Farm specific natural resource base data for estimating greenhouse gas emissions

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Abstract

Models for an holistic analysis of a farm's greenhouse gas emissions are available, e. g. HolosNor . They require access to a farm's management data and its soil and climatic conditions. The objective of this investigation was to demonstrate how available soil and climatic data can be used to provide the required inputs of a farm's natural resource base. Soil type recordings from six municipalities representing main agroclimatic zones of Norway were used. By means of a soil moisture model a combined index of soil moisture and temperature was estimated for use in a carbon balance model, also taking crop species into account. Water filled pore space to saturation and soil temperature were estimated for calculation of emission of nitrous oxide. Input variables for calculation of greenhouse gas emissions varied considerably among municipalities and among farms therein.

Keywords: climatic data, indices, soil carbon, soil moisture and temperature, soil type records

Introduction

The total greenhouse gas (GHG) emission from a farm has to be determined by an holistic analysis at the farm level (Janzen et al. 2006). Systems analyses of Norwegian grain farms (Bonesmo et al. 2012), dairy farms (Bonesmo et al. 2013a), as well as pig farms (Bonesmo et al. 2013b) have demonstrated an application of the model HolosNor as a country wide work tool. It is an empirical model based on the Holos model (Little et al. 2008) and the methodology of the Intergovernmental Panel on Climate

Change (IPCC 2006) with modifications that recognize the distinctness of Norwegian conditions. The following GHG sources are considered: enteric CH_4 and manure-derived CH_4 and N_2O; on-farm N_2O emissions from soils; off-farm N_2O emissions from N leaching, run-off and volatilization (indirect N_2O emissions); on-farm CO_2 emissions or carbon sequestration due to soil C changes; CO_2 emissions from energy used on-farm; and off-farm CO_2 and N_2O emissions from supply of inputs.

Thus, an ability to explore possible changes in management practices for reduced GHG emissions at individual farms might be at hand. However, the value of such a tool depends not at least on its access to reliable input data. Whilst management data of a farm can be obtained from its accountancy system, provision of data on its natural resource base poses different challenges.

Soil type recordings are required for estimation of the soil moisture capacity and initial soil carbon at the farm. Furthermore, long term daily weather data representative for the farm are needed. This is considered to be an indispensible condition for use of the HolosNor model as a reliable advisory tool at individual farm levels.

The objective of this investigation has been to demonstrate how at the farm level it may be possible by access to soil and weather data to provide the required inputs on the natural resource base to the HolosNor model. Further, future users of HolosNor should be shown the range and variation in such input data to be encountered all over the country as well as within municipalities.

Materials and methods

The Norwegian Forest and Landscape Institute has detailed soil type recordings for about half of the cultivated land of the country, dominantly covering the grain production areas in the southeast and the central parts of the country (Arnoldussen 2005). We selected six municipalities located in different parts of the country, all with soil type recordings (Table 1). Records of homogenous soil type mapping units down to 0.4 ha were available; each with descriptions of top soil and subsoil layers such as: layer depth, texture (distribution of mineral particles < 2 mm), content of organic matter, gravel, and bulk density. From these records soil moisture capacities were derived by using the pedotransfer functions of Riley (1996) for: saturation to field capacity (matric potential 0 to -10 kPa), readily plant available water (matric potential -10 to -100 kPa), and less available water (matric potential -100 to -1500 kPa), for each of six soil layers: 0-15 cm and 15-65 cm divided into 10 cm layers. Top soil was defined as the two uppermost layers (25 cm). The parameters ‘U’ and ‘α’ of Ritchie’s (1972) soil moisture model were derived from soil texture according to Skjelvåg (1981). All these characteristics as well as soil organic carbon content of top soil (25 cm) at each soil type mapping unit were averaged to farm level by weighting according to area of each mapping unit at the farm.

Table 1. Characteristics of six municipalities representing climatic regions of Norway. Latitude and longitude of administrative centre Altitudes of six selected farms, two at each altitude. Number of farms with soil survey records.

