Responses to referees' comments
and marked-up version of the manuscript

Responses to referees' comments

Referee #1

Comment 1:

This is an excellent manuscript and falls well within the scope of The Cryosphere. By integrating various ground-based and remote sensing-based information, the authors showcased a novel method to map the permafrost extent, types and the changes under future climate change scenarios. The methods and algorithms were well thought through and could be considered an improvement over the traditional empirical/statistical based permafrost mapping. The following are a few points this reviewer found impressive:
1) The extent of data integrated in this study was massive, especially in the permafrost regions where the accessibility is extremely poor.
2) The process-based NEST model served well in integrating all the available inputs.
3) The probabilistic algorithm used to quantify the uncertainty of ground cover types is novel. With further validations in other regions, it may provide a new method to address similar problems that are common in permafrost studies.
In general, this reviewer found this manuscript was well written. The objectives and methodology were stated clearly; results are very well presented and limitations of the current study were discussed. Therefore this reviewer recommends that this manuscript be accepted for publication with only very minor revisions as listed below:
1) Eq.(3), page 1901: Although it is stated that x0 was defined by satisfy the x and F(x)'s non-negative condition, the readers may wonder if there is any physical meaning to relate this term.
Response: Agree. We added a sentence describing the physical meaning of x_0 (x_0 is the minimum organic layer thickness for a land cover type) and also reformulated the equations (1-3) by eliminating the intermediate variable '*a*'.

Comment 2:

2) Line 13-15, page 1904: could you add a few explanatory words to state why use 1971-2000 as climate normal period while more recent data are available?
Response: The spatial thirty-year normals provided by McKenney et al. (2012) cover the period 1971 to 2000.

Comment 3:

3) Line 24-25, Page 1908: I could not find in the paper that the lower simulation depth was specified, i.e. at which depth to apply this geothermal flux.
Response: The lower simulation depth was 120 m. We added a sentence about this and slightly revised the last sentence accordingly.

Comment 4:

4) Typos and minor corrections:
a) line 6 page 1900: "typ.";

Response: Corrected.

Comment 5:
b) line 19, page 1901: “nounit” maybe replaced by “dimensionless” or “unitless”;
Response: This intermediate variable ‘*a*’ was eliminated in the equations.

Comment 6:
c) Line 23 , page 1902 to line 1, page 1903: consider revising the sentence started with “ permafrost conditions: : :.”. it was a hard read.
Response: Revised. The long sentence was split and revised.

Referee #2

Comment 1:
General Comments:
The research paper titled “A new approach to mapping permafrost and change incorporating uncertainties in ground conditions and climate projections” by Zhang et al., examines an intergraded approach to examining the distribution and change of permafrost in the present and into the future under low, medium and high levels of climate warming. This approach utilizes a commination of field-collected data with remote sensing and then models the permafrost distribution and active layer attributes using the NEST process-based model. I think this method provides a very novel way of examining how permafrost in the discontinuous zone is controlled in areas where elevation is not the dominant controlling factor such as those in mountain areas of the discontinuous zone. Overall I find this paper well written but more importantly well suited to addressing an important gap in the knowledge of permafrost distribution and evolution in the discontinuous zone. The paper also sheds light on the important influence ecosystem plays in the distribution of permafrost in this zone. One place were I do feel the paper is lacking is that I feel the paper has failed to reference some of the key conceptual material and studies that are reverent (listed below) as a result I feel that they must be added. Besides this I see no reason why the paper should not be published in TC pending the minor revisions that I will suggest on this review.
Specific comments:
1) I feel as if the title of the paper is a bit clumsy in its current form, I would consider shortening it and revising.
Response: The title is a bit long, but we cannot find a shorter and clearer way to covey the idea and content of the paper. Therefore we will just keep it that way.

Comment 2:
2) Throughout the paper degree days should be written as degree-days.
Responses: Corrected.

Comment 3:
3) On Page 1901, line 2; is the range of warming scenarios incorrect? 0.25 is mentioned twice.
Response: They are correct. The three numbers are for the probabilities of three representative climate scenarios.

Comment 4:
4) Page 1905, line 25, it is mentioned that for classes that were not measured in the field that data from an area near Tuktoyaktuk was used. This is very far away from the main study area, please comment more on any error that might have been introduced by this workaround.
Response: Agree. A sentence was added to indicate that "these observations may over-estimate the OLT in our study area, especially when bedrock is near the surface."

Comment 5:
5) Page 1907, line 3, please put in a reference to back up the statement that LAI would reach pre-burn levels in 50 years.
Response: The paper of Bond-Lamberty et al. (2002) was added as a reference.

