This is the post-peer review, pre-copyedit version of an article published in Agricultural Systems.
The final authenticated version is available online at: http://dx.doi.org/10.1016/j.agsy.2017.07.004

Combining models to estimate the impacts of future climate scenarios on feed supply, greenhouse gas emissions and economic performance on dairy farms in Norway

Şeyda Özkan Gülzari[1,2,*], Bente Aspeholen Åby[1], Tomas Persson[2], Mats Höglind[2] and Klaus Mittenzwei[2]

[1] Department of Animal and Aquacultural Sciences, Faculty of Veterinary Medicine and Biosciences, Norwegian University of Life Sciences, Post box 5003, Ås 1430 Norway

[2] Norwegian Institute for Bioeconomy Research, Post box 115, Ås 1431 Norway

*Corresponding author. seyda.ozkan@nibio.no

Abstract

There is a scientific consensus that the future climate change will affect grass and crop dry matter (DM) yields. Such yield changes may entail alterations to farm management practices to fulfill the feed requirements and reduce the farm greenhouse gas (GHG) emissions from dairy farms. While a large number of studies have focused on the impacts of projected climate change on a single farm output (e.g. GHG emissions or economic performance), several attempts have been made to combine bio-economic systems models with GHG accounting frameworks. In this study, we aimed to determine the physical impacts of future climate scenarios on grass and wheat DM yields, and demonstrate the effects such changes in future feed supply may have on farm GHG emissions and decision-making processes. For this purpose, we combined four models: BASGRA and CSM-CERES-Wheat models for simulating forage grass DM and wheat DM grain yields respectively; HolosNor for estimating the farm GHG emissions; and JORDMOD for calculating the impacts of changes in the climate and management on land use and farm economics. Four locations, with varying climate and soil conditions were included in the study: south-east Norway, south-west

Norway, central Norway and northern Norway. Simulations were carried out for baseline (1961−1990) and future (2046−2065) climate conditions (projections based on two global climate models and the Special Report on Emissions Scenarios (SRES) A1B GHG emission scenario), and for production conditions with and without a milk quota. The GHG emissions intensities (kilogram carbon dioxide equivalent: kgCO_2e emissions per kg fat and protein corrected milk: FPCM) varied between 0.8 kg and 1.23 kg CO_2e (kg FPCM)$^{-1}$, with the lowest and highest emissions found in central Norway and south-east Norway, respectively. Emission intensities were generally lower under future compared to baseline conditions due mainly to higher future milk yields and to some extent to higher crop yields. The median seasonal above-ground timothy grass yield varied between 11,000 kg and 16,000 kg DM ha^{-1} and was higher in all projected future climate conditions than in the baseline. The spring wheat grain DM yields simulated for the same weather conditions within each climate projection varied between 2200 kg and 6800 kg DM ha^{-1}. Similarly, the farm profitability as expressed by total national land rents varied between 1900 million Norwegian krone (NOK) for median yields under baseline climate conditions up to 3900 million NOK for median yield under future projected climate conditions.

Key words: climate change, dairy farming, dry matter yield, economics, greenhouse gas emission, modelling

1. Introduction

The projected change in climate during the 21st century is expected to affect grass and crop dry matter (DM) production, causing changes in forage and grain feed supply throughout the world (Morley, 1978; Olesen et al., 2011). Such changes may, in turn, alter the effects of agricultural production on the environment through emissions of greenhouse gases (GHG), necessitating changes in farm management practices and land use (Cederberg and Mattson, 2000). In Norway, agriculture contributes 8.5% of the national GHG emissions (The Norwegian Environment Agency, 2014), of which livestock accounts for 90% (Grønlund and Harstad, 2014). The contribution from the livestock to climate change occurs mainly in the form of methane (CH_4) and nitrous oxide (N_2O) emissions (FAO, 2010). Greenhouse gas emissions on dairy farms can be reduced by adapting alternative feeding strategies. Such changes in management may result in varying levels of costs and benefits, which eventually determine if the activity is implemented on the farm (Özkan et al., 2016).

The projected climate in Norway until the mid-21st century entails increased air temperature and an increased number of rainy days in all seasons across the whole country (Hansen-Bauer et al., 2015). Climate change can impact livestock production through its effects on availability of resources such as water and feed as well as farm profitability and the need for new management practices and environmental policies (Krol et al., 2006). Therefore, it would be useful to evaluate bio-geophysical and economic aspects of GHG emissions from livestock sector under plausible climate conditions in an interdisciplinary study (Özkan et al., 2016). In this study, we aimed to determine the physical impacts of future climate scenarios on grass and wheat DM yields, and how such changes in future feed supply affect farm GHG emissions and decision-making processes. For this purpose, we combined four models: BASGRA (Höglind et al., 2016) and CSM-CERES-Wheat (Ritchie et al., 1998) for simulating forage grass DM and wheat DM grain yields respectively; HolosNor (Bonesmo et al., 2013) for estimating the farm GHG emissions; and JORDMOD (Bullock et al., 2016) for calculating the impacts of change on land use and farm economics. These models have previously been used individually to address specific challenges within their system boundaries. For example, BASGRA was recently used to simulate the impacts of climate change on timothy grass productivity, harvest security and yields in northern Europe and Norway (Persson and Höglind, 2014). Similarly, CSM-CERES was used to simulate the impacts of climate change on wheat yields in Norway (Persson and Kværnø 2016) and in other main wheat production locations under current climate conditions (e.g. Persson et al., 2010; Thorp et al., 2010; Xiong et al., 2008). HolosNor has been used to estimate the GHG emissions associated with current dairy production in Norway (Bonesmo et al., 2013), and to compare the impacts of the climate and feed base (Hutchings et al., unpublished results), and impaired animal health on GHG emissions (Özkan Gülzari et al., unpublished results). JORDMOD model was previously used by Brunstad et al. (2005a) to evaluate the relationship between public goods, and by Bullock et al. (2016) to determine the trade-offs between conflicting public goods. In this study, the grass and wheat grain DM yields simulated by BASGRA and CSM-CERES models were processed and combined with farm and herd data in HolosNor to assess the GHG emissions under current and future climate and production conditions at farm level. The same grass and wheat grain DM yields were also used in JORDMOD together with data from HolosNor on feed intake, milk yield and GHG emissions to further evaluate the impacts of these production conditions on land use, economics and GHG emissions at national level.

2. Materials and methods

2.1. Locations

Climate, soil and farm management practices (e.g. cutting time and number of cuts per season for forage grasses, length of pasture period, and the use of concentrates and forage:concentrate ratio in the dairy cow diet) for four dairy farms representative of four production locations were included. The locations compared were south-east Norway (SEN), south-west Norway (SWN), central Norway (CN) and northern Norway (NN) (Fig. 1). Economic production analyses were performed at a national level based on the conditions in these locations.

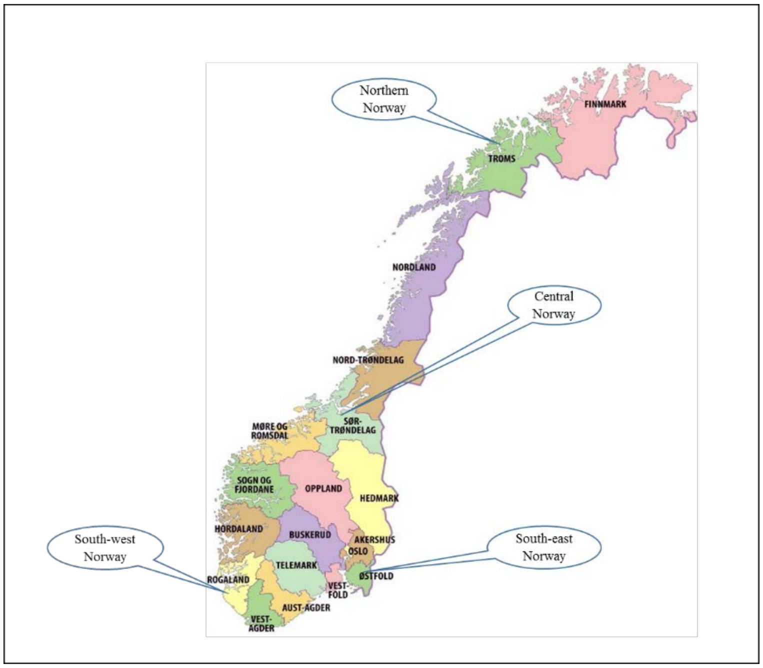

Fig. 1. Map showing the locations of the modelled farms in Norway

2.2. Models used

Forage grass DM and spring wheat grain yields were simulated with BASGRA and CSM-CERES-Wheat model, respectively, and fed into HolosNor model to estimate the GHG emissions at farm level. Finally, JORDMOD was used to scale-up the farm-level results from HolosNor to evaluate the production of grains and milk, land rents, food production and imports of agricultural products, and the GHG emissions at national level. A brief description of the models and their applications in this study is provided below.

2.2.1. Grass and crop models (BASGRA and CSM-CERES-Wheat)

The BASGRA model was used to simulate the multiple annual harvest of above-ground tissue and the subsequent regrowth (Höglind et al., 2016). Spring wheat, a major feed concentrate component, was simulated with the CSM-CERES-Wheat model (Ritchie et al., 1998), in the Decision Support System for Agrotechnology Transfer (DSSAT) software v.4.5 (Hoogenboom et al., 2010). In these two process-driven models, growth development and yield of wheat and timothy grass, respectively are dynamically simulated as a function of weather, soil, management and crop genetics with a time step of one day. Growth is limited by sub-optimal soil water conditions in both models. In BASGRA, the soil is represented by one single layer with homogenous hydraulic properties, whereas the CSM-CERES-Wheat model in DSSAT includes multiple homogenous soil layers, of which the water content is affected by infiltration, evaporation and plant water uptake. The BASGRA assumes optimal nitrogen (N) status whereas CSM-CERES-Wheat includes functions for soil and plant N as affected by crop management, plant, soil and weather conditions. Plant N uptake is regulated by the ratio between the actual N concentration in the plant and the critical plant concentration for growth, and the availability of mineral soil N (Godwin and Singh, 1998; Jones et al., 2003).

Simulations of crop yield

The climate, soil and management practices used as input data for the grass and wheat simulations represented the locations in Fig. 1. The weather data used in the simulations represented the period 1961−1990, which were used as a baseline reference since is the latest full normal period, and projected future climate for the period 2046−2065 according to the Special Report on Emission Scenarios (SRES) GHG emissions scenario A1B (Nakicenovic et al., 2000). This scenario represents the intermediate future GHG emissions in the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (Pachauri and Reisinger, 2007).