Region	Municipality	N(°)	E(°)	m a.s.l.	Number of farms
Southeast, inland	Ringsaker	69.9	10.9	123, 310, 483	1084
Southeast, coast	Rygge	59.4	10.7	7, 29, 40	232
Southwest	Sola	58.9	5.7	10, 30, 50	485
Central, mountain	Oppdal	62.6	9.7	400, 590, 800	502
Central, lowland	Stjørdal	63.5	10.9	10, 125, 230	1055
North	Tromsø	69.7	18.9	3, 70, 140	266

Note: m a.s.l._metre above sea level.

The Norwegian Meteorological Institute provides gridded estimates of daily weather data for the country (Engeset et al. 2004; Mohr 2009). At present data can be supplied for grid points at 1 km distance, restricted to the areas with cultivated land within each community. Daily weather data for the period 1980-2009 were interpolated. Each grid point got estimates of: altitude, diurnal mean temperature, relative air humidity, wind speed, cloud cover, precipitation, and potential evapotranspiration (Tveito et al. 2005). In addition global radiation was calculated by a function of extraterrestrial radiation and cloud cover. This functional relationship was derived from recordings of global radiation at representative stations of the agrometeorological network of the Norwegian Institute of Agricultural and Environmental Research (http://www.bioforsk.no) and cloud cover records at a nearby weather station of the Norwegian Meteorological Institute. Weather data of individual farms were taken from the nearest grid point.

Soil moisture conditions were estimated by soil water evaporation and plant evapotranspiration separately (Ritchie 1972); and a further expansion to include a soil moisture budget (Skjelvåg 1981). The combined model calculated potential and actual evapotranspiration from plants on the basis of potential evapotranspiration, leaf area index (LAI), and the content of plant readily and less available moisture in the current root zone. Soil water filled up by precipitation to more than half the total pore volume above field capacity, was allowed to remain in this fraction above field capacity for a maximum of four days; and for two days only with filling up to half or less of the pore volume between saturation and field capacity.

The plant part of the soil moisture model was configured for ‘Avle’ spring wheat for the regions where it regularly reaches maturity, and for ‘Thule’ spring barley elsewhere and at the southwest coast. Sowing date was determined by the soil moisture model, starting when the current seven day diurnal mean temperature passed 5ºC for the first time after April 1st, assuming soil moisture of the top soil at field capacity on this day; and choosing as sowing day the first time soil moisture content passed to less than 80 per cent of field capacity (Skjelvåg 1986). Day of emergence was set to a temperature sum 100 d ºC above 0 ºC for both species. Separate functions, derived during crop modelling work (Bleken 2001), were applied for the subsequent phases to heading and physiological (yellow) ripeness.

The LAI of the grain crop was set to 0.1 at day of emergence, allowed to increase exponentially to a typical value of 4.0 at heading; the level at which it remained until twenty days before yellow ripeness, after which it was reduced linearly with time to a typical value of 2.0 of a canopy with yellow stems and leaves. From the day of yellow ripeness it was kept at 2.0 until the end of the year, assuming that stubble and straw remained in the field after harvesting. Interception of precipitation during this period was calculated according to Chang et al. (2010), in order to handle the separation of evaporation from soil and plant material. From January 1st to day of emergence LAI was kept at zero. Root depth was set to 5 cm at day of emergence, from which it was increased linearly with time to 65 cm at day of heading. After day of harvesting, assumed to occur fourteen days after day of yellow ripeness, soil moisture reduction was due only to soil evaporation from underneath the mulch of stubble and straw.

Additional steps for grassland were: (1) the initial day of grass growth in spring was set to the first day after April 1st that the 7-day mean temperature exceeded 5.0°C. When this occurred before snow thaw, calculation of seven day current mean temperature started at first day of bare soil given by the snow cover characteristics taken from the nearest weather or precipitation station ; (2) from January 1st to the initial day of growth leaf area index (LAI) was arbitrarily set to 0.1 and root depth to 10 cm; (3) after the initial day of growth LAI was calculated from estimates of harvestable herbage dry matter yield according to the FORPRO model (Torssell & Kornher 1983), adjusted for the gradual photoperiodic effect on growth cessation during autumn (Wu et al. 2004); (4) initial root depth was set to 10 cm after each harvest and increased linearly with LAI to maximum 70 cm at LAI = 7.0, except for the last harvest when current root depth was retained and increased according to LAI development until day of growth cessation; (5) the first harvest of the spring growth was taken at heading, estimated by the photothermal model of Bonesmo (1999), the second and the third harvests were taken when their estimated DM yields reached 70% of the DM yields of their preceding harvests, respectively. In cases when yield at the first cut was very low, a minimum yield of the first regrowth was set.

