Effects of climate change on Norwegian agriculture

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Abstract:
This is a brief report on a model study of how production systems in two regions of Norway are affected by expected climate change, and how these soil-plant ecosystems functions as reactors in the climate system. A cluster of models simulating heat and water transport, plant growth, soil C- and N-transformations and transport have been run based on historical weather and weather generated by dynamic downscaling of historical and future global climate (IPCC A2). Estimated product functions and greenhouse gas emissions as affected by intensity and management alternatives have been used to estimate economic optimum fertilization levels and costs for mitigation options.

Plant productivity is potentially enhanced by the predicted global warming, much more in the northern region (Trøndelag) than in south east Norway (Follo), but for grain production this requires new plant varieties with slower phenological development. The poor response in Follo is attributed to increased summer drought predicted by the downscaled A2 scenario for this region. This is a highly uncertain prediction however; underscoring the problematic status of predicting the outcome of future climates by dynamic ecosystem modelling with high mechanistic resolution. Soil organic carbon is declining with the current practice of grain production in Norway, global warming will accelerate this degradation, and this can only partly be counteracted by management which secure higher inputs of organic materials (catch crops and incorporation of plant reidues). The predicted emissions of N\textsubscript{2}O suggest that N\textsubscript{2}O plays a crucial role in determining the total performance of the soil-plant ecosystems as a reactor in global change (CO\textsubscript{2} equivalents). The net cooling effect of carbon sequestration in soil may be effectively countedacted by increased emissions of N\textsubscript{2}O. In this context, we notice a remarkable effect of timing on the stochiometry of C- versus N transformations (carbon storage versus N\textsubscript{2}O emissions, catch crops versus straw incorporation). This identifies altered stochiometries in the agroecosystem as an interesting topic for future research, both by modelling and empirical investigations.

1 Introduction

Climate change - reasons to be concerned
Paleoclimatic research has revealed several incidents of rapid changes in annual temperature and precipitation, not driven by human activities but by positive feedback loops within system earth which aggravate the effect of otherwise minor impacts (NRC, 2002). The ongoing anthropogenic emission of greenhouse gases is such a “minor impact” which is expected to induce a substantial increase in global temperature over the coming decades and centuries (Weart, 2008). Monitoring of temperature has demonstrated a significant increase of global temperature over the last decades, and projections into the near future (100 years) shows great uncertainty. The various attempts to predict future changes in global temperature range from minor (presumably tolerable) changes to worst case scenarios which implies significant negative impacts on human welfare, ecosystems’ functions and biodiversity. This legitimizes the current investments in research on effects of climate change, regardless of the relative importance of anthropogenic emissions in driving the ongoing changes.
Impacts on terrestrial ecosystem services and feedbacks

The functioning of terrestrial ecosystems will be affected by climate change (Parmesan and Yohe 2003), hence ecosystem services such as food production will be affected (Wittwer, 1995, Fuhr 2009). This alone is a good reason to explore the possible outcomes of global change on the productivity of agroecosystems. But these systems are not only passively impacted by the climate; they may produce significant feedbacks (positive or negative) in the climate system through altered emissions of greenhouse gases (Goh 2004). Soil organic C is a significant and dynamic carbon pool, representing a positive or negative feedback in global warming depending on the input of C from primary production and CO₂ emission from mineralization. The nitrogen transformations and losses from terrestrial ecosystems may also be enhanced by warming, which in theory may result in higher emissions of N₂O, be it from the surface soils affected or the recipients of the extra losses of reactive nitrogen (aquifers, water bodies and sediments).

Effects are region specific

For obvious reasons, increase in overall global temperature will not have the same effect in all regions. For instance, the temperature increase alone will probably have a negative effect on terrestrial productivity in warm and critically dry regions and a positive one in cold and wet regions. However, a rise in global temperature will also affect the weather patterns, and these changes are expected to vary profoundly between regions. Thus, temperature, wind patterns and precipitation (annual as well as seasonal distribution) will be affected in different ways in different regions. These are all crucial variables which determine the productivity of agriculture as well as natural ecosystems. Thus, forecasts of ecosystem services’ response to climate change must be based on regionalized climate forecasts. Such forecasts implies that the simulations of future global climate (General Circulation Models, GSM) must be downscaled to regional level, either by statistical methods (regressions) or by “dynamic downscaling”. The latter is equivalent to weather forecasting, using boundary conditions provided by GSM models.

Biogeochemical forecasts

The atmosphere’s concentration of CH₄, N₂O and CO₂ are affected by the biogeochemistry of C and N in terrestrial ecosystems (Ray et al 2008), which again is profoundly affected by the climate. Thus, terrestrial ecosystems are “reactors” in global change. This fact is the raison d’être for terrestrial biogeochemistry in global change research, and the reason why new global circulation models include dynamic coupling to the biogeochemistry of land areas, as pioneered by Cox et al (2000).

The human factor, homo economicus

The biogeochemistry of terrestrial ecosystems is affected by mankind through pollution, constructions (cities, roads), forestry and agricultural activities, all of them significant offences (Hall et al 1999). Although construction works (cities, roads, railroads etc) are locally destructive, their global impact is moderate since a small fraction of the land is affected. Agriculture, on the other hand, represents an activity which historically has irreversibly destroyed ecosystem on a large scale (Pointing 1991), and profoundly affected the biogeochemistry of others (Bolek 2002, Bondeau et al 2007, Jackson et al 2000). Among the human professions, farming ranks high in terms of global impact through soil erosion, nutrient losses and enhanced emissions of greenhouse gases (N₂O, CH₄, CO₂). This means that the terrestrial ecosystems as reactors in global change includes a human factor, the
farmers. Farmers’ choice of technology and cultivation practice has consequences for their ecosystems’ role as reactors in global change, such as the emissions of \(\text{N}_2\text{O}\), \(\text{CH}_4\) and \(\text{CO}_2\) (Bakken et al 1994), and the losses of nitrogen to the external environment outside agriculture (Bleken and Bakken 1997). Farmers’ choice of cultivation practice is driven by economic prospects (Vatn et al 2006), which depends on expected weather. Thus, expected global warming may have implications for the farmers’ choice of agronomic practice, which in turn will affect its performance as a reactor in climate change.

The scenarios
The present scenario analyses were inspired by the prospects of downscaling global circulation modeling of future climate (Hanssen-Bauer et al 2003). The idea was that if we know the future weather conditions (climate) of different regions of Norway, we will be able to predict the outcome of global warming for plant production, and hence the economic and ecological performance of plant production in different regions of Norway. Our approach was to do this analyses within the framework of the ECECMOD (Vatn et al 1999, 2006), which is a complex of soils-plant- and economic models originally designed to analyse the outcome of agronomic policies for agroecosystems (Figure 1). In this model, the farming practice (on model farms) is predicted by economic optimization (homo economicus), based on product functions. The product functions (grain and grass production) as well as the downstream effects of the chosen agronomic practice were simulated by dynamic modeling of plant growth and soil processes (C and N transformations), both of these models were driven by soil temperature, moisture and water infiltration as predicted by the heat and water transport model (COUP), which again was driven by daily values of air temperature, radiation, and precipitation. Soil erosion was simulated as well, but not as an integrated part of the soil-plant biogeochemical modeling (Lundekvam 2004).