Downscaled daily data on weather variables, including minimum and maximum air temperature, precipitation and solar radiation, for the farm locations and the two periods were stochastically generated by the Long Ashton Research Station Weather Generator (LARS-WG) (Semenov, 2010). For the period 2046−2065 four sets of 100 years of daily weather data were generated based on two Global Climate Models (GCM): BCM2.0 and HadCM3 as previously described by Persson and Höglind (2014). Soil input data including particle size distribution, organic carbon (C) and hydraulic characteristics were obtained from Bonesmo et al. (2013).

Timothy grass was simulated for all four geographic locations whereas spring wheat was simulated only for SEN and CN following the current regional production allocation of forage grass and cereal crops in Norway. We kept these geographic simulation settings for all scenarios since it is reasonable to argue that the rainfall patterns in western and northern Norway will continue to be adverse to spring cereal conditions also under projected future climate conditions. Weather inputs were obtained from LARS-WG calibrations against observed weather from Ås, Akershus County (59°40′ N; 10°48′ E; 89 m asl) for SEN, Sola, Rogaland County (58°53’N; 5°39’E) for SWN, Værnes, Nord-Trøndelag County (63°27’N; 10°55’E) for CN, and Tromsø, Troms County (69°39’N; 18°57’E) for NN.

Soil input represented one farm in Marker municipality, Østfold County (SEN), one farm in Time municipality Rogaland county (SWN), one farm in Trondheim municipality Sør-Trøndelag county (CN), and one farm in Tromsø municipality, Troms county (NN). The atmospheric carbon dioxide (CO_2) concentration was set to 350 ppm for the period 1961−1990, and 532 ppm for the period 2046−2065 according to the SRES A1B GHG emission scenario. In order to encompass most of the expected inter-annual weather variability and its potential impact on the results, 100 simulations were carried out, each with unique weather input data for each crop, location, soil type and set of weather data. The BASGRA simulations represented the cultivar Grindstad (Persson et al., 2014), which has been one of the most grown timothy cultivars for several decades under a wide range of climate and soil condition, and management practices in northern Europe.

Consequently, its characteristics were assumed to be representative for all regions and climate scenarios in this study.

The start of the growing season in the spring was set to occur the fifth day the first period in the year that the average air temperature exceeded 5 °C five consecutive days (Bonesmo and Skjelvåg, 1999). The first cut was simulated to occur 500 °C-days over a temperature base of 0 °C after the initialization of the growing season. The temperature sum between cuts was set to 600 °C-days over the same base temperature. This cutting frequency regime represents cutting at the mid-heading stage, which is recommended for intensive dairy production. The spring wheat parameters represented the cultivar Zebra (Persson and Kværnø, 2016). We are not aware of any applicable methods to project future plant breeding advances and to calibrate of cultivar specific model parameters against such advances. Therefore, we found it the most suitable approach to keep the cultivar specific constant across climate scenarios.

The planting date was set to May 3 for the 1961−1990 period and April 19 for the simulations that represented the period 2046−2065. The reason for choosing April 19 as planting date was that the mean daily temperature was the same for this date under conditions representing the mean of the GCMs BCM2.0, CSIRO-M.k3.0, GISS-AOM and HadCM3 for the SRES A1B GHG emission scenario conditions was the same as for mean daily temperature on May 3 for the period 1961-1990 (Persson and Kværnø, 2016). Harvest was set to occur at maturity. Nitrogen was applied at planting with an amount of 132 kg/ha in all wheat simulations.

2.2.2. The whole farm model (HolosNor)

HolosNor was used to estimate GHG emission intensities (kilogram carbon dioxide equivalent: kg CO_2e emissions produced per kg fat and protein corrected milk: FPCM). The model is based on the Canadian HOLOS model (Little, 2008) utilising the IPCC methodology (IPCC, 2006) modified for Norwegian conditions by Bonesmo et al. (2013). The calculations of all emissions (enteric CH_4, manure CH_4, soil N_2O, N_2O from N leaching, run-off and volatilization, on-farm CO_2-emissions or C sequestration due to soil C changes and on-farm CO_2 emissions from energy use, and off-farm CO_2 emissions from supply of inputs such as fertilizers, pesticides, fuel and electricity) are explained in detail by Bonesmo et al. (2013). The boundary of the model is at farm gate; however, GHG emissions from the production of inputs used on-farm (e.g. fertilizers, electricity and fuel) are also included. The GHG emissions associated with the production of forage are determined by the CO_2 emissions associated with the production of fertilizers, pesticides and fuel (i.e. machinery operations), the use of fuel on-farm and direct N_2O emissions from soils, in addition to indirect N_2O emissions resulting from nitrate leaching, N in run off and ammonia volatilization. Soil N_2O emissions are related to the total N input (sum of N fertilizer applied, grass residual N and mineralised N), adjusted for seasonal variation in soil temperature and moisture. Emissions from purchased concentrates are calculated from grains produced off-farm and imported soybean meal required to supply the amount of energy and crude protein used on farm. Barley and oats grown on farm are assumed to be used as feed and replace off-farm grains in the concentrates as described by Bonesmo et al. (2013). Direct emissions from fuel and inputs used on-farm are calculated using emission factors described in Bonesmo et al. (2012). The emissions from grass and crop renovation (e.g., seeds) is not included in the model.

Climate and soil data

HolosNor requires seasonal soil water filled pore space (WFPS) and soil temperature (ST) at 30 cm depth (see Supplementary material, Table 1 for WFPS and WS for the four locations). The CSM-CERES-Wheat simulations in DSSAT provided the spring and summer WFPS and ST data for wheat in SEN and CN, but the model did not provide climate data for winter and autumn. Since wheat production was not simulated in SWN and NN, no soil temperature and water simulation output data were available for these two locations. Therefore, we adjusted the WFPS and ST data from SEN to SWN and from CN to NN by accounting for the differences between the two locations using data from Bonesmo et al. (2013) from these locations as baseline, assuming that the same difference between SEN and SWN, and CN and NN would persist in 2050. The WFPS and ST data obtained from DSSAT for spring wheat were also applied to grassland because the sensitivity of the HolosNor model outputs towards small changes in WFPS and ST was very low. Bonesmo et al. (2013) provided climate data for winter and autumn in all locations, however due to the significant differences between the ST and WFPS for spring and summer obtained from DSSAT and Bonesmo et al. (2013), we made a new baseline. Data for winter and autumn were calibrated to reflect the regional variation according to Bonesmo et al. (2013) and the level of ST and WFPS from DSSAT by subtracting the difference between the ST in summer and winter in the baseline of Bonesmo et al. (2013) from the ST in summer (DSSAT output), thereby obtaining a ST in winter. The same procedure was applied to obtain the WFPS in winter for the new baseline too. The 10^{th}, the 50^{th} and the 90^{th} percentiles of the grass yields in different locations for 100 individual simulations with unique weather input data were used to calculate low (ly), median (my) and high (hy) yielding years. The corresponding spring and summer WFPS and ST data as well as the wheat yield for the selected years were used as inputs.

Herd characteristics

Herd characteristics and management differences between the locations are based on Bonesmo et al. (2013), which reflect actual farms in each location. In Norway, most cows (90%) are Norwegian Reds, and the normal practice is year round calving with fattening of bulls on farm. Details of the herd characteristics for the baseline are reported in Bonesmo et al. (2013). Briefly, herd size was highest in SWN (28 dairy cows) and lowest in NN (16 dairy cows). South-west region had the highest milk yield per cow (6958 kg FPCM), and CN the lowest (5511 kg FPCM. The highest and lowest concentrate use per dairy cow was observed in NN and CN (2138 kg and 1373 kg DM, respectively). The lay area per cow was highest in NN, and lowest in SWN, reflecting differences in yield due to climatic conditions. For the same reason, the proportion of time spent on grazing was highest in SEN (42%), and lowest in NN (20%). The proportion of culled cows per dairy cow was highest in CN (0.53) and lowest in NN (0.13). Culled animals were replaced with first lactating cows. The herds consisted of the following animal groups: milking cows, dry cows, first lactating cows, heifers older and younger than 1-year-old, bulls older and younger than 1-year-old, and calves. The ratio of milking cows and heifers in Bonesmo et al. (2013) in four locations was used to calculate the number of heifers in different production conditions. The highest live weight at slaughter for the fattened young bulls was in SWN and lowest in SEN, whereas the slaughter age was lowest in CN (21 months) and highest in SEN (26 months). Central Norway showed the highest use of concentrates for fattening of bulls (2967 kg DM compared to 1830 kg and 1730 kg DM in SEN and SWN, respectively). There were no fattening of bulls on farm in NN.

Production conditions

Two different production conditions, reflecting the current and potential future structure of the dairy systems in Norway were included. In addition, a baseline was formed using the production and herd data from 2008 (Bonesmo et al., 2013). Milk yield in 2050 was extrapolated using a 1% annual increase in milk yield, based on the recent records of production in Norway (TINE Advisory Services, 2014) (Table 1). Under the first future condition, we assumed that the current domestic milk quota (MQ) of 1500 million liters was still in effect, resulting in a reduction in the number of dairy cows in the herd due to the increased milk yields. Therefore, the grass area was reduced in response to the higher future grass yields, to match the consumed amount of silage on farm. Under the second future production condition, MQ was assumed to be abolished (no milk quota: NMQ), allowing the model to increase the number of dairy cows in response to the higher future grass yields within the limits of the silage area on farm. Milk yield per cow was assumed to be the same in both production conditions (MQ and NMQ). Milk delivered from the farm to dairy was set to 93% of the net milk production (TINE Advisory Services, 2014).

Table 1. Kilogram fat and protein corrected milk (kg FPCM) produced per cow per year in the baseline and the two production conditions for four locations

Location	**Milk yield (kg FPCM cow^{-1} year^{-1})**	
	Baseline	**MQ/NMQ[b]**
SEN[a]	6986	10,810
SWN[a]	6333	9892
CN[a]	5519	9106
NN[a]	6115	9725

[a]SEN: South-east Norway; SWN: South-west Norway; CN: Central Norway; NN: Northern Norway

[b]MQ: Milk quota; NMQ: No milk quota

Feedstuffs used in the ration and feeding practice

Feedstuffs used were concentrates consisting of barley and oats grown on- and off-farm, imported soybean meal and forage. Non-simulated cereal yield was assumed to be related to simulated spring wheat yield according to the following: Winter wheat, oats and barley grain yields were assumed to be 45%, 34% and 7% higher than that of simulated spring wheat yield, i.e. the same ratios between the yields of different cereal crops, as used by Bonesmo et al. (2013), were assumed for all climate projections. The area allocated for only grazing was 6.7 ha in NN. For the rest of the locations, area used for silage making was also used for grazing. The area allocated to a specific cereal crop production and grass as well as the applications of N fertilizers and pesticides were adjusted according to Bonesmo et al. (2013) for different locations. Unharvested above-ground stubble biomass of grass was considered as 885 kg/ha per harvest (Höglind et al., 2005). The DM content of the grass was set to 25%. Losses associated with making and feeding the silage was set to 20% (Randby et al., 2015) and 10% (Bonesmo et al., 2013). Silage nutritive value of the baseline for each location was set as in Bonesmo et al. (2013) and these nutritive values were also used for the future projections. Concentrate requirements for milk yield in 2050 was estimated using a linear regression model developed from the feed requirements of dairy cows with varying levels of milk production presented by Volden (2013). Higher milk yields require a higher use of concentrates, thus changing the grass:concentrate ratio in the diet from the baseline (i.e. MQ). Table 2 shows silage area and concentrate consumption (kg DM cow^{-1}) for the two production conditions in four locations.

