotland; (iv) comparison with similar CC strategic studies in Nordic countries (Norway, Sweden, Ireland). As a second priority they suggest the exploration of the linkages between the main driving forces of single sectors in the society, and the impacts of climate. Also the linkages to the impacts of emission targets should be explored. They mention specifically: Public perception, land use strategies, requirements to reduce greenhouse gas emissions, and business opportunities.

Do we know about the effects of climate extremes on agriculture?

-Kerr *et al.* (1999) stated that the effects of climate extremes on agricultural production have yet to be fully understood.

6. Climate change impacts in relation to natural resources and globalisation

Climate is one among a number of other factors influencing agricultural production and that expected to change in future. Also the availability of resources used for input to the production might change, as well as the market for the products, as the globalisation gets Swedish agricultural production more close to the global agricultural market. In addition the use of agricultural land will be related to alternative use e.g. production of ecosystem services, or non-agricultural activities. In this section we aim at describing results of studies trying to assess how effects of changing availability of natural resources and globalisation on agricultural production might be related to changing climate. This section is structured with respect to central factors “drivers”, except for CC, that are expected to influence agricultural production, i.e. natural resources and globalisation, but also factors that the changes effects act upon, i.e. ecosystem services etc, and factors that both are drivers and response factors like land use.

What might be the relation between agricultural drivers and global change?
-Vitousek (1994) listed three well documented factors changed in association with global change, that are important for agriculture: increasing concentrations of CO_2 in the atmosphere, alterations in the biochemistry of the global nitrogen cycle, and an ongoing land use/land cover change. (1) CO_2 has increased from 280 to 355 ppm since 1800, the increase is unique at least for the past 160 000 years. This has climatic consequences and direct effects on biota in all Earth’s terrestrial ecosystems. (2) More N is fixed annually by human activities (N fertilizer fabrication, growing of legumes crops and as a by-product in fossil fuel combustion) than by all natural pathways combined. This added N alters the chemistry of the atmosphere and of aquatic ecosystems, contributes to eutrophication of the biosphere, and has effects on biodiversity in the most affected areas. (3) Human land use/land cover change has transformed one third to one half of the Earth’s ice-free surface. This is probably the most important component of global change now and for some decades to come; it has profound effect on biological diversity. The difference between pristine ecosystems and human-altered areas may have existed in the past, but has now vanished. These three and other equally certain components of global change are the primary causes to the anticipated climate changes and of ongoing losses in biological diversity. They are caused by the extraordinary growth in human population.

6. Natural resources

Which methods exist to predict energy use?
-A model for fossil energy use was developed in Denmark (Dalgaard *et al.*, 2001).

How does energy use efficiency depend on cropping system?
-Fossil energy use was compared in organic and conventional farms in a simulation study in Denmark (Dalgaard *et al.*, 2001). Conventional farms had the highest energy consumption. Energy use and also yields were lower on the organic farms, but organic crops had the highest energy efficiency. Energy use in animal production was also studied.

Can energy supply of agriculture in Ireland be reduced without influencing yields?
-Rice (2003) concluded for Irish conditions that engine fuel is agriculture’s main direct energy input. It was estimated that a reduction of 15-20% in this input over the next five years would appear to be reasonable. The reasons might be, for instance, a diversion of land out of agriculture, and an improvement in energy efficiency. It was concluded that nitrogenous fertilizer is the biggest indirect energy input, and suggested that a reduction of 20% over five years, without reducing output, should be achievable by a greater precision in N use and an increased substitution of slurry for mineral-N.

How much land area is needed for bioenergy production in Ireland?
-Rice (2003) concluded that for Ireland biofuel production from the existing set-aside area could supply about 10% of the agricultural fuel demand. It was also concluded, that about 0.5 Mha would be required to meet 10% of the total national primary energy demand, when energy crop is utilized in a heating or CHP (Combined Heat and Power) plant. This could be set as a medium-term target that could be achieved without major disruptions in the existing food production.

How much energy might be achieved from biomass in future, and which are the reasons of uncertainties?

-Berndes *et al*. (2003) discuss the possible contribution of biomass to the future global energy supply, based on a review of 17 other studies on this subject. Some of their findings are: The reviewed studies have arrived at widely different results about the possible contribution of biomass to the global energy in the future, varying from below 100 EJ yr^{-1} to above 400 EJ yr^{-1} in 2050 (1 EJ (exajoule) = 1018 Joule). (For comparison: The global consumption of fossil fuels, nuclear energy and hydro electricity in 1999-2000, was ~365 EJ yr^{-1}.) The major reason for this large differences is said to be that the two most crucial parameters for these estimates – land availability and yield levels in energy crop production – are very uncertain, and subject to very different opinions.

-Reilly and Paltsev (2007) describes a method for incorporating biomass energy production and competition for land into the MIT Emissions Predictions and Policy Analysis (EPPA) model, that is a computable general equilibrium model of the world economy. Multiple scenarios where greenhouse gas emissions are abated or not were examined. They estimated that the global increase in biomass energy use in a reference scenario, without "climate change policy", would be about 30 EJ yr^{-1} by 2050 and ~180 EJ yr^{-1} by the year 2100. This deployment is driven primarily on an oil price that is about 4.5 times higher than the price in the year 2000. In the scenarios of stabilization GHG concentrations, the global biomass energy production increases to 50-150 EJ yr^{-1} by 2050, and to about 220-250 EJ yr^{-1} by 2100. The estimated area of land required to produce 180-250 EJ yr^{-1} is estimated to be about 2 Gha, which is in the magnitude of the current global crop area. Their general conclusion is, that the scale of energy use in the USA and the rest of the world, relative to biomass potential, is so large that a biofuel industry that were able to supply a substantial part of liquid fuel demand, would have very significant effects on land use and conventional agricultural markets.

Can land area be a limiting factor to the production of bioenergy fuels?

-Boverket/Naturvårdsverket (2000a) states that the availability of land can present a limiting factor for the production of energy fuels, since the conversion of solar energy to viable energy is very low for bioenergy (<1%) which implies the requirement of large areas of land.

-Helmfrid and Haden (2006) [the report is part of a co-operative work between KSLA and CUL (Centrum för uthålligt lantbruk, SLU) addressing questions coupled to the expected scarcity of oil in the future] conclude the following: (i) To cover the need of fuels (petrol and diesel) within the agricultural (food producing) system itself with biofuels (ethanol and RME), would require ~1 Mha (i.e. about 40 %) of the total arable area in Sweden; (ii) to substitute all the present Swedish fuel consumption with biofuels (produced in Sweden) would require an area of more than 6 Mha – an alternative "beyond all realism" as stated by the authors; (iii) the corresponding calculus for covering all of the Swedish fuel consumption with liquid fuels produced from wood as primary product, indicates a need for more than 15 Mha of forest area, corresponding to about 80 % of the present yearly cuttings.

Which are the most promising technologies for bioenergy production?

-Rice (2003) listed the most promising technologies for the conversion of farm biomass to energy: vegetable oils and animal fats as engine fuels in vehicles or CHP plants; ethanol as a replacement for MTBE (methyl tertiary butyl ether) in petrol, either converted to ETBE or used directly; methane production from animal slurries, used in heating or CHP plants; direct combustion or gasification of wood or other energy crops.

6. Globalisation

How will the food demand change in the future?

-In a simulation study of ecosystems services, Alcamo *et al*. (2003) predicted, on a global scale, an increased demand in 2050 of wheat consumption by a factor of 1.5 to 1.7, of fish consumption by a factor of 1.3 to 1.4, of water withdrawals by a factor of 1.3 to 2.0 and by biofuel production by a factor of 5.1 to 11.3.

6. Ecosystem services

Is cropping sensitive to CC, in comparison to other factors that are expected to change in the future?

-Holman *et al*. (2005) evaluated interactions between four major sectors driving landscape change (agriculture, biodiversity, coasts and floodplains, and water resources) using the Drivers-Pressure-State-Impact-Response (DPSIR) approach. For UK it was found that despite yield changes, cropping was generally insensitive to climate change but very sensitive to changes in socio-economic changes.

-Ewert *et al*. (2005) estimated an increase in crop productivity by 2020 to 2080. Technology development was identified as the most important driver for this increase, essentially more important than CC. The relative crop yield increases were 11-32% for CO_2 increase, based on crop modelling, whereas the corresponding factor for technology development was 20-140% assuming a constant relative change over time.

-Technology development will have a greater impact on increase in future crop productivity than climate change (Ewert *et al.* 2005). Countries with high technological potential will have an advantage in terms of increasing crop acreage.

