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2015 Environ. Res. Lett. 10 095007

(http://iopscience.iop.org/1748-9326/10/9/095007)

Environmental Research Letters

OPEN ACCESS

RECEIVED
15 January 2015

REVISED
13 August 2015

ACCEPTED FOR PUBLICATION
14 August 2015

PUBLISHED
8 September 2015

LETTER

Impacts of snow season on ground-ice accumulation, soil frost and primary productivity in a grassland of sub-Arctic Norway

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Keywords: climate change, crop yield, ice, NDVI, plant mortality, snow dynamics, winter climate

Supplementary material for this article is available online

Abstract

Europe's and the World's northernmost agriculture is very vulnerable to harsh overwintering conditions. It is important from both an economic and societal standpoint to have accurate methods of predicting the severity and impact of the current snow season. Technology has advanced to enable such measurements to be regularly recorded but despite this, a detailed assessment, involving remote sensing , of the impacts of various types of snow season on agricultural yields in northernmost Europe has not previously been undertaken. Here we characterize variation in snow types and concomitant soil frost and ground-ice accumulation at a Norwegian sub-Arctic, maritime-buffered site (Tromsø, Troms County, 69 °N) during the period 1989/90 to 2013/14 and analyse how winter conditions affect agricultural productivity (both measured in the field and using remote sensing). These data were then used to build important predictive modelling approaches. In total, five contrasting types of snow season were identified, from snow-rich with no soil frost and no ground-ice to low snow and considerable soil frost and ground-ice. Conditions of low snow and low soil frost and ground-ice that result from numerous warming events were rare within the time period studied but are predicted to become the dominant snow season type. Agricultural productivity was lowest and claim settlements paid to farmers were highest after winters with high accumulation of plant-damaging, hermetic ground-ice. Deep soil frost *per se* did not affect primary productivity. Overall, our results together with information from other sources, suggest that icy, low snow conditions are the most challenging of all seasonal types for both the environment and livelihoods in sub-Arctic Norway. Winters with extremely deep snow also cause considerable problems. As winters are expected to warm more than summers, it is likely that the winter climate will become an even stronger regulator of northern primary productivity. To better understand the physical and biological effects of the changing winter climate, there is a requirement for continued and increasing monitoring of winter processes, especially related to frost and ice in the rhizosphere, as this is currently not well covered in national monitoring programs. Continued monitoring will enable further refinement of predictions and will support the better community planning for greatest agricultural benefit.

1. Introduction

Snow insulates ground vegetation and soil from ambient winter temperatures. At high latitudes and altitudes ground vegetation may spend more than half its lifetime overwintering in the subnivean environment (Sakai and Larcher 1987, Williams *et al* 2015). However, ongoing winter warming has led to a shallower snowpack shorter in duration over large areas of high northern latitudes (Liston and Hiemstra 2011), a trend which is projected to continue (Overland *et al* 2011). Increased exposure of the ground to ambient temperatures can cause the soil to become colder and freeze deeper, especially when winter warming events are followed by cold spells (Venäläinen *et al* 2001a, Campbell *et al* 2010, Brown and DeGaetano 2011). Disturbance of the snowpack may also have major impacts on the aboveground tissues of winter-hibernating plants, including perennial crops. Full or partial snow melt during warming events can prompt spring-like development which renders plants less winter-hardened (Sakai and Larcher 1987, Ögren 1996, Jørgensen *et al* 2010), and so any return to normal freezing winter temperatures can kill or damage plants over large areas (Bokhorst *et al* 2009, 2010, 2012a, Bjerke *et al* 2014). If ground vegetation remains without snow cover by late winter, health of the vegetation may be further reduced through desiccation, as the leaves start to transpire upon solar warming, while the roots are still frozen and unable to transport water (Sakai and Larcher 1987, Bjerke *et al* 2014). This is a type of injury that also frequently occurs in evergreen trees and shrubs during winters with deep soil frost (Hagemann 1904, Kullman 1989, 1997, 2014). Winter warming events, especially when associated with rain falling on snow (Putkonen and Roe 2003), can also lead to extensive build-up of ground-ice, which is detrimental to the plants that become encapsulated in ice, both in agro-ecosystems (Andrews 1996, Gudleifsson 2009, Höglind *et al* 2010) and natural ecosystems (Bjerke 2011, Preece *et al* 2012). Ground-ice is one of the major threats to northern agriculture, potentially causing severe economic losses for farmers (Andrews 1996, Bjerke *et al* 2014).

While knowledge of the impact of reduced snowpack thickness on aboveground processes has increased substantially in recent years, the belowground physical and biological processes are much less understood (Henry 2008, Makoto *et al* 2014). Increased soil freezing can affect nutrient leaching, root injury, alongside biodiversity and abundance of soil microarthropods (Henry 2008, Bokhorst *et al* 2012b). More freeze-thaw cycles due to the absence of a buffering snowpack (Sharratt 1993, Bokhorst *et al* 2012b) can have major consequences on carbon and nutrient budgets, root vitality and soil microbiota (Henry 2008, Bokhorst *et al* 2012b, Pauli *et al* 2013, Makoto *et al* 2014).

High northern latitudes are predicted to experience the greatest winter warming (Overland *et al* 2011) and therefore the most pronounced changes in snow cover (Callaghan *et al* 2011). While an estimated 75% of the Pan-Arctic region had a reduction in the duration of snow-cover from 1979 to 2009, 25% of the region, with areas scattered throughout Eurasia and North America, had an estimated increase in the duration of snow-cover duration (Liston and Hiemstra 2011). Analyses of historical soil freezing dynamics indicate that there is large interannual and spatial variation in soil-freeze cycles, soil freezing days and frost depth. Maximum annual frost depth at a forest site in north-eastern United States did not show any long-term trend from 1956 to 2008 (Campbell *et al* 2010), whereas data from 31 sites in Canada, ranging from the temperate to the Arctic zone, show that annual soil freezing days declined with increasing mean winter air temperature, despite reductions in snow depth and snow cover (Henry 2008). A dataset from Germany covering the years from 1950 to 2000 shows similar trends, namely increases in minimum soil temperature and a uniform decline in the number of freeze-thaw cycles despite decreasing snow depth (Kreyling and Henry 2011). In the Qinghai-Tibet Plateau, winter warming has led to a reduction in the number of soil freezing days, especially within the area where soil frost was deepest (Zhao *et al* 2004). These studies from various parts of the Northern Hemisphere experiencing seasonally frozen ground emphasize the importance of regional studies for rendering a more complete understanding of historical trends and interannual variation as well as a tool to develop models for future trends. However, to date, none of these studies have included high northern maritime-buffered stations.