Table 2. Silage area and concentrate consumption (kg dry matter: DM) in the projected climate conditions in four locations of Norway. The low (ly), median (my) and high yielding (hy) years refer to grass yielding years at 10^{th}, 50^{th} and 90^{th} percentiles, respectively

Projected climate condition in four locations	**Silage area (ha)**		**Concentrate consumption (kg DM cow^{-1} $year^{-1}$)**	
	Production condition			
	MQ[b]	**NMQ[b]**	**MQ[b]**	**NMQ[b]**
SEN[a]				
Baseline – my	20			

This is the post-peer review, pre-copyedit version of an article published in Agricultural Systems.
The final authenticated version is available online at: http://dx.doi.org/10.1016/j.agsy.2017.07.004

BCM2.0 – ly	13	20		
BCM2.0 – my	11	20		
BCM2.0 – hy	10	20	1823	3711
HadCM3 – ly	23	20		
HadCM3 – my	12	20		
HadCM3– hy	9	20		
SWN[a]				
Baseline – my	28			
BCM2.0 – ly	20	28		
BCM2.0 – my	15	28		
BCM2.0 – hy	14	28	1972	3603
HadCM3 – ly	18	28		
HadCM3 – my	12	28		
HadCM3 –hy	11	28		
CN[a]				
Baseline – my	34			
BCM2.0 – ly	21	34		
BCM2.0 – my	18	34		
BCM2.0 – hy	17	34	1376	3056
HadCM3 – ly	22	34		
HadCM3 – my	18	34		
HadCM3 – hy	17	34		
NN[a]				
Baseline – my	38			
BCM2.0 – ly	21	38		

BCM2.0 – my	17	38		
BCM2.0 – hy	16	38	2138	3407
HadCM3 – ly	24	38		
HadCM3 – my	19	38		
HadCM3 – hy	16	38		

[a]SEN: South-east Norway; SWN: South-west Norway; CN: Central Norway; NN: Northern Norway

[b]MQ: Milk quota; NMQ: No milk quota

The silage available for feeding was calculated from the BASGRA model outputs of timothy grass. The yields represent the location and specific management practice e.g. number of cuts. The grazing season (% of the days in a year when the animals had access to pasture) was set to 42% and 9% in SEN, 39% and 9% in SWN, 39% and 33% in CN, and 20% and 25% in NN for cows and heifers (Bonesmo et al., 2013).

Farm management

Pesticides were applied to grass- and cropland. An average pesticide use of 40 MJ ha^{-1} was used for grasslands in all locations (Bonesmo et al., 2013). This figure is related to the energy used to produce the pesticides as described by Audsley et al. (2009). Pesticides applied to field crops was set to 144 MJ for barley and oats, 180 MJ for spring wheat and 427 MJ ha^{-1} for winter wheat. The N fertilizer applied to silage area was 297 kg, 139 kg, 116 kg and 68 kg ha^{-1} in SEN, SWN, CN and NN, respectively. Silage additive used was 0.00079 kg, 0.0022 kg, 0.0014 kg and 0.0006 kg CH_2O_2 (kg silage)$^{-1}$ in SEN, SWN, CN and NN, respectively (Bonesmo et al., 2013). Number of grass cuts were 3 in baseline, 4 in BCM2.0, and 5 in HadCM3 in SEN and CN; 4 in baseline and BCM2.0, and 5 in HadCM3 in the SWN; and 2 in baseline, 3 in both BCM2.0 and HadCM3 in the NN, which corresponded to the output of the BASGRA simulations using the cutting frequency explained above. As the number of cuts differed between baseline and the future, total fuel consumption was calculated based on the fuel consumption per grass cut (1740 L, 2104 L, 2204 L and 1240 L cut^{-1} in SEN, SWN, CN and NN, respectively), in addition to the fuel consumption for grains. Fuel consumption per grass cut was estimated based on the proportion of total area allocated to grass and cereal crops, and the number of grass cuts in the baseline. These proportions of the land allocated to cereal crops and silage making in different locations in the baseline period were 40:60 in SEN and 35:65 in CN. A fixed value for the electricity consumption per cow per year (1093 kWh, 616 kWh, 1050 kWh and 2058 kWh year^{-1} in SEN, SWN, CN and NN, respectively) was used to calculate the total electricity consumption on farm (Bonesmo et al., 2013).

2.2.3. Economic model (JORDMOD)

The economic model, JORDMOD, is a spatial, price-endogenous partial equilibrium model for Norwegian agriculture (Bullock et al., 2016). It is divided into two modules: a supply module and a market module.

Supply module

The supply module follows a whole farm approach by which profits for about 320 specialized farms are maximized. The approach generates minimum costs at the farm level, which are translated into supply functions. The module distinguishes between 11 different types of production (cereals, potatoes, fruits and berries, vegetables, cow milk, goat milk, beef, sheep, pork, poultry and egg) in 32 Norwegian regions that differ with respect to natural conditions and payment rates. The model covers 37 farm inputs (e.g. various types of seed, plant protection, fertilizer, machinery, energy, veterinary, capital, land and labor) and 28 farm outputs (e.g. grains, potatoes, oilseeds, protein crops, milk, different types of meats and egg). The relationship between most inputs and outputs is mostly fixed with parameters calibrated to observations at farm level and national level. Crop yields were obtained from CSM-CERES-Wheat and BASGRA while milk yields and feeding ratios were taken from HolosNor in order to ensure consistency between the models. Timothy grass was considered as a crop. The fact that simulated yields from CSM-CERES-Wheat and BASGRA were higher than the yields achieved by farmers (i.e. “yield gap”) and those assumed in previous applications of JORDMOD, crop yields had to be adjusted before they entered JORDMOD. Therefore, relative yield changes compared to the baseline for each simulation derived from the CSM-CERES-Wheat and BASGRA were applied to the calibrated yields in JORDMOD. By doing this yield calibration, we could eliminate the potential deviation from what is normal for the region in question that any non-representability of the of the soil and climate conditions that were assumed in the crop simulations had within climates related to each period and GCM. Any effects of possible interaction between soil and climate related to each GCM on yield could not be excluded in this method. However, previous studies showed rather similar effects on different soil types in Norway on wheat (Persson and Kværnø 2016) and timothy grass yield (Persson et al 2015) under current and projected future climate. Further, crop yields in JORDMOD are a function of N input. As such, this model allows for an adjustment of N intensity as a response to a change in relative prices between N and crop output.

Unlike BASGRA and HolosNor, which were applied to four specific locations, and CSM-CERES-Wheat, which was applied to two specific locations, JORDMOD represented the entire country, making assumptions at national level. Upscaling from the farm level to the regional level was achieved by applying the same relative crop yield changes, milk yield changes and feeding ratios to those locations that were not covered by the three other models. In particular, the relative yield changes of SEN in the three other models were applied to the most fertile regions in SEN in

JORDMOD. South-west Norway is a particular region with agricultural conditions not found in other regions in Norway. Therefore, relative changes in SWN were applied to this location only. The relative changes in the remaining locations in SEN and SWN in JORDMOD were adjusted, using relative changes for CN in the three other models, while changes in NN in JORDMOD were adjusted with the relative changes for NN in the other three models. The actual mix of inputs and outputs for each farm type is determined by maximizing farm profit for given producer prices, agronomic constraints and other regulations e.g. maximum size for farms producing pork, poultry and egg or the milk quota regime limiting the amount of milk that can be delivered per farm. Milk quotas are tradable between farms in the same county. Farm size measured in farmland or number of animals per farm is determined as part of the profit maximization procedure.

The model includes the main support schemes such as output payments and direct support schemes to farmland and animals. Payment rates are often differentiated by region and farm size. Per unit rates are higher in NN compared to SN, and they are higher for the first units of farm land and animals compared to the last units. Some payments are capped. In the baseline, budget support to agriculture amounted to 23,770 NOK per ha farmed land.

Outputs at the farm level are processed into final demand products. The model distinguishes 40 products demanded by consumers, amongst which 16 are meat products and 14 are dairy. The remaining products cover plant products (e.g. bread grains, potatoes, different kinds of fruits and vegetables) and eggs. Processing margins for meat and dairy products depend on domestic production quantity delivered by farms, the number of producers, the number and size of processing plants as well as the geographical location of producers and processors.

Market module

The core of the market module is a system of supply and demand functions for the 40 products that consumers demand. Supply functions are derived from the farms types in the supply module. Final demand for food is expressed by linear demand functions. World market prices are taken as given and establish a price floor. Trade policies such as import tariffs, import quotas and export subsidies apply. The model allows for imports and exports given trade policies for all 40 market products. In addition, trade is allowed for intermediate products such as carcasses of livestock, pigs and sheep. Import occurs when the world market price plus the relevant import tariff is lower than the costs of domestic production (both for primary agriculture and processing). The model finds an equilibrium solution by maximizing the sum of producer and consumer surplus in the 40 markets. The solution generates equilibrium quantities and prices in the markets. This information is incorporated back to the supply module to repeat the optimization of inputs and outputs for each farm type. This process creates a loop, which is finalized when the equilibrium prices derived in the market module are consistent with the producer prices used in the farm optimization process in the supply module.

The model's equilibrium solution in the base year does not coincide with observed numbers because the model assumes a long-term adjustment to known economic conditions like prices and subsidies. In reality, those conditions may change more frequently so that farmers constantly adapt to new situations. In order to prevent the model from yielding base years' results too far from observed numbers (e.g. production, land use and labor input), input-output parameters of the model were calibrated. The base year was "2011", which was defined as the unweighted average of the years 2010−2012 with rates of subsidy applicable to calendar year 2011. The simulation year was set to 2050 in order to achieve consistency with BASGRA, CSM-CERES-Wheat and HolosNor. For population growth, a forecast for the simulation year was taken from Statistics Norway (2015).