Farms in the mountains and the North had climatic conditions allowing for only two harvests. For Stjørdal and Sola there were used two and three harvests, respectively, and one more per season in those with very vigorous growth. All farms got estimates of small dry matter production from the last harvest to growth cessation in fall. Time of end cessation was set to the day when 7-day mean temperature passed 5ºC. Thereafter LAI remained at about 0.8.

For both cereals and grass the daily values and annual means of the combined soil moisture and temperature index $r_w \times r_t$ of ICBM (Introductory Carbon Balance Model by Andrén et al. 2004) were calculated based on the above mentioned data. However, the model has been developed from field experiment data during the period 1956-1990 at Ultuna, Sweden, and $r_w \times r_t$ was normalised to 1.0 for this data set. Thus, the same procedures and software were applied with weather and soil records from the experimental field, with exception of extreme treatments such as fallow or addition of sawdust (Kirchmann & Gerzabeck 1999). This yielded a 35 year mean of $r_w \times r_t$ at 0.066 with a range from 0.030 in 1959 to 0.105 in 1961. Given the normalisation of $r_w \times r_t$ to 1.0 for this data set, the calculated annual $r_w \times r_t$ (for convenience named r_t r_w in the following) values of each farm were adjusted by dividing them by the 35 year mean of 0.066 for further modelling work, cf. Table 2..

For the N_2O emission, calculations were based on Sozanska et al. (2002) with soil temperature at 30 cm depth according to Kätterer & Andrén (2009) and per cent soil moisture saturation of the top soil to characterise natural conditions, both based on daily time steps and averaged to seasonal means during the time period 1980-2009.

Results

Soil and climatic characteristics

Figure 1 shows a considerable variation among farms in capacity of plant available soil moisture of the 25 cm top soil layer. The municipalities Ringsaker, Oppdal and Stjørdal showed the least variation among farms, but at different levels of soil moisture capacity with the lowest capacity in Ringsaker. Rygge and Sola had more similar distribution patterns. Tromsø exhibited the widest distribution of farms on soil moisture capacity groups. For further analyses we selected six farms from each municipality, two from each of low, medium, and high altitudes. The two farms at each altitude level represented low and high soil moisture capacity.