Comment 6:
6) I think a better justification needs do be used as to why two different modelling groups were used for the same A1B scenario for the medium and high climate warming scenarios. Why wasn't a scenario like A2 (which produces more warming by the end of the 21 century) used? If this is because A1B warms more than A2 by 2050 (which is the case based on the nature of the scenario) this should be stated. Otherwise I still feel justification is needed as to why CCCma's models were not used throughout.
Response: To select future climate scenarios, we first selected 18 climate projections of six climate models (CCCma, ECHAM, HadCM, GFDL, MIROC and NRCAR) under three greenhouse gas emissions scenarios (A2, A1B and B1), then we selected three climate change scenarios generated by CCCma (B1), CCCma (A1B) and MIROC (A1B) to represent low, medium and high warming scenarios based on their temperature projections (Fig. 4). We did not select CCCma (A2) because the projected air temperature is lower than several other projections and it is similar and sometimes lower than that of CCCma (A1B) before the 2050s. We added this information to the paragraph.

Comment 7:
7) In the paper both Mean Annual Air Temperature (MAAT) and Annual Mean Air Temperature (AMAT) were used to describe the same thing, this should be consistent throughout the paper.
Response: We checked these two terms in the paper. The three instances of "mean annual air temperature" describe averages over 30-year or longer. The two instances of "annual mean air temperature" refer to the average for one year. They are slightly different and the usages are correct.

Comment 8:
8) Page 1911, the subject heading for section 3.3 reads "Result validation" I strongly think this should be changed to "result verification". Although this is a good model addressing gaps in the field, it cannot be validated in the true sense but some verification can be done which is what is described here.
Response: Agree and revised.

Comment 9:
9) I feel that the maps presented in figures 3, 5 and 7 should use a classified colour scheme rather than a continuous graduated one. In the current format I find the maps difficult to read both printed and on screen. Consider adapting the same colour scheme used in other permafrost probability studies such that used in the references below.

Response: We tested the figure 5 using 10, 20 and 100 categories for permafrost probability (using ranges of 10%, 5% and 1% for each category, respectively). The difference among the figures is very small and the clarity does not improve much. So we will keep the current form.

Comment 10:

References I feel should be added to this paper:

Bonnaventure P.P. and Lewkowicz A.G. 2013. Impacts of mean annual air temperature change on a regional permafrost probability model for the southern Yukon and northern British Columbia, Canada. The Cryosphere, 7: 935-946. doi: 10.5194/tcd-6-4517-2012.

- This paper also uses climate change scenarios to examine how permafrost probability and spatial distribution changes in a discontinuous permafrost environment. Although the methods are not the same I think it should also be mentioned.

Response: Agree. Added and cited.

Comment 11:

Bonnaventure P.P. and Lamoureux S.F. 2013.The active layer: a conceptual review of monitoring, modelling techniques and changes in a warming climate. Progress in Physical Geography. 37: 352-376. doi: 10.1177/0309133313478314.

- Add this reference to speak about the type of active layer (e.g. page 1900 line 2, you are describing a Type 4 active layer); this reference also speaks about the evolution of changing active layers in different permafrost environments and ecosystems.

Response: Agree. Added and cited.

Comment 12:

Kremer M., Lewkowicz A.G., Bonnaventure P.P. and Sawada M.C. 2011. Utility of classification and regression tree analyses and vegetation in mountain permafrost distribution models, Yukon Territory, Canada. Permafrost and Periglacial Processes. 22: 163-178, doi:10.1002/ppp.719.

- There are very few examples where vegetation is incorporated into permafrost modelling however, this is one and it should be mentioned in the introduction.

Response: We cited three references about mapping permafrost directly using satellite images. The major idea is to show their advantages and limitations. Our reference list is already quite long so we will not include this one and some other papers, such as by Panda et al. (Remote sensing and field-based mapping of permafrost distribution along the Alaska Highway Corridor, interior Alaska, Permafrost and Periglac. Process. 21: 271–281, 2010).

Comment 13:

Jorgenson, M.T., Romanovsky, V., Harden, J., Shur, Y., O'Donnell, J., Schuur, E.A.G., Kanevskiy, M. and Marchenko, S. 2010. Resilience and vulnerability of permafrost to climate change. Canadian Journal of Forest Research, 40: 1219-1236.

Shur, Y. and Jorgenson, M.T. 2007. Patterns of Permafrost Formation and Degradation in Relation to Climate and Ecosystems. Permafrost and Periglacial Processes, 18: 7-19, DOI: 10.1002/ppp.582.