In this study, we examined climate, snow and soil frost data from a strongly maritime-buffered, sub-Arctic agricultural site in North Norway (figure S.1) in order to understand the temporal variation in these parameters and to fully characterize snow season types. The chosen site is the northernmost agricultural region of the World; grassland forage production is undertaken northwards to the low-Arctic region to 71 °N, only 30 km away from the North Cape, while potatoes and other vegetables are grown commercially to ca. 70 °N (Bartholsen 1979, Finnmark County Authority 2015). The non-growing seasonal conditions within this region can vary considerably yet a detailed analysis of the various snow season types have, to the best of our knowledge, not been previously undertaken. Snow cover is projected to increase in certain northern regions where warmer winter temperatures will be associated with increasing precipitation rates (Brown and Mote 2009, Callaghan *et al* 2011). Situated at high northern latitudes (66 to 70 °N), sub-Arctic Norway is within the area predicted to have strong climate warming, especially in winter (Overland *et al* 2011) with winter temperatures projected to increase by 10–12 °C until 2100 (Førland *et al* 2010, Overland *et al* 2011). However, in the recent past the winter climate has been variable. Upland areas have experienced prolonged annual snow-cover with lowland areas experiencing the opposite trend (Liston and Hiemstra 2011). Two extremely snow-rich winters with near-normal temperatures (1996/97 and 1999/2000, figure 1) prompted residents to worry whether this was the start of a new climate trend (Ryvold and Røe 1997, various news articles in local media). Mean winter temperatures have varied considerably during the last 50 years, both at upland and lowland stations (Førland *et al* 2010). Projected climate change will result in average winter temperatures above freezing in areas where average winter temperatures are currently below freezing (Førland *et al* 2010). Certainly, this will

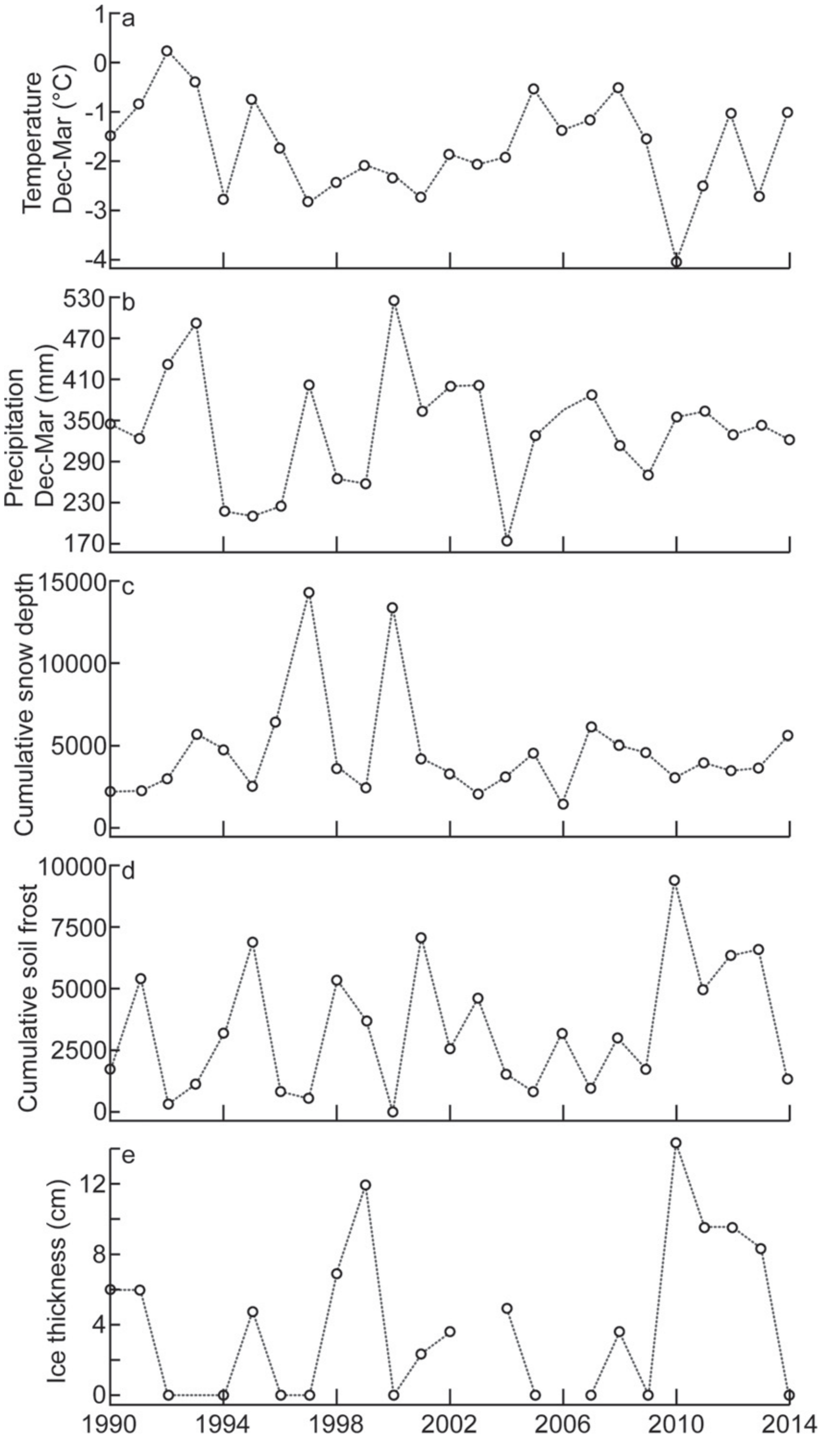

Figure 1. Climatological snow season data from Holt, Tromsø. '1990' means the snow season 1989/90. (a) Average December–March temperature; (b) December–March precipitation; (c) cumulative snow depth (cm-d); (d) cumulative soil frost (cm-d); (e) ice thickness at the end of snow season (data lacking for two years). Cumulative snow depth and cumulative soil frost are inversely correlated ($r = -0.499, P = 0.011$).

have strong implications for snow depth, soil frost trends and plants, microbes and animals living in both the subnivean environment and in the soil (Crawford 2000, Bokhorst *et al* 2012b, Pauli *et al* 2013, Williams *et al* 2015).

At these high northern latitudes, the growing season is short, often lasting no longer than 100 days (Karlsen *et al* 2009). The much longer non-growing season may therefore have potentially large impact on the survival and productivity of perennial crops (Uleberg *et al* 2014). Despite this, a detailed evaluation, including application of remote sensing techniques, of the impact of various snow season types on agricultural yields in this region has not been previously undertaken. Thus, a further objective of this study was to use historical data to elucidate the impacts of

Table 1. Parameters used for statistical trend analyses, ordination analyses and linear regression modelling of the Tromsø (Holt) dataset. (a) Aboveground winter climate (ambient temperature, precipitation, and snow cover), (b) Belowground winter climate (soil frost parameters), and (c). Weather and biological variables in following summer.