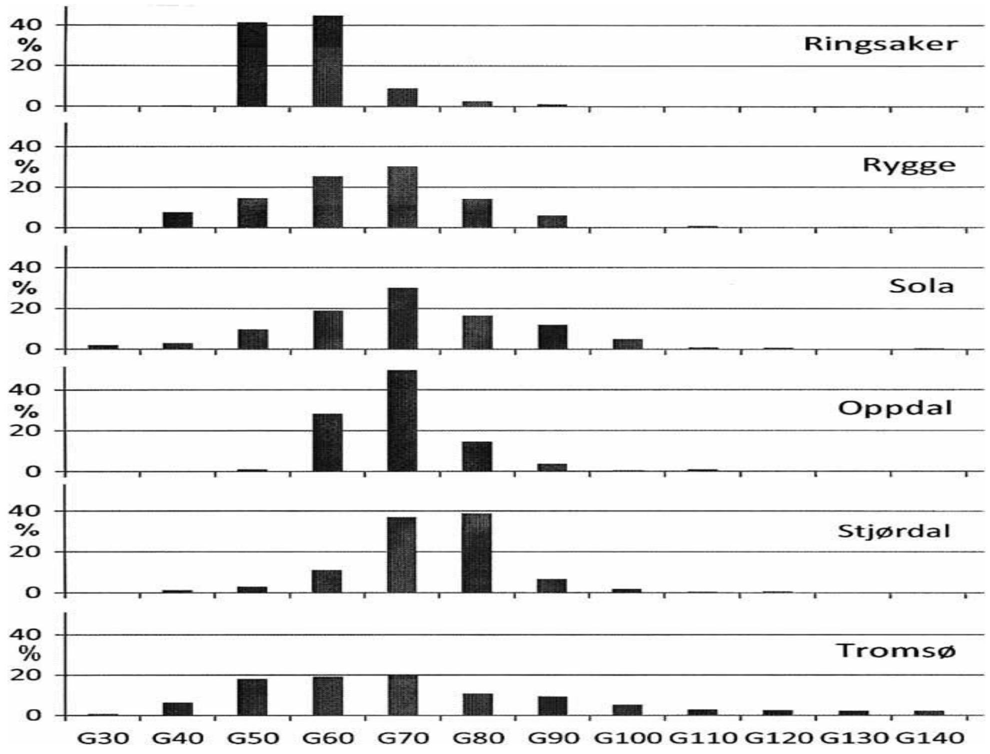

Figure 1. Relative distribution (%) of farms in six municipalities with top soil (25 cm) capacity groups of plant available soil moisture. G30 = 20-30 mm until G140 = 130-140 mm.

Table 2. Annual mean indices of soil temperature (r_t), soil moisture (r_w) and combined ($r_t r_w = r_t \cdot r_w$ on a daily basis) as defined by Andrén et al. (2004), calculated for relevant crops in six municipalities during the period 1980-2009. Thirty-year means of three pairs of farms at different altitudes (cf. Table I) and with high or low soil moisture capacity at each altitude level. Standard deviation (S) is calculated for six farms, or in bottom line for eight combinations of municipalities and crops. Adj. $r_t r_w = r_t r_w / 0.066$ for use in the ICBM model normalised to Ultuna, Sweden.

Municipality	Crop	r_t	S_{rt}	r_w	S_{rw}	$r_t r_w$	S_{rtrw}	Adj. $r_t r_w$
Ringsaker	Barley	0.097	0.0128	0.878	0.026	0.070	0.0048	1.058
Rygge	Wheat	**0.123**	0.0016	0.864	0.033	0.088	0.0085	1.334
Sola	Barley	0.121	0.0017	0.919	0.036	**0.103**	0.0072	1.563
Sola	Grass	0.069	0.0017	0.885	0.040	0.096	0.0077	1.460
Oppdal	Grass	0.096	0.0127	**0.822**	0.068	**0.043**	0.0032	0.653
Stjørdal	Barley	0.096	0.0081	**0.924**	0.031	0.080	0.0046	1.217
Stjørdal	Grass	0.096	0.0081	0.891	0.046	0.074	0.0056	1.119
Tromsø	Grass	**0.067**	0.0027	0.872	0.027	0.047	0.0035	0.706
Standard deviation		0.022		0.032		0.022		

Note: Maximum and minimum values of each index are given in bold.

The soil organic carbon content contributes to the variation in soil moisture capacity. Its variation displays a somewhat different distribution pattern among municipalities and some common traits (Fig. 2), e. g. the widest range in both characteristics is in Tromsø, a wider range in soil carbon in Stjørdal than in Oppdal and thus a displacement to higher soil moisture capacities in Stjørdal can be observed, the similar distributions of soil moisture capacity in Rygge and Sola are definitely based on different texture compositions with a higher soil carbon content in Sola. However, an equal importance of the soil carbon content is its characterisation of initial values for the carbon balance calculations of ICBM.