How will ecosystem services be changed in future?

-In a simulation study of ecosystems services Alcamo *et al.* (2003) predicted in general a positive balance of increasing services, especially in the developing countries. They also predicted a negative balance of increasing risks and tradeoffs of services. The challenge then is to avoid a future curtailment of ecosystem services.

Is biodiversity sensitive to CC in comparison to expected changes of other drivers?

-Holman *et al.* (2005) evaluated interactions between four major sectors driving landscape change (agriculture, biodiversity, coasts and floodplains, and water resources) using the Drivers-Pressure-State-Impact-Response (DPSIR) approach. For UK it was found that the sensitivity of biodiversity to CC was regional, habitat and species specific. However, biodiversity within regions depend to a large extent on planned adaptation in the other sectors.

Which forest species distribution and productivity under CC are projected for Sweden?

-In a study by Koca *et al.* (2006) the potential of a processed-based regional ecosystem model (LPJ-GUESS) are discussed. The model is driven by climate scenarios generated by a RCM to give projections of climatic and CO_2 change on the key ecosystem services of carbon uptake and storage. Scenarios compatible with SRES A2 and B2 emission scenarios were used in the simulations to explore changes in tree species distribution, vegetation structure, productivity and ecosystem carbon stocks for the late 21st century. The results suggest that shifts in climatic zones may lead to changes in species distribution and community composition among seven major tree species of Swedish forests. The model also predicted substantial increases in vegetation net primary productivity (NPP), especially in central Sweden. Expansion of forest cover and increased local biomass enhanced the net carbon sink over central and northern Sweden. In southern Sweden, reduced soil moisture levels during the growing season counterbalanced the positive effects of a longer growing season, with the result that many areas were converted from a sink to a source of carbon towards the end of the century.

6. Environment

What is the feedback of vegetation on the climate system?

-A coupled global vegetation-climate model was used to investigate the effect of vegetation feedbacks on climatic change due to doubling the atmospheric CO_2 (Bergengren *et al*., 2001). Large effects of vegetation feedbacks in the interactive simulations are found in the northern and southern ecotones of the boreal forest. Poleward migration of boreal forests into tundra is enhanced by strong snow-masking albedo feedback. Changes in the southern tropics are also described.

How can energy crops be used for environmental purposes?

-Boverket/Naturvårdsverket (2000a) states that an environmentally soundly adapted cultivation of perennial energy crops (e.g. energy forests and energy grass) based on optimal design, localisation and management, implies e.g. that the agricultural burden on the environment in shape of nutrient leakage, erosion and emissions of greenhouse gases may decrease. With use of selected clones of *Salix* the concentrations of cadmium in arable soils may be reduced. Trials concerning the possibilities to reduce nitrate concentrations in ground water through irrigation and uptake in *Salix* cultivations have been performed. Cultivation of energy crops can also be used for cleaning of wastewater and leachate from waste storages ("lakvatten" in Swedish).

6. Land use

Which factors other than climate influence land use?

How does neighbour farmer choice of crop influence land use?

-Schmit and Rounsevell (2006) found that imitation is not an important determinant of agricultural land use patterns. Neighbouring parcels cultivated by farmers who live in close proximity are only slightly more similar than neighbouring parcels cultivated by farmers who live further away from one another. This questions the validity of the assumptions underlying agent-based models that try to explain agricultural land use through imitation behaviour. A methodology based solely on spatial data to analyse whether, and to what extent, farmer imitation leaves an observable footprint on an agricultural landscape is proposed. Geographical Information

System (GIS) analysis of parcel and farm location data of a study region in central Belgium was developed as an alternative methodology to farmer interviews. The proposed methodology has two limitations. First the imitation effect could not be separated from all other factors that influence agricultural land use. Secondly, the method was applied to aggregated land use classes for a single year, which did not allow for the effect of crop rotations in understanding imitation behaviour.

Does Sweden has enough area to cover the consumption of its population?

-Boverket och Naturvårdsverket (2000b) present results for Sweden. With an ecological footprint (EF) corresponding to 6-7 ha per capita and an ecological carrying capacity (ECC) of 7-8 ha per capita, has a small surplus of carrying capacity, disregarding the fact that the "footprint" is calculated in relation to the whole world, while the carrying capacity only relates to Sweden's surface area. They conclude that in relation to resource needs there is a shortage of ECC in both industrialized and developing countries. Studies of land use in Sweden show that the area used for agriculture roughly corresponds to that needed to produce the food we consume, including the large areas used for animal products. Note: ECC in the report, is not identical with 'productive area', which for Sweden sums up to ~3.65 ha/person (agricultural land 0.41; forest 2.66 and water areas for fishery 0.58 ha/person, respectively). This is due to the use of 'compensation' and 'yield' factors in the calculation procedure to allow for differences in yield potential between different regions or countries for a certain crop or other product. (*Ecological carrying capacity* is a measure of the productive capacity of the areas that are available in the world as a whole, in a country or in a smaller area, whereas the *ecological footprint* represents the total area needed to produce everything consumed by an individual or a population, and to absorb the emissions that result from this consumption.)

For what purposes other than agriculture can agricultural land be used under CC?

-Climate change may reduce area of fresh water wetlands in Eastern Europe and costal wetlands in Estonia (Hartig and Rosenzweig, 1997).

-In an extensive simulation of ecosystems services supply Schröter *et al* (2005) predicted increased forest production in Northern Europe but severe damage to forest vegetation in Southern Europe.

-"Stakeholders major concerns were in total amount of land available for farming (Schröter *et al.,* 2005)."

Is the large forest area of Sweden used for storage of carbon dioxide?

-Boverket och Naturvårdsverket (2000b) states that studies of land use in Sweden shows that the forest area is much larger than is needed for the purposes of domestic consumption, but is used for export production rather than for 'permanent' storage of carbon dioxide emitted from the use of imported fossil fuels.

Is land set aside in Sweden to reduce environmental impacts?

-Boverket och Naturvårdsverket (2000b) states that studies of land use in Sweden shows that land is not set aside to absorb nutrient leakage or protect ground water.

How is land use predicted to change in the future?

How is land use predicted to change on a global scale?

-In a simulation study of ecosystem services Alcamo *et al.* (2003) predicted, on a global scale, an expansion of agricultural land between 2000 and 2050, causing a 10-20% decrease in grassland and woodland areas.

How is land use predicted to change in Europe?

-Rounsevell *et al.* (2006) predict land use changes of the EU15 countries, Norway and Switzerland for different socio-economic scenarios. The most striking change is a large decline in agricultural land use. Forestland areas increase in all scenarios, although such changes will occur slowly and largely reflect assumed policy objectives. Increases in urban areas (arising from population and economic change) are similar for each scenario, but the spatial patterns are very different. The base is an interpretation of the global storylines of the Intergovernmental Panel on Climate Change (IPCC) that are presented in the special report on emissions scenarios (SRES). The results are based on assumptions about future crop yield development. All scenarios assume some increases in the area of bioenergy crops with some scenarios assuming a major development of this new land use. The scenarios also consider changes in protected areas (for conservation or recreation goals) and how these might provide a break on future land use change. The approach to estimate new protected areas is based in part on the use of models of species distribution and richness.

How is Swedish agricultural land used at a high price of oil?

-Jonasson (2005) estimated the fraction of land used for different crops when oil will cost 100 dollars per barrel. Using a model where the choice of land use is based on a strive for achieving maximal profit, they estimated that of the Swedish agricultural area 44% would be used for food or fodder production, 34% for energy production and 22% was fallow. The corresponding figures for the whole of EU25 were 78%, 20% and 2% respectively. No references to literature were given.

How sensitive is land use to CC in comparison with socio-economic changes?

-Audsley *et al.* (2006) found that the main effects of both climate and socio-economic changes were in the agriculturally marginal areas of Europe. The results showed that the effect of different climates is relatively small, whereas there are large variations when economic scenarios are included. Only Finland's agricultural area significantly responds to climate. It will increase at the expense of forests in several scenarios. The scenario modelling identified several regions where there is a need to be watchful, but few where all scenario results agree, suggesting a great uncertainty in future projections. All results agree, however, that in Central Europe changes are likely to be relatively small. They used models of crop growth and farm decision-making in combination to predict profitability over the whole of Europe. The models were driven solely by soil and climate at each location. Each location was then classified by its profitability as intensive or extensive agriculture or not suitable for agriculture.

Which methods are used to assess land use changes?

Which methods are used to assess landscape changes?