For other exogenous parameters like world market prices, interest rates and wage rates, no reliable forecasts for such a long time-period exist. Instead, forecasts with a time frame that was as long as possible were used. For instance, world market prices were prolonged to 2050 using the same annual percentage change as in the forecast results in OECD-FAO (2015) for the years 2015–2024.

Model output and simulations

The main outputs from JORDMOD are domestic food production and consumption, imports and exports, market prices and derived producer prices, employment in primary agriculture, land use, capital used in primary agriculture, support to agriculture (budget support and import protection) and economic surplus. Total food production is measured in energy units and excludes feed grains to avoid double counting as feed grains is an input to milk and meat production. Agricultural income is defined as land rents and calculated by deducting costs including labor and capital from the sum of market incomes and budget support. Land rents, hence, represent the remuneration to land after all other inputs have been remunerated. Greenhouse gas emissions related to dairy production are calculated using GHG emissions intensity coefficients from HolosNor and scaling up to the national level based on the regional production levels.

The simulations in JORDMOD follow the set-up of simulations in HolosNor and uses results from HolosNor with regard to crop yields, milk output and dairy feeding regime. The model is run for each of the two future climate scenarios, for MQ and NMQ production conditions, and for three different levels of grass and grain yields (ly, my and hy) and associated feedings regimes and milk output. JORDMOD abstracts from uncertainty, meaning that the producer perfectly knows the weather in advance of production and management decisions. In this respect, the model is unable to mirror the anticipated increased variation in the future climate.

2.2.4. Input-output interactions between the models

Fig. 2 below shows how the models were combined. The three models have different base years as the plant models are calibrated to the 1965-1990 period, HolosNor uses 2008, and the base year of JORDMOD is 2011. However, the simulation year 2050 is common for all three models. We regard the differences in the base years insignificant compared to the fact that the simulation year lies about 40 years ahead.

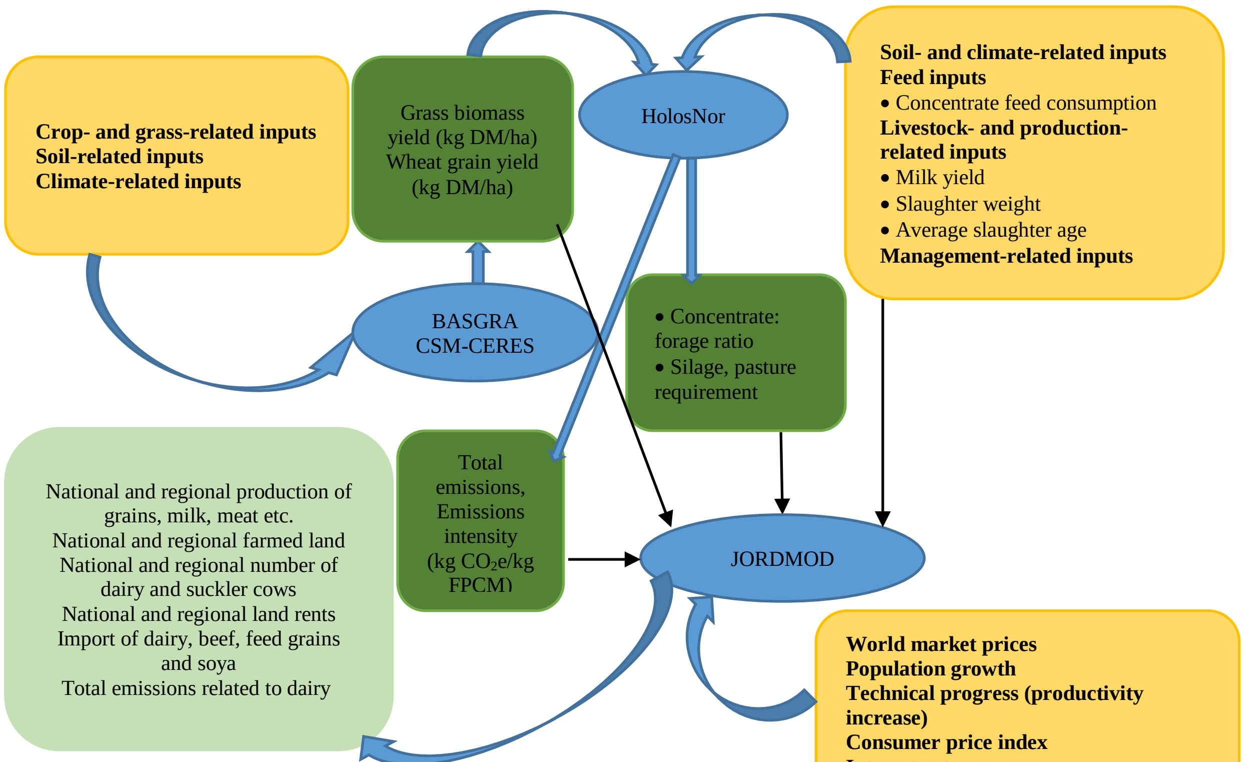

Fig. 2. Model interactions. FPCM: Fat protein corrected milk, DM: dry matter, kg CO_2e: kilogram carbon dioxide equivalents. Black arrows refer to BASGRA, CSM-CERES-Wheat and HolosNor variables used in JORDMOD model; yellow-shaded area refers to main inputs used in BASGRA, CSM-CERES-Wheat and HolosNor models; dark-green-shaded area refers to outputs of a

particular model used by another model; light-green-shaded area refers to outputs of a model not used further by another model (i.e. JORDMOD results); and finally blue-shaded area refers to models used.

3. Results

3.1. Grass and wheat yields

Selected grass DM and wheat grain yields (kg DM ha^{-1}) in different locations of Norway under baseline (1961−1990) and future (2046−2065) climate conditions as projected under the A1B GHG emission scenario in IPCC AR4 report and two different GCMs are presented in Table 3.

Table 3. Simulated grass and cereal dry matter (DM) yields using BASGRA and CSM-CERES-Wheat, respectively, under baseline (1961−1990) and future (2046−2065) climate conditions as projected by two different Global Climate Models (BCM2.0 and HadCM3). For each simulation case, the average temperature and accumulated precipitation during the growing season, the length of the growing season for timothy grass as defined by Bonesmo and Skjelvåg (1999), and the temperature sum (above 0 °C) are also presented. The low (ly), median (my) and high (hy) yielding years refer to grass yielding years at 10th, 50th and 90th percentiles, respectively

			Growing season			
Projected climate condition in four locations	**Grass yield (kg above-ground DM ha^{-1})** [b]	**Wheat yield (kg grain DM ha^{-1})**	**Daily average temperature (°C)**	**Accumulated precipitation (mm)**	**Length (days)**	**Temp. sum (°C days)**
SEN[a]						
Baseline – my	11,323	2269	11.1	655	208	2310
BCM2.0 – ly	10,962	6097	12.9	540	236	2860
BCM2.0 – my	13,431	6590	12.3	490	225	2762

BCM2.0 – hy	14,993	6731	12.7	610	216	2737
HadCM3 – ly	6127	6061	13,8	454	205	2830
HadCM3 – my	11,982	6835	14.0	757	200	2809
HadCM3 – hy	16,761	6809	13.5	680	220	2972
SWN[a]						
Baseline – my	10,777	-	10.4	755	224	2341
BCM2.0 – ly	9700	-	10.7	1077	289	3803
BCM2.0 – my	12,707	-	10.9	970	279	3043
BCM2.0 – hy	13,959	-	10.9	1009	277	3038
HadCM3 – ly	10,881	-	11.6	956	283	3280
HadCM3 – my	15,869	-	11.8	998	286	3260
HadCM3 – hy	18,046	-	11.8	1012	269	3182
CN[a]						
Baseline – my	11,843	4499	10.6	492	191	2029
BCM2.0 – ly	11,260	4916	11.0	643	227	2490
BCM2.0 – my	13,398	4896	11.1	613	229	2540
BCM2.0 – hy	14,012	4864	11.6	766	211	2460
HadCM3 – ly	10,777	5255	10.9	792	233	2549
HadCM3 – my	13,320	5414	11.0	744	246	2719
HadCM3 – hy	14,000	5517	12.6	557	209	2600
NN[a]						
Baseline – my	6483	-	8.6	309	143	1239
BCM2.0 – ly	7870	-	9.6	754	220	2126
BCM2.0 – my	9531	-	10.0	809	187	1878
BCM2.0 – hy	10,294	-	9.9	596	209	2064

HadCM3 – ly	6886	-	8.8	682	224	1986
HadCM3 – my	8595	-	9.9	482	172	1709
HadCM3 – hy	10,130	-	10.5	648	170	1777

[a]SEN: South-east Norway; SWN: South-west Norway; CN: Central Norway; NN: Northern Norway

[b]Grass yield includes a harvest loss of 885 kg DM ha^{-1} $harvest^{-1}$ (Höglind et al., 2005)

The median grass yields in the baseline period ranged between 6483 kg and 11,323 kg DM ha^{-1}, whereas in the future period they varied between 8595 kg and 15,869 kg DM ha^{-1} between locations and climate projections. The median grass yield increased from the baseline to the future period in all locations and climate projections. The largest increase 5092 kg DM ha^{-1} was simulated for SWN in the HadCM3 climate projection. The inter-annual variability in grass yields varied between location and climate projection. The widest span between a high and a low yielding year, 10,634 kg DM ha^{-1}, was simulated for SEN in the HadCM3 climate projection.

The corresponding wheat grain DM yields that were simulated under the same weather conditions within each projected climate as the high median and low timothy grass yields increased from the baseline to the future period in both wheat producing locations and for all climate projections.

3.2. GHG emissions intensity for milk production

The GHG emissions intensities ranged between 0.8 kg and 1.23 kg CO_2e (kg FPCM)$^{-1}$ in all production conditions and locations (Table 4). Overall, emissions intensities were lower in 2046−2065 compared to the baseline in all locations and for all GCMs and production conditions, except for a low yielding year in HadCM3 climate projection in SEN where emissions intensities were higher than those in the baseline. The lowest and highest emissions intensities were achieved in CN in the BCM2.0 and SEN in the HadCM3 climate projection in a low timothy grass yielding year and in a future production condition where milk quotas were removed, respectively. These figures were 13% lower and 6% higher than the baseline values in the given locations. In all scenarios, emissions intensities were lower in the high yielding years than the median yielding years, and lower in the median yielding years than the low yielding years. The production conditions where milk quota was removed resulted in lower emissions intensities than those where the milk quota was still in effect, except for the low yielding year in the HadCM3 climate projection in SEN where the production condition with milk quota exhibited 2.5% higher emissions intensity than the NMQ condition.