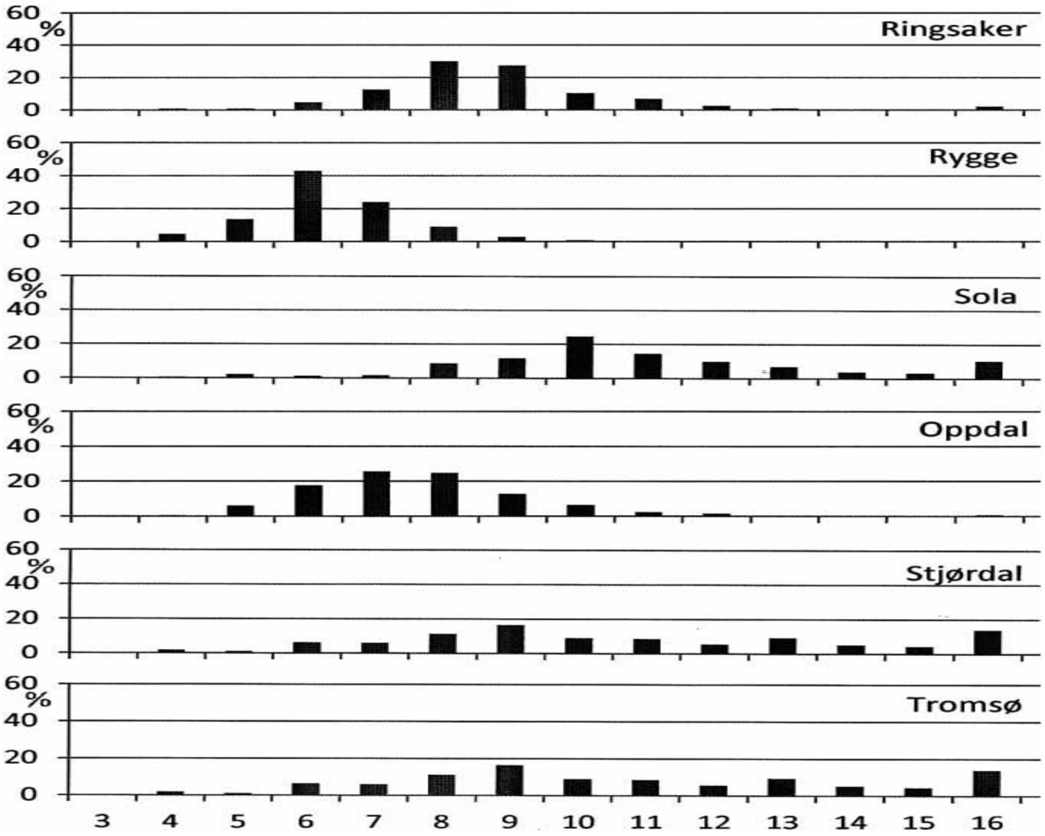

Figure 2. Relative distribution (%) of farms on groups of soil organic carbon in kg m^{-2} (given as: 4 = 3.01-4.00 kg m^{-2} a.s.f. until 16 = contents >15 kg mm^{-2}) down to 25 cm depth of top soil among farms in six municipalities.

Figure 3 shows a range in long term mean July temperature from 10.4 to 16.6 ^{o}C, at the highest located farms in the mountains (Oppdal) and at the lowest located ones in the southeast (Rygge), respectively. During the month of January the range was from -7.5 ^{o}C at farms situated high in southeast inland (Ringsaker) to 1.8 ^{o}C close to the coast in the southwest part of the country (Sola).

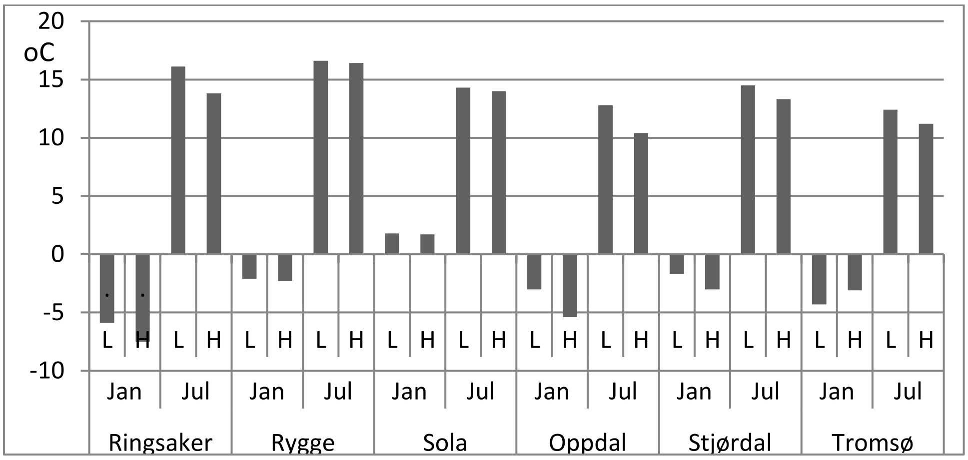

Figure 3. Gridded mean temperature for the period 1980-2009 in six municipalities during the months of January and July for farms situated at low (L) and high (H) altitudes within the municipalities.