-Holman *et al.* (2005) developed a methodology for stakeholder-led, regional climate change impact assessment that explicitly evaluated cross-sectoral interactions between four major sectors driving landscape change (agriculture, biodiversity, coasts and floodplains and water resources), and adaptation options, on a local and regional (sub-national) scale. In particular, the role of scenarios, error propagation in linked models, model validity, transparency and transportability were examined. Also the use of integrated assessment to evaluate adaptation options to climate change was examined. The study was made for East Anglia and North West England' (RegIS). The 'Drivers-Pressure-State-Impact-Response' (DPSIR) approach provided a structure for linking the modelling and scenario techniques. A 5 x 5 km grid was chosen for numerical modelling input (climate and socio-economic scenarios) and output, as a compromise between the climate scenario resolution (10 x 10 km) and the detailed spatial resolution output desired by stakeholders.

Which methods are used to assess agricultural land use changes?

-Abildtrup *et al.* (2006) present an approach for the analysis of climate change impacts on European agricultural land use, based on socio-economic scenarios. The scenarios are interpreted from the storylines described in the intergovernmental panel on climate change (IPCC) special report on emission scenarios (SRES), which provide internal consistency between the evolution of socio-economics and climate change. The land use estimates is made with the ACCELERATES integrated land use model which needs inputs of socio-economic parameters, e.g. prices and productivity. The consistency of SRES and CC scenarios allows a stepwise downscaling procedure to be used for quantification of parameters. First, the global driving forces are identified and quantified for each of the four SRES scenario families (see "1. Scenarios" in this report). Second, agricultural driving forces are derived for each scenario from global driving forces. Finally, parameters for the agricultural land use model are quantified. Furthermore, the pairwise comparison approach developed by Saaty [Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw Hill, New York] provides a useful tool for the quantification from narrative storylines of scenario drivers and model parameters.

-Rounsevell *et al.* (2006) present a methodology for making land use scenarios including urban, cropland, grassland and forestland, as well as introducing new land use classes such as bioenergy crops. The estimates are based on a qualitative interpretation of the SRES storylines for the European region, estimation of the aggregated totals of land use change (using various land use change models), and the allocation of these aggregated quantities in space (using spatially explicit rules). The spatial patterns are further downscaled from a resolution of 10 min to 250 m using statistical downscaling procedures. A range of future, spatially explicit, land use change scenarios for the EU15, Norway and Switzerland are presented. Several technical and conceptual difficulties in developing future land use change scenarios are discussed. These include the problems of the subjective nature of qualitative interpretations, the land use change models used, the problem of validating future change scenarios, the quality of the observed baseline, and statistical downscaling techniques.

6. Market

How large will the population be in 2050?

-Alexandratos (2005) points out that recent long-term demographic projections suggest a fast decrease in global population growth and the eventual peaking of world population later in this century at about 9.2 billion, (50 % above present level). However, some low-income and food-insecure countries, have projected populations for 2050 that are very high, and in some of these, agriculture must play a leading role in their development efforts. For those with scarce agricultural resources, the high population growth rates may not be compatible with their development potential. Their demographic projections may need to be revised, taking into account the inadequate agricultural resources.

Will CC help agriculture covering global food demand?

-World population will increase threefold by the next half century. Climate change is likely to lower crop yields, especially in food-insecure regions. We therefore have to maximize the efficiency and sustainability of production methods according to McMichael (2001).

-There is an increasing global demand for food, which has to be met by increased intensification of production (Gregory *et al.* 2002)

-Ewert *et al.* (2005) estimated an increase in crop productivity by 2020 to 2080 between 25% and 163%. This estimated increase exceeded the estimated increase in food demand for Europe, concluding that the surplus of agricultural land used for food production today will remain or even be accentuated in the future.

Will food be more expensive under CC?

-Reilly *et al.* (2003) found that the global change was positive for the US consumers, but negative for the producers, due to declining prices. They studied the impacts on U.S. agriculture of transient CC as simulated by two global general circulation models focusing on the decades of the 2030s and 2090s. CC impacts on crops, grazing and pasture, livestock, pesticide use, irrigation water supply and demand, and the sensitivity to international trade assumptions were considered, finding that the aggregate of these effects resulted in declining crop prices.

-Globally, prices of agricultural products can rise and profitability of Finish agriculture increase (Carter and Kankaanpää, 2003).

Who will gain on increased yields due to CC?

-Kettunen (1996) suggested that the national economy will benefit from increased yield under CC, although increased cost for disease and pest control will reduce the benefits to some extent yields (a 10% increase in yield would increase farm income by 6%). The farm is not expected to increase its income as subsidises might be reduced accordingly.

At what price are biofules a cost efficient method for reducing greenhouse gas emissions?

-Schneider and McCarl (2003) found that carbon prices below $40 per ton of carbon equivalent made biofuels not cost efficient for reducing net greenhouse gas emissions. At these incentive levels, emission reductions via reduced soil tillage and aforestation are more cost efficient. Therefore subsidies are needed to make agricultural biofuel production economically feasible. For carbon prices above $70, biofuels dominate all other agricultural mitigation strategies. To explore the economic potential of biofuels in a greenhouse gas mitigation market, data was incorporated on production and biofuel processing for the energy crops switchgrass, hybrid poplar, and willow in an U. S. Agricultural Sector Model along with data on traditional crop-livestock production and processing, and aforestation of cropland. Net emission coefficients on all included agricultural practices were estimated through crop growth simulation models or taken from the literature. Potential emission mitigation policies or markets are simulated via hypothetical carbon prices. At each carbon price level, a new market equilibrium was computed, revealing agricultural commodity prices, regionally specific production, input use, and welfare levels, environmental impacts, and adoption of alternative management practices such as biofuel production.

Is it important that the municipalities maintain a high level of planning readiness as regards an increased establishment of bioenergy?

-Boverket/Naturvårdsverket (2000a) states that an environmentally soundly adapted cultivation of perennial energy crops is often very cost effective from the point of view of the municipalities.

What spatial scale is needed to make proper economic impact assessments?

-Adams *et al*. (2003) found for the United States that the spatial scale of climate scenarios affected the estimates of both regional changes in crop yields and the economic impact on the agricultural sector as a whole. An assessment based on the finer scale climatic information consistently yielded a less favourable assessment of the implications of CC. Regional indicators of economic activity were of opposite sign in some regions, based on the scenario scale. Past CC assessments may therefore misstate the economic consequences of such changes. The estimates were derived via a set of procedures and an analytical model that has been used previously in CC assessments. They suggest that refinement of the spatial scale of scenarios in the economic calculations of the effect of CC should be carefully considered in future impacts research. Resolution in climate scenarios is a key uncertainty in climate impact studies and regional integrated assessments and may affect the magnitude of economic estimates of CC, with implications for the public policy debates concerning the efficiency of CO_2 control options.

How would industry need to adapt to agriculture under CC?

-Food industries need to be prepared to a changing global market and changing prices on raw material (Carter and Kankaanpää, 2003).

Is it possible to predict management, yields and N leaching from optimal economical terms?

-Vatn *et al.* (2005) presented a comprehensive method (ECECMOD) for evaluating the effect of market and policy factors on yield and losses of N, P and organic matter in agricultural production. Process models for simulating yield and losses were the bases for the evaluation. They simulated what would be the yields and losses if the farmer would chose management methods in an optimal economical way. They compared simulations with regional statistics for four regions in Norway, together comprising 10% (or 100 000 ha) of the Norwegian agricultural land.

Are simple climate-economy models reliable?

-Füssel, H.-M. (2007) argues that one of the main arguments brought forward in favour of the use of simple climate-economy models is their transparency, which should enable researchers to easily interpret the simulation results In the paper, he investigates to which degree this claim is supported in the case of the DICE (Dynamic Integrated model of Climate and the Economy) model, but claims that most of the findings are relevant also for other welfare-optimizing climate-economy models as well. Specifically, this paper reviews the handling of time discounting in social welfare functions, the combination of different social welfare functions, the calibration of uncertain climate parameters, the representation of uncertainty about future climate change, and more. He finds that each of these aspects has been treated inconsistently in the past. In the paper, the methodological questions arising from these problems are discussed, and some specific recommendations how to avoid these problems in the future are given.

What is the role of economy in the reduction of biodiversity?

-Norgaard (1994) suggest additional ways of modelling the interaction between human activity and biological systems to provide further insight into how man might better maintain biological biodiversity.

Are windbreaks efficient for mitigating effects of drought on employment in agriculture?