![Figure 1. Outline of the ECECMOD, a system of natural scientific and economic models constructed for analyses of how agronomic policies affect the economic and ecological performance of farms (From Vatn et al 2006)](image)

The first attempts to use dynamically downscaled climate scenarios revealed some fundamental shortcomings of the first versions of the scenarios (using the HIRHAM weather forecast model; Hansen-Bauer et al 2003). Comparisons of historical weather (obs80-99) with simulated (Scen80-99) for the period 1980-99 showed clear differences for the summer season both regarding precipitation (much too high in sim80-99) and temperature (Scen80-99 was 1-2 degrees too low), both having consequences for our agroecosystem modeling. Preliminary corrections were made by adjusting the simulated precipitation by using data from the empirical downscaling (Skaugen et al 2003). This solved the most severe problem.
with grossly overestimated soil erosion and soakingly wet soil through the whole spring period (which would preclude tillage and sowing). But the Scen80-99 still deviated in various ways from Obs80-99: too high precipitation in late summer period, too high frequency of rainy days (0.69 versus 0.47) and the average length of wet spells were too high (5.1 versus 3 days).

Despite these shortcomings, scenarios were run as a preliminary exercise reported in EACC reports 1-6/2004. In these simulations, we compared the economic and ecological performance of grain production in south east Norway for the period 1980-99 with the predictions for 2030-49 based on downsampling of the global simulations with the ECHAM4/OPYC4 GSDIO model (Max Planck) using the emission scenario IS92a. The results can be summarized as follows: The downscaled scenario for 2030-49 predicted a substantial increase in winter temperature, but he simulated average soil temperature through the winter (October-March) was practically unaltered due to reduction of snow cover. The lack of snow cover resulted in 50% higher frequencies of freeze/thaw cycles in the upper 10 cm of the soil. As a result of these changes, soil erosion was substantially increased, primarily due to higher frequency of rain and surface runoff on frozen (hence impermeable) soil. The nitrogen mineralization in the soil through the winter was not much altered, but the annual gross mineralization increased with approximately 1 g N m^-2 year^-1 due to higher temperatures in the warm parts of the year. About 30% of this extra mineralization was assimilated by the plants, 25% was lost by denitrification and nitrate leaching, the remaining 45% was immobilized. Further, the global warming stimulated grain production slightly (2-3%, barely statistically significant). As a result of altered crop responses to fertilizer N (i.e. product functions), the economic optimal N-level was substantially higher in Scen80-99 and Scen30-49 than in Obs80-99, resulting in a higher economic output and nitrate leaching for economically optimal farming practice.

Later versions of the downscaled scenarios were adjusted by more sophisticated use of data from the statistical downsampling, largely solving the identified problems (Skaugen 2007). In the present simulations, these correction algorithms were adopted when producing input data for a simulation of a more severe global warming scenario (A2).

2 Modeling
2.1 Climate scenarios, short description
The climatic scenario in this report was produced by the coupled Atmosphere-Ocean General Circulation Model (AOGCM) HadAm3 from the Hadley centre in UK (Gordon et al 2000) with a spatial resolution of ~300 * 300 km2. Results from the HadAm3 were dynamically downscaled with the regional climate model HIRHAM (Bjørge et al 2000) using a spatial resolution of ~55 * 55 km2.

The future scenario used was the HadAM3H-simulation based on the IPCC emission scenario A2 (http://www.grida.no/publications/other/ipcc_set/), and we used the simulations for the period 2070-2100. (http://www.grida.no/publications/other/ipcc_set/?src=/climate/ipcc/emission/99.htm), to be compared with the simulations for the historical climate (“Control”, 1960-90) and the historical weather for the same period (“Observed”). The validity of the downscaled scenarios for the present model applications were evaluated by comparing the simulated control scenario with historical weather for the same period regarding distribution of precipitation (seasonal) and temperature, as well as the SPN simulations (plant growth, soil organic nitrogen turnover, leaching, denitrification and N2O emissions. Previous exercises (with scenarios for south east Norway only) identified the following problems: much too wet soil during early spring (April
may), effectively precluding tillage operations, much too wet late summer (august/september) which would result in harvesting problems (too wet to harvest) and probably poor grain quality (http://statisk.umb.no/forskning/mildri/publikasjoner/eacc_report1.pdf). As a result, algorithms for adjusting the dynamically downscaled scenarios with information from empirical observations were developed (Skauge 2007, Appendix 2.1), and used to provide the driving data for the current project.

2.2 Model of the soil heat- and water-balance
The soil water and energy balance was simulated with the one-dimensional COUP-model (Jansson and Karlberg, 2004). The time resolution is one day, and the model is driven by the following inputs (from the downscaled scenarios): air temperature, precipitation, air humidity, wind speed and global radiation/cloudiness.

The model simulates one-dimensional water and heat dynamics in a layered soil with or without vegetation by solving numerically the relevant differential equations. The main equations include the law of conservation of mass and energy together with flow equations for water (Darcy’s law) and heat (Fourier’s law). Simulations were based on the soil characteristic at the experimental field together with estimated plant canopy characteristics (leaf area index, canopy height, root depth, daily estimates). Validation of the COUP simulations for the actual sites are documented in Appendix 2.2.

2.3 Model of the soil C and N and plant growth
We used the SPN model, which integrates the simulation of soil C and N processes by a modified version of the SOILN_NO model (Vold et al., 1999) with the dynamic simulation of plant growth by the KONOR model (Bleken, 2001).

The soil C and N pools considered by the model are humus, microbial biomass, two plant litter pools and faeces (i.e. solid organic matter of the slurry), all with first order decay rates controlled by soil moisture and temperature (Johnsson et al 1987). Partitioning of C between mineralization (to CO\textsubscript{2}) and microbial biomass is constant (yield), and a fraction of biomass-decay (first order) is channelled into the slowly decomposing humus pool (“humification”). The net nitrogen transformations (immobilization or mineralization) are driven by the C-transformations assuming fixed stoichiometry (C/N ratio) in the microbial transformations (Vold et al 1999). Nitrification is first order, and denitrification is simulated by a recently implemented NGAS algorithm, taken from the DAYCENT model (Del Grosso et al 2000). The NGAS algorithm predicts denitrification as a function of waterfilled porespace, microbial respiration and nitrate concentrations. The product stoichiometry of denitrification (N\textsubscript{2}O/N\textsubscript{2}) is a nonlinear function of respiration, nitrate concentrations and waterfilled porespace. A recent modification of the SPN model is the emulation of frost- and tillage effects on mineralization by transferring a fraction of the microbial C and N to a labile pool (at tillage and when the soil freeze).