- The two above papers speak about how the distribution of permafrost and the nature of the ecosystem effect how it will be impacted by climate change giving a relative time frame. I really feel they should both be added, as the concepts are relevant to this paper.

Response: Agree. Added and cited.

Other revisions

1. In the second and first part of the third paragraph in the introduction section, we slightly revised the review part of the previous mapping approaches, and included three comprehensive review papers in the references.

2. In the discussion section, we added a paragraph (the second paragraph) to highlight the difference of this new mapping approach comparing to the traditional zonal maps and the equilibrium modelling approaches.

Marked-up version of the manuscript

A new approach to mapping permafrost and change incorporating uncertainties in ground conditions and climate projections

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Abstract

Spatially detailed information on permafrost distribution and change with climate is important for land-use planning, infrastructure development and environmental assessments. However, the required soil and surficial geology maps in the North are coarse, and projected climate scenarios vary widely. Considering these uncertainties, we propose a new approach to mapping permafrost distribution and change by integrating remote sensing data, field measurements, and a process-based model. Land-cover types from satellite imagery are used to capture the general land conditions and to improve the resolution of existing permafrost maps. For each land-cover type, field observations are used to estimate the probability of different ground conditions. A process-based model is used to quantify the evolution of permafrost for each ground condition under three representative climate scenarios (low, medium and high warming). From the model results, the probability of permafrost occurrence and the most likely permafrost conditions are determined. We apply this approach at 20 m resolution to a large area in Northwest Territories, Canada. Mapped permafrost conditions are in agreement with field observations and other studies. The data requirements, model robustness and computation time are reasonable, and this approach may serve as a practical means to mapping permafrost and changes at high resolution in other regions.

1 Introduction

About a quarter of the land in the northern hemisphere is underlain by permafrost (Zhang et al., 1999). Climate in northern high latitudes has warmed at about twice the rate of the global average during the 20th century, and continued warming is projected for the 21st century (ACIA, 2005). Climate warming causes ground temperature increasing, active-layer thickening, talik formation, and thawing of permafrost (Vaughan et al., 2013). These changes have significant impacts on infrastructure foundations, hydrology, ecosystems, and feedbacks to the climate system (ACIA, 2005). Mapping the distribution of permafrost and its possible changes with climate is important for land-use planning, infrastructure development, ecological and environmental assessments, and modelling the climate system.

Different approaches have been used to map permafrost. Due to lack of field data in the early years, Wild (1882) delineated the southern boundary of permafrost in Russia using a model and air temperature. Later on, more field data were included in drawing the boundary of permafrost (see reviews by Nelson, 1989; Heginbottom, 2002; Shiklomanov, 2005). With more field experience and observations available, permafrost distribution was divided into continuous and discontinuous zones, and the latter was further divided into two to four sub-zones (Heginbottom, 2002). Permafrost zones were defined based on spatial continuity, i.e., the proportion of an area underlain by permafrost (Heginbottom et al., 1995; Brown et al., 1998). The most widely used permafrost maps are based on this concept, with boundaries delineated using mean annual air temperature, field observations, and regional physiography (Nikiforoff, 1928; Heginbottom et al., 1995; Brown et al., 1998). These maps are coarse in spatial resolution (usually without an explicit spatial resolution) with broad categories; therefore they have limited utility for practical land-use planning and engineering applications or as a basis for assessing the impacts of climate change on permafrost.

Permafrost distribution can be mapped at high spatial resolution by aerial-photography interpretation for some regions (Vitt et al. (1994; Reger and Solie, 2008). However, the association between land surface features and permafrost conditions has to be clear and interpretation needs good knowledge and experience. Several studies map permafrost distribution by classifying satellite images (e.g., Morrisey et al., 1986; Leverington and Duguay, 1997; Nguyen et al., 2009). These studies show the importance of ground conditions (vegetation, soil and hydrological conditions) on permafrost distribution. Since permafrost cannot presently be directly imaged by optical satellite-based sensors, permafrost condition

Comment [ZY1]: Minor revision of the words and sentences. See other revisons 1 must be indirectly derived from permafrost related and remote-sensing detectable geophysical or surface factors. However, the relation between these factors and permafrost conditions are complex and may change with space and time (Leverington and Duguay, 1997; Duguay et al., 2005).