Table 4. Greenhouse gas emissions intensity (kg CO_2e (kg fat and protein corrected milk: FPCM)$^{-1}$) in four locations under baseline (1961−1990) and future (2046−2065) climate conditions as projected by two different Global Climate Models (BCM2.0 and HadCM3). The low (ly), median (my) and high (hy) yielding years refer to grass yielding years at 10th, 50th and 90th percentiles, respectively

Greenhouse gas emissions intensity (kg CO_2e (kg FPCM)$^{-1}$	**Locations**			
	SEN[a]	**SWN**[a]	**CN**[a]	**NN**[a]
Baseline – my	1.16	1.05	0.92	1.00
BCM2.0 – ly	1.03[b] and 1.01[c]	0.99[b] and 0.98[c]	0.83[b] and 0.80[c]	0.89[b] and 0.87[c]
BCM2.0 – my	0.99[b] and 0.96[c]	0.95[b] and 0.92[c]	0.82[b] and 0.77[c]	0.87[b] and 0.85[c]
BCM2.0 – hy	0.97[b] and 0.93[c]	0.95[b] and 0.91[c]	0.82[b] and 0.77[c]	0.86[b] and 0.84[c]
HadCM3 – ly	1.2[b] and 1.23[c]	0.98[b] and 0.95[c]	0.84[b] and 0.81[c]	0.90[b] and 0.89[c]
HadCM3– my	1.02[b] and 0.99[c]	0.94[b] and 0.89[c]	0.82[b] and 0.77[c]	0.88[b] and 0.86[c]
HadCM3– hy	0.97[b] and 0.92[c]	0.94[b] and 0.89[c]	0.82[b] and 0.77[c]	0.86[b] and 0.84[c]

[a]SEN: South-east Norway; SWN: South-west Norway; CN: Central Norway; NN: Northern Norway

[b]Milk quota

[c]No milk quota

Table 5 shows the emissions per kg FPCM for individual emission sources for the four locations under the two production conditions and GCMs. Compared to CN, SEN had higher N_2O emissions from soils and higher CO_2 emissions from energy use, in addition to a lower C sequestration in the soil. Both BCM2.0 and HadCM3 resulted in lower enteric CH_4, manure N_2O and soil N_2O compared to the baseline. The CO_2 emissions associated with energy use were lower in the NMQ than in the MQ. Similarly, NMQ conditions resulted in lower N_2O emissions from soils than the MQ, with the exception being low yielding year in HadCM3 climate conditions in SEN and high yielding year in NN for the same GCM. The CO_2 emissions related to both imported soybean meal and off-farm purchased barley and oats were higher in the NMQ than those of MQ in SEN only, and remained at similar levels except for CN where the CO_2 emissions from imported soybean meal only and for NN where the CO_2 emissions from purchased barley and oats only were higher in the NMQ than in the MQ (except for a low yielding year in HadCM3 in NN).

Table 5. Greenhouse gas emission intensities (kg CO_2e (kg fat and protein corrected milk: FPCM) $^{-1}$) from individual emission sources in four locations under baseline (1961−1990) and future (2046−2065) climate conditions as projected by two different Global Climate Models (GCMs) (BCM2.0 and HadCM3) and milk production conditions with milk quota (MQ) and without milk quota (NMQ). The low (ly), median (ay) and high (hy) yielding years refer to grass yielding years at 10th, 50th and 90th percentiles, respectively

Greenhouse gas emissions intensity (kg CO_2e (kg FPCM)$^{-1}$)	**Production conditions and GCMs**												
		MQ						**NMQ**					
	Baseline	**BCM2.0**			**HadCM3**			**BCM2.0**			**HadCM3**		
		ly	my	hy	ly	my	hy	ly	my	hy	ly	my	hy
SEN[a]													
Soil C	-0.01	-0.02	-0.03	-0.04	0,03	-0.03	-0.04	-0.03	-0.04	-0.04	0.01	-0.04	-0.05
Enteric CH_4	0.44	0.37	0.37	0.37	0.37	0.37	0.37	0.38	0.38	0.38	0.37	0.38	0.38
Manure CH_4	0.05	0.04	0.04	0.04	0.05	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05
Manure N_2O	0.10	0.08	0.08	0.08	0.09	0.08	0.07	0.09	0.09	0.09	0.08	0.09	0.09
Soil N_2O	0.28	0.27	0.26	0.25	0.34	0.27	0.25	0.24	0.22	0.20	0.36	0.23	0.19
Feed CO_2 soybean meal[b]	0.07	0.04	0.03	0.03	0.04	0.02	0.02	0.07	0.08	0.09	0.02	0.07	0.09
Feed CO_2 off-farm feed[c]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.04	0.05	0.00	0.04	0.05

Energy use (direct & indirect)	0.23	0.25	0.24	0.23	0.30	0.26	0.25	0.18	0.15	0.14	0.34	0.18	0.13
SWN[a]													
Soil C	-0.04	-0.03	-0.05	-0.05	-0.04	-0.06	-0.06	-0.03	-0.05	-0.05	-0.04	-0.06	-0.06
Enteric CH_4	0.45	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Manure CH_4	0.08	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Manure N_2O	0.14	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Soil N_2O	0.16	0.14	0.12	0.12	0.12	0.11	0.11	0.14	0.12	0.12	0.12	0.11	0.11
Feed CO_2 soybean meal[b]	0.10	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Feed CO_2 off-farm feed[c]	0.06	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Energy use (direct & indirect)	0.10	0.10	0.10	0.09	0.112	0.11	0.11	0.08	0.06	0.06	0.09	0.06	0.05
CN[a]													
Soil C	-0.06	-0.05	-0.06	-0.06	-0.06	-0.06	-0.07	-0.06	-0.07	-0.07	-0.06	-0.07	-0.07
Enteric CH_4	0.47	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Manure CH_4	0.07	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.06
Manure N_2O	0.13	0.11	0.10	0.10	0.11	0.10	0.10	0.11	0.11	0.11	0.11	0.11	0.11
Soil N_2O	0.18	0.18	0.18	0.18	0.19	0.18	0.18	0.15	0.14	0.14	0.16	0.14	0.14
Feed CO_2 soybean meal[b]	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.05	0.06	0.06	0.04	0.05	0.06
Feed CO_2 off-farm feed[c]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Energy use (direct & indirect)	0.13	0.15	0.14	0.14	0.16	0.15	0.15	0.10	0.08	0.08	0.11	0.09	0.09
NN[a]													
Soil C	-0.10	-0.10	-0.10	-0.11	-0.09	-0.10	-0.11	-0.10	-0.10	-0.11	-0.09	-0.10	-0.11
Enteric CH_4	0.48	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
Manure CH_4	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Manure N_2O	0.13	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Soil N_2O	0.15	0.11	0.11	0.11	0.12	0.11	0.10	0.11	0.11	0.11	0.12	0.11	0.11
Feed CO_2 soybean meal[b]	0.12	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Feed CO_2 off-farm feed[c]	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.08	0.08	0.07	0.08	0.08
Energy use (direct & indirect)	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.04	0.03	0.03	0.05	0.04	0.03

[a]SEN: South-east Norway; SWN: South-west Norway; CN: Central Norway; NN: Northern Norway

[b]CO_2 emissions from imported soybean meal

[c]CO_2 emissions from off-farm produced barley and oats

3.3. Economic evaluation

Tables 6 and 7 present key results of JORDMOD on agricultural activity, farm income, production and trade under the different GCMs and production conditions.

National cereal grain production increased in all future simulations compared to the baseline (Table 6). However, higher grain yields did not always lead to higher domestic production, which was particularly evident in the NMQ condition. In these simulations, domestic grain production was the highest when grain yields were the lowest. Low grain yields reduced the profitability of beef produced on suckler cows more than the profitability of grain production, whereby suckler cow production was reduced, and grassland used for suckler cows was converted to produce grain.

The JORDMOD simulations indicate a large potential for increased domestic milk production in the future. For example, milk production increased from 1632 million liters (ML) in the baseline to 1832 ML in the MQ condition and more than 2800 ML in the NMQ condition, reflecting an 86% increase in the median yielding year for HadCM3 in the NMQ condition compared to the baseline. Land rents varied between 1914 (baseline) and 3901 million NOK (for the median yielding year in the BCM2.0 and NMQ production condition).

Table 6. Production of grains, milk, beef, farm land, number of dairy and suckler cows and land rents simulated by JORDMOD under baseline (1961−1990) and future (2050) climate conditions projected by the two Global Climate Models (BCM2.0 and HadCM3) and production conditions with milk quota (MQ) and without milk quota (NMQ). The low (ly), median (my) and high (hy) yielding years refer to grass yielding years at 10th, 50th and 90th percentiles, respectively. FPCM: Fat protein corrected milk, NOK: Norwegian krone

	Grain production (1000 tonnes)	**Milk production (million kg FPCM)**	**Beef production (million kg)**	**Farmed land (1000 ha)**	**Dairy cows (1000 heads)**	**Suckler cows (1000 heads)**	**Land rents (million 2011 NOK)**
Baseline – my	1091	1632	83	934	275	36	1914
BCM2.0 – ly, MQ[a]	1285	1832	70	964	208	111	2360
BCM2.0 – my, MQ[a]	1258	1832	109	1050	208	240	3267
BCM2.0 – hy, MQ[a]	1253	1832	110	1016	208	243	3006
HadCM3 – ly, MQ[a]	1253	1832	43	860	209	15	2149
HadCM3 – my, MQ[a]	1416	1832	93	1052	208	179	2957
HadCM3 – hy, MQ[a]	1362	1832	111	1004	208	237	2927
BCM2.0 – ly, NMQ[b]	1441	2733	69	992	307	35	3202
BCM2.0 – my, NMQ[b]	1222	2761	110	1006	310	127	3901
BCM2.0 – hy, NMQ[b]	1268	2748	110	999	308	136	3425
HadCM3 – ly, NMQ[b]	1448	2626	61	987	304	0	3375
HadCM3 – my, NMQ[b]	1266	2819	104	1071	318	134	3554
HadCM3 – hy, NMQ[b]	1377	2744	111	988	307	125	3175

[a]MQ:Milk quota

[b]NMQ: No milk quota

The amount of farmed land varied relative to the increase in crop yields. In general, higher yields increased the profitability of farmed land and led to the allocation of a larger land area for agricultural production. However, changes in the relative profitability between productions and final consumer demand also determine the mix and size of domestic production. For example, the amount of farmed land was higher in the average yielding years compared to low and high yielding years.