The climatic factors determining soil moisture conditions are precipitation and potential evapotranspiration. A precipitation deficit occurred only during the growing season. This difference between recorded rainfall and potential evapotranspiration varied from deficits of 79 and 83 mm at the low sites in Ringsaker and Oppdal, respectively, to a surplus of 127 mm at the high sites in Stjørdal (Fig. 4). At the low sites, there was a deficit in all municipalities except for Sola. For the high sites there was a surplus except for Rygge, and close to a balance in Tromsø.

Indices of ICBM

The temperature index (r_t) of the ICBM model was about 1.8 times higher in Rygge situated in southeast of the country than in the northernmost location Tromsø (Table 2). The different temperature regimes of Rygge and the southwest location Sola (cf. Fig. 3) produced mean annual indices at the same level. The variation among farms within municipality expressed by the standard deviation (S_{rt}) reflected their ranges in altitudes of the farms (cf. Table 1).

The soil moisture index (r_w) varied numerically more among municipalities, from 0.822 in Oppdal to 0.924 for barley in Stjørdal, also shown by the standard deviation over municipalities (Table 2). The greatest variation (S_{rw}) among farms was found for Oppdal with its precipitation deficit at lower

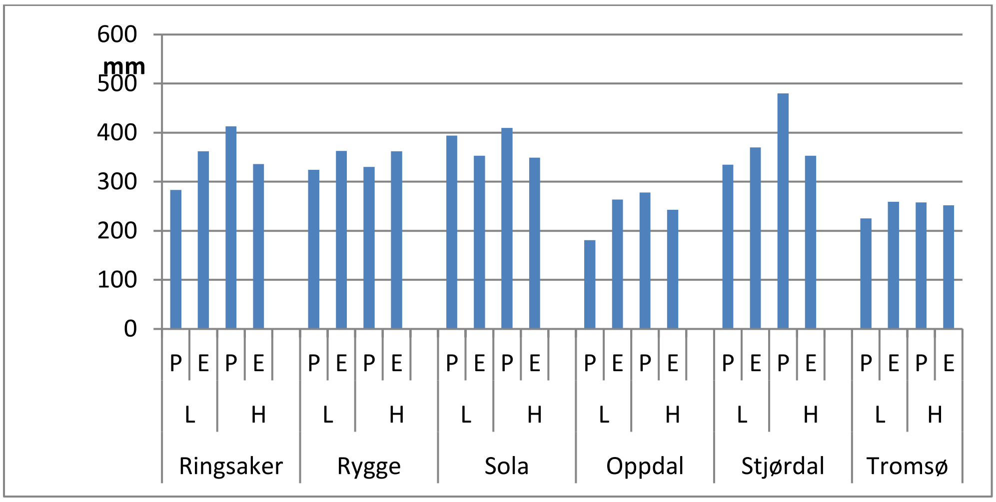

Figure 4. Sum of precipitation (P) and of potential evapotranspiration (E) during the months of May-August for Ringsaker, Rygge, Sola and Stjørdal; and during June-August for Oppdal and Tromsø for the time period 1980-2009. L and H for farms located at low and high altitudes in the municipality.

altitudes and a surplus at the higher ones (cf. Fig. 4). A similar situation is seen for Ringsaker, but there was a bigger surplus at the higher farms, and the variation among farms in r_w was much less.

The combined effect of temperature and soil moisture on soil carbon decomposition is shown by the r_t r_w index with a range in values of about 2.4 times from 0.043 for Oppdal to 0.103 for barley in Sola (Table 2). Also within municipalities there was a considerable variation in r_t r_w shown by S_{rtrw}. Calculated by coefficient of variation there was a range from 5.77 to 9.67 per cent (not shown).