Model parameters were estimated by optimisation against laboratory incubations (Vold et al., 1999; Korsæth et al., 2001) and field experimental data (Korsæth et al., 2002, 2003). Initial pool sizes were further adjusted to local conditions in the two regions simulated, by comparison with observed mineralization rates of incubated soil samples as well as observed nitrogen dynamics in local field experiments. The temperature response factor, Q10, which regulates all first order reactions of the C- and N-model is crucial for the predicted effect of warming on degradation. In the present simulations we have used a conservative value of 2.5
reaction rates are increased by a factor of 2.5 when temperature increase with 10 °C). This factor has been discussed at length during the last decade, and for variably valid reasons it has been claimed that the factor should be higher for recalcitrant material. Harley and Ineson (2008) report that by combining simple first order modelling with long term incubation experiments, Q10 could be substantially higher (3-3.3) for recalcitrant soil organic matter. If accepted, this would mean that our simulations have underestimated the response to increasing temperature.

The determination of initial C- and N-pool sizes of the SPN based on observed mineral N kinetics in long term laboratory incubations of soils from Voll are shown in Appendix 2.3, and its performance regarding the mineral N dynamics in a field experiment in plants is shown in Appendix 2.4.

2.4 Dynamic plant modelling
The original spring barley module is documented by Bleken (2001). Essentially it is a ‘one leaf model’, the albedo is neglected and the absorption of photosynthetically active radiation (PAR) is simulated as radiation extinction according to Beer’s law. The daily biomass increase is the product of the absorbed PAR and the radiation use efficiency (RUE, dry matter increment per absorbed PAR (g MJ⁻¹)). This ‘potential’ growth is limited by drought (ratio of actual to potential transpiration), and the N status of the plant. The daily partitioning of the biomass increment to the roots is modeled as a linear decreasing function of the crop phenological age, and it increases in the case of drought or N deficiency. The phenological age is modeled as temperature function, with distinct base temperatures and day-degree temperature sums for plant emergence after sowing, heading and yellow ripeness. For present cultivars the base and sum temperatures were parameterized based on empirical data for the most common cultivars in the regions studied.

In a warmer climate the phenological development will be accelerated, effectively reducing the time available for photosynthesis and thus the yield. This effect of increased temperature can be counteracted by using late varieties with higher temperature sums requirements, which ripen more slowly. Late varieties where chosen so that under the Hadley A2 scenario the growing period would be 2-3 days longer than for present varieties under the observed climate. This may seem a small change, but in order to obtain this the temperature sums had to be increased by about 25% for the period before heading, and between 9 and 175 percent from heading to yellow ripeness. In Follo none of the cultivars and breeding material presently under testing fulfills this requirement.

The nitrogen state of the plant is defined by the concept of critical N concentration (Greenwood and Draycott, 1989), the maximum and the (tentative) minimum concentration curves, all of them being exponentially decreasing functions of the standing plant biomass

\[ DM \text{ (in g DM m}^{-2}\text{)} \text{ according to the equation: } N_{conc} = \begin{cases} \alpha \cdot (\beta)^{-\nu} & |DM \leq \beta| \\ \alpha \cdot (DM)^{-\nu} & |DM > \beta| \end{cases} \text{, where } N_{conc} \text{ is the } N \text{ concentration in percent.} \]

Field experiments with frequent monitoring of plant growth and soil mineral N throughout two growing seasons at the actual sites were used to evaluate the model performance. These exercises shows adequate model performance for each site and for early barley, which is the plant species used for the Control simulations. A previous study with the same model demonstrated that the simulated grain production through a 18 year period for Voll effectively simulated the average grain production for the whole district, the simulated grain
crop per m² were with ± 25% of that achieved in field trials for 12 out of 18 years regression for the entire dataset showed that the simulations explained only a fraction (r² = 0.20 for regression of simulated grain dry weight versus that measured and 0.40 for regression of simulated straw+grain versus that measured) of the inter annual variation (see Appendix 2.4).

2.5 Economics
In order to assess the effect of climate change on the farmers’ income, we need to model the choices of the farmers. Nitrogen is the major controllable limiting factor for crop growth in Norway, and we have thus left out the other input factors in the analysis. The choices farmers make are linked to the objectives of farming, but it is beyond the scope of this paper to discuss this in length. Even though farming income is not the major income source for many Norwegian farmers, income from farming is important. We will therefore assume that the farmers are maximizing income. In mathematical terms this means that she is trying to maximize the following expression:

\[ \text{Max } \pi(N) = pf(N) - vN - FC \]  

where \( p \) is the output price (grain), \( f(N) \) is the production function, \( v \) is the input price, \( N \) is the input (nitrogen) and FC is fixed costs.

The first order condition for this optimization problem is:

\[ \frac{\partial \pi}{\partial N} = p \frac{\partial f(N)}{\partial N} - v = 0 \]  

This equation may be solved with respect to \( N \) in order to find optimal fertilization. If the production functions are globally concave, we know that the second order (necessary and sufficient) condition holds, i.e., the solution of Equation [2] is a maximum of Equation [1]. The interpretation of this condition is that the value of the marginal product \((pf'(N))\) should equal the marginal costs \((v)\).

The same methodology as in Vatn et al. (2006) was used to estimate expected yield response to fertilizer. The functions are polynomials of degree three with a plateau:

\[ f_i(N) = \begin{cases} \beta_{i0} + \beta_{i1}N + \beta_{i2}N^2 + \beta_{i3}N^3 & \forall N \leq N_{ib} \\ \beta_{i0} + \beta_{i1}N_{ib} + \beta_{i2}N_{ib}^2 + \beta_{i3}N_{ib}^3 & \forall N > N_{ib} \end{cases} \]  

where \( f_i(N) \) is the production function (g/m²) under climate scenario \( i \), \( \beta_{ij} \) are parameters to be estimated, \( N \) is nitrogen applied (g/m²) and \( N_{ib} \) is the plateau point (g N/m²) to be estimated.

This functional form was chosen because it is sufficiently flexible and the plateau ensures global concavity, which is important for the economic analysis. Roughly speaking, global concavity of the profit function ensures that there is only one extremum and that it is a maximum. From an economic perspective, it is most important to have reliable curvature around the optimal N-level. This means that the fit at low N-levels (e.g., below 8 g N/m²) and high N-levels (e.g., above 15 g N/m²) is not that relevant. The production functions (Equation [3]) were estimated using PROC NLIN in SAS (SAS Institute 1992) based on the simulations in SPN for the different scenarios and different nitrogen levels.

The choices of the farmers, in this case the nitrogen application, will affect the environmental performance of the system (see Figure 1). In order to estimate the losses from the agronomic
system (nitrate loss, N₂O loss and yearly change in the humus N pool) we have used cubic response functions:

\[ f_{ij}^b(N) = \alpha_{ij0} + \alpha_{ij1}N + \alpha_{ij2}N^2 + \alpha_{ij3}N^3 \]  

[4]

where \( f_{ij}^b(N) \) is the response function (g/m²) under climate scenario i for environmental indicator j (nitrate loss, N₂O loss and yearly change in the humus N pool), \( \alpha_{ij} \) are parameters to be estimated and N is nitrogen applied (g/m²).