-Seck *et al*. (2005) evaluated changes since 1970 in Senegal due to plantations of dense perennial hedges as windbreaks during a period of increased frequency of drought. They found increased crop production providing increased employment. Methodology is not indicated in abstract.

What are the cost benefits of an El Niño forecasting system?

-Adams *et al*. (2003) calculated that the benefits of an ENSO (El Niño-Sothern Oscillation) early warning system for Mexico is approximately US$ 10 million annually, based on a 51-year time period of ENSO frequencies and when a forecast skill of 70% is assumed. The values estimated here should be viewed as lower bound estimates. To assess the economic consequences of climate arising from various ENSO phases, estimates of regional crop yield sensitivity for key crops were modelled using a crop biophysical simulator. The value of a forecast is then measured by the expected increase in economic benefits due to changes in cropping patterns, production and consumption arising from the yield changes under each ENSO phase forecast. These economic estimates are derived from an economic model of Mexican agriculture. The economic model is a stochastic, price endogenous, mathematical programming model that represents agronomic and economic conditions in a five-state Mexican region. The value of the ENSO information will depend on its accuracy in terms of predictions of the weather consequences of each phase.

How can stakeholder-led CC impact assessments be made?
-Holman *et al.* (2005) developed a method for evaluating regional and local scale adaptation options in terms of (unclear in abstract) interactions between four major sectors driving landscape change (agriculture, biodiversity, coasts and floodplains, and water resources). The Drivers-Pressure-State-Impact-Response (DPSIR) approach provides a structure for linking modelling and scenario technique. The method was used for UK with a grid scale of 5 x 5 km, and evaluated for role of scenarios, error propagation in linked models, model validity, transparency and transportability.

6. Policy

Which policy measures could be taken to adapt agriculture to society under CC?
-Carter and Kankaanpää (2003) listed a number of policy measures that might be appropriate for Finland: Integrating environmental, agricultural and cultural policies to preserve the heritage of rural development.

How successful are different systems for seed distribution during drought periods?
-Orindi and Ochieng (2005) found for drought periods during 1991-2004 in eastern Kenya that seed fairs organised by local communities were more cost efficient in distributing seeds to the most needed sections of society than conventional commercial channels, that wrongly assumed local seed varieties to be unavailable.

6. Vulnerability

How can global scenarios be scaled down to regional scenarios?
-GECAFS (2006): GECAFS (Global Environmental Change and Food Systems) used four global Millennium Ecosystem Assessment (MEA) scenarios as a base for making the corresponding regional scenarios for food security in the Caribbean region. First the effects of the four MEA scenarios were assessed for (i) Demographic and economic development, (ii) International, socio-political and cultural development, and (iii) Agricultural (society related) developments in the Caribbean region. Then, Global Environmental Changes (GEC) (climate variables) were converted into regional changes, which were used to assess the effects on five drivers of the food production system: Flooding, Land use, Water availability, Fishing and Pollution. These five drivers were then used together with the regional effects of MEA scenarios, as drivers for assessing food security in the Caribbean region.

How can vulnerability of food systems be assessed?
-Fraser *et al.* (2005) proposed a preliminary framework to assess the vulnerability of food systems to future chocks, based on the Panarchy Framework used in landscape ecology. Vulnerability is determined by three characteristics: (i) wealth available within the system, (ii) connections of the system, and (iii) diversity within the system. Wealth is estimated from how poverty affects food security (method from economy). Connectivity is evaluated from assessing importance of pathways (method from chemistry). Diversity is estimated using tools investors use to assess financial risks.
-Metzger (2005) (thesis based on a number of studies) presented a methodology for assessing vulnerability. Vulnerability was defined as being dependent on two terms, the potential impact of environmental changes excluding adaptation (PI), and the adaptive capacity (AC), where adaptation is defined as the adjustment in natural and human systems. Vulnerability (V) was assessed qualitatively by comparing PI and AC. High PI increased V but high AC decreased it.

How can adaptive capacity of societies be assessed?
-Metzger *et al.* (2006) described the AC model. Adaptive capacity of a society (AC) was regarded as a function of three Components (Awareness, Ability and Action) describing the societies capacity to react on a change. The Components were functions of other Determinants: Awareness = f(Equity and Knowledge), Ability = f(Technology, Infrastructure), Action = f(Flexibility and Economic Power). To find values on the Determinants they were set as functions of observable Indicators: Equity = f(Female activity rate, Income inequality), Knowledge = f(Literacy rate, Environment ratio), Technology = f(Research and development (R&D) expenditure, Number of patents), Infrastructure = f(Nr of telephone lines, Nr of doctors), Flexibility = f(GDP per capita, Dependency ratio), and Economic Power = f(Budget surplus, World trade share). In total 12 Indicators in this way are Drivers of the AC model.

How can potential impacts of changes be assessed?

-Metzger *et al.* (2006) described the PI model. The potential impact of environmental changes excluding adaptation (PI) was defined as the difference between Ecosystem Service provision after the change in environment (ES) and that before the change (ESbaseline). ES was a function of ES of five Indicators: Food production, Fibre production, Energy production, Farmer livelihood and Outdoor recreation. ES of the single indicators could be estimated using ecological models for biodiversity, agriculture, forestry, hydrology and carbon sequestration (see ATEAM, Ewert *et al*., 2005). However, a simplified method was used, assuming ES to be a function of land use types (which in turn are functions of ES estimated using ecosystem models, Rounsvell *et al*., 2005a). The five ES Indicators were related to the area of nine land use types (Urban, Cropland, Grassland, Forest, Bioenergy crops, Protected cropland, Protected grassland, Others, and Surplus). For instance Energy production was a function of the area of land use type Bioenergy crops, which was estimated from effects of environmental changes on production levels (or ES) by the ATEAM model.

How can food security be assessed?

-GECAFS (2006): The food security of the Caribbean region for the future was assessed by first assessing the effects of four global scenarios on regional conditions. This gave four regional scenarios that were drivers of a conceptual model of food system activities. The model consisted of four food system activities: Producing, Processing, Distributing and Consuming. This gave Outputs for: Production, Distribution and Exchange (Outcome = Food availability); Affordability, Allocation, and Preference (Outcome = Food access); Nutritional value, Social value and Food safety (Outcome = Food utilization), from which Food security could be assessed.

How might food supply to the population of Mali change under CC?

-Butt *et al*. (2005) assessed the national crop yield levels in Mali to change between –17% and +6% under CC, forage yields –5 to –36%, and weight of livestock animals –14% to –16%. This would correspond to an economic loss of 70-140 million $, and that the percentage of population at risk of hunger doubles, from the current estimate of 34% to 64-72%.

How might risk of hunger differ between SRES emissions scenarios?

-Parry *et al*. (2005) reported results of a number of projects that aimed at evaluating the risk of hunger under different emissions and climate scenarios. Effects of three categories of scenarios were evaluated: Business as usual climate scenario (IS92a), Stabilisation emission scenarios at 550 and 750 ppm respectively, and SRES (Special Report on Emission Scenarios) emission scenarios (A2, B2 etc). The main conclusion was that the region of greatest risk is Africa. It was also concluded that stabilisation at 750 ppm avoid some risk but most risk remains, whereas stabilisation at 550 ppm avoids most risk and a minor part remains. At last it was concluded that the relation between risk of hunger and climate change is mainly through the development of the society, and that the SRES B2 scenario (environmental concern, regional) is associated with lower risk than the SRES A2 scenario (strong economical growth, regional) due to the larger differences in income and technology in the latter case.

How can vulnerability to CC of different regions be compared?

How can ecosystem service provisions be compared between regions?

-Metzger *et al*. (2006) compared the vulnerability of different regions (grids) in Europe by relating the value of a specific ecosystem service (ES) to the highest ecosystem service value of the region (strata) concerned (ESref). The ratio ESstr = ES/ESref gave a value between 0 and 1 representing the relative importance of the specific ecosystem service compared to the highest, within the region (strata?). The potential impact of environmental changes (PIstr) was then estimated as the difference between the relative ecosystem service value in the future (ESstr) and that of the baseline (ESstrBaseline). The differences (ESstr - ESstrBaseline) were compared between regions.

Which areas will be most vulnerable economically to CC?