(a) Aboveground winter climate

Parameter	Unit	Time interval	Min. value	Median	Max. value
First day of snow in autumn (start of snow cover; October 1 = day 1)	d	1989–2013	1	36	79
Last day of snow in spring	d	1990–2014	193	205	240
Maximum snow depth	cm	89/90–13/14	27	58	140
Number of periods during winter without snow after first snowfall in autumn	no.	89/90–13/14	0	2	6
Snow period duration	d	89/90–13/14	133	174	226
Snow depth at time of maximum soil frost	cm	89/90-13/14	5	30	58[c]
Snow depth at time of maximal soil freeze accumulation (cm week^{-1})	cm	89/90–13/14	0	5	45[c]
Cumulative snow depth (sum of daily values)	cm-d	89/90–13/14	1626	3844	14 316
Average temperature[a]	°C	89/90–13/14	−4.0	−1.7	0.2
Days with mean temperature above threshold temperature[a,b]	d	89/90–13/14	18	44	62
Precipitation sum[a]	mm	89/90–13/14	177	344	523
Precipitation on days with mean temperature above threshold temperature[a,b]	mm	89/90–13/14	71	198	291
Proportion of precipitation on days with mean temperature above threshold temperature[a,b]	%	89/90–13/14	31	59	74
Mean temperature of 7-d period around day with maximal soil freeze	°C	89/90–13/14	−10.0	−2.5	1.2
Snow-free days with freezing temperatures [a]	d	89/90–13/14	0	4	34
Temperature sum of snow-free days with freezing temperatures[a]	°C	89/90–13/14	−134	−7	0
Snow-free days with mean temperature above 0.0 °C	d	89/90–13/14	0	5	31
Temperature sum of snow-free days with mean temperature above 0.0 °C	°C	89/90–13/14	0	10	78
Ground-ice thickness in late winter	cm	1990–2014	0	3	12

(b) Belowground winter climate

Parameter	Unit	Time interval	Min. value	Median	Max. value
First day of recorded soil frost in autumn	d	1989–2013	8	47	—[c]
First day of soil frost at 10 cm depth	d	1989–2013	40	95	—[c]
Soil frost duration at 0 cm depth	d	89/90–13/14	0	156	185
Soil frost duration at 10 cm depth	d	89/90–13/14	0	115	175
Maximum soil frost depth	cm	89/90–13/14	0	−26	−100[d]
Cumulative soil frost (sum of daily values)	cm-d	89/90–13/14	0	2983	9300
Day for maximum soil frost depth	d	89/90–13/14	—[c]	149	200
Last day of soil frost in spring	d	1990–2014	—[c]	211	249
Last day of soil frost in spring at 10 cm depth	d	1990–2014	—[c]	200	229
Depth of last soil frost in spring (point where thaw from above and below meets)	cm	1990–2014	—[c]	−21	−56
Length of longest period with continuous soil frost accumulation	d	89/90–13/14	0	11	71
Total number of days with soil frost accumulation	d	89/90–13/14	0	21	78
Days with soil thaw between periods of increasing soil frost	d	89/90–13/14	0	19	66

(c) Weather and biological variables in following summer

Parameter	Unit	Time interval	Min. value	Median	Max. value
Mean temperature for growing season months May–July (separately and overall mean)[e]	°C	1990–2014	9.4	10.9	12.4
Precipitation sum for growing season months (separately and overall mean)[e]	mm	1990–2014	15	61	113
Mean temperature for early growing season (15 May–14 June)	°C	1990–2014	5.0	7.7	11.5
Hay yield Troms County	kg m^{-2}	2000–2013	0.277	0.351	0.401
Potato yield Troms County	Kg m^{-2}	2000–2013	0.626	1.722	1.969
Early-season vegetation greenness (GIMMS $NDVI_{3g}$ for 1-15 June)		1990–2013	0.317	0.565	0.783
Maximum vegetation greenness (GIMMS $NDVI_{3g}$ max)		1990–2013	0.642	0.859	0.902
Time-integrated vegetation greenness (GIMMS TI-NDVI for 1 June-15 July)		1990–2013	0.532	0.695	0.830
Early-season vegetation greenness (MODIS NDVI for 1–8 June)		2000–2013	0.103	0.619	0.745
Maximum vegetation greenness (MODIS NDVI max)		2000–2013	0.722	0.787	0.829

Table 1. (Continued.)

(a) Aboveground winter climate					
Parameter	Unit	Time interval	Min. value	Median	Max. value
Claim settlements for winter-damaged grasslands	KNOK	1993–2012	6	317	11 451
Claim settlements for crop failure	KNOK	1995–2012	0	745	56 715

[a] Two periods considered: full winter, including shoulder seasons, i.e. October–April, and midwinter, i.e. December–March. Minimum, median and maximum values shown are December–March values.

[b] Two threshold temperatures used: 0.0 °C and 3.0 °C. Minimum, median and maximum values shown are for >0.0 °C.

[c] During one snow season (1999/2000), soil was completely frost-free, and three additional winters had shallow frost that did not reach to 10 cm depth.

[d] Estimated maximum value, as soil tube only measures to 75 cm depth.

[e] For each of the months, and mean temperature for the entire period.

variable snow season conditions on soil freeze dynamics and damage to sub-Arctic agricultural fields.

The specific objectives are. (1) Classify winters at the studied sub-Arctic site into snow season types. (2) Test for temporal trends in winter temperatures, snow and soil frost conditions. (3) Analyse the impacts of contrasting snow season types on grassland and potato yields and remote-sensed vegetation greenness (NDVI) in Troms County. (4) Briefly review the wider environmental and societal impacts of problematic snow season types. (5) Predict which snow season types will dominate in the next decades and assess their potential impacts on agriculture and the wider society.

2. Materials and methods

2.1. Study site

There are only a few sites in North Norway (i.e. Norway north of 65 °N) that have a long series of soil frost measurements. Only one station, the Holt Station, has uninterrupted soil frost and meteorological data for more than 20 years. We use station data from 1989/90 to 2013/14. Holt is located in the city of Tromsø (Troms County, 69.7 °N, 18.9 °E) and was initially established in an agricultural grassland with sandy loam. The station is characterized by a maritime-buffered, middle boreal climate with mean monthly temperatures ranging from −3.5 °C (January, February) to 12.0 °C (July) (Hanssen-Bauer and Nordli 1998, Moen 1999). The mean annual precipitation rate is 1000 mm, with the highest rates from September to December (100–130 mm per month) and lowest rates in May and June (45–55 mm per month). Other time series available from North Norway are either shorter, do not cover the most recent years, have some missing winters, or have less than one data entry per week. We briefly present these data series in the supplementary information.

2.2. Field measurements

Soil frost depth was measured using a soil frost tube containing a solution of methylene blue dye. When frozen, the solution becomes colourless (Rickard and Brown 1972). Although soil frost tubes provide less information than soil temperature sensors at various depths, they provide valuable data on year-to-year variation in soil freezing depths and the length of the soil frost season (DeGaetano *et al* 2001, Thorsen *et al* 2010). The snow depth was measured at a single point with a graduated rod. Both snow and soil frost depths were measured manually once per week, but occasionally with longer intervals between observations. The thickness of hard-packed snow layers, for which a knife blade is required for cutting, and termed ground-ice were measured as soon as this layer became exposed in late winter (Colbeck *et al* 1990, Johansson *et al* 2011). Information on ground-ice was lacking for two of the winters and for the winters from 2010 to 2014, ice thickness was not measured by the technicians checking the soil frost tube, but during inspections of the same grassland where the soil tube is installed.

2.3. Agricultural yield and productivity

Time series data on the yields of hay and potato, the two most important agricultural products of sub-Arctic Norway (Kvalvik *et al* 2011), are publicly available at county level from 2003 onwards (Statistics Norway 2014). Time series on claim settlements to farmers were retrieved from publicly available statistics from 1994 onwards (The Norwegian Agricultural Authority 2014). We compared these data from Troms County with site data from Tromsø.