The response functions were estimated using PROC REG in SAS (SAS Institute 1992) based on the results from the SPN simulations.

3 Results

3.1 Evaluation of the climate scenarios, temperature, precipitation, energy and water transport

Table 3.1.1 summarize some essential variables for the contrasting scenarios for the two regions analysed. The beginning and end of growth season is defined by air temperature (moving 7-days average passing +5°C, see Figure 3.1.1). The growth season is reported as the total length for the two climates and the shift in onset of the growth season in Hadley A2 versus Control (“Increase in spring”) and the equivalent shift of the end of growth season (“Increase in autumn”). The increase in average temperature and potential evapotranspiration is substantial for both regions. Annual precipitation is increased, about 100 mm, in Hadley A2 for Trøndelag, but not for Follo. Consequently, the Hadley A2 climate for 2070-2100 indicates a somewhat drier growth season than the Control scenario (1960-90) for Follo, but not for Trøndelag.

Table 3.1.1. Average yearly values (for 30 years) for the control scenario (1961-1990) and the Hadley A2 scenario (2071-2100) for two regions.

<table>
<thead>
<tr>
<th>Region</th>
<th>Follo Control</th>
<th>Hadley A2</th>
<th>Trøndelag Control</th>
<th>Hadley A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average annual air temperature (°C)</td>
<td>5.7</td>
<td>9.4</td>
<td>5.3</td>
<td>8.5</td>
</tr>
<tr>
<td>Growth season (days)</td>
<td>180</td>
<td>223</td>
<td>171</td>
<td>218</td>
</tr>
<tr>
<td>Increase in spring</td>
<td>+16</td>
<td>+18</td>
<td>+27</td>
<td>+30</td>
</tr>
<tr>
<td>Increase in autumn</td>
<td>+27</td>
<td>+30</td>
<td>+27</td>
<td>+30</td>
</tr>
<tr>
<td>Precipitation (mm)</td>
<td>763</td>
<td>778</td>
<td>892</td>
<td>1009</td>
</tr>
<tr>
<td>Potential evapotranspiration (mm)</td>
<td>553</td>
<td>659</td>
<td>319</td>
<td>405</td>
</tr>
</tbody>
</table>

1) Two sites in Trøndelag: Kvithamar and Værnes.
2) Potential evapotranspiration calculated with Penman-Monteith for standard reference conditions (FAO56).
The 16-18 days earlier onset of the growth season could in theory be exploited by an equivalent earlier sowing data, but in practice the sowing date is constrained by the wetness of the soil. In previous exercises, we tried to calculate the possible sowing from the simulated soil matrix potential in the plow layer. (matric potential <= -100 cm H$_2$O for a minimum of three days (to do the whole soil managements operations). These calculations indicated a severely delayed sowing dates for the earliest (du har kanskje en henvisning her?) future climate scenarios. This problem was less severe with new climate scenario Hadley A2, probably due to the corrections made (Skaugen 2007), but it was decided to simplify the matter by assuming a constant 20 days (daynumber 105 versus 125 (kun til orienteering)) earlier sowing date for Hadley A2 than for the Control scenario, and also to compare two alternative sowing dates for Hadely A2.

The soil temperature regime through the winter season is important for the present simulations global warming effects on the biogeochemistry of the system, since it will determine the off-season nitrogen mineralization, hence the propensity of the system to loose nitrate by leaching. Three factors are important for correct simulation of nitrogen mineralization as well as soil erosion: the depth of soil frost, the temperature curves for the entire winter period and the frequency of freeze/thaw cycles. Although the winter air temperature is substantially higher in Hadley A2 than in the Control scenario, the outcome is not necessarily and increased soil temperature throughout the winter, since the effect of higher air temperature can be offset by reduced snow cover.

The effect of snow cover on the depth of soil frost and water transport is illustrated in Figure 3.1.2, which shows measured and simulated snow cover and soil frost at the Monitoring Station Groset (950 m a.s.l.) (Colleuille et al 2007). The winter 1995/96 had little snow cover and deep soil frost which effectively reduce the water transport to the groundwater. Only a small amount of the melting water reached the groundwater this spring and it took an extra year to refill the groundwater reservoir.
We have tried various approaches to answer the question of how global warming will affect the soil temperature regime throughout the winter in Follo and Trøndelag (Hadley A2 versus Control) as well as in contrasting locations in Norway:

- existing meteorological data and model simulations
  - comparing snow depth and soil temperature for meteorological stations at different height above sea level (figure 3.1.3)
- comparing the winter conditions for the present and future climate
  - using climatic scenarios (figure 3.1.4)
  - using weather generator with increasing air temperature during the winter month without changing the other climatic variables (figure 3.1.5).

The results show generally a decreasing number of days with soil frost and an increasing frequency of freezing/thawing events with increasing air temperature in especially January and February. Figure 3.1.4 shows the result of simulations for the Kvithamar soil profile (Trøndelag). The upper part shows the 50 percentile from simulations with the present climate, in the middle the same for the Hadley A2 scenario (2071-2100). At the bottom is the difference between the present and Hadley A2. Look closely at the figure – negative values means an increase in soil temperature with the future climate. It is interesting to note that the smallest difference between the present and the future climate is in January-February. The largest difference in simulated soil temperature is early spring and late autumn. The figure indicates higher soil temperatures during the growing season.
Same soil – different climate

<table>
<thead>
<tr>
<th></th>
<th>Rygge</th>
<th>Ås</th>
<th>Tryvann</th>
<th>Groset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude (m a.s.l.)</td>
<td>40</td>
<td>90</td>
<td>520</td>
<td>920</td>
</tr>
<tr>
<td>Observations (1981-97)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average precipitation (mm)</td>
<td>494</td>
<td>463</td>
<td>688</td>
<td>473</td>
</tr>
<tr>
<td>Average air temperature (°C)</td>
<td>0.8</td>
<td>0.3</td>
<td>-1.3</td>
<td>-3.9</td>
</tr>
<tr>
<td>Simulations (1981-97)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average maximum frost depth</td>
<td>-0.4</td>
<td>-0.5</td>
<td>-0.3</td>
<td>-0.6</td>
</tr>
<tr>
<td>Average number of days with frost (1 cm depth)</td>
<td>84 (±46)</td>
<td>96 (±50)</td>
<td>141 (±61)</td>
<td>171 (±24)</td>
</tr>
<tr>
<td>Average freezing/thawing events (1 cm depth)</td>
<td>8.0 (±1.2)</td>
<td>8.3 (±1.5)</td>
<td>4.4 (±1.7)</td>
<td>2.9 (±1.9)</td>
</tr>
<tr>
<td>Soil temperature* (°C)</td>
<td>75 percentile</td>
<td>-0.2</td>
<td>-0.2</td>
<td>-0.3</td>
</tr>
<tr>
<td>Soil temperature* (°C)</td>
<td>50 percentile</td>
<td>-0.6</td>
<td>-0.8</td>
<td>-0.2</td>
</tr>
<tr>
<td>Soil temperature* (°C)</td>
<td>25 percentile</td>
<td>-1.8</td>
<td>-2</td>
<td>-0.5</td>
</tr>
</tbody>
</table>