Driving variables of N_2O emission

The water filled pore space (Wfps) up to saturation of the top soil was, with one exception for Tromsø during summer, for all seasons lower in Ringsaker and Rygge than in the other municipalities (Table 3). The greater standard deviation for Rygge than for Ringsaker can be ascribed to the wider range in soil moisture capacities in Rygge (cf. Fig. 1). Except for Ringsaker the standard deviations among farms within municipalities were greater than that among municipality means.

Table 3. Water filled pore space to saturation (% Wfps) in 25 cm top soil during four seasons (1=December-March), 2=April-May, 3=June-August and 4=September-November) for six municipalities with relevant crops during the period 1980-2009. Thirty-year means for three pairs of farms at different altitudes, each pair with high or low soil moisture capacity. Standard deviation (S_{wfpsx}) is calculated over six farms, or in bottom line for eight combinations of municipalities and crops.

Municipality	Crop	Wfps1	S_{wfps1}	Wfps2	S_{wfps2}	Wfps3	S_{wfps3}	Wfps4	S_{wfps4}
Ringsaker	Barley	64.7	2.81	50.7	2.84	47.8	5.18	64.5	3.07
Rygge	Wheat	**62.9**	17.96	**50.5**	16.35	**40.0**	18.55	**62.2**	18.66
Sola	Barley	71.1	13.05	55.7	17.38	49.0	17.69	72.5	12.71
Sola	Grass	71.1	13.04	52.5	17.38	44.5	16.63	71.6	12.79
Oppdal	Grass	**73.9**	5.13	56.6	5.92	44.7	11.85	64.8	9.78
Stjørdal	Barley	73.8	9.52	**61.8**	9.91	**57.1**	12.58	**73.8**	9.79
Stjørdal	Grass	73.8	9.54	58.9	11.14	52.0	13.52	72.5	10.32
Tromsø	Grass	70.8	8.14	58.2	10.20	39.6	11.39	68.7	7.87
Standard deviation		4.22		4.08		5.94		4.44	

Note: Maximum and minimum values of each Wfps are given in bold.

The Wfps under a grass crop was lower than under a grain crop during summer (Table 3, Sola and Stjørdal), a smaller difference appeared during spring and an even smaller one during autumn.

The functional relationships of soil temperature at 30 cm depth to recorded air temperature also included leaf area index (Kätterer & Andrén 2009). The greatest effect of this was a reduced soil temperature, by 0.5 and 0.3 °C in Sola and Stjørdal, respectively, under a grass than a barley crop during spring (Table 4). During autumn there was a 0.1 °C rise in soil temperature under grass. Besides this the estimated soil temperature reflected the variation in air temperature among and within municipalities.

Table 4. Soil temperature in 30 cm depth (T_s) according to Kätterer and Andrén (2009) during four seasons (1=December-March), 2=April-May, 3=June-August and 4=September-November) in six municipalities with relevant crops during the period 1980-2009. Thirty-year means for three pairs of farms at different altitudes, each pair with high or low soil moisture capacity. Standard deviation (S_{Ts_x}) is calculated over six farms.

Municipality	Crop	T_{s_1}	S_{Ts_1}	T_{s_2}	S_{Ts_1}	T_{s_1}	S_{Ts_1}	T_{s_1}	S_{Ts_1}
Ringsaker	Barley	**-0.7**	0.27	5.6	1.06	13.8	0.98	5.2	0.83
Rygge	Wheat	0.8	0.05	**7.7**	0.10	**15.4**	0.10	7.5	0.11
Sola	Barley	**2.8**	0.05	**7.7**	0.15	13.5	0.14	9.0	0.08
Sola	Grass	**2.8**	0.05	7.2	0.12	13.5	0.15	**9.1**	0.08
Oppdal	Grass	-0.4	0.46	3.8	1.05	10.8	1.05	**4.1**	1.02
Stjørdal	Barley	0.7	0.30	6.0	0.73	13.0	0.54	6.0	0.57
Stjørdal	Grass	0.7	0.30	5.7	0.67	13.0	0.56	6.1	0.58
Tromsø	Grass	-0.1	0.12	**3.2**	0.22	**10.7**	0.43	4.4	0.09

Note: Maximum and minimum values of each Ts_x are given in bold.