In order to have both the best time and spatial resolution for our study, time series data from the commonly used satellite-based normalized difference vegetation index, NDVI, were retrieved from the AVHRR GIMMS $NDVI_{3g}$ (Xu *et al* 2013, Pinzon and Tucker 2014) and the Terra MODIS NDVI data based on the MOD09Q1 250 m eight days reflectance data product (Bjerke *et al* 2014). The $GIMMS_{3g}$ dataset starts in 1981, while the MODIS dataset starts in 2000. We selected pixels covering the grasslands where the soil frost tube at Holt is installed.

2.4. Environmental parameters and statistical analyses

Several parameters of interest were calculated from the time series data. These are in three categories (table 1): (a) aboveground winter climate (ambient temperature, precipitation, and snow depth), (b) belowground winter climate (13 soil frost parameters, e.g. maximum soil frost depth, and last day of soil frost in spring), and (c) weather and biological variables in following summer (growing season temperature and precipitation, agricultural yields, remotely sensed NDVI, and claim settlements). The parameters are shown in italics in the text.

We defined 1 October as the start of the snow season. It coincides well with the first accumulation of snow at our Tromsø site and is the date used internationally as the start of a water year. Hence, Day 1 refers to 1 October, meaning that 1 January is Day 93 and 1 April is Day 183 in non-leap years and 184 in leap years. One winter (i.e. snow season) had no soil frost and because of this, parameters related to soil frost were omitted from some of the ordination analyses (see below).

Two temperature thresholds for ambient temperature were applied. These are 0 and 3 °C. The first was selected as it represents freeze and thaw of snow and soil. The second threshold was selected to represent warm spells with longer-lasting impacts on snowpack and soil frost parameters.

Cumulative metrics for snow and soil frost depths have the unit cm-d referring to the annual sum of daily values (Campbell *et al* 2010). For soil frost depth, we used linear interpolation between two measurements to obtain daily values. Since snow depth may fluctuate much more than soil frost depth within a week, we used temperature, precipitation and snow depth observations from the nearby station run by the Norwegian Meteorological Institute for interpolating between each Holt observation. The distance between these two weather stations is 1.1 km. Changes in daily temperatures and precipitation rates from the two stations were compared, and were strongly linked (Daily average temperature: $r = 0.996$; daily precipitation rates: $r = 0.926$). Hence, relative daily changes in snow depth at the Meteorological Institute station were applied to the Holt snow series and adjusted so that the interpolated value became identical to observed value at the end of each 7-d interpolation series.

Days were defined as snow-free when snow depth was 5 cm or lower. We used this value instead of 0 cm, since a 5 cm snow depth generally represents a mosaic of snow-covered and totally snow-free patches and renders little, if any, insulation to the ground vegetation and soil (Sharratt *et al* 1992, Sharratt 1993). Thus, from a plant-ecological point of view, a 5 cm snow depth has the same impact as a completely snow-free surface.

We used the Principal Component Analysis (PCA) ordination technique (ter Braak and Šmilauer 2002) to explore the variation in snow season types and analyses were undertaken in Canoco for Windows version 4.5 (Microcomputer Power, Ithaca, NY, USA). Snow seasons were first ordinated using aboveground parameters, thereafter belowground parameters were used as predictor variables. Finally, an ordination was made combining aboveground and soil frost parameters.

Past climate trends and correlations in various soil frost parameters were evaluated with standard Pearson's correlation coefficients. The effects of climate and soil frost on various response variables were tested using multiple linear regression analyses. For example, maximum soil frost was tested against aboveground winter climate (table 1(a)), whereas hay yield was tested against aboveground, belowground (table 1(b)) and growing season climate parameters (table 1(c)). These tests were done using SPSS Statistics version 22 (IBM Co.). Data reduction was performed prior to the application of model selection procedures to remove redundant, highly correlated ($|r| > 0.75$) variables. The forward stepwise model selection was used. Outliers were trimmed automatically by the software and Akaike Information Criterion values were used to rank candidate models (Burnham and Anderson 2002). Confidence level for models was set to 95%.

3. Results

The data series from Tromsø displayed large interannual variation in mean winter temperature, precipitation and cumulative snow and soil frost depths (figure 1), and none of these showed significant temporal trends for the period 1989–2014.

The snow seasons were grouped differently depending on the types of parameters used for ordination (figures 2(a) and 3(a)). Belowground snow season types were largely dependent on *soil frost accumulation* and *duration*, which explains much of the dispersion along the x-axis (figures 2(b) and (c)). However, *the number of winter thaw days* explains the variation along the y-axis (figure 2(d)). The snow season 1999/2000 has an isolated position (figure 2(a)) since this was the only snow season without any *soil frost*. The *start of snow cover* and *cumulative snow depth* explained much of the aboveground climate variation along the vertical and horizontal axes, respectively (figures 3(b) and (c)). The snow season 1994/95 has an isolated position in the ordination (figure 3(a)) due to very early *start of snow cover* (figure 3(b)).

The combination of aboveground and belowground parameters rendered an ordination similar to that for belowground parameters alone, meaning that *soil frost accumulation* and *duration* determine much of the snow season classification (figure 3(d), compare with figure 2(a)). However, snow variables also played a role in this grouping. For example, the winter of