* Average soil temperature (2 cm depth) for frozen soils

Preliminary conclusion 1: "Warmer climate" – decreasing number of days with frost
But increasing freezing/thawing events

Figure 3.1.3. Simulated soil winter conditions for the same soil with different climatic conditions. Averages for the period 1981-1997 for 4 different meteorological stations (met.no). (Haugen and Colleuille 200x)

Simulated median soil temperature as a function of day number (x) and depth (y)

Figure 3.1.4. Simulated median soil temperature as a function of day number and depth for a clayey soil in Trøndelag.
Figure 3.1.5. Left: Average air temperature for December, January and February for different climatic scenarios (magenta line) (Observed 1961-1990 (Oslo-Blindern), control scenario 1961-1990, MPI 2020-2049, Hadley A2 2071-2100 (“left to right”)) and air temperature estimated by a weather generator (LARS-WG) with an 1°C increase from -2 °C lower than the present average to +5 °C. Right: Number of simulated freezing/thawing episodes in the upper 0-10 cm of a clayey soil. Magenta line for the climatic scenarios and blue line for the air temperature generated by a weather generator. The climatic data generated by the weather generator are just for the air temperature and there are no changes in the other climatic variables.

Figure 3.1.5 shows small differences between observation and control (left of the curve) both in average air temperature and number of simulated freezing/thawing episodes in 0-10 cm depth. The two scenarios MPI and Hadley A2 shows higher average air temperature and a small decrease (not significant) in freezing/thawing episodes. The average air temperature shows close relationship between the scenarios and the temperature from the normal (0 °) to an increase of 4 °C in the temperature in DJF. Climatic data containing daily observation for 50 years were used as input to the weather generator (“background information”) and it was only air temperature that was manipulated. The other climatic driving variables for model simulations were not changed. It is interesting to note that with this data set number of episodes increase before reaching a plateau and then decareasing. At present we can only point out that it is the combination of an increased air temperature and the other climatic variables on a day to day base that has to be exploited further. At present it seems like the scenarios are to uncertain on a day to day base to be useful in answering the question: “A colder soil in a warmer world?”

In figure 3.1.6 some effects of the future climate on the winter conditions in Trøndelag are shown. The model simulations are for small grain production with a constant sowing date - 5/5 for the present climate and 15/4 for the future climate. The main results are a decrease in snow depth and length of season with snow cover together with shallower soil frost depth and shorter duration. There is a tendency to a shallower groundwater level during January and February.
Figure 3.1.6. Simulated snow mass (mm water in snow) (upper), soil frost depth (middle) and groundwater level (bottom) for the present and future climate for a clayey soil in Trøndelag.
Median (-) and 25th (...) and 75th (...) percentiles are shown for both simulations and calculated from 30 years of daily values..

3.2 Crop growth

The average grain DM yield showed a variable response to the new climate (Had) compared to Cont (Figure 3.2.1). The inter-annual variation exceeded single contrasts between Cont and any of the Had-scenarios, but some consistent trends can be observed: For Follo, the new climate (Had) did not give higher yields than Cont unless a new late cultivars was used, and the sowing date anticipated by 20 days to 15th April. In Trøndelag simulations for the new climate gave higher grain yields than Cont, but unexpectedly an early sowing date was not advantageous relative to the presently sowing time around 5th May (compare Had_lb_105 with Had_lb_125). It is also of interest the fact that there was no loss of yield under the future scenario even when the cultivar and sowing time were kept unchanged as for the present conditions.

![Figure 3.2.1. Average grain dry weight (g m⁻²) at fertilizer level =10 gN m⁻² for Trøndelag and 12 gN m⁻² for Follo. Average values for four simulations: Cont= control scenario, early Barley, sowing date 125, Had_eb_125 = Hadley (2070-2100) early Barley sowing date 125, Had_lb_105= Hadley (2070-2100) late Barley, sowing date 105, Had_lb_125= Hadley (2070-2100) late Barley, sowing date 125. For each simulation, the annual variability is substantial (Standard deviation =72-150)
The inter-annual variability was, as mentioned, very large. In Follo there was no dramatic increase in the variability of the grain yield in the new climate relative the average yield (Figure 3.2.2), while in Trøndelag (Figure 3.2.3) Had combined with a late cultivar definitely
Figure 3.2.2. Cumulative frequency plot of grain yield in Follo. Frequency on the y-axis, grain yield (g dm m$^{-2}$) on the x-axis.

Figure 3.2.3. Cumulative frequency plot of grain yield at Kvithamar. Frequency on the y-axis, grain yield (g dm m$^{-2}$) on the y-axis. Results for Værnes were similar. Notice change of scale of the x-axis compared to Figure 3.2.2.
increased the yield variability (results for Værnes and Kvithamar are similar).

Had reduced the duration of the growing season, as expected. However, in Follo a combined use of the late cultivar and anticipated sowing increased the growing season by about 20 days, or approximately 20% of the present. Some of this time was spent in a longer germination period, and thus not useful for photosynthesis. Nevertheless the fact that grain yield did not increase proportionally indicates the presence of drought events. The less steep curve of the cumulative frequency effectively summarizes the larger temperature variability of the Had scenario (Figure 3.2.4)

In Trøndelag, however, use of the late cultivar and late (5th May) sowing date did not increase the variability of the growing season compared to Cont. Notice however the larger variability of the present growth season (less steep slopes) in Trøndelag compared to Follo (Figure 3.2.4 and 3.2.5).
In summary, a conclusion for Trøndelag could be that yield loss is not expected with business as usual, and that there is a potential for increased yield with later varieties, in the earliness class already available in Norway, but one should not anticipate sowing. Keeping the sowing date at the beginning of May will still give about two days shorter growing season and thus better harvesting conditions, which are often a limiting factor in Trøndelag.

In Follo the use of later varieties, in an earliness class which is not present in Norway now, and not yet used in official variety test, will be necessary. The choice of sowing date appears to be more flexible.

Appendix 3.2.1-3 summarize the statistics (average, mean and max values) for plant variables and a number of soil C and N variables, simulated for a standard fertilization regime for each region (10 g N m\(^{-2}\) y\(^{-1}\) for Trøndelag (Kvithamar and Vaernes) and 12 g N m\(^{-2}\) y\(^{-1}\) for Follo(Voll)).

Appendix 3.2.4 shows plots of simulated variables (plant production, soil C-and N variables) as functions of N-fertilizer levels.