Permafrost is a ground thermal condition rather than a substance. The impact of climate change on permafrost distribution was recognized long-time ago (Wild, 1882), and now it is an important issue for northern land-use planning, infrastructure development and global climate projections (ACIA, 2005). Woo et al. (1992) estimated the shift in boundaries of continuous and discontinuous permafrost in Canada by assuming a 4-5 °C increase in surface temperature across the country. The Stefan solution, the frost-index method (Nelson and Outcalt, 1983; 1987), Kudryavtsev's approach (Kudryavtsev et al. 1974), and the temperature at the top of permafrost (TTOP) model (Smith and Riseborough, 1996) are some of the major developments for mapping permafrost in recent years. These approaches integrate the effects of air temperature, snow and ground conditions in simplified ways and can be used to map permafrost spatially explicitly and to assess the effects of climate change (e.g., Anisimov and Nelson, 1997; Wright et al. 2003). For mountain regions, Haeberli (1973) developed a method to map permafrost using the Basal Temperature of Snow (BTS) in Alps and it has been used in many high elevation areas. The method was further improved by including the effects of topography on air temperature, solar radiation, and snow conditions, and by incorporating field observations using permafrost probabilities for high resolution permafrost mapping (e.g., Lewkowicz and Ednie, 2004; Bonnaventure et al., 2012) and spatial sensitivity analysis to climate change (Bonnaventure and Lewkowicz, 2013). Recently, Gruber (2012) developed a global high-resolution (30 arc-second, or < 1 km) permafrost map using relations between air temperature and probability of permafrost occurrence. Although these methods emphasized the importance of climate on permafrost, they assume that permafrost is in equilibrium with the atmospheric climate (therefore, they are categorized as equilibrium models by Riseborough et al. (2008)). However, ground temperature observations show that current permafrost conditions are not in equilibrium (Osterkamp, 2005), and modelling studies show that the response of permafrost to climate warming during the 21st century will be transient and non-equilibrium (Zhang et al., 2008; Zhang, 2013). In addition, these methods use simple parameterization and statistic representation to consider the effects of ground conditions on permafrost (e.g., the seasonal n-factor). They tend to under-estimate the complexity and importance of ground conditions on permafrost dynamics, and the empirical parameters may change with time and space.

In the past two decades, process-based models have been used to quantify the impacts of climate change on permafrost conditions and their spatial distributions. Process-based models can integrate climate and ground variables and capture transient processes from seasonal to long-term changes, but they require detailed input data and computation time. Most spatial modelling studies, especially at national to global scales, have been conducted at half-degree latitude/longitude or coarser spatial resolutions (e.g., Lawrence and Slater, 2005; Marchenko et al., 2008; Zhang et al., 2008). At such resolutions, it is difficult to consider detailed spatial variations in vegetation and ground conditions, and the results are not suitable for land-use planning and engineering applications. Recently, several studies have modelled and mapped permafrost at finer spatial resolutions (Duchesne et al., 2008; Jafarov et al., 2012; Zhang et al., 2012; 2013). In the North, however, the required maps for soil and ground conditions are coarse, with polygons in soil and surficial geology maps usually covering more than a hundred square kilometres. The lack of detailed soil and ground information is a major source of uncertainty for high resolution permafrost mapping (Zhang et al., 2012; 2013). Another source of uncertainty is climate change projections. Projected permafrost conditions differ significantly under different climate scenarios (Anisimov and Reneva, 2006; Zhang et al., 2008; 2012, 2013; Zhang, 2013), and consequently such results are difficult for decision makers to use.

In this study, we develop a new approach to mapping permafrost and change in a more objective, replicable and quantitative way and incorporating uncertainties in ground conditions and climate projections. This approach integrates remote sensing, field observations, and modelling in a practical way to map permafrost at high spatial resolution. The mapped permafrost probability is similar to the concept of the traditional permafrost zones. In the paper, we describe the methodology of the approach and demonstrate its application for a large area in northern Canada.

2 Methodology

2.1 Approach and methods

2.1.1 A general description of the approach

Figure 1 shows the scheme of the new permafrost mapping approach. A land-cover map from satellite images is used to represent the general land conditions and to improve the spatial resolution of the final products. For each land-cover type, the probability of different ground conditions is estimated based on field observations. The evolution of permafrost was simulated using a process-based model for each ground-type under three representative climate change scenarios (low, medium and high warming). From these model outputs, the probability of permafrost occurrence and the most likely permafrost conditions are determined for each land-cover type. The following is the rationale and feasibility of the approach.