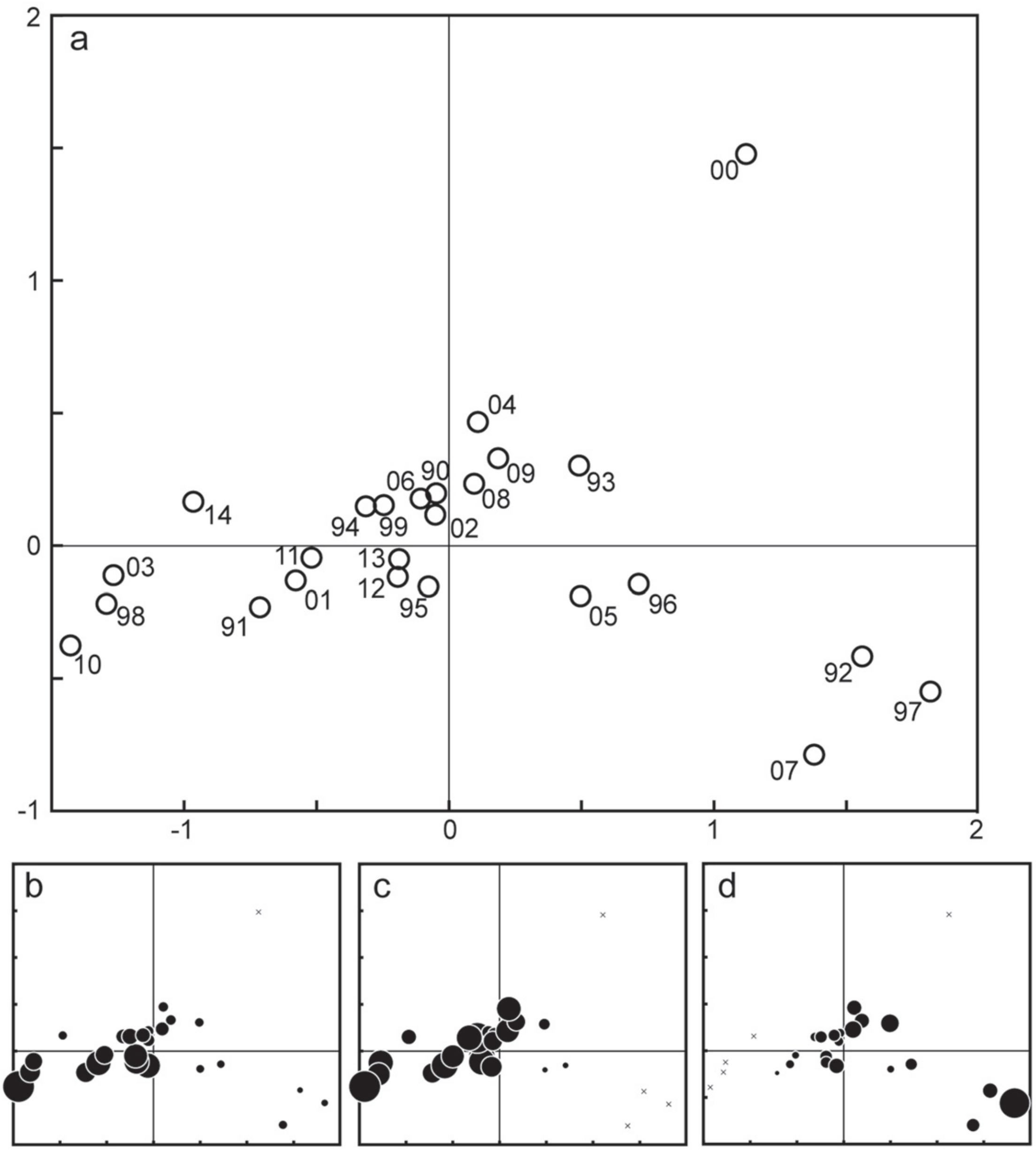

Figure 2. PCA ordination of winters based on the seven soil frost parameters that are available for all winters, including the frost-free winter of 1999/2000. (a) Main ordination with each winter from 1989/90 to 2013/14 marked with open circles. Each winter is coded by the two last digits of the year in which the winter seizes. Example: '90' = the winter of 1989/90. The two first axes explain 92.6% of the variation (eigenvalues: Axis 1 = 70.4%; Axis 2 = 17.1%). (b) Attribute plot of cumulative soil frost. (c) Attribute plot of duration of soil frost at 10 cm depth. (d) Attribute plot of winter thaw days, i.e. thaw taking place between freezing events. The sizes of the points reflect value. Crosses represent zero values.

1994/95 has a more isolated position as it has in the ordination based on aboveground variables (figure 3(a)). Overall, the combined ordination (figure 3(d)) shows a division into five main types of snow seasons: (1) early *start of snow cover*, high *cumulative snow depth* and no *soil frost* (upper right). (2) Later *start of snow cover* and moderate to large *cumulative snow depth* with little *soil frost* (lower right). (3) Early *start of snow cover* but overall modest *cumulative snow depth* due to many *winter thaw days* (lower left). (4) Little *cumulative snow depth*, high *cumulative soil frost*, and *accumulation of ground-ice* (upper left). (5) Snow seasons varying within these ranges thereby being close to normal (centre). Examples of these five types of snow seasons are shown in figure 4 with a focus on soil frost and snow variables.

Cumulative *soil frost* and *maximum soil frost* were strongly correlated ($r = 0.98$). Using aboveground parameters as predictors, these two response variables were explained with high significance and accuracy by almost identical linear models (table 2). The best model consisted of six predictor variables, of which the most important was the *number of snow-free days with freezing temperatures*. This variable alone showed a very strong linear relationship with *soil frost* (*cumulative*: $r = 0.77$, *maximum*: $r = 0.82$). The variable of

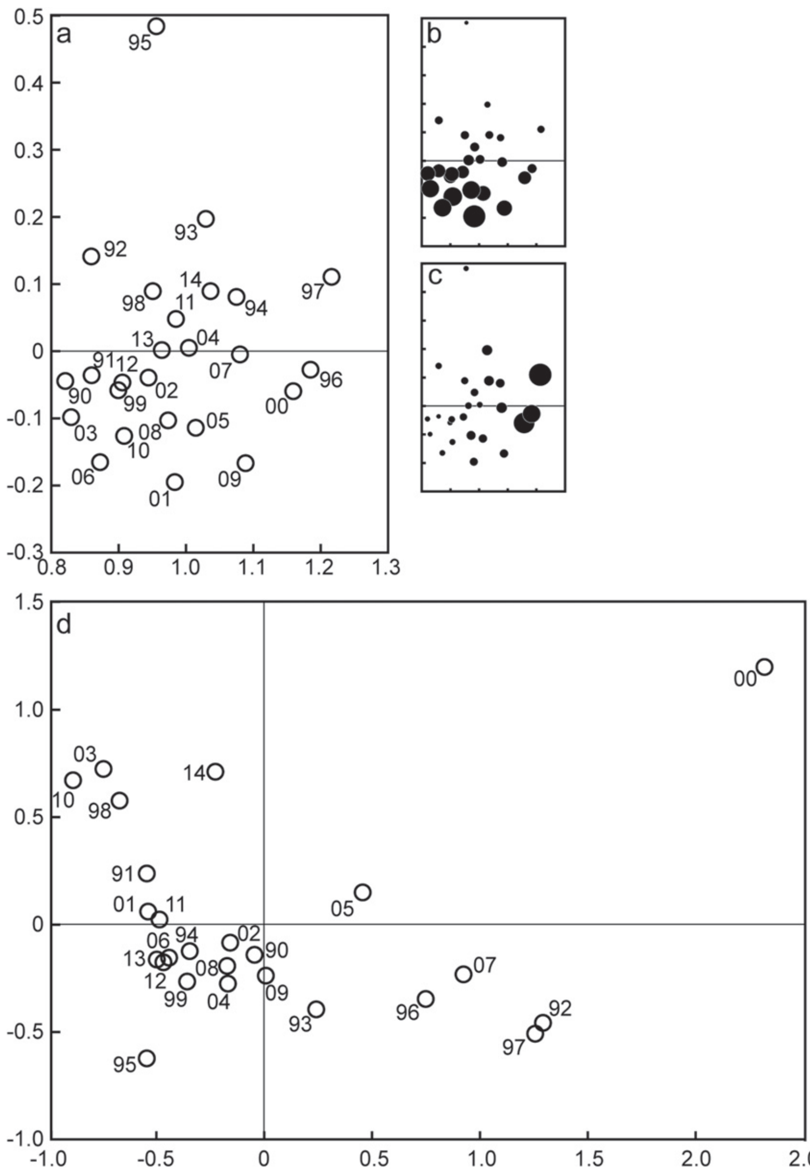

Figure 3. PCA ordination of winters based on above- and belowground physical parameters. (a) Main ordination with aboveground parameters only, i.e. snow and weather parameters. The two first axes explain 99.9% of the variation (eigenvalues: Axis 1 = 97.9%; Axis 2 = 1.9%). Five parameters were included: *first day of snow in autumn*, *last day of snow in spring*, *number of periods without snow*, *snow period duration*, and *cumulative snow depth*. (b) Attribute plot of start of snow season. Small points mean early start of snow season, the earliest start is 1 October (first day of snow season). (c) Attribute plot of cumulative snow cover. (d) Main ordination with both aboveground and soil frost parameters, 11 parameters in total. The two first axes explain 76.6% of the variation (eigenvalues: Axis 1 = 57.1%; Axis 2 = 19.5%; Axis 3 = 10.6%; Axis 4 = 5.6%—axes 3 and 4 not shown).

the *number of days with mean temperature above* 3.0 °*C from October to April* was the second most important, showing a negative, albeit weak, relationship with *soil frost* (*cumulative*: $r = -0.26$, *maximum*: $r = -0.19$), meaning that winters with many such days tended to have less soil frost than winters with fewer of these days. Four other variables have a relative importance between 4% and 9% (table 2).