The simulations indicate that future crop yields and dairy management choices can be quite sensitive to the size of the agricultural sector and its sub-sectors. For instance, beef production varied between 43 and 111 million kg and the number of suckler cows varied between 15,000 and 237,000 heads for the HadCM3 climate projection in presence of the MQ policy for the low and high yielding years, respectively. In contrast, the number of dairy cows showed less variation with respect to different grass yielding years. Milk yields per cow were fixed in the simulations and milk production was constrained by the quota (in the MQ condition). Hence, the number of dairy cows did not change. Without MQ, the number of dairy cows followed the development of milk production.

Land rents were higher in all simulations compared to the baseline, and higher in the NMQ than in the MQ for the same grass yielding years and GCMs. This reflects the fact that higher yields increased the profitability of the land. Moreover, land rents depended on the future of the MQ regime. Without MQ, land rents were considerably higher than under the MQ regime due to higher dairy production per unit land area.

Table 7 below presents the key findings for the simulated food production and imports of dairy, beef, feed grains and feed protein for baseline (1961−1990) and future (2050) climate conditions. Total domestic food production in energy terms increased compared to the baseline in all simulations. Further, total domestic food production was considerably higher in the NMQ regime compared to the simulations where MQ was in place.

Amount and composition of imports were also closely related to domestic production. Dairy imports increased considerably with the MQ regime due to population growth. Even without MQ, dairy imports were higher in the future compared to the baseline period. The development of beef imports was sensitive to the climate projections applied. Median and high yielding years most often led to lower imports, while low yielding years exhibited the opposite effect.

Table 7. Food production and imports of dairy, beef and feed protein simulated by JORDMOD under baseline (1961−1990) and future (2050) climate conditions projected by two Global Climate Models (BCM2.0 and HadCM3) and production conditions with milk quota (MQ) and without milk quota (NMQ). The low (ly), median (my) and high (hy) yielding years refer to grass yielding years at 10^{th}, 50^{th} and 90^{th} percentiles, respectively.

	Food production (1000 GJ)	Imports (1000 tonnes)			
		Dairy	Beef	Feed grains	Feed protein (soya)
Baseline – my	12.1	17	16	68	214
BCM2.0 – ly, MQ[a]	13.1	181	39	0	253
BCM2.0 – my, MQ[a]	13.6	181	1	156	276
BCM2.0 – hy, MQ[a]	12.9	181	1	107	275
HadCM3 – ly, MQ[a]	12.9	181	65	0	271
HadCM3 – my, MQ[a]	13.9	181	15	0	276
HadCM3 – hy, MQ[a]	13.2	181	1	23	275
BCM2.0 – ly, NMQ[b]	16.5	37	41	86	258
BCM2.0 – my, NMQ[b]	16.8	36	1	422	290
BCM2.0 – hy, NMQ[b]	16.5	37	1	351	289
HadCM3 – ly, NMQ[b]	16.2	70	49	30	257
HadCM3 – my, NMQ[b]	17.1	35	5	396	292
HadCM3 – hy, NMQ[b]	16.8	37	1	270	219

[b]MQ:Milk quota

[c]NMQ: No milk quota

The import of feed grains and feed protein depended on the size of the domestic milk and meat production. Low yields are in general associated with low beef production and reduce the demand for feed grains. Land prices shrank when beef production went down and counteracted lower yields in grain production. The share of domestic feed grain on total feed grain demand improved, and in some of the simulations, Norway was self-supplied with feed grains.

The relative increase in domestic milk production from the baseline to the future period (Table 6) was mirrored by a relatively smaller increase in GHG emissions (Table 8). For instance, for the BCM2.0 climate scenario in a low yielding year under the MQ regime, domestic milk production increased by 21% while the emissions related to milk production increased by only 10%. This pattern held throughout all simulations and reflects the fact that more intensive production (caused by higher yields) reduced the emissions intensity. Still, this effect was not strong enough to keep the absolute amount of GHG emissions below the baseline value. For the HadCM3 climate model under the MQ regime and high yielding years, a 21% increase in milk production corresponded to a 6% increase in GHG emissions.

Table 8. Milk production and greenhouse gas emission intensities (kg CO_2e (kg fat and protein corrected milk: FPCM) $^{-1}$) from dairy simulated by JORDMOD under baseline (1961−1990) and future (2050) climate conditions projected by two Global Climate Models (BCM2.0 and HadCM3) and production conditions with milk quota (MQ) and without milk quota (NMQ). The low (ly), median (my) and high (hy) yielding years refer to grass yielding years at 10th, 50th and 90th percentiles, respectively.

	Greenhouse gas emissions intensity	**Total emissions**	**CO_2 emissions in percent of baseline**
	kg CO_2e (kg FPCM)$^{-1}$	**1000 t CO_2e**	
Baseline – my	0.96	1461	100
BCM2.0 – ly, MQ[a]	0.94	1599	110
BCM2.0 – my, MQ[a]	0.92	1567	107
BCM2.0 – hy, MQ[a]	0.92	1557	107
HadCM3 – ly, MQ[a]	1.01	1725	118
HadCM3 – my, MQ[a]	0.93	1573	108
HadCM3 – hy, MQ[a]	0.91	1553	106
BCM2.0 – ly, NMQ[b]	0.92	2323	159
BCM2.0 – my, NMQ[b]	0.88	2257	155

BCM2.0 – hy, NMQ[b]	0.87	2213	151
HadCM3 – ly, NMQ[b]	0.79	1926	132
HadCM3 – my, NMQ[b]	0.89	2335	160
HadCM3 – hy, NMQ[b]	0.86	2190	150

[a]MQ: Milk quota

[b]NMQ: No milk quota

4. Discussion

4.1. Synthesis of simulation results

The current study takes a step-forward from the previous modelling studies on the performance of northern European agriculture in a changing climate by combining crop, livestock and economic models to estimate the impacts of future climate scenarios on feed supply, dairy farm GHG emissions intensity and the economic performances in Norway.

The positive impact of the projected climate change on crop yields agrees with previous simulation studies of timothy grass (Höglind et al., 2013; Jing et al., 2013; Persson and Höglind, 2014) and spring wheat yield (Persson and Kværnø (2016) under projected future climate in high latitude regions. However, these results contrast with the reduction in expected grass (Norton et al., 2016) and cereal (Bindi and Olesen, 2011; Teixeira et al., 2013) production in regions where projected climate will become warmer and drier.

The lower GHG emission intensities observed in all four locations for low and median yielding years, and in three locations for high yielding years in 2046−2065 compared to the baseline were due partly to the increases in crop yields and largely to the projected higher milk yields per cow. The relatively small differences in emissions intensities between the two GCMs (HadCM3 and BCM2.0) and the low, median and high yielding years in the period 2046−2065 where the milk yield did not change, suggest that the differences in the climate had a relatively low influence on the emissions intensity. The exception being the HadCM3 GCM in SEN where the grass yield was extremely low, and a larger grassland area was required to compensate for the decreased yield. This resulted in increased emission intensity of the N_2O from soils, which was not compensated for by the reduced GHG emissions intensity caused by the projected increased milk yield.

The generally higher GHG intensities in the SEN than in the CN can largely be explained by higher N_2O emissions from soils, higher CO_2 emissions from energy use due to higher N fertilizer application rates associated with the longer growing season and higher grass yield levels, and higher requirement for purchased concentrates due to higher milk yield in the SEN than in the CN. The variation between locations is within the variation of that reported by Bonesmo et al. (2013) who used the same methodology for calculating the GHG emissions intensities for 30 farms in Norway in the year 2008 and consistent with variations reported by Crosson et al. (2011) for other conditions and modelling approaches.

Currently, MQ and milk yield per cow determine the size of dairy cow population in Norwegian dairy production, and the results presented here indicate that regardless of a quota, projected future conditions will have important consequences for the GHG emissions. In general, lower GHG emissions intensities under the NMQ than the MQ conditions were mainly due to lower emissions from energy use per kg milk in the NMQ. It should also be noted that, in an MQ system, increased milk yields per cow will lead to fewer dairy calves available for beef production and therefore more suckler cows will be needed to maintain beef production provided that the consumption and import of beef remain unchanged. Thus, the lower GHG emissions per kg milk in 2050 compared to the baseline for the MQ system would not necessarily result in lowered total emission from the total domestic cattle population (Åby et al., 2015). In line with this, Özkan Gülzari et al.

(unpublished results) reported that cows with 7020 kg milk yield year^{-1} produced 3.7% lower emissions intensity than the cows with 6300 kg milk yield year^{-1} although total emissions were higher in cows with higher milk yield due to higher feed intake than those with lower milk production.

The results of the JORDMOD showed that the projected climate conditions have the potential to raise domestic production. Nevertheless, JORDMOD simulations demonstrated that increased grass and grain DM yields do not necessarily translate into higher total domestic agricultural production or higher farm profitability measured as land rents, reflecting simultaneous changes in the relative profitability of different agricultural products. As exemplified in the MQ regime, political conditions and market development are expected to continue to influence production and profitability in the future. The main reason for increased domestic milk production simulated by JORDMOD stems from the projected population increase, 1% annually, boosting the demand for dairy products, which was met by domestic production in the NMQ scenario, and by import under MQ.

In the economic simulations, lower grain yields in low yielding years than median yielding years sometimes reduced market incomes so that production was not profitable in marginal regions. Hence, land with low productivity in these regions was taken out of production. Also higher grain yields, sometimes slightly reduced the total domestic production by reducing the cereal cropping area due to the transition from grain production to more profitable suckler production. Higher crop yields due to projected climate change tended to increase the value of land compared to the baseline situation as no further inputs were applied in order to achieve the higher yields. The simulations with low yielding years were frequently associated with lower land rents. However, changes in the composition of crop and animal production in these scenarios discussed above entailed that the difference in yields between median and high yielding years did not always translate into higher land rents.

With the MQ in place, the number of dairy cows reduced from the baseline to the future conditions due to increased milk yields. The profitability of beef production and the number of suckler cows were positively correlated with higher grass yields. Domestic beef production increased until beef imports outside the current import quotas were replaced by domestic production. Thereafter, domestic beef production was constrained by the size of the domestic market. When milk production was no longer constrained by a MQ, imports fell considerably. However, there was always a positive net import partly due to import quotas for dairy products and partly to a milk fat deficit in the domestic production. It was less profitable to increase the domestic milk production and export the overproduction of milk protein (in the form of cheese) to balance the higher demand for milk fat than milk protein.

The import quantity of feed grains depended on the profitability of domestic production of this commodity and the domestic production of milk and meat. The necessity of imports seems to be highest under the low and high yielding simulations. The import of protein feed (i.e., soybean meal) increased compared to the baseline in all simulations and remained at a fairly high level across simulations reflecting the increased demand for protein feed that comes with higher milk yields. Domestic food production measured by energy increased in all simulations of future conditions compared to the baseline, and it was considerably higher in the NMQ than in the MQ condition.