Climate, especially air temperature, is the dominant factor controlling the spatial distribution of permafrost at large scales (from a hundred kilometres to continental scales). However, in a small area within which the climate is somewhat similar, permafrost can be present or absent, and if present, the permafrost conditions can be significantly different from place to place (Shur and Jorgenson, 2007). Such local variation depends primarily on the distribution of vegetation and ground conditions, including soil composition, snow, topography, and drainage (e.g., Brown, 1973; Shur and Jorgenson, 2007; Morse et al., 2012). High resolution land-cover maps developed from satellite imagery can capture some general features of soil and hydrological conditions, which can explain some of the major differences in permafrost conditions (Nelson et al., 1997; Nguyen et al., 2009; Jorgenson et al., 2010). However, satellite images, especially optical images, only contain information about vegetation and near surface conditions. Therefore ground conditions within a land-cover type developed by satellite images can vary substantially. For example, hollows and hummocks are common at local scales, and there are also topographically controlled variations at large scales. Such differences can cause significant variations in permafrost conditions (Duguay et al., 2005; Zhang et al., 2013). Field observations show that organic layer thickness (OLT) on the top of the mineral soil, including mosses and lichens, is a dominant factor affecting active-layer thickness and ground temperature (e.g., Harris, 1987; Kasischke and Johnstone, 2005; Johnson et al., 2013). Model sensitivity tests also indicate that OLT is the most sensitive factor affecting active-layer thickness and ground thermal conditions (Yi et al., 2007; Zhang et al., 2012; Riseborough et al., 2013). Therefore, we used OLT to divide soil conditions into several ground-types within a land-cover type. As current remote sensing technologies have difficulties measuring OLT, we estimated the probability distribution of OLT based on field observations for each land-cover type. Other input parameters for ground conditions, including mineral soil texture, organic matter content in mineral soils, gravel fractions, drainage parameters, and snow-drifting parameters, can be estimated based on land-cover features, field observations, and soil and surficial geology maps. These parameters may be unique for each ground-type or the same for all ground-types within a land-cover type. Land-cover maps can be developed from satellite remote sensing images. Leaf area indices (LAI) and wild fire history can also be estimated using optical satellite images.

Higher spatial resolution monthly climate data, necessary for spatial modelling, have been developed by interpolating station observations (Wang et al., 2006; McKenney et al., 2011). The temporal patterns of air temperature and precipitation can be estimated using observations at climate stations (Zhang et al., 2012; 2013) or from re-analysis of climate observations. Water vapour pressure can be estimated based on daily minimum air temperature, and daily total insolation without topographic effects can be estimated using latitude, the day of the year, the diurnal temperature range (Zhang et al., 2012). Topographical effects on solar radiation can be calculated using a digital elevation model (Zhang et al., 2013). To consider the uncertainty of future climate projections, three scenarios (low, medium and high warming) can be selected to represent the medium and general range of the probable scenarios based on climate model projections. If we assume that the low and high warming scenarios represent the lower and upper quartiles of the probable scenarios and the medium warming scenario represents the two middle quartiles, the probabilities of the low, medium and high warming scenarios would be 0.25, 0.5, and 0.25, respectively.

To map permafrost and its evolution, permafrost dynamics for each grid cell are modelled under the possible ground-types and the three representative climate scenarios. The probability of permafrost occurrence in a grid cell can be determined based on the probabilities of the ground-types and climate scenarios. In turn, the distributions of permafrost probability and the most likely permafrost conditions can be mapped. The probability of permafrost within a grid cell can be interpreted as a probability due to the uncertainties in ground conditions and climate projections, or can be interpreted as permafrost proportion or extent due to spatial heterogeneity within the grid cell, especially when the grid cell is large.

2.1.2 Estimating the probability of ground-types within each land-cover type

The probability distribution of ground-types in all the areas of a land-cover type was estimated using a modified logistic function based on field sampling observations of OLT at different locations. We did the modification because OLT cannot be negative and is usually thicker than a certain value for peatlands and some other northern land types.

$$F(x) = (1 - e_x / e_{x0}) / (1 + e_x) \qquad (x \geq x_0), \tag{1}$$

where

$$e_x = \exp[-(x - \mu)/s], \tag{2}$$

$$e_{x0} = \exp[-(x_0 - \mu)/s]. \tag{3}$$

Where x is OLT (cm) and $F(x)$ is the cumulative distribution probability of OLT for a land-cover type. x_0 is the minimum OLT (cm) of the land-cover type, μ and s (in centimetres) are the average and the standard deviation of the logistic distribution. The probability density can be derived as,

$$f(x) = \frac{e_x(1 + e_{x0})}{s \cdot e_{x0}(1 + e_x)^2} \qquad (x \geq x_0), \tag{4}$$