Only two of the examined soil frost and snow parameters showed significant linear temporal trends (figure 6). Specifically, *duration of longest period with soil frost accumulation* (figure 5(a), $r = 0.558$, $P = 0.004$) and the *total number of days with soil frost accumulation* (figure 5(b), $r = 0.611$, $P = 0.003$) both increased in time.

The best linear model for *early-season vegetation greenness* (GIMMS $NDVI_{3g}$) had an accuracy of 70% and consisted of four predictor variables (table 2). The most important was the *last day of snow cover*, which had a strong negative relationship with vegetation greenness ($r = -0.673$, $P < 0.001$; figure 6(b)). The second most important predictor variable included in the model was *precipitation sum for days with mean temperature above* 3 °C *from December to March*, while *mean temperature from mid-May to mid-June* and *precipitation rates in May* were the last two predictors. No model could be established to explain the variation in peak GIMMS $NDVI_{3g}$. Time-integrated NDVI was best explained by *mean temperatures in May and June* and *precipitation sum for days with mean temperature*

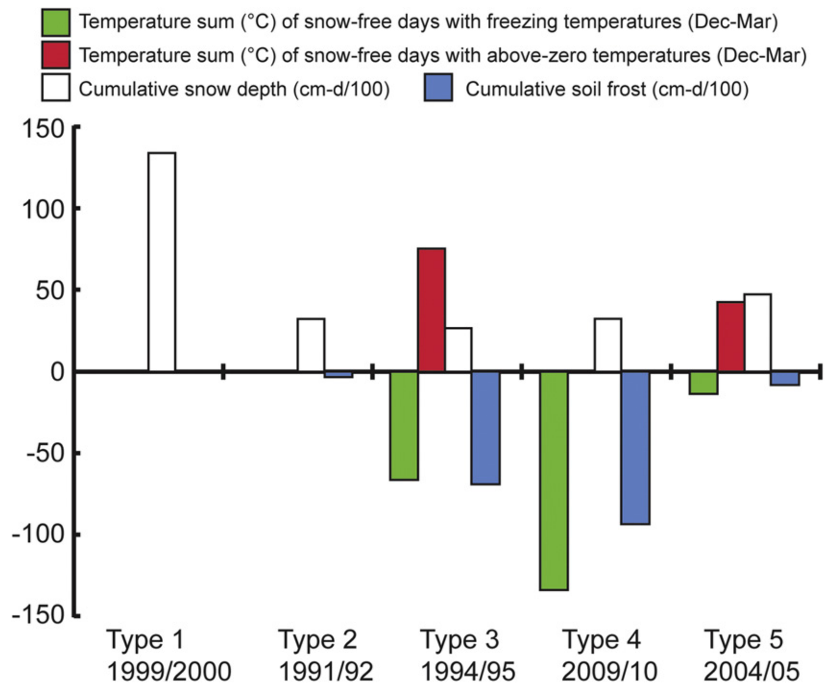

Figure 4. Above- and belowground characteristics of five contrasting snow seasons corresponding to the five types described in the text and based on figure 3(d). Unit on vertical axis depends on parameter, see legend for parameters.

above 3 °C *from December to March* (table 2). The MODIS NDVI started in 2000, and linear model analyses were therefore not undertaken for these datasets. Simple linear correlations show that early-season MODIS NDVI was also strongly related to the last day of snow cover ($r = -0.725, P = 0.005$).

The best model explaining the variation in *ground-ice thickness* had an accuracy of 64% and consisted of two weather variables. As for soil frost, the *number of snow-free days with freezing temperatures* was the most important predictor (table 2). The relationship was positive ($r = 0.529$, $P = 0.001$), meaning that the ground-ice grew thicker on days with these conditions. *Maximum snow depth* was also important, and was negatively correlated with *ground-ice thickness* ($r = -0.418, P = 0.047$).

Hay yields varied much among years (table 1(c)). The model best explaining the variation in hay yields consisted of three predictor variables with by far most important being *ground-ice thickness* (table 2). The relationship was negative ($r = -0.675$, $P = 0.016$), meaning that grassland productivity was low after winters with considerable ground-ice accumulation (figure 6(a)). The predictor *temperature sum for snow-free days with freezing temperatures* explained the variation in *potato yields* (table 2, $r = 0.599$, $P = 0.02$). Accuracy was low (36%), suggesting that additional drivers not included in the analysis were also important for potato yields. An important observation for these two types of agricultural yields is that none of the variables for *growing season temperature* was included in the selected models.

Claim settlements paid to farmers for grasslands damaged during winter varied much between years (figure S.2(a)). The best model for the settlement has an accuracy of 69%. The *number of snow-free days with freezing temperatures* during winter was the most important predictor (table 2), showing a positive relationship with claim settlement sums ($r = 0.611$, $P = 0.004$, figure S.2(b)). Compensation from the more general *claim settlement system for crop failure* showed a strong correlation with the more specific winter damage claim settlement ($r = 0.848$, $P < 0.001$, figure S.2(a)). By far the most important predictor for crop failure was frost sum (*temperature sum of snow-free days with daily mean temperature below* 0 °C; $r = -0.818$, $P < 0.001$), meaning high compensation sums after winters with many *snow-free days with freezing temperatures* (figure S.2(c)). *Mean June–July temperature* was also included in the model with a relative importance of 22% ($r = -0.473$).

4. Discussion

This sub-Arctic maritime-buffered site had a 9-fold year-on-year variation in *cumulative snow depth*, and this strongly affected soil frost and ground-ice accumulation, as observed previously in studies from more continental and/or High-Arctic regions (Venäläinen *et al* 2001b, Campbell *et al* 2010, Brown and DeGaetano 2011, Hansen *et al* 2014). By combining above-ground and belowground parameters, we discerned five snow season types, ranging from considerable snow and no soil frost to little snow and considerable

Table 2. Best linear models for soil frost, ground-ice and primary productivity variables. The second column shows the variation explained (accuracy) of the best model in the range from 0 (worst) to 100 (best). All presented models and predictors are significant at *P*-level of 0.05. Predictors in the best models with $P > 0.05$ are excluded from the table. First cell value shows the predictor's relative importance (in percentage). Arrows show direction of coefficient ($\uparrow$ = positive, $\downarrow$ = negative). Last value (in italics) shows significance.