-Antle *et al*. (2005) got results that support the hypothesis that the most adverse impacts on net returns distributions tend to occur in the areas with the poorest resource endowments and where mitigating effects of CO_2 fertilization and adaptation are absent. Relative and absolute measures of vulnerability depend on complex interactions between CC, CO_2 level, adaptation, and economic conditions such as relative output prices. The relationship between relative vulnerability and resource endowments varies with assumptions about CC, adaptation, and economic conditions. Vulnerability measured with respect to an absolute threshold is inversely related to resource endowments in all cases investigated. Coupled, site-specific ecosystem and economic simulation models were used with two key features: it represents adaptation as an endogenous, non-marginal economic response to CC; and it provides the capability to represent the spatial variability in bio-physical and economic conditions that interact with adaptive responses. Study area: the dryland grain production systems of the Northern Plains region of the United States

How vulnerable is European agriculture to CC?

-Vulnerability to climate change in Europe is discussed in a report from the European Environment Agency (EEA, 2005). A large body of literature on relevant topics was reviewed (e.g. IPCC reports, relevant chapters of national communications to the UNFCCC etc.), and, secondly, a questionnaire to gather first hand and up-to-date information on national vulnerability assessments, adaptation strategies etc. was developed. Some of the statements in the report concerning the agricultural sector are: (i) Agriculture accounts for only a small part of gross domestic production (GDP) in Europe. Therefore, the overall vulnerability of the European economy to changes that affect agriculture is low. (ii) Regionally and nationally, however, effects may be substantial, particularly in southern and central European countries. Intensive farming systems in western Europe generally have a low sensitivity to climate change, and farmers are well resourced to cope with changes. (iii) The agricultural sector in southern European countries may be among the most vulnerable to the direct and indirect impacts of projected climate change. (iv) The distribution and intensity of existing pests, diseases and weeds are likely to be more abundant. Currently exotic species may appear under a warmer climate. The need for plant protection will grow and the use of pesticides and fungicides may increase. (v) Particularly vulnerable regions in Europe are those where there is a large reliance on traditional farming systems.

Will Scottish agriculture be vulnerable to CC, or will it benefit?

-Kerr *et al*. (1999) concluded that the strongest negative effect of CC on Scottish agriculture would probably be increased variability in weather variables. Increased difficulties to access water logged fields are identified as the major effect of CC, but this effect is small in comparison with other drivers influencing agriculture. The expected increased diversity of crops would leave the farmers less dependent on one commodity and therefore more insulated against the market.

How is vulnerability of agriculture and biodiversity related?

-Berry *et al*. (2006): Model assessments showed that the vulnerability of both farmers and species is dependent on the scenario under consideration. In agriculture, it is the socio-economic scenarios that particularly lead to different patterns of intensification, extensification and abandonment. For species, vulnerability is more related to the climate change scenarios. The conceptual linking of the two sectors shows that impacts on, and adaptation of the agricultural sector, could have a significant effect on the adaptation potential of species. The results demonstrate the importance of cross-sectoral assessments of vulnerability and highlight the importance of sectoral integration in policy development and implementation.

-Rounsevell *et al*. (2006) found that there are potential benefits to conservation management that arise from agricultural land abandonment, but this increases the vulnerability of farmers. They suggest that policy and conservation strategies should not tackle the vulnerability of agriculture and biodiversity independently. Positive outcomes in one sector might have adverse effects elsewhere. Or, potential changes within one sector may result in important opportunities that another sector might exploit. The conflicts that arise between agriculture and the conservation of biodiversity in the future have to be solved. The scientific community can contribute to this process by reducing the uncertainties, through the development of better and more integrated modelling and scenario development to interpret cross-sectoral vulnerability. The ACCELERATES project aimed to assess the vulnerability of European agro-ecosystems to environmental change in support of the conventions of climate change and biological diversity. The approach integrated existing models of agricultural land use, species distribution and habitat fragmentation within a common scenario framework, so that impacts could be synthesised for different global change problems.

7. Appendix 1: Climate change models *(GCMs, RCMs, EMICs and DGVMs)*

Climate modelling and projections (climate scenarios) on the global scale are based on General Circulation Models, GCMs (GCM sometimes also meaning "Global Climate Model"), developed at a limited number of research centres and institutes around the world, e.g. (with example of GCMs from the respective centres also given in some cases): (i) Canadian Centre for Climate Modelling and Analysis (CCCma) – CGCM2; (ii) Commonwealth Scientific and Industrial Research Organisation (CSIRO)/Australian Climate Change Science Program (ACCSP), Melbourne – CSIRO-Mk3.0; (iii) European Centre for Medium Range Weather Forecasts (ECMWF), UK; (iv) NOAA [4] /Geophysical Fluid Dynamics Laboratory (GFDL), Princeton – GFDL-CM2, GFDL-R30; (v) NASA/Goddard Institute for Space Studies (GISS), New York – GISS-Model II, GISS-Model E; (vi) Hadley Centre for Climate Prediction and Research, Meteorological Office, UK – HadCM3; (vii) Max Planck Institute for Meteorology (MPI), Hamburg – ECHAM4 (in cooper. with ECMWF) ; (viii) National Centre of Atmospheric Research (NCAR), Boulder, US – NCAR-PCM, NCAR- CCSM3, to mention about half of these centres.

Separate GCMs for the atmosphere/land-surface system (AGCMs) and for the ocean system (OGCMs), respectively, have been developed, but also models integrating the two systems in the same model, so called coupled models ((AOGCMs); often with the addition of other sub-models describing e.g. sea ice, biospheric processes or the carbon cycle.

Model descriptions and simulation characteristics regarding some of the above mentioned GCMs (or other versions of them) are given in e.g.: CGCM2: Flato and Boer (2001); CSIRO-Mk2: Hirst *et al.* (2000), CSIRO-Mk3: Gordon *et al.* (2002); GFDL-R30: Delworth *et al.* (2002); GFDL-CM2: Delworth *et al.*, (2006); GISS-Model E: Schmidt *et al.* (2006), Hansen *et al.* (2007); GISS-Model II/AOM: Rosenzweig and Abramopoulos (1997), Hansen *et al.* (2002), Schmidt *et al.* (2004); HadAM3/HadCM3: Pope *et al.* (2000), Gordon *et al.* (2000), HadGEM1: Johns *et al.* (2005); ECHAM4: Roeckner *et al.* (1996); NCAR-PCM: Washington *et al.* (2000), NCAR- CCSM3: Collins *et al.* (2006), Kiehl *et al.* (2006).

The Intergovernmental Panel on Climate Change (IPCC) compiles and assesses results/climate scenarios from dominating GCMs and presents the conclusions in the IPCC Assessment reports, e.g.: IPCC, 1997, 2000a,b, 2001a,b,c, 2007a,b,c,d.

On the regional scale a higher spatial resolution is desired. This higher resolution may be achieved by either of the following approaches: (i) using an AGCM with a high resolution grid and boundary conditions from a coupled GCM; (ii) statistical downscaling to the regional/local scale from outputs of a driving AOGCM; (iii) Dynamic Regional Climate Models (RCMs) – with a typical horizontal resolution of 50x50 km – with boundary conditions derived either from GCM simulations or from observations.

In Europe RCMs have been developed at Hadley Centre, UK (e.g. HadRM3), MPI in Germany (REMO), DMI (Danmarks Meteorologiske Institut), Denmark (HIRHAM), at Rossby Centre /SMHI, Sweden (RCAO), and in several other countries.

Regional climate model descriptions and examples of applications, relating to the above mentioned RCMs are given in e.g.: HadRM3: Hudson and Jones (2002); REMO: Jacob, D. (2001); Hennemuth *et al.* (2003); HIRHAM: Christensen *et al.* (1996) and Christensen *et al.* (2001); RCAO: Jones *et al.* (2004b) and Räisänen *et al.* (2004).

An increasing trend in climate modelling work is to extend the atmosphere-ocean models (AOGCMs) to encompass also other systems on the earth influencing the climate. Thus, submodels for atmospheric chemistry, the carbon cycle or ecosystem processes may be incorporated by coupling different submodels simulating such processes to a GCM, giving so-called Earth System Models (ESMs). Examples of such model developments are the QUEST-project, coordinated by the UK´s National Centre for Atmospheric Science (NCAS-Climate) at Reading. Many different modelling consortia in U.K. are involved in the QUEST (Quantifying and

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[4] NOAA: National Oceanic and Atmospheric Administration (at US Dept. of Commerce)

Understanding the Earth System) – project. The development of QESM (the QUEST Earth System Model) includes the following components/submodels:
-HadGAM1a (Hadley Centre Global Atmosphere Model) + ocean and sea-ice models
-UKCA (UK atmospheric chemistry-aerosols model)
-JULES (Joint UK Land Environment Simulator) – simulating land and ecosystem processes
-QPFT (Quantifying Plant/Plankton Functional Types model) – representing the marine biosphere.