Comment [ZY2]: Reformulated (eliminated variable 'a') based on comment 1 from refeee #1

where $f(x)$ is the probability density function. The probability of a ground-type i can be determined using Equation (4)

$$p(i) = \int_{ai}^{bi} f(x)dx = (1 + 1/e_{x0})[1/(1 + e_{bi}) - 1/(1 + e_{ai})], \tag{5}$$

where $p(i)$ is the probability of a ground-type i for OLT ranging from a_i to b_i. The values of e_{ai} and e_{bi} are calculated from Equation (2) when x equals a_i and b_i, respectively. The value of i ranges from 1 to N, where N is the number of ground-types. The thinnest and thickest OLT ground-types can be determined from Equation (5) using a predetermined probability level (e.g., 0.1). Then, the OLT ranges of the other ground-types can be defined. The three parameters in Equation (1) (x_0, μ and s) can be determined by comparing the fitted cumulative probability with the observed relative cumulative frequency. Figure 2 shows an example of distribution of ground-types in a land-cover type. For the model input, the OLT of a ground-type was represented by $0.5(a_i+b_i)$, except for the thinnest and thickest OLT ground-types, which were determined as the OLT at which the cumulative probability $F(x)$ equals a predetermined probability level (0.05 and 0.95 for the thinnest and thickest OLT ground-types, respectively).

Sensitivity tests showed that the modelled average permafrost conditions converged quickly with the increase in the number of ground-types. Permafrost conditions were similar when the difference of the OLT was less than 5 cm, especially when OLT was thicker than 30 cm. Permafrost conditions were not sensitive to the changes in OLT when OLT was thicker than 50 cm (Zhang et al., 2012; Riseborough et al., 2013). Based on this response we can select the thickness and the number of ground-types.

2.1.3 The model

The permafrost condition and its changes with climate for each ground-type were quantified using the Northern Ecosystem Soil Temperature model (NEST). NEST is a one-dimensional transient model that considers the effects of climate, vegetation, snow, and soil conditions on ground thermal dynamics based on energy and mass transfer through the soil-vegetation-atmosphere system (Zhang et al., 2003). Ground temperature is calculated by solving the one-dimensional heat conduction equation. The dynamics of snow depth, snow density and their effects on ground temperature are considered. Soil water dynamics are simulated considering water input (rainfall and snowmelt), output (evaporation and transpiration), and distribution among soil layers. Soil thawing and freezing, and associated changes in fractions of ice and liquid water, are determined based on energy conservation. Detailed description of the model and validations can be found in Zhang et al. (2003; 2005; 2006). Lateral flows and snow drifting are parameterized in a simplified way (Zhang et al., 2002; 2012). The model can also consider the effects of topography on solar radiation (Zhang et al., 2013).

2.2 Applying the approach to an area in northern Canada

2.2.1 Study area and field observations

We applied this approach to a 94 km by 94 km area in Northwest Territories, Canada, centred at 62.77° N, 114.27° W (Fig. 3a). The area is located in the Great Slave Geological Province, a region of high mineral resource development in northern Canada, where seasonal and all-weather roads and other infrastructure are important. With the effects of the last glacial ice sheet and the glacial lake McConnell, most of the surficial geology consists of fine-grained glaciolacustrine sediments and wave-washed bedrock (Wolfe et al., 2013). The study area includes the Great Slave Lowlands and Uplands with vegetation ranging from dense forest to arctic tundra (Ecological Classification Group, 2007). The Great Slave Lowlands are poorly-drained low relief terrain characterized by numerous water bodies separated by fens, peatlands, mixed woodlands, white birch (*Betula papyrifera*) and black spruce (*Picea mariana*) forests, whereas the Uplands are areas of higher relief and bedrock outcrops. Permafrost in the region is discontinuous and highly variable, usually with abrupt transitions from frozen to unfrozen ground over short distances (Wolfe et al., 2011). Therefore it is important to provide spatially detailed information about permafrost conditions and possible changes with climate warming. We selected this area also because it covers a large spatial environmental and vegetation gradient and many field observations are available. In this area, the thirty-year (1971-2000) mean annual air temperature ranged from -6.9 °C to -4.9 °C (Fig. 3f), and mean annual total precipitation ranged from 288 mm to 309 mm. Monthly mean air temperature varied from -29 °C in January to 16 °C in July.

We conducted fieldwork in this area in 2005 and 2011. Data were collected on land-cover types, vegetation conditions, surface OLT, and soil profile conditions (depths of the horizons, texture and organic matter content), drainage, and summer thaw depths. We also collected observations made by other investigators in this area (Gaanderse, 2011; Brown, 1973; Karunaratne et al., 2008; Roujanski et al., 2012). In total, we compiled 124 observation sites (Fig. 3b). Most sites were located near roads in the south providing easy access. Wolfe et al. (2014) also identified 1777 lithalsas in the Great Slave Lowlands and Uplands using 1:60000 scale aerial photos acquired between 1978 and 1980, in which 955 sites were within our study area (Fig. 3b). Lithalsas are permafrost mounds formed by ice segregation within mineral soil. These field data and lithalsa observations were used to validate the modelled permafrost distribution.