Predictor (right) and response (below) variables	Accuracy	Freeze on snow-free days (Dec–Mar)[a]	# days with mean temperature above 3 °C (Oct–Apr)	Precipitation on thaw days[b]	Mean Dec–Mar temperature	First day of snow	Snow depth[c]	Ground-ice thickness	Last day of snow	Early season temperature[d]	May precipitation	Snow-free periods after first snow	Mean June–July temperature
Cumulative soil frost	89%	45 ↑ < *.001*	29 ↓ < *.001*	8 ↑ *.003*	4 ↓ *.027*	9 ↑ *.002*	5 ↓ *.012*						
Maximum soil frost	92%	65 ↑ < *.001*	16 ↓ < *.001*	6 ↑ *.003*	5 ↓ *.005*	5 ↑ *.006*	4 ↓ *.015*						
Ground-ice thickness	61%	48 ↑ *.001*					32 ↓ *.005*						
Hay yield	71%	26 ↑ *.005*				18 ↓ *.013*		56 ↓ < *.001*					
Potato yield	36%	100 ↑ *.013*											
Early-season GIMMS NDVI	70%			26 ↑ *.009*					34 ↓ *.003*	22 ↑ *.016*	19 ↓ *.022*		
GIMMS TI-NDVI	61%			28 ↑ .004						50 ↑ < *.001* 22 ↑ *.009*			
Claim settlements for winter damage	69%	33 ↑ *.010*	18 ↓ *.049*								30 ↓ *.013*	19 ↑ *.044*	
Claim settlements for crop failure	82%	78 ↓ < *.001*											22 ↓ *.001*

[a] The predictor is number of snow-free days with freezing temperatures for soil frost, ground-ice and hay yield, and temperature sum of the snow-free days with freezing temperatures for potato yield and claim settlements for crop failure. Note that temperature sum is negative, meaning high claim settlements after winters with much frost, and high potato yields after winters with little frost.

[b] For soil frost variables and GIMMS peak-season NDVI, the predictor is proportion of precipitation on days with mean temperature above 0 °C from October to April, while for GIMMS $NDVI_{3g}$, this is the precipitation sum for days with mean temperature above 3 °C from December to March.

[c] For soil frost and ground-ice variables, the predictor is maximum snow depth, while for GIMMS $NDVI_{3g}$, this is cumulative snow depth.

[d] For GIMMS early-season NDVI, the predictor is mean temperature for the period 15 May–14 June, while for TI-NDVI this is mean June (first line) and May (second line) temperatures.

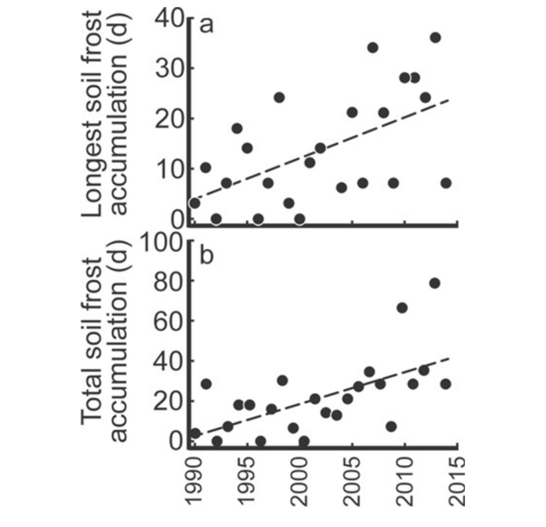

Figure 5. Significant temporal trends in soil frost parameters. (a) Duration of longest period with soil frost accumulation not interrupted by thaw events. (b) Total number of days with soil frost accumulation.

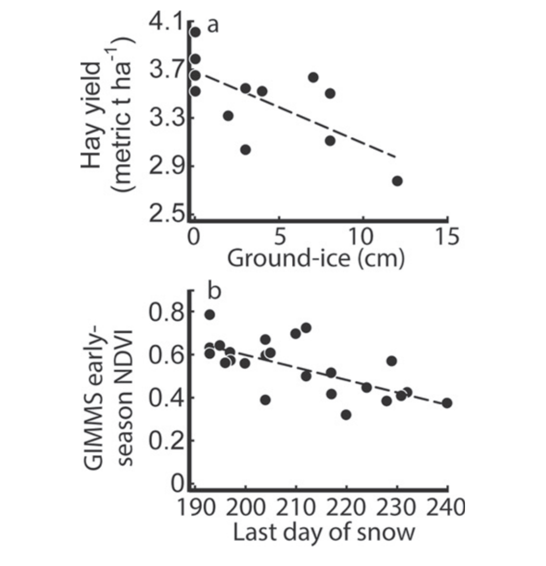

Figure 6. (a). Relationship between hay yield and ground-ice thickness the preceding winter. (b) Relationship between early-season vegetation greenness (GIMMS $NDVI_{3g}$ 1–15 June; unitless) and snow melt timing (Day 1 = first day of snow season, i.e. 1 October; Day 240 is 28 May in non-leap years).

soil frost, but also a type characterized by low *cumulative snow depth* and low *cumulative soil frost* due to many thaw days. We have not found any similar attempts of classifying snow seasons in the way that has been undertaken here. Generally, the focus is on regional variation in snow cover, snow water equivalents and snow hardness without any attempt to classify into snow season types (e.g. Hanssen-Bauer and Nordli 1998, Førland *et al* 2010, Riseth *et al* 2011). Our analyses show that belowground parameters add extra information and lead to a quite contrasting classification of snow seasons compared to classification based on aboveground parameters alone.

The snow season type with low cumulative snow depth and low cumulative soil frost due to multiple warming events and an overall mild winter climate (Type 3) resemble the climate of winters in temperate regions (Kreyling and Henry 2011). Although this type of winter climate was rare during the time span studied, it may very well become the dominant winter climate in the chosen study area in the next decades, given the strong projected increase in winter temperature (Førland *et al* 2010, Overland *et al* 2011). The study area is within the large region where strong declines in the duration of snow cover is expected, with as much as 80 days reduction in the snow cover season along the coast (Vikhamar-Schuler *et al* 2006, Førland *et al* 2010). Thus, although some recent snow-rich winters have led to shallow soil frost or no soil frost at all, it is more likely that future low *cumulative soil frost* will result from warmer winter weather rather than high *cumulative snow depths*.

Hermetic ground-ice is a well-known threat to northern agriculture (Andrews 1996, Kvalvik *et al* 2011, Uleberg *et al* 2014). To date, the largest claim settlement for winter damage to grasslands in Troms County was paid out after the icy 2009/10 winter (Bjerke *et al* 2014, see also figure S.2). The linear model selection shows that claim settlements are high after winters with considerable *frost on snow-free days*, which again is associated with high levels of *ground-ice accumulation*. Ground-ice in spring is detrimental to grasslands, as it leads to anoxic conditions for plants under the ice (Andrews 1996, Höglind *et al* 2010). Without access to ambient air, the plants turn to anaerobic respiration, and eventually, high contents of ethanol and lactic acid in the leaves kill the plants. In addition, roots may still be in frozen soil, hampering the transport of water to the photosynthesizing leaves thereby imposing desiccation stress. Moreover, *freezing on snow-free days* leads to increased *cumulative soil frost*, which requires more energy to thaw out in spring, thereby delaying the onset of the growing season of farmlands (Kvalvik *et al* 2011, Uleberg *et al* 2014).