Another example of ESM development of this type is carried out by the Earth System Model Development Team (ESMDT) at Princeton University by NOAA/Geophysical Fluid Dynamics Laboratory (NOAA/GFDL) with support and participation of many other U.S. authorities and modelling centra. Also here GCMs (GFDL´s CM2 coupled climate models) are adapted for linkage with different sub-modules for atmospheric chemistry, ocean biochemistry and ecology, land/soil hydrology land/soil biochemistry/ecology etc.

Such Earth System Models, with a GCM (or the atmospheric part of a GCM) as the original, basic platform are primarily adapted for simulating the behaviour of the climate system (e.g. mean temperature, atmospheric dynamics etc.). These types of models, due to their origin, are often the preferred models for simulating changes over (comparatively) shorter timescales like a century or less, and at higher spatial resolution.

7. EMICs (Earth system Models of Intermediate Complexity)

Another approach in the ESM-development field is represented by the so-called Earth system Models of Intermediate Complexity (EMICs) which are constructed already from the outset to include also other critical biogeophysical processes (beside the atmospheric part) with a more equal weight, and a more equivalent level of detail, in the model. EMICs, compared with GCM-based models, are also more apt for simulating very long-term dynamics of the Earth system (mainly due to their lower spatial resolution and in some parts simplified governing equations, which makes them computationally faster), and are also said to be more skilful at exploring the dynamics of abrupt changes and threshold effects, such as the potential collapse or slowing down of the Atlantic thermohaline circulation (the 'motor' behind the "Gulf Stream"). A general discussion on EMICs is given in (Claussen, M., Mysak, L.A. *et al.*, 2002). In the article, they propose a new perspective on the hierarchy of climate models which goes beyond the "classical" climate modelling pyramid that is restricted mainly to atmospheric processes. EMICs appear to be closer to comprehensive coupled models of atmospheric and oceanic circulation (CGCMs) than to "conceptual" or "box" models. They claim that EMICs should be considered as complementary to all of these types, because of the advantage of having a spectrum of climate system models which are designed to tackle specific aspects of climate.
Below, a selection of examples on EMICs in use up to 2005 (Claussen, M., 2005) are listed together with very brief characteristics of the models, and also with some references containing examples of applications:

-CLIMBER -3α (Potsdam Institute for Climate Impact Research, Germany): Like its predecessor (CLIMBER-2, Petoukhov *et al.*, 2000) it is designed to explore the dynamics of the natural Earth system. Compared to more comprehensive coupled atmosphere-ocean general circulation models (AOGCMs), it has a computationally faster atmospheric component, which makes the performance of large numbers of long-term simulations more feasible. The model is said to be especially suitable for investigating the role of the oceans in climate dynamics. Beside the atmospheric and oceanic-sea ice model components, it includes a dynamic global vegetation submodel [VECODE] (Brovkin *et al.*, 2002) and also a marine ecosystem model. CLIMBER-3α is described in (Montoya *et al.*, 2005). Examples of application of the model on the doubling of CO_2 - question is given in (Petoukhov *et al.*, 2005). In this paper, also results from an intercomparison project of eight EMICs (including most of those mentioned above) to investigate the variation and scatter in the results of simulating e.g. the equilibrium and transient responses to a CO_2 doubling are presented.
ISAM-2 (Dept. of Atmospheric Sciences, Univ. of Illinois): Integrated Science Assessment Model (ISAM) Framework of the Earth system retains rather sophisticated climate, chemistry and carbon cycle components, but has simplified the ocean dynamics. Therefore, the ISAM (like most EMICs) provides a much more computationally efficient modelling framework, which allows extensive exploration of many key physical, chemical and biological interactions among the individual components of the earth system. ISAM thus includes coupled modules for the atmosphere, ocean, ocean carbon cycle, sea ice, a fairly elaborated terrestrial ecosystem description ($0,5^o$ x $0,5^o$ spatial resolution, with each grid cell occupied by at least one of twelve natural land coverage classes or croplands, and by at least one of 105 soil types; within each grid cell, the carbon dynamics of each land-coverage are described by an ecosystem model representing, separately, each of the following: ground vegetation, non-woody tree parts, woody tree parts, two litter reservoirs, and three soil reservoirs [microbial biomass, humified organic matter, and inert organic matter]. The model also includes effects of biomass

regrowth in response to enhanced CO_2-levels and temperature effects on photosynthesis and respiration. Also the effects on key reactive greenhouse gases (CO, NMHCs [non-methane hydrocarbons] and NO_x) and CO_2 from biomass burning or biogenic emissions are included. (Cao and Jain, 2005; Jain and Yang, 2005)

-LOVECLIM (UCL-ASTR, Louvain-la-Neuve, Belgium; KNMI, Utrecht, The Netherlands; PIK, Potsdam, Germany, and others): The objective is to analyse processes linking ocean, sea ice, atmosphere and vegetation on time scales from decades to thousands of years, and also the interactions between climate change and the global carbon cycle. A particular attention has been paid to high latitudes and the role of sea-ice processes and the thermohaline circulation in the ocean. The model contains modules for the atmosphere (ECBILT; Opsteegh *et al*., 1998), ocean-sea ice (CLIO; Goosse *et al*., 2000), terrestrial vegetation (VECODE; Brovkin *et al*., 1997), terrestrial and marine carbon cycle (VECODE and LOCH, respectively), and also for ice sheets. (Examples of applications in: Goosse *et al*., 2001, Goosse *et al*., 2005.)

-The MIT Integrated Global System Model (Massachusetts Institute of Technology [MIT], Dept. of Earth, Atmosphere and Planetary Sciences): The MIT model is said to be designed for simulations of global changes that may arise due to anthropogenic causes, the uncertainties associated with projected changes, and the effects of proposed policies on such changes. The outputs from the climate part of the model (a modified version of an atmospheric GCM coupled with an oceanic GCM; Kamenkovich *et al*., 2002) drive a terrestrial model which predicts land vegetation changes, fluxes of CO_2, CH_4 and N_2O and soil composition, with feedback to the coupled atmospheric chemistry/climate part of the model. The terrestrial module includes dynamically linked sub-models for hydrology, terrestrial ecology (including carbon dynamics; Zhuang *et al*., 2003), and methane and nitrogen exchange respectively.

-The MIT model also includes a sub-model for anthropogenic emissions etc. In this model the world economic sphere is modelled as 16 regions, with 7 non-energy sectors, and 15 sectors for energy supply, in each region (Paltsev *et al*., 2005). It projects economic and emission variables like gross domestic production (GDP), energy use, consumption, emissions of greenhouse gases and other pollutants etc. The model structure here provides possibilities for higher spatial resolution for special studies. For example, finer geographical detail for studying effects of the European climate policy, or greater agriculture sector detail for studies of the economic effects of changes in crop productivity due to climate change. A description of the MIT IGSM is given in (Sokolov *et al*., 2005). Examples of applications are given in: Forest *et al*., 2002; Kamenkovich *et al*., 2003.

-The UVic Earth System Climate Model (University of Victoria, BC, Canada): The underlying philosophy behind the development of this model, it is said, that on time scales greater than a decade, the ocean, with its dynamic and thermodynamic features and its ability to transport heat and freshwater, are a key component of the climate system. The model has been built to resolve as many processes and feedbacks as possible, that affect climate sensitivity and oceanic heat uptake on long time scales. It contains the following system components: an energy-moisture balance atmospheric model, a three-dimensional ocean GCM, submodels for sea ice and ice sheets, a full ocean carbon cycle model (including biology; Giraud *et al*., 2000) and also submodels for the land surface (Cox *et al*., 1999) coupled to a dynamic terrestrial vegetation module (the Hadley Centre “TRIFFID” model; Cox, 2001). The UVic model is described in (Weaver *et al*., 2001). Examples of applications are given in: Ewen *et al*., 2004, Matthews *et al*., 2004.

Also the European Network for Earth System Modelling (ENES) and the European Union’s Program for Integrated Earth System Modelling (PRISM), whose ‘infrastructure project’ aims at designing a user-friendly software environment to assemble and run earth system models could be mentioned here (Valcke *et al*. 2006).