4.2. Limitations of the current study

Despite the fact that both the DM yields and the GHG emissions align with the existing literature, the uncertainty associated with predicting those warrants further discussion. For example, Höglind et al. (2013) used 14 GCMs and found that the median annual forage grass yield for a Norwegian site differed by more than 5,000 kg DM ha^{-1} between the highest and lowest yielding GCMs due to the projected differences in temperature and precipitation, reflecting that other climate change scenarios and crop responses could change the results of the current study. Similarly, the fixed forage cutting regime and nutrient value did not take into account any possible impact of climate change on harvesting (Persson and Höglind, 2014) and feed nutritive quality (Dumont et al., 2015). Notably altered precipitation patterns could lead to adjustments in cutting regimes and harvesting practices with further implications for farm GHG emissions and profitability.

Uncertainty in farm scale systems modelling to estimate GHG emissions were discussed by Crosson et al. (2011) who reported that the quality and representability of the farm data in relation to the region they represent, and the emission factors used may have a large impact on the output from the model. Thus, if the same approach was applied to evaluate the dairy GHG emissions in the locations other than those reported here or if a different model was used to evaluate the farm emissions, results are expected to vary. It is, however, important to note that the emissions intensities may remain in the range of those reported here and internationally, while the individual emissions may differ. This is further discussed in Hutchings et al. (unpublished results) who attribute the differences in contributory emissions to the differences in the biological process and the extent to which management factors, especially quality and quantity of feed, are internalized in the model. An additional source of uncertainty relates to the future livestock production potential assumed in the analysis. The extrapolation of milk yield in HolosNor based on the observed current trend in milk yield per cow (TINE Advisory Services, 2016) is uncertain as future breeding progress and herd management conditions are difficult to predict.

Similarly, if the profitability assessment was conducted based on the input variables other than those used in the current study, different results would be expected. When scaling up the yields from farm level to regional level in JORDMOD, the relative yield increases from locations for which farm level results were available were applied to locations for which no farm level results were available from HolosNor. Given the diversity and heterogeneity of farm structure as well as natural and climatic conditions in Norway, this is a rough approximation, which could be overcome by using a tighter net of farm and weather data for baseline and future conditions across Norway. It should be also noted that every farm is unique in their structure and management, therefore different responses to variability in grass availability, and prices of feed and milk should be expected on different farms (Armstrong et al., 2010).

The results should also be interpreted in light of the strengths and weaknesses of JORDMOD. Small changes in profitability of domestic production compared with the world market can provide disproportionally large changes in domestic production versus imports, which may overestimate the sector's adjustments to a change in yield or a policy reform. At the same time, using average technology with rather limited adjustment possibilities between inputs and outputs, the model may also underestimate the sectors' adaptation to such changes. In addition, simulating long-run future climate and production in the economic modelling is controversial as the uncertainty of parameter values increases with time. In order to ensure consistency between models, the economic model was run for 2050 involving a time frame of 39 years from the baseline, while previous simulations of JORDMOD were made in a time frame of 10−15 years (Brunstad et al., 1999, 2005a; Brunstad et al., 2005b; Bullock et al., 2016). World market prices were forecasted based on the OECD-FAO forecast model, which has a time frame of 9 years (OECD-FAO, 2015). For other variables like the rate of technical progress, inflation and interest rate, historical trends were used.

4.3. Implications of the current study and recommendations for future research

Projected changes in climate in the future seems to decelerate the production of GHG emissions from dairy production in the locations assessed in this study due to higher milk yields per cow and partly to higher crop yields. The relatively high impact of increased milk yield on reduction in GHG emissions intensity suggests that management and animal breeding efforts to achieve such yield increases are vital to mitigate the GHG emissions. As increased milk yields are likely to lead to increased beef production to replace the decreased beef output from dairy cows, future efforts are also warranted to minimize GHG emissions from this alternative type of beef production.

Increased temperature may result in opportunities to increase the use of crops that are currently restricted by sub-optimal growth temperatures, such as maize silage in the south-west and south-east of Norway. Impacts of including maize in the diet of dairy cows on GHG emissions was investigated using HolosNor by Hutchings et al. (unpublished results) who reported that the increased nutritive value of this crop relative to grass silage reduced the requirements of the cows for DM intake, resulting in reduced silage and concentrate intake. However, to what extent it will be possible to grow maize silage successfully in this location in the future needs to be investigated in more detail.

Another impact of future climate change in Norwegian dairy farming may be to utilize the projected longer growing seasons for grazing. Increasing grazing season by one month may result in reduction in overall GHG emissions, ammonia emissions and manure CH_4 emissions; however larger nitrate leaching losses, slightly larger N_2O emissions and enteric CH_4 emissions (Del Prado et al., 2013). On the other hand, increased DM yields of grass will lead to extra grassland area available. Management strategies to utilize this land may lead to the introduction of suckler cows or sheep or a more extensive feeding scheme to utilize the surplus forage. Therefore, further studies comparing the GHG emissions from suckler cows, or sheep to utilize the extra grassland are recommended. The effect of alternative feeding regimes such as proportion of concentrate, and milk yield on GHG emissions from dairy production could also be investigated further.

The combination of the models in integrated studies could be improved by incorporating feedback mechanism among the models. For example, feeding the fertilizer application rates from JORDMOD back into the crop models would result in yield levels for economically optimal fertilizer application rates. In studies where different models are combined and the focus is not only the quantification of the GHG emissions but also to explore the pathways by which they can be mitigated, an economic assessment is recommended to compare the financial consequences of different mitigation and adaptation strategies (Del Prado et al., 2013). In our study, the economic assessment did not aim to compare different, targeted mitigation strategies, but instead to study land use adaption and profitability changes that followed from higher DM yields. Since the input-output relationships in JORDMOD are mostly fixed, adaptation occurs through change in production, e.g. from grain production to beef production based on suckler cows. A natural follow-up would be to make input-output relationships in JORDMOD more flexible by either allowing the model to choose between several such relationships or by introducing flexible functional forms.

5. Conclusions

This study shows that climate change may benefit the agriculture in Norway through not only higher DM yields but also reduced GHG emissions intensity. Higher grass and crop yields due to climate change also increase the value of land, leading to increased profitability. The uncertainty associated with future climate and the decision making at farm level reflect that the implications of the future climate projections will vary from farm to farm.

Acknowledgements

This study was funded by the Research Council of Norway under grant number 222943/E40 and conducted within the framework of the FACCE-JPI Modelling European Agriculture with Climate Change for Food Security (MACSUR) knowledge hub. Authors also thank Helge Bonesmo for the farm data, and the two anonymous reviewers for their comments on the manuscript.

References

Armstrong, D., Tarrant, K., Ho, C., Malcolm, L., Wales, W., 2010. Evaluating development options for a rain-fed dairy farm in Gippsland. Anim. Prod. Sci 50, 363–370.

Asseng, S., Ewert, F., Rosenzweig, C., Jones, J., Hatfield, J., Ruane, A., Boote, K., Thorburn, P., Rötter, R., Cammarano, D., 2013. Uncertainty in simulating wheat yields under climate change. Nat. Clim. Change 3, 827–832.

Audsley, E., Stacey, K., Parsons, D.J., Williams, A.G., 2009. Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use. Cranfield University, Bedford, UK, p. 20.

Bindi, M., Olesen, J.E., 2011. The responses of agriculture in Europe to climate change. Reg. Environ. Change 11, 151–158.

Bonesmo, H., Beauchemin, K.A., Harstad, O.M., Skjelvåg, A.O., 2013. Greenhouse gas emission intensities of grass silage based dairy and beef production: A systems analysis of Norwegian farms. Livest. Sci. 152, 239–252.

Bonesmo, H., Skjelvag, A.O., 1999. Regrowth rates of timothy and meadow fescue cut at five phenological stages. Acta Agr. Scand. Sec. B-Soil Plant Sci. 49, 209–215.

Brunstad, R.J., Gaasland, I., Vardal, E., 1999. Agricultural production and the optimal level of landscape preservation. Land Econ. 75, 538–546.

Brunstad, R.J., Gaasland, I., Vardal, E., 2005a. Multifunctionality of agriculture: an inquiry into the complementarity between landscape preservation and food security. Europ. Rev. Agr. Econ. 32, 469–488.

Brunstad, R.J., Gaasland, I., Vårdal, E., 2005b. Efficiency losses in milk marketing boards: the importance of exports. Nordic J. Polit. Economy 31, 77–97.

Bullock, D.S., Mittenzwei, K., Wangsness, P.B., 2016. Balancing public goods in agriculture through safe minimum standards. Europ. Rev. Agr. Econ., jbv037.

Cederberg, C., Mattson, B., 2000. Life cycle assessment of milk production - a comparison of conventional and organic farming. J Clean. Prod. 8, 49–60.

Crosson, P., Shalloo, L., O'Brien, D., Lanigan, G., Foley, P., Boland, T., Kenny, D., 2011. A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. Anim. Feed Sci. Technol. 166, 29–45.

Del Prado, A., Crosson, P., Olesen, J.E., Rotz, C., 2013. Whole-farm models to quantify greenhouse gas emissions and their potential use for linking climate change mitigation and adaptation in temperate grassland ruminant-based farming systems. Animal 7, 373–385.

Dumont, B., Andueza, D., Niderkorn, V., Lüscher, A., Porqueddu, C., Picon-Cochard, C., 2015. A meta-analysis of climate change effects on forage quality in grasslands: specificities of mountain and Mediterranean areas. Grass Forage Sci. 70, 239–254.

FAO, 2010. Greenhouse gas emissions from the dairy sector. a life cycle assessment. Food and Agriculture organization of the united nations (FAO), Animal production and health division, Rome, Italy.

Godwin, D.C., Singh, U., 1998. Nitrogen balance and crop response to nitrogen in upland and lowland cropping systems, in: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht/Boston/London, pp. 55–77.

Grønlund, A., Harstad, O., 2014. Klimagasser fra jordbruket. Kunnskapsstatus om utslippskilder og tiltak for å redusere utslippene (in Norwegian): Greenhouse gasses from agriculture. Knowledge status on emission sources and measures to reduce the emissions. Bioforsk Rapport 9, 53.

Hansen-Bauer, I., EJ Førland, I Haddeland, H Hisdal, S Mayer, A Nesje, JEØ Nilsen, S Sandven, AB Sandø, A Sorteberg, B Ådlandsvik, 2015. Klima i Norge 2100 Kunnskapsgrunnlag for klimatilpasning oppdatert i 2015 (in Norwegian): Climate in Norway 2100 Knowledge base for climate adaptation updated in 2015 . NCCS report, Oslo, p. 203.