2.2.2 Land-cover types and the probability of ground-types

The land-cover types (Fig. 3c) were classified using SPOT High-Resolution Visible and Infrared images. The area is covered by a SPOT 4 image acquired on 7 August 2008 and a SPOT 5 image from 4 August 2011, both at 20 m spatial resolution. Radiometric normalization was performed using robust Theil-Sen regression on the overlap between the two scenes to adjust the 2008 radiometry to match the 2011 image. The Enhancement

Classification Method (Beaubien et al., 1999) was used to improve image contrast by stretching the dynamic range representing land features to the full 8-bit dynamic range while compressing water, cloud and shadow. A large number of spectral clusters were generated from the enhanced multispectral data using fuzzy *K*-means clustering and applying a pseudo-colour table to represent the enhanced colours. The Classification by Progressive Generalization approach (Cihlar et al., 1998) was used to manually merge and label clusters to 16 land-cover types considering spectral similarity and spatial proximity to depict land-cover features visible in high resolution images in Google Earth™ and our field data. Validation of a national land-cover product (Olthof et al., 2013) that includes this study area suggests an overall accuracy in the range of 70 %. We modelled permafrost conditions for 13 land-cover types, which exclude water, roads and recently disturbed areas (Table 1).

We estimated the probability distribution of the ground-types in each land-cover type using field observations of OLT. Most of the land-cover types had five to eight ground-types (Table 2). Rock outcrop was assumed as one ground-type without organic layer. The parameters were determined by fitting the observed relative cumulative frequency with the modified logistic function (Table 2). Our field observations in the study area did not include land-cover types of erect shrubs, shrub-herb mixture and herbs (types S, SH and H, respectively). To fill this data gap, we used field observations of these land-cover types that were conducted in 2013 near Tuktoyaktuk (69.44° N, 133.03° W) and Fort McPherson (67.44° N, 134.88° W). These observations may over-estimate the OLT in our study area, especially when bedrock is near the surface.

Comment [ZY3]: Added based on the comment 4 from referee #2

2.2.3 Leaf area indices and fire disturbances

Leaf area indices in mid-summer (Fig. 3d) were mapped using Landsat-5 imagery (acquired on 21 July 2002) based on Abuelgasim and Leblanc (2011), who developed an equation of LAI using field observations and the reduced simple ratio index of Landsat channels 3, 4 and 5. As they normalized their Landsat scenes based on SPOT VGT composite in the summer of 2005, we first normalized our Landsat images to the same SPOT VGT composite and then calculated LAI using their LAI equation.

A digital database of historically burned areas and year of burning (Fig. 3e) was obtained from the Government of Northwest Territories Centre for Geomatics (http://www.geomatics.gov.nt.ca/). In the study area, about 26.2 % of the land area experienced wildfire since 1967. The major fires were in 1973 and 1998, which accounted for 71.6 % and 19.3 % of the total burned area, respectively. Fires consume vegetation and soil organic matter. The amount of consumption and the post-fire regeneration process depend on fire intensity, vegetation condition, soil moisture and local topography (Turetsky et al., 2011). For simplicity, we assumed that fires consumed all the foliage, and the remaining standing woody parts had little effect on radiation and surface energy exchanges. The albedo of the land surface in snow-free period was reduced by 50 % immediately after the fire (Yoshikawa et al., 2003; Mack et al., 2011). We assumed that fire could consume a maximum of 13 cm of mosses and top organic matter except for wetland and fen (type W), where we used half of this depth due to their wet conditions (Johnestone et al., 2010; Turetsky et al., 2011).

Although trees can take several decades to re-establish, the regeneration and re-establishment of sedges and shrubs occur rapidly (Bond-Lamberty et al., 2002). Based on the LAI map for this area (representing the conditions in 2002), the average LAI in the area burned after 1994 (mostly in 1998) was about 60 % of the average LAI in the non-burned area, and the average LAI in the area burned before 1973 was about 120 % of the non-burned area. Based on these results and other studies (Bond-Lamberty et al., 2002), we assumed that land-cover types dominated by sedges and shrubs would regenerate in the following year after a fire and LAI would reach pre-burn levels in 5 and 15 years, respectively. Tree-dominated land types would regenerate in 5 years after a fire and LAI would reach pre-burn level in 50 years (Bond-Lamberty et al., 2002). We also assumed that the surface organic matter and mosses consumed by fire would recover in 50 years (Mack et al., 2011). The albedo of the land surface would also return to the pre-burn level. The increases in LAI, albedo and surface organic layer were treated as linear patterns with time after regeneration. After recovery, the land-cover types will be the same as pre-burn conditions, and summer LAI will not change with time (LAI varies seasonally). We did not consider new fires after 2013.