Discussion

A complete analysis of all the 3624 farms available (Table 1) was not possible because of lack of a suitable computer software. However, a stratified selection of municipalities and of farms therein at different altitudes and on soils with low and high moisture capacities was assumed to display the variation in the natural conditions that may be met in the country. The standard deviation in r_t among municipalities was 0.022, which, as expected, is much higher than the standard deviations within municipalities (Table 2).The soil moisture index, r_w, showed a standard deviation of 0.032 among municipalities, which is at the same order of magnitude as the values within municipalities. Difference in altitude among farms within municipalities is the main variable affecting temperature and r_t. The variation in the soil moisture index r_w among farms is a result of selected farms with high and low soil moisture capacity (Fig. 1), increasing precipitation and decreasing evapotranspiration with altitude (Fig. 4).

The daily calculation of r_t r_w takes into account the independent dynamics of both r_t and r_w before their multiplication into r_t r_w. The similarity in order of magnitude of r_t r_w and r_t and in their standard deviations indicate that r_t is the predominant determinant of r_t r_w. However, looking for some details reveals an increase in standard deviations within municipalities from r_t to r_t r_w for Rygge, Sola, and Tromsø, all with wide ranges in soil moisture capacity groups (Fig. 1). In Ringsaker, Oppdal, and Stjørdal, with narrower ranges in soil moisture capacity groups and larger ranges in altitude, S_{rtrw} was lower than S_{rt} (Table 2). This simply emphasises that r_t r_w is a product of the interaction between r_t and r_w and their dynamics throughout the year.

The grass crop in Sola and Stjørdal produced a lower r_w and r_t r_w than the barley crop (Table 2). Correspondingly the Wfps during spring, summer, and autumn was lower in the grass than in the barley crop (Table 3). A larger, transpiring LAI of grass earlier in the spring, partly during summer, and during autumn will produce such a result. As LAI is a parameter of the functional relationships of soil temperature at 30 cm depth, grass has also got a lower temperature than barley in spring (Table 4). During autumn there is a slight tendency to increased soil temperature under the grass crop. This is a result of the modelling assumption with straw mulch left on the grain field after harvesting. This mulch, corresponding to an LAI of 2.0, does not extract water from the soil; it simply reduces evaporation directly from the soil, which is reflected in a slightly higher Wfps4 of the barley crop (Table 3).The variation in Wfps shows a little different picture than the variation in r_w, the standard deviation of the latter being of similar magnitude within as among municipalities. With exception for Ringsaker the standard deviation in Wfps among municipalities as mean for all seasons (not shown) was less than those within municipalities (Table 3). The Wfps takes into account the filling up of water until saturation, whilst r_w is based on variation between field capacity and wilting point only (Andrén et al. 2004). However, the soil moisture model adjusts the r_w to a maximum value of 1.0 for soil moisture content higher than field capacity. By comparing the ranking of r_w according to magnitude with that of a mean Wfps across all seasons they corresponded well. Mostly there was a difference in ordinal number of 1 except for Oppdal changing from the lowest (8th) r_w value to the fourth highest in mean Wfps. Adjustment of r_w to a maximum of 1.0 at field capacity may explain this change.

Conclusion

There is a considerable variation in the driving variables of the carbon balance model among Norwegian municipalities and among farms within the municipalities. Among farms the variation in the soil moisture index r_w is a result of selected farms with high and low soil moisture capacity, increasing precipitation and decreasing evapotranspiration with altitude. The temperature index r_t was the more pronounced over municipalities. The driving variables of N_2O gas emission given by soil moisture saturation of top soil and soil temperature showed a corresponding variation among municipalities in different parts of the country and within municipalities. The access of soil type records and of gridded weather data opens for calculations of input variables to models that can be used as relevant characteristics of the soil and climatic conditions of individual farms in Norway; and thus, further in reliable advisory tools to mitigate the farm's greenhouse gas emissions.

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