Höglind, M., Hanslin, H.M., Van Oijen, M., 2005. Timothy regrowth, tillering and leaf area dynamics following spring harvest at two growth stages. Field Crop. Res. 93, 51–63.

Höglind, M., Thorsen, S.M., Semenov, M.A., 2013. Assessing uncertainties in impact of climate change on grass production in Northern Europe using ensembles of global climate models. Agr. Forest Meteorol. 170, 103–113.

Höglind, M., Van Oijen, M., Cameron, D., Persson, T., 2016. Process-based simulation of growth and overwintering of grassland using the BASGRA model. Ecol. Model. 335, 1–15.

Hoogenboom, G., Jones, J.W., Wilkens, P.W., Porter, C.H., Boote, K.J., Hunt, L.A., Singh, U., Lizaso, J.I., White, J.W., Uryasev, O., Royce, F.S., Ogoshi, R.M., Gijsman, A.J., Tsuji, G.Y., 2010. Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.5 [CD-ROM]. University of Hawaii, Honolulu, Hawaii.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, in: Eggleston, S., Buendia, L., Miwa, K., Nagara, T., Tanabe, K. (Eds.), Institute for Global Environmental Strategies, Kanagawa, Japan.

Jing, Q., Bélanger, G., Qian, B., Baron, V., 2013. Timothy yield and nutritive value under climate change in Canada. Agron. J. 105, 1683–1694.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. Europ. J. Agron. 18, 235–265.

Krol, M., Jaeger, A., Bronstert, A., Güntner, A., 2006. Integrated modelling of climate, water, soil, agricultural and socio-economic processes: A general introduction of the methodology and some exemplary results from the semi-arid north-east of Brazil. J. Hydrol. 328, 417–431.

Little, S., 2008. Holos, a tool to estimate and reduce greenhouse gases from farms: methodology and algorithms for version 1.1. x. Agriculture and Agri-Food Canada.

Morley, F.H.W., 1978. Animal production studies on grassland, in: 'tMannetje, L. (Ed.), Measurement of grassland vegetation and animal production. CAB International, Brisbane, pp. 103–162.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A., Jung, T.Y., Kram, T., Lebre La Rovere, E., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H.-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N., Dadi, Z., 2000. Emissions Scenarios, in: Nakicenovic and Swart (Eds.), Intergovernamental Panel on Climate Change Special Report, Intergovernmental Panel on Climate Change, Cambridge University Press, UK, p. 570.

Norton, M.R., Malinowski, D.P., Volaire, F., 2016. Plant drought survival under climate change and strategies to improve perennial grasses. A review. Agron. Sustainable Dev. 36, 1–15.

OECD-FAO, 2015. OECD-FAO Agricultural Outlook 2015-2024, OECD Paris.

Olesen, J.E., Trnka, M., Kersebaum, K., Skjelvåg, A., Seguin, B., Peltonen-Sainio, P., Rossi, F., Kozyra, J., Micale, F., 2011. Impacts and adaptation of European crop production systems to climate change. Eur. J. Agron. 34, 96–112.

Özkan, Ş., Vitali, A., Lacetera, N., Amon, B., Bannink, A., Bartley, D.J., Blanco-Penedo, I., De Haas, Y., Dufrasne, I., Elliott, J., Eory, V., Fox, N., Garnsworthy, P.C., Gengler, N., Hammami, H., Kyriazakis, I., Leclère, D., Lessire, F., Macleod, M., Robinson, T.P., Ruete, A., Sandars, D., Shrestha, S., Stott, A.W., Twardy, S., Vanrobays, M.-L., Vosough Ahmadi, B., Weindl, I., Wheelhouse, N., Williams, A.G., Williams, H.W., Wilson, A., Østergaard, S., Kipling, R.P., 2016. Challenges and priorities for modelling livestock health and pathogens in the context of climate change. Environ. Res. 151, 130–144.

Pachauri, R.K., Reisinger, A., 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Geneva, Switzerland, p. 104.

Persson, T., Garcia, A.G.Y., Paz, J., Fraisse, C., Hoogenboom, G., 2010. Reduction in greenhouse gas emissions due to the use of bio-ethanol from wheat grain and straw produced in the south-eastern USA. J. Agr. Sci. 148, 511–527.

Persson, T., Höglind, M., 2014. Impact of climate change on harvest security and biomass yield of two timothy ley harvesting systems in Norway. J. Agr. Sci. 152, 205–216.

Persson, T., Höglind, M., Gustavsson, A.-M., Halling, M., Jauhiainen, L., Niemeläinen, O., Thorvaldsson, G., Virkajärvi, P., 2014. Evaluation of the LINGRA timothy model under Nordic conditions. Field Crop. Res. 161, 87–97.

Persson, T., Kværnø, S., 2016. Impact of projected mid-21st century climate and soil extrapolation on simulated spring wheat grain yield in south-eastern Norway. Journal of Agricultural Science (Accepted).

Randby, Å., Bakken, A., Heggset, S., Steinshamn, H., 2015. Tap av tørrstoff ved grashøsting, lagring og foring (in Norwegian): Dry matter losses from harvesting, storage and feeding of grass. Buskap 3.

Ritchie, J.T., Singh, U., Godwin, D.C., Bowen, W.T., 1998. Cereal growth, development and yield, in: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers Dordrecht, pp. 79–98.

Semenov, M.A., 2010. LARS-WG stochastic weather generator. Rothamsted Research.

Statistics Norway. 2015. Population projections. Statistics Norway. Oslo.

Teixeira, E.I., Fischer, G., van Velthuizen, H., Walter, C., Ewert, F., 2013. Global hot-spots of heat stress on agricultural crops due to climate change. Agr. Forest Meteorol. 170, 206–215.

The Norwegian Environment Agency, 2014. Greenhouse Gas Emissions 1990–2012, National Inventory Report. The Norwegian Environment Agency.

Thorp, K.R., Hunsaker, D.J., French, A.N., White, J.W., Clarke, T.R., Pinter Jr, P.J., 2010. Evaluation of the CSM-CROPSIM-CERES-Wheat model as a tool for crop water management. Trans. ASABE 53, 87–102.

TINE Advisory Services, 2014. Statistikksamling 2013 (in Norwegian): Statistics 2013. Tine Rådgiving, Ås.p 69.

TINE Advisory Services, 2016. Robotrevolusjon på gårdene (in Norwegian): Milk robot revolution on farms. Tine Rådgiving, Ås

Volden, H., 2013. Avdråttsnivå i melkeprodulsjonen – fôr og arealbehov (in Norwegian): Yield level in milk production – feed and area requirement, in: Fløistad, E., Günther, M. (Eds.), Bioforsk-konferansen 2013. Bioforsk, Ås, pp. 42–44.

Xiong, W., Conway, D., Holman, I., Lin, E., 2008. Evaluation of CERES-Wheat simulation of wheat production in China. Agron. J. 100, 1720–1728.

Åby, B.A., Crosson, P., Aass, L., Harstad, O.M., 2015. Effects of increased milk yield per cow on GHG emissions from milk and beef production. Proceedings at European Association of Animal Production, Warsaw, Poland, 31 August-4 September 2015.

Supplementary material

Table 1. Climate and soil data used in HolosNor

Production category	Soil and climate data							
SEN[a]								
	Soil temperature (30 cm depth, °C)				**Water filled pore space (%)**			
	W[b]	**Sp[b]**	**S[b]**	**A[b]**	**W[b]**	**Sp[b]**	**S[b]**	**A[b]**
Baseline average yielding year	2.6	9.4	17.6	8.6	94.2	78.4	80.2	93.5
Low yielding year								
BCM2.0	4.8	11.4	19.9	10.8	79.5	83.5	65.5	78.8
HadCM3	6.3	12.6	21.3	12.3	70.0	76.7	56.0	69.3
Average yielding year								
BCM2.0	5.6	11.8	20.6	11.6	81	83.3	67.5	80.8
HadCM3	6.0	11.6	21.0	12.0	80.9	80.2	66.9	80.2
High yielding year								
BCM2.0	4.5	11.4	19.5	10.5	91.0	83.1	77.0	90.3
HadCM3	5.7	11.5	20.7	11.7	89.7	83.7	75.7	89.0
SWN[a]								
Baseline average yielding year	4.9	8.2	16.1	10.5	71.0	69.5	52.1	72.4
Low yielding year								
BCM2.0	6.9	11.5	18.1	12.5	87.1	66.2	68.2	88.5
HadCM3	8.6	11.9	19.8	14.2	59.9	61.1	41.0	61.3

Average yielding year								
BCM2.0	7.3	12.0	18.5	12.9	73	65.9	53.7	74.0
HadCM3	8.6	10.8	19.8	14.3	63.7	66.7	44.8	65.1
High yielding year								
BCM2.0	7.4	11.0	18.6	13.1	85.2	67.8	66.3	86.6
HadCM3	8.3	11.0	19.5	13.9	76.5	67.7	57.6	77.9
CN[a]								
Baseline average yielding year	2.4	8.2	15.1	7.9	81.7	71.7	68.9	83.7
Low yielding year								
BCM2.0	3.3	10.0	16.0	8.8	81.8	71.2	69.0	83.8
HadCM3	4.5	9.2	17.1	10.0	84.4	72.4	71.6	86.4
Average yielding year								
BCM2.0	4.3	10.0	17.0	9.8	84	66.1	70.7	85.5
HadCM3	5.1	10.6	17.7	10.6	74.3	66.2	61.5	76.3
High yielding year								
BCM2.0	3.9	10.1	16.6	9.4	81.7	70.6	68.9	83.7
HadCM3	5.0	10.6	17.7	10.6	74.7	70.6	61.9	76.7
NN[a]								
Baseline average yielding year	2.0	4.1	12.1	6.8	70.8	75.8	47.3	75.7
Low yielding year								

BCM2.0	3.3	6.3	13.3	8.0	69.4	73.8	45.9	74.3
HadCM3	4.4	8.0	14.4	9.1	67.8	73.1	44.3	72.7
Average yielding year								
BCM2.0	3.0	6.7	13.0	7.7	74.5	73.8	51.0	79.4
HadCM3	3.8	7.8	13.9	8.6	63.1	70.9	39.6	68.0
High yielding year								
BCM2.0	2.8	7.3	12.8	7.5	73.9	73.7	50.4	78.8
HadCM3	5.1	7.1	15.1	9.8	63.6	75.1	40.1	68.5

[a]SEN: South-east Norway; SWN: South-west Norway; CN: Central Norway; NN: Northern Norway

[b]W: Winter, Sp: Spring, S: Summer, A: Autumn