3.3 Nitrogen and carbon transformations.

Validation of the control scenario. Comparison of simulated average values for the Control scenario (Cont) versus that for the observed weather (Obs) for the two regions (and the two soils in Trøndelag) shows good agreement regarding plant growth and the biogeochemical
variables: Average grain yields for Cont were within ±3% of those for Obs. Average annual nitrate leaching for Cont was within ±7% of that for Obs. Similar agreements were also observed for root growth (±7%), annual denitrification (±5%) and N\textsubscript{2}O emission (11%). None of these contrasts were statistically significant, considering the large annual variability (see Appendix 3.2.1-3). The only variable where Cont seemed to deviate systematically was the net decay of humus pool, which on the average was 2-13% faster in Obs compared to Cont. Again, however, the differences were not statistically different.

Nitrogen in grains

Figure 3.3.1 and 3.3.2 shows N removed by harvest (grains) for a standard fertilization in the two regions. The values show a positive effect of late barley versus early barley in the new climate, most clearly for Follo. Catch crops had a generally positive effect (notice that assimilation of the catch crop is included) whereas the effect of straw incorporation depend on the time of ploughing (negative at spring ploughing and a neutral or weakly positive effect when ploghen into the soil in the autumn).

![Plant uptake of N in growth season of barley Voll](image)

**Figure 3.3.1 Plant N-assimilation, Follo (Voll).** Average nitrogen assimilation (g N m\textsuperscript{-2}) during the growth season of barley at fertilizer level =12 gN m\textsuperscript{-2} Average values for four simulations: Cont= control scenario Had_eb_125 = Hadley A2 (2071-2100) early barley sowing date 125, HadA2_lb_105= Hadley A2 (2070-2100) late barley, sowing date 105, Had_lb_125= Hadley (2070-2100) late barley, sowing date 125. Managements are CC= catch crop, ploughed in spring, AP= No catch crops, autumn ploughing, Sinc=straw incorporated, Srem=straw harvested.
Nitrogen removal by harvest showed a similar response pattern (results not shown), but higher values were obtained for treatments where straw was harvested (Srem); the harvested straw contained 1.1-2.2 (avg 1.6) g N m\(^{-2}\) y\(^{-1}\) in Follo, and 1.6-3.4 (avg 2.6) g N m\(^{-2}\) y\(^{-1}\) in Trøndelag. The annual variability of nitrogen in grains showed some contrast between the two regions; in Follo the annual variability of N in harvested grains was substantially higher in Hadley A2 scenario than in the Control (Figure 3.3.3), whereas in Trøndelag no such effect of the future climate can be seen (Figure 3.3.4)
Figure 3.3.3. Cumulative frequency plot of N in the grain yield in Follo. Frequency (%) on the y-axis, N yield (g N m\(^{-2}\)) on the x-axis. Results for continuous grain cropping and straw incorporation by autumn ploughing.

Figure 3.3.4. Cumulative frequency plot of N in the grain yield at Kvithamar. Frequency (%) on the Y-axis, N yield (g N m\(^{-2}\)) on the x-axis. Results for continuous grain cropping and straw incorporation by autumn ploughing. At Værens the Had_lb_105 scenario resembles Cont. Note change of scale for the x-axis compared to Figure 3.3.2

The estimated annual nitrate leaching in Follo is shown in Figure 3.3.5. Nitrate leaching increased substantially by climate change (Had versus Control) if the early barley was grown in 2070-2100, but the effect was marginal if a later barley variety was introduced combined with earlier sowing date (lb-105). The incorporation of straw in the autumn (AP Sinc versus AP Srem) reduced nitrate leaching substantially, whereas straw incorporation in the spring (CC Sinc versus CC Srem) had a marginal effect. Catch crop reduced nitrate leaching consistently. These management effects are plausible results of straw- and catch-crop-effects on the seasonal timing of net nitrogen mineralization versus immobilization in a climate like that in Follo where most of the water transport through the soil profile occurs off-season (i.e. outside the growing season of the grain crop).

The nitrate leaching in Trøndelag (Kvithamar) showed a similar response to climate change for the early barley variety (Figure 3.3.6, Had_pb_125 versus Control), and a positive effect (reduced nitrate leaching) by introducing a later barley variety (lb versus eb in Had). Catch crops and straw incorporation had weaker and more variable effect than in Follo; which can be ascribed to a different distribution of precipitation in Trøndelag (more surplus during the growth season).
Figure 3.3.5 Annual nitrate leaching in Follo (g N m\(^{-2}\)) for different scenarios and managements, annual fertilizer dose was 12 g N m\(^{-2}\) for all cases (codes and managements as for Figure 3.3.2.1).

Figure 3.3.6 Annual nitrate leaching in Trøndelag (Kvithamar) (g N m\(^{-2}\)) for different scenarios and managements, annual fertilizer dose was 10 g N m\(^{-2}\) for all cases (codes and managements as for Figure 3.3.2.1).

The estimated annual denitrification for Follo and Trøndelag are shown in Figure 3.3.7 and 3.3.8. The generally lower denitrification in Trøndelag is due to the high porosity of the top soil (55 vol\%, Kvithamar). Climate change (Had versus Control) had a marginal effect (notice the scaling for Trøndelag). Straw incorporation had a marked positive effect in Follo, but a weak and variable effect in Trøndelag. As for nitrate leaching, this contrasting response in the two regions are attributable to timing of straw induced net nitrogen assimilation (which
is its dominating effect at low soil moisture) versus straw-induced denitrification (which
dominate when the soil is very wet).

Figure 3.3.8 Annual denitrification in Follo (Voll) (g N m\(^{-2}\) throughout the entire soil
profile) for different scenarios and managements, annual fertilizer dose was 12 g N m\(^{-2}\) for
all cases (codes and managements as for Figure 3.3.2.1)

Figure 3.3.8 Annual denitrification in Trøndelag (Kvithamar) (g N m\(^{-2}\) throughout the
entire soil profile) for different scenarios and managements, annual fertilizer dose was 10 g
N m\(^{-2}\) for all cases (codes and managements as for Figure 3.3.2.1)

The estimated annual N\(_2\)O-emission for the two regions are shown in Figure 3.3.9 and 3.3.10.
The annual emissions are remarkably similar despite the lower denitrification rate in
Kvithamar than in Follo. This reflects the model’s prediction of denitrification product
stoichiometry (R= N\(_2\)O/(N\(_2\)+N\(_2\)O) as a function of air filled porosity.
Figure 3.3.9 Annual N$_2$O emission in Follo (g N$_2$O-N m$^{-2}$) for different scenarios and managements, annual fertilizer dose was 12 g N m$^{-2}$ for all cases (codes and managements as for Figure 3.3.2.1)

Figure 3.3.10 Annual N$_2$O emission in Trøndelag (Voll) (g N$_2$O-N m$^{-2}$) for different scenarios and managements, annual fertilizer dose was 10 g N m$^{-2}$ for all cases (codes and managements as for Figure 3.3.2.1)

Figure 3.3.11 and 3.3.12 shows the estimated annual reduction of soil organic C (SOC, stable humus pool) in the soils. The effect of global warming (Had versus control) was to increase the net reduction of SOC (10-20 g C m$^{-2}$ y$^{-1}$), the reduction was only marginally affected by introducing a late barley variety in the future scenario (Had). Catch crop and straw had a substantial effect, amounting to approximately 13% of the extra input of plant residues in these treatments. This percentage is a trivial result of two parameters, the microbial growth yield (0.33) and the “humification fraction” (the fraction of dead microbial biomass transferred to the pool of stable humus).
The absolute levels of SOC-reduction are uncertain, since it reflects the long term history of the soil profile at each individual site (in the model this is determined by the initial pool size of SOC). The estimated net reduction of SOC in our simulations amount to 0.3% of measured SOC in the soil at Voll (whole soil profile). The marginal effects of managements and the effect of global warming on the annual % mineralization is probably more valid, although conservative (possibly slightly underestimated) due to uncertainties regarding the temperature response factors for recalcitrant materials (see chapter 2.3).