This study has primarily focused on farmland productivity and vegetation greenness, but the effects of snow season types reach further to natural environments and society. Natural ecosystems are indeed affected by ground-ice and shallow snow depths. Although there is currently no means of monitoring soil frost and ground-ice in natural ecosystems in sub-Arctic Norway, the Tromsø grassland study site is also representative of natural environments. After the extreme winter of 2009/10, conifers in northern Scandinavia experienced high dieback ratios and low crown densities, which was due to winter and spring desiccation caused by frozen soil and sudden steep increases in temperatures (Bjerke *et al* 2014, Kullman 2014). Such winter conditions also often lead to starvation and population crashes in reindeer herds, as the ice or hard snow blocks the reindeer's access to their winter forage resources (Riseth *et al* 2011). Ground-ice is also a threat to other large and small herbivores, e.g. lemmings and other rodents, ptarmigan, muskox, and moose, because it blocks the access to the food resources or destroys their subnivean environment (Kausrud *et al* 2008, Hansen *et al* 2013, Pauli *et al* 2013). The anoxic atmosphere under the ice can also damage the tundra vegetation (Bjerke 2011) and snow mould occasionally grows vigorously under ice (Kumpula *et al* 2000). The mould may produce a series of secondary metabolites known to have toxic effects on herbivores (Kumpula *et al* 2000, Riseth *et al* 2011). Furthermore, the delayed onset of the growing season caused by deep soil frost has negative effects on primary productivity (Bjerke *et al* 2014) and herbivores (Tveraa *et al* 2013). In 2010, frozen soil was recorded in the lowlands as late as mid-July (E. Malnes, pers. comm.). Such extremely late soil thaw is very rare in Scandinavia, but has also occurred in upland areas after the snow-poor 1986/87 winter when forest soil remained frozen until August and peat hummock until October (Kullman and Högberg 1989).

The accumulating ground-ice often leads to choked roadway subdrains and culverts (Livingston and Johnson 1979, Rolland 2013). Any abrupt change to rainy weather under such conditions leads to the icing of roadways (Hansen *et al* 2014) isolating villages, and forcing water to flow into houses, as normal run-off pathways are blocked, as was seen in Troms County in March 2010 (Nitteberg 2010). Airports may have to close (Hansen *et al* 2014). Such icy conditions also lead to higher incidents of bone fractures, especially femoral, as the risk of falling increases (Wasmuth *et al* 1992, Fretland and Krüger 1998). Deep soil frost also causes water to freeze in water pipes, causing nuisance and inconvenience for northern residents.

These examples suggest that Type 4 (Little *cumulative snow depth*, high *cumulative soil frost*, and much *accumulation of ground-ice*) is the most challenging of all snow season types for the sub-Arctic, northern European societies. It may be that this type of snow season is dominating while the winter climate is in a process of change, thereby giving variation to the periods between freezing and thaw. This domination may continue until a warmer winter climate with lower frequency of freezing events becomes more frequent (Type 3). Type 4 will probably be frequent in upland areas for the rest of this century as winters there will still have long periods of freezing temperatures and only minor reductions in snow season duration (Vikhamar-Schuler *et al* 2006, Førland *et al* 2010). However, Type 4 may become less frequent in the lowlands during this century, as the snow season will be reduced by 80 days or more, and mean winter temperatures of the coldest month may tip to being positive (Vikhamar-Schuler *et al* 2006, Førland *et al* 2010).

Model selections suggest that *cumulative* and *maximum soil frost per se* did not affect grassland productivity and vegetation greenness. As the soils are normally frozen during winter, plant roots are adapted to these conditions. Thus, whether soil freezes to 30 or 100 cm has no direct relevance for plant survival. Instead, we proved that the closely correlated variable *freeze on snow-free days during winter*, either as number of days or as frost sum, is a good predictor for sub-Arctic agricultural yields the following growing season. This variable is also closely related to *ground-ice accumulation.* Hence, the following summer's yields can be estimated by the end of the snow season. Normally, such estimates are made after reporting by farmers of the visible grassland damage (Norwegian Agricultural Authority 2015), but by monitoring *freeze on snow-free days during winter*, it is possible to estimate damage levels and forthcoming yields without having to wait for the farmers' reports.

The model selections further suggest that potato yields were reliant on *frost sum of snow-free winter days*. The most likely reason for this dependence is that high frost sums lead to delayed soil thaw, and hence delayed planting of seed potatoes in spring. An unpublished long-term dataset from the study site shows that the time of seed potato planting ranges by more than a month, from 14 May to 17 June. Given the short growing season at these latitudes (Karlsen *et al* 2009), it is not surprising that winter conditions can affect potato yields, as well as primary productivity in natural ecosystems.

Given the projected increasing risk for overwintering damage to cultivated grasslands and the increasing temperature in the growing season, a plausible adaptive measure for agriculture in sub-Arctic Norway is to use and breed new plant material that can cope with this stress while at the same time utilise the longer vegetation period. A warmer and longer growing season can open up the possibility of growing more productive crops and cultivars of vegetables, potatoes and forages than cultivated currently (Höglind *et al* 2010, Uleberg *et al* 2014). However, the higher instability of weather (increased intensity of precipitation, flooding, etc) may lead to more uncertainty regarding production yields, which to a certain degree may counteract the positive implications of climate change in this region. These adaptive measures and challenges may also be relevant for agriculture in the transition zone between the sub-Arctic (northern boreal) and the low-Arctic regions (e.g. Russia, Iceland and southern Greenland).

5. Conclusions

Winter climate is important for primary productivity of natural ecosystems in maritime-buffered northern regions of Europe, primarily through the potentially large damaging effects of certain snow season types (Crawford 2000, Bokhorst *et al* 2009, 2012b, Bjerke *et al* 2014). We here see that it is of similar importance for sub-Arctic grassland and crop productivity. As winters will warm more than summers (Overland *et al* 2011), it is likely that winter climate will become an even stronger regulator of northern primary productivity and may counteract any positive effects of a warmer and longer growing season. This may necessitate changes in management and use of plant material and crops (Uleberg *et al* 2014). Therefore, we need continued and increasing monitoring of winter processes, especially related to frost and ice in the rhizosphere. Most of the time series on soil frost from the study area are of short duration. Currently, snow layers are not routinely checked in North Norway. However, a unique long-term monitoring is ongoing in Abisko, northern Sweden, and this is providing an invaluable dataset for snowpack trend analyses (Johansson *et al* 2011). We recommend that the on-going soil frost monitoring sites are made permanent, that more soil temperature probes are installed and that snow-pack properties be included in all snow monitoring programmes. Data from this type of monitoring would be invaluable to understand current and future biologically relevant responses to contrasting winter climates.

Acknowledgments

This work was financially supported by the Research Council of Norway (contract no. 216434/E10) and FRAM—Centre for Climate and the Environment. We acknowledge the NASA GIMMS group for sharing the $NDVI_{3g}$ data through the ArcticBiomass project (Research Council of Norway, contract no. 227064/E10). We thank Bård-Jørgen Bårdsen, Stein Rune Karlsen, Dagrun Vikhamar-Schuler, Eirik Malnes, Eivind Uleberg, Svein Erik Olsen, Ellen Elverland, Hermod Nilsen, and staff at Bioforsk Svanhovd, Bioforsk Vågønes, and the Norwegian Water Resources and Energy Directorate for various types of information and assistance, Lisa Baldwin for language editing, and anonymous referees for helpful comments.

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