7. DGVMs (Dynamic Global Vegetation Models)

Finally, some of the Dynamic Global Vegetation Models (DGVMs) or other biogeochemical models in use will be mentioned. These models integrate biogeography, soil biogeochemistry and/or soil-vegetation-atmosphere transfer components into the same framework, allowing for vegetation characteristics (e.g. LAI, height, biomass, type, etc.), soil moisture, and nutrient availability to respond to atmospheric forcing (i.e. changes in climate and [CO_2]) and land management change (Kucharik *et al*., 2006). Some of the DGVMs are also designed for direct incorporation as modules in global climate models, either GCMs or EMICs.
Table A1 gives a brief summary of some the DGVMs (or other types of terrestrial ecosystem models) in use in the early 2000s (not complete).

Table A1. *Summary of some dynamic global vegetation models (DGVMs)*

Model	**Spec. characteristics, etc.**	**GCM/EMIC-coupling**	**References**
HYBRID	Detailed descript. of plant physiol. proc. incl. water, C and N cycles.		Friend *et al.* (1997), Friend and White (2000)
SDGVM: the "Sheffield Dynamic Global Vegetation Model"	As above; six main components: soil C and N dyn., hydrology, calc. of NPP, phenol., veget. growth, veget. dynamics		Woodward *et al.* (1995), Woodward and Lomas (2004) Mao *et al.* (2007)
IBIS: "Integrated Biosphere Simulator"	Simul. of surface water balance and terrestr. C balance; vegetat.structure, dynam. and competition; detailed physiological formulation	NCAR/DOE-PCTM, NCAR-GENESIS	Foley *et al.* (1996, 2000), Thompson *et al.* (2004)
TRIFFID: "Top-down Representation of Interactive Foliage and Flora Including Dynamics"	Competition among PFTs explicitly simul. (concept. differ. from most DGVMs); physiology and PFTs similar to most other DGVMs. (The veget. compon. in Hadley C. GCM.)	Hadley Cent. GCMs	Cox *et al.* (1998), Cox (2001) Hughes *et al.* (2006)
VECODE: "Vegetation Continuous Description model"	Simul. of veget. dynam. and C cycle within the climate system model CLIMBER-2 on time scales from decades and longer. No N dynamics.	CLIMBER-2, ECBilt - CLIO-VECODE, LOVECLIM	Brovkin *et al.* (1997, 2002), Renssen *et al.* (2006)
LPJ, LPJmL: Lund-Potsdam-Jena [mL: managed Lands] DGVM	Primarily a veget. dynamics model with coupled C and water cycles of natural, semi-nat. (and managed [agricultural] land) ecosystems	SPEEDY	Sitch *et al.* (2003), Bondeau *et al.* (2007)
ORCHIDEE: "Organizing Carbon and Hydrology In Dynamic EcosystEms"	C, energy and water fluxes on ½-hourly basis (time step of veg. dynam. 1 yr). Possibil. to assimilate variables from detailed crop model STICS	IPSL-CM4/LMDZ	Krinner *et al.* (2005), de Noblet-Ducoudré *et al.* (2004), Marti *et al.* (2005)
CTEM: Canadian Terrestrial Ecosystem Model	Competition equations that permits (~equilibr.) coexist. between diff. PFTs; robust repr. of leaf phenol., that is functionally rel. to climate (and climate change)	CCCma-CGCM	Arora (2003), Arora and Boer (2005, 2006)
JULES: "Joint UK Land Environment Simulator"	Land surface model based on MOSES (Met Office Surface Exchange Syst.) and coupled to the veg. dynamics model TRIFFID (see above)	Hadley Centre – HadGEM	Essery *et al.* (2003), Johns *et al.* (2006), http://www.jchmr.org.uk/jules
MC1: MAPSS-CENTURY-MCFIRE	Assessment of pot. impacts of CC on ecosyst. structure and function on landscape to global scale		Bachelet *et al.* (2001), Neilson (1995), Parton *et al.* (1987)

8. Appendix 2: Models for assessing climate change impacts

The present knowledge of the plant and environmental processes relevant for assessment of the impacts of global climate change (CC) is to a large extent summarized in computer simulation models, Table A2. According to their relevance for assessments of effects of CC they may be grouped into models of crop production, grassland production, carbon dynamics, water balance, nitrogen dynamics, pests, weeds and land use. Although these models cover very broad fields of science, there are, particularly for Scandinavian applications some fields missing. The missing fields within CC modelling concern primarily:

- Checking of production models for previously unknown combinations of CO_2, radiation, temperature and day length
- Hardening and over-wintering of fall-sown crops and temporary grasslands
- Development of ice crusts during winter (landscape scale)
- Population dynamics of weeds and pests
- Nitrogen dynamics of crops and grasslands during winter

Table A2. *Process simulation models, ordered according to subject and year of publication*

Model type and Subject	Reference	Name
Crop production		
Wheat production in relation to climate variabillity	Mearns *et al.* 1992	
Crop production, modified to increased CO_2	Stockle *et al.* 1992a,b	EPIC
Wheat production with stochastic weather generator	Semenov and Porter (1995)	AFRCWHEAT2
Wheat production in relation to CO_2 and temperature	Mitchell *et al.* (1995)	ARCWEAT1
Crop production	Grashoff *et al.* (1995)	
Barley production	Kleemola and Karvonen (1996)	
Multi-Crop model	Harrison and Butterfield (1996)	
Multi-Crop model	Peiris *et al.* (1996)	
Lettuce growth- environmental changes	Pearson *et al.* (1997)	
Yield variation between years	Olesen *et al.* (2000)	
Crop production	Van Minnen (2000)	
Maize production	Southworth *et al.* (2000)	
Sugar beet production in relation to water and radiation use efficiency	Richter *et al.* (2001); Pidgeon *et al.* (2001)	
Radiation penetration in a plant stand on the bases of canopy architecture	Birch *et al.* (2003)	
A model to scale leaf photosynthesis and transpiration up to large spatial scale	Chen and Coughenour (2004)	GEMTM
Multi-Crop model	Carter and Kankaanpää (2003)	
Multi-Crop model	Ewert *et al.* (2005)	
Crop production	Smith, *et al.* (2005b)	EPIC
Grassland production		
General grassland model of the plant-soil ecosystem	Hall *et al.* (1995)	CENTURY
Grassland ecosystem model linking biochemical, ecophysiological and ecosystem processes	Chen *et al.* (1996)	GEM2
Pasture dynamics model for dry matter production, and fluxes of carbon, nitrogen, water and energy	Riedo *et al.* (1998)	
Pasture growth and nitrogen balance	Thornley and Cannell (2000)	The Hurley Pasture model
Grassland production, landscape scale	Riedo *et al.* (2001)	PaSim
Forage-meat-milk production change	Holden *et al.* (2003)	
Regional NPP and transpiration in Central Grassland Region, USA	Chen and Coughenour (2004)	Simplification of GEMTM
Carbon dynamics		
Simple dynamic model to quantify long-term C dynamics in crop land	Evrendilek and Wali (2001)	
Soil C organic matter	Eckersten *et al.* (2001)	SOIL/SOILN
Net CO_2 emission for full carbon cycle analysis of agricultural systems	West and Marland (2002a,b)	
Carbon fluxes from agricultural soils	Vleeshouwers and Verhagen (2002).	
Carbon fluxes from agricultural soils	West and Marland (2002 a,b)	
Conceptual model of the dynamics of soil carbon in Swedish soils	Andrén *et al.* (2004)	

A simple carbon accounting approach. IPCC	Lal (2005)	
Soil C organic matter	Sindhöj *et al*. (2006)	ICBM
Water balance		
Snow dynamics and soil temperature	Kleemola and Karvonen (1996)	
Water-balance, European scale	Schröter *et al* (2005)	
Water recourses	Smith, *et al*. (2005b)	HUMUS
Nitrogen dynamics		
Greenhouse gas fluxes between the terrestrial biosphere and the atmosphere	Leemans and Vandenborn (1994)	IMAGE 2.0 and TVM
Pasture growth and nitrogen balance	Thornley and Cannell (2000)	The Hurley Pasture model
An alternative and compatible method to the IPCC guidelines for estimates of gaseous emissions	Fribauer (2002).	
Another alternative and compatible method to the IPCC guidelines,	Flynn *et al*. (2005)	
Land use	Rounsevell *et al*. (2003)	
N_2O emission from humid grassland, Ireland	Heleh *et al*. (2005)	
N_2O emission from grassland, Scotland	Flynn *et al*. (2005)	
N_2O emission from crops and grasslands, regional scale	Roelandt *et al*. (2005)	
Commodity demand	Schröter *et al*. (2005)	IMAGE 2.2
Land use		
Whole farm model for agricultural land use	Audsley (1993)	SFARMOD
Global distribution of C3 and C4 grasses	Collatz *et al*. (1998)	
Timeliness in crop production	Mayer et. (1996)	ACCESS
Pests		
Whole cropping systems, pest interactions	Jones *et al*. (2003)	
Pest risk assessment model	Yonow *et al*. (2004	CLIMEX
Cereal aphids population dynamics	Newman (2005)	
Dynamic ecophysiological model of ant colony growth	Morrison *et al*. (2005)	
State-space model of insect population	Yamamura *et al*. (2006)	