Figure 3.3.11 Annual net reduction of soil organic C in Follo (Voll) (g C m\(^{-2}\)) for different scenarios and managements, annual fertilizer dose was 12 g N m\(^{-2}\) for all cases (codes and managements as for Figure 3.3.2.1). The annual reduction by fallow (no plant growth) was 66 and 78 g C m\(^{-2}\) y\(^{-1}\) for Control and HadA2, respectively.

Figure 3.3.12 Annual net reduction of soil organic C in Trøndelag (Kvithamar) (g C m\(^{-2}\)) for different scenarios and managements, annual fertilizer dose was 12 g N m\(^{-2}\) for all cases (codes and managements as for Figure 3.3.2.1). The annual reduction by fallow (no plant growth) was 51 and 70 g C m\(^{-2}\) y\(^{-1}\) for Control and HadA2, respectively.
The fertilizer driven N2O emission shows an interesting response to the climate scenarios, as illustrated in Figure 3.3.13. The low values for Kvithamar reflect the high values for zero-fertilizer treatment in this soil compared to that of the two other soils, and a more moderate increase in N2O emission with increasing nitrogen fertilizer level. The estimated numbers in Figure 3.3.13 are equivalent to the summary of field experiments where N2O-emission is measured in response to increasing fertilizer levels (see for instance Bouwman and Boumans, 2002), which is the basis for the IPCC guidelines for national greenhouse gas inventories. The percentages for Værnes and Kvithamar are close to the ~1% direct fertilizer-derived N2O emission used by IPCC. The values for Kvithamar, which has very high porosity, hence low denitrification rates, are substantially lower.

Figure 3.3.13 Fertilizer-induced N2O-emission as expressed as % of fertilizer N, for the different scenarios (codes and managements as for Figure 3.3.2.1). The values are N2O-emission at the actual fertilizer levels (10 and 12 g N m⁻² for Trøndelag and Follo respectively) minus the simulated N2O emission for zero fertilizer treatments (see curves in Appendix 3.2.4).

3.4 Economics
The farmers are the main decision makers in the agri-environmental system, and they adapt to changes in changes in the growth conditions and changes in prices, agri-environmental polices, etc. As mentioned above, we have assumed that farmers are maximizing income, and yield response to nitrogen is estimated by using third degree polynomials. Estimated production functions fit the results from the simulations very well. Under these assumptions, the optimal nitrogen fertilization level (the farmers’ response to prices and environmental “parameters”) is the solution to Equation 2. The explicit form for climate scenario is:
\[ N_i^* = \text{MIN} \left[ \frac{-\beta_{i3} - \sqrt{\beta_{i2}^2 - 3\beta_{i3} \left( \beta_{i1} - \frac{v}{p} \right)}}{3\beta_{i3}} \right], N_{ib} \]  

where \( \beta \)'s are production function parameters, \( v \) is the nitrogen price, \( p \) is the output (grain) price and \( N_{ib} \) is the plateau level (see above).

As can be seen from the equation above, the optimal \( N \)-level depends on the relative prices, i.e., the ratio between the input and output prices. These prices are determined by demand and supply, but also by the agricultural policy. The latter is illustrated by the fact that current prices received by Norwegian farmers are roughly two times the world market prices (OECD, 200x). How the prices and polices will develop over the next 60 to 90 years is highly uncertain. As a reference case, we have assumed that prices remain at their current levels.

The figure below shows the economic optimal fertilization level for the different climate scenarios and locations, relative to that for the control climate scenario.

![Figure 3.4.1. Economic optimal fertilization levels given current fertilizer and grain prices. Figures are relative to the control climate scenario (Cont).](image)

In Trøndelag (locations Kvithamar and Værnes) the optimal fertilization levels increase under all future scenarios (Kvithamar: 5 – 14 %, Værnes: 2 – 12 %). This is due to an increase in the yield response to nitrogen (Appendix 3.2.4 figures 1-8). Yield increases occur at all nitrogen levels, leading to an increase in the optimal fertilization level. For Follo (location Voll), the results show a reduction in the optimal N-levels; Had\_eb\_125 results in a rather large reduction in yields, and this holds for all fertilization levels (Appendix 3.2.4 Figures 9-12). The reduction in optimal fertilization for this scenario is 21%. For the two other scenarios the reductions are smaller (9 – 14 %). Yield levels are slightly higher for Had\_lb\_105 compared to Cont, but the economic optimal nitrogen level is still lower. This is due to differences in the curvatures of the production functions.
The next step is to have a look at how the changes in optimal fertilization levels and yields from Cont translates into changes in income – here measured in terms of the gross margin. The figure below shows that the economic effects show roughly the same patterns as for optimal fertilization.

**Figure 3.4.3. Relative gross margins base on economic optimization given current fertilizer and grain prices. Figures are relative to the control climate scenario (Cont).**

We see that the economic effects of a new climate are positive in Trøndelag for both cultivars and sowing dates. The Had_lb_125 scenario shows a substantial increase in gross margin, 42 and 34% for Kvithamar and Værnes, respectively. Loosely speaking, the cost of increased fertilizers is more than offset by the value of the increase in yields. For Follo the results show that given the right choice of cultivar and time of sowing, the gross margin will remain at about the same level (1% increase for Had_lb_105 and 4% reduction for Had_lb_125). Using the current cultivar and time of sowing under the future climate (i.e., Had_eb_125), will lead to a 29% reduction in gross margin.

The main conclusion from the economics analysis is that it seems to be possible to adapt to the isolated climate effects, i.e., assuming current prices and polices, without reduced income as a consequence – mainly due to increased yields. It should be emphasized that this adaption is not a trivial task. Since we have assumed current prices, the results should of course not be taken to mean that they represent the actual outcomes in the future.

The environmental effects of farmers’ adaptation to changes in climate conditions may be partitioned into the changes in the interplay between the plants and the environment, as described in previous sections, and the changes in agricultural practices, especially changes in nitrogen application. Our modeling cluster is well suited for this kind of analysis. The losses to the environment from agriculture are in different compounds (e.g., nitrate, N\textsubscript{2}O and CO\textsubscript{2}) and different magnitudes. Since the main objective of the project is to study climate effects, it was natural to focus on the emissions of climate gases. We have used g CO\textsubscript{2} equivalents/m\textsuperscript{2} as the functional unit and we have only estimated losses from the plant – soil system. This means that all losses in e.g. the production of chemical fertilizers, transportation, farming operations, etc are excluded from the analyses. These losses are indeed important, especially since the use of fossil fuels is the major reason for the potential climate changes in the first
place. However, the estimated losses in the (distant) future will necessarily be rather loose speculations.

We have used the following main assumptions in the analysis: the global warming potential (GWP) of N\textsubscript{2}O equals 310 kg CO\textsubscript{2}-equivalents pr kg N\textsubscript{2}O (Forster et al., 2007), 3% of leached nitrate-N end up in the form of N\textsubscript{2}O (Crutzen et al. 2007), and the emission of CO\textsubscript{2} is estimated by using the average yearly change in the humus carbon pool. The latter means that emissions from the other carbon pools are seen as short term recycling of carbon and do not affect the more long term net emissions of CO\textsubscript{2} from the plant – soil system. The results are shown in the figure below.

![Figure 3.4.3. Relative environmental performance (emissions measured in CO2-equivalents) based on economic optimization given current fertilizer and grain prices. Figures are relative to the control climate scenario (Cont).](image)

In all regions there are reductions in N\textsubscript{2}O emissions (6 – 12%), while nitrate losses and mineralization of humus increases. In Trøndelag (locations Kvithamar and Værnes) the increases in drainage losses and humus decay are substantial, leading to a rather large increase in climate gas emissions. For all locations the effects of the Had\textsubscript{eb}_125 scenario are mainly due to changes in processes in the plant – soil system, while for the other two, the effects are mainly due to changed fertilization.

We also see that the choice of management practice (cultivar and time of sowing) affects the environmental performance. If we compare the results in Figure 3.4.2 and 3.4.3 we see that there is good correspondence between environmental and economic performance. In cases where the best alternative in economic terms is not the best in environmental terms, the extra environmental damage by choosing the best economic alternative is rather small.

The toolbox we have developed is well suited for analyzing the effects of different agri-environmental policy measures. In order to illustrate this we have estimated the abatement costs of reduced climate gas emissions by reducing nitrogen application from the economic optimal level. This means that we are not really analyzing a policy instrument, rather a change in agronomic practice. Reduced nitrogen application may be brought about by e.g. taxing nitrogen in synthetic fertilizers and nitrogen quotas (Rørstad, 2008, Rørstad and...
Romstad, 2008). In addition to the assumptions mentioned above, we have included the reduction in climate gas emission in fertilizer production when fertilizer use is reduced. The emission in fertilizer production is estimated to be 6.2 kg CO$_2$ equivalents per kg nitrogen (as ammonium nitrate) (Frank Brentrup, Yara International, personal communication). In this simulation we have used the observed climate in order to get an as accurate estimate as possible. The results are shown in the figure below.

![Figure 3.4.4. Abatement costs, NOK/kg CO$_2$-equivalents reduced emission under observed climate 1960 – 1990 and current prices.](image)

Up to a reduction in the range of 0.6 to 0.8 g N/m$^2$ depending location, it is cheaper to “use” agriculture than to buy emission quotas, given the current spot price on CO$_2$ allowances. At the crossing points the reductions in emission are 13.8, 9.5 and 15.2 g CO$_2$ equivalents/m$^2$ for Kvithamar, Værnes and Voll, respectively. If we for illustrative purposes suppose that the mean value (12.8) is representative for the whole grain area in Norway (=3.2 $10^9$ m$^2$), we find that it is possible to reduce the emissions by 41000 tons CO$_2$ equivalents/year in agriculture at a competitive price. This is less than one % of current total emission in Norway. In addition, the costs of policy measures to bring about this reduction are not included. Such costs would reduce the “competitiveness” of agriculture further. Hence, the possible contribution from agriculture seems small. On the other hand, this analysis is based on the current CO$_2$ price, and this is expected to increase in the future. This would increase the potential for cheap, in a relative sense, reductions in agriculture. But for now, agriculture does not stand out as the place to look for reduction possibilities.
4 Summary
Model exercises like this are useful, not for precise predictions but for getting a sense of proportions regarding the role of agroecosystems as “reactors in global change”. We call them reactors in global change because agroecosystems exist at the mercy of the weather, and they may affect the weather (climate) via emission of greenhouse gases (and altered albedo, altered hydrology etc). Numerous attempts to find agronomic practice that makes agroecosystem more climate friendly (read cooling) have been suggested over the last few years. Large sums of research money have been invested (not the least in US) to investigate the potential for C sequestration in agricultural soils. Large sums of money will probably be spent on other options as well. At the end of the day, such mitigations will have to be proven by measurement, which then has to take into account the full complexity of side effects of any action taken to change the agroecosystems. Such exercises may reveal the futility of actions invented by considering parts of the system and not the whole.

The current model predictions show that Norwegian farmers generally have reasons to be optimistic about the future climate regarding the potential crop production, the economy of farming and the environmental performance of their systems. Production may expand to higher altitudes, opening for substantial increase of the cultivated areas, at least for grain production. Crop productivity will generally increase, and soil erosion and nitrate leaching will not be severely affected provided that they adopt adequate agronomic practice. The content of soil organic C will decline, probably towards a new pseudo-equilibrium in a distant future.

Our modeling also helps to moderate the expectations regarding the potential for C-sequestration in the soil by incorporation of more organic material in soils. Not because it does not work, but because it will have side effects (increased N$_2$O emissions). We also demonstrate that reducing nitrogen losses represent a major challenge for future agronomists, not only because it helps to improve the local environment (water bodies), but because it is one factor that may improve the total performance of the system as a source of greenhouse gases at large.

The factors which have not been included in our simulations are the nitrogen losses by ammonia volatilization and nitrate leaching driven by excess amounts of manure in regions with high density of animals. This is where most nitrogen is lost from the agriculture, and this is where the great battle should begin.

One of the great unknowns with major implications for the effects of nitrogen losses, is the stoichiometry of denitrification; the reduction of nitrate to N$_2$ via N$_2$O. State of the art models (like ours) are incapable of capturing the phenomena regulating this stoichiometry of denitrification in the various environments which gradually return the anthropogenic nitrogen (fertilizer N and biologically fixed nitrogen in agroecosystems) back to the atmosphere.

The credibility of model outputs like the current depends on validation of the models. The current models are fairly well anchored in empirical datasets for the sites investigated. Generalizations to larger areas are uncertain regarding the absolute levels of crop yields, nitrate leaching and net emission of CO$_2$ and N$_2$O. We are more confident, however,
regarding our predicted relative changes of these variables in response to climate change and changing agronomic practice are to be trusted. Which is the most important outcome, from a practical point of view.

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