9. Appendix 3: Effects of elevated CO_2

A large proportion of the literature on CC concerns the impacts of elevated CO_2, in most cases a comparison between ambient and doubled CO_2 concentration. Recent observations of such effects may be grouped into those on observed NPP, on stomatal resistance, on transpiration, on soil carbon and on nitrogen dynamics, (Table A3). In crops (wheat, faba beans, soy beans, pea nuts, lettuce) yield increases between 7-58 % has been observed, and in grasslands (native vegetation, temperate grassland, pure grass or legume swards and grass-legume mixtures) the range is more narrow (10-43 %). Other observed effects are increase in optimum temperature from 22 ºC to 26 ºC (Chen and Coughenour, 2004) increased root allocation (Newton *et al*., 1995,1996; Schapendonk *et al*., 1997)) and increased legume competition in grass-legume mixtures (Newton *et al*., 1995; Schenk *et al*., 1997; Picon-Cochard *et al*., 2004).

Table A3. *Observed effects of elevated CO_2, ordered according to type of effect and year of publication*

Species	**Effect of elevated COB$_{2B}$ on observed NPP**	**Reference**
Grass	22 ºC and 26 ºC optimal temperature at current ambient and doubled CO_2 concentration, respectively	Chen and Coughenour (2004).
Crops		
Beans, wheat	Yield increase 58% for faba bean, 35% for spring wheat, 19% for winter wheat	Grashoff *et al*. (1995)
Crops	Variations in yield between years can be explained by differences in weather conditions (temperature)	Grashoff *et al*. (1995
Wheat	Dry matter production increased 27% and grain yield 39%	Mitchell *et al*. (1995)
Lettuce	+32% yield	Pearson *et al*. (1997)
Wheat	7-35% increase in production	Batts *et al*. (1998)
C3 peanut and a C4 grass (Paspalium)	25% yield increase in the legume.. This response was larger for the legume than for the C4 grass.	Newman *et al*. (2001)
Wheat	Large variation in the experimental results. Model improvement in terms of morphologic development and sink size is suggested	Wolf *et al*. (2002).
C_3 crops	Stimulates yield, improves resource use efficiency and reduces O_3 toxicity	Fuhrer (2003)
Soybean	Yield increase by 18-15%	Morgan *et al*. (2005)
Grasslands		
Temperate grassland species	Regrowth over 3 week interval increased slightly in controlled environment experiments. Net primary productivity below ground stimulated	Newton *et al*. (1995)
Two limestone grassland communities	Above ground production not stimulated at any time during two seasons. Rate of photosynthesis and respiration increased.	Wolfenden and Diggle (1995)
Grass-legume mixtures	*Paspalium* and *Lolium* abundance declined and white clover increased, due to CO_2 induced differences in axillary bud activity.	Newton *et al*. (1995)
Rye grass	Harvestable annual yield + 20%, the effect differed during the season and between years..	Jones *et al*. (1996)
Native short-grass steppe swards	Total biomass increased after two seasons with 19%, no significant differences between C3 and C4 grasses.	Hunt *et al*. (1996)
Grassland	After 428 days the total amount CO_2 fixed increased 33%, during water stress growth continued particularly below ground	Newton *et al*. (1996)
Short-grass steppe swards	Effect greater in C3 grasses at normal temp. Effect greater in C4 grasses at elevated temp. No effect on root/shoot ratio or production of seed heads	Hunt *et al*. (1996)
Perennial ryegrass	Above ground dry matter yield of the W- swards increased by19% at N- and by 14% at N+.	Casella *et al*. (1996)
White clover and perennial rye grass	Seasonal yield increase 16-38% in white clover monocultures, 12-29% for mixed swards and 5-9% for ryegrass monocultures.	Schenk *et al*. (1997)
Perennial ryegrass	Above ground NPP increased by 29% and 43% in two years, there was a preferential allocation of extra C to the root and soil.	Schapendonk *et al*. (1997)
Perennial ryegrass	More primary production allocated to roots	van Ginkel *et al*. (1999)
Grass-legume swards	Production increased 10% to 17%.	Campbell and Smith (2000).
White clover	Increased vegetative and reproductive growth at two N-treatments	Ainsworth *et al*. (2003a)
Perennial ryegrass	Over 10 years: 43% higher rate of light saturated leaf photosynthesis, 36% increase in daily integral of leaf CO_2 uptake.	Ainsworth *et al*. (2003b)
Phalaris aquatica	20 months of growth: 11% yield increase, no temperature effect, negative (-19%) defoliation response. Positive CO_2 response only in the spring.	Volder *et al*. (2004)
Grassland	DM yields increased by 26%. Effect on plant competition in favour of the	Picon-Cochard *et al*.

	legumes. Decline in stem to leaf ratio.	(2004).
	Effect of elevated CO_2 on stomatal resistance	
Rye grass	Decrease in LAI and canopy conductance.	Jones *et al*. (1996)
Perennial ryegrass	Decreased specific respiration rate of the shoots, total canopy respiration not effected, due to higher amount of standing biomass.	Schapendonk *et al*. (1997)
Perennial ryegrass	Over 10 years: 30% decrease in stomatal conductance.	Ainsworth *et al*. (2003b)
	Effect of elevated CO_2 on transpiration	
Perennial ryegrass	Slightly reduced evapotranspiration during the growing season, increased drainage by 9 % during winter.	Casella *et al.* (1996)
Perennial ryegrass	Water use efficiency of the swards increased by a factor of 1.5	Schapendonk *et al*. (1997)
Wheat	Reduced midday latent heat fluxes by 50 W /m^2 at high N, and by 100 W /m^2 at low N, dependent on wind speed. Reduced simulated and measured evapotranspiration by 7-9% at high N and by 16-19% at low N	Grant *et al*. (2001)
	Effect of elevated CO_2 on soil carbon	
Soil	NPP below ground and CO_2-C production increased in the soil. Microbial biomass unchanged, but enchytraeids became more abundant.	Newton *et al*. (1995)
Grasslands	General increase in soil fauna	Tate and Ross (1997)
Semi-arid grassland	C loss from roots increased from 53% to 57% during a 160 day period	Sindhöj *et al*. (2006)
	Effect of elevated CO_2 on nitrogen dynamics	
Avena	Increased plant N acquisition from the soil	Hu *et al*. (2005).
-	No effect on N mineralization	Newton *et al*. (1995)
Ryegrass 18	Increased C/N ratio in the tissues (lower protein content). No effect on digestibility.	Jones *et al.* (1996)
Perennial ryegrass	Leaf- N concentration per unit mass at cutting reduced by 25 to 33 % and declined with increasing DM Reduced critical leaf N concentration.	Soussana *et al*. (1996)
White clover	Clover content was significantly enhanced	Schenk *et al*. (1997)
Grass - clover swards	Crude protein content reduced at the beginning of the season only, but increasing in the course of the experiment. The yield of N was significantly enhanced. K and Na decreased, Ca increased and P was unchanged. Yield of P, S, Mg and Ca significantly enhanced. Crude fibre content decreased throughout the season.	Schenk *et al*. (1997)
Agrostis, ryegrass, white clover	Reductions in apparent Rubisco activity, reductions in total leaf nitrogen content on a unit area, increased photosynthetic nitrogen use efficiency	Davey *et al*. (1999)
Perennial rye grass sward	Reduced the total amount of N harvested in the clipped parts of the sward	Loiseau and Soussana (2000)
Grassland	Enriched organic matter in plant and soils with C, leading to removal of N from the soil mineral N pools into plant biomass, soil biomass and soil organic matter	Thornley and Cannell (2000)
Ryegrass and mixture with white clover	Increased N_2O emission from high fertilized swards	Baggs *et al*. (2003)
-	N-yields increased by 30%. Effect on plant competition in favour of the legumes. Improved digestibility by decline in cell wall constituents .	Picon-Cochard *et al*. (2004).
Lolium, Holcus, Festuca	Increased N-use efficiency, and decreased N uptake, appeared to favour the grasses	Soussana *et al*. (2005)

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