Comment [ZY4]: Added based on the comment 5 from referee #2

2.2.4 Climate data

The 5 arc-minutes (about 10 km) spatial 30 year averages (1971-2000) of monthly air temperature (Fig. 3f) and precipitation were from McKenney et al. (2012). The data were interpolated from station observations. We interpolated these monthly data to 20 m resolution using bi-linear interpolation, and calculated annual total degree-days when air temperature was above 0 °C. Based on annual total degree-days and annual total precipitation, the climate was clustered into 20 classes. The average relative errors were 0.25 % and 0.45 % for the annual total degree-days and annual total precipitation, respectively. Temporal climate changes were estimated using daily observations at the Yellowknife airport climate station as a template. A detailed description of the method can be found at Zhang et al. (2013). From the 1940s to the recent past decade (2003-2012), annual mean air temperature increased by 2.1 °C. The increase mainly occurred after the mid-1960s. Annual total precipitation increased by 99 mm from the 1940s to the past decade.

The climate scenario data were downloaded from the World Data Center for Climate (http://mud.dkrz.de/wdc-for-climate/ accessed in April 2011). First, we selected 18 climate projections of six climate models (CCCma, ECHAM, HadCM, GFDL, MIROC and NRCAR) under three greenhouse gas emissions scenarios (B1, A1B and A2), then we selected three climate change scenarios to represent low, medium and high warming scenarios based on their temperature projections. They were generated by CCCma (B1), CCCma (A1B) and MIROC (A1B) (Fig. 4). We did not select CCCma (A2) because the projected air temperature is lower than several other projections and it is similar and sometimes lower than that of CCCma (A1B) before the 2050s. Under the selected three scenarios, air temperature is projected to increase 0.4, 1.7 and 2.7 °C, respectively, from the recent past decade to the 2050s; and to increase 1.0, 3.4 and 4.9 °C, respectively, from the recent past decade to the 2090s. The projected changes in precipitation are not very significant (Fig. 4b).

Comment [ZY5]: Revised based on the comment 6 from referee #2

2.2.5 Other input parameters

In addition to OLT, the model also requires inputs about mineral soil conditions and hydrological parameters. Field surveys and coring indicate differences in sediment types above and below an elevation of about 205 m above sea level (a.s.l.), likely related to sedimentation within the glacial lake McConnell (Stevens et al., 2012). Therefore, we first divided the study area into two regions using the 205 m a.s.l. isoline (Fig. 3b) and then defined the mineral soil conditions for each region. This delineation also closely corresponds to the separation of the Great Slave Lowlands and Uplands (Ecological Classification Group, 2007). At elevations below 205 m, mineral soils are mainly composed of clay (Wolfe et al., 2011). Above 205 m., mineral soils were assigned as sandy loam for the low-vegetation or barren land (type L) and low- to medium-density coniferous forest (type C3), and as silty clay for other land-cover types based on the general patterns of field observations (Stevens et al., 2012; Wolfe et al., 2011). The organic matter content in mineral soils was estimated based on the general patterns observed by Hossain et al. (2007). Except for low vegetation and bedrock

(Types L and R), the depth of all surficial deposits (including peat and mineral soils) are assumed to be 7 m for bogs and wetlands (types C5 and W) and 5 m for other land types based on most of the borehole observations (Wolfe et al., 2011). The soil thickness for the low vegetation type was assumed to be 2.5 m and we assumed no soil on bedrock outcrops. The thermal conductivity of bedrock was 0.026 W m^{-1} $°C^{-1}$ (Brown, 1973). The depth of the ground profile simulated was 120 m, and heat flux at the bottom of the ground profile was assumed as 0.007 W m^{-2} (Majorowicz and Grasby, 2010).

Comment [ZY6]: Added based on the comment 3 from referee #1

The model also requires several parameters to estimate lateral water flows (Zhang et al., 2002, 2012). We defined these parameters based on the general drainage conditions and the range of water table for different land-cover types (Table 3). The model also has a parameter to consider the effects of snow-drifting due to wind (Zhang et al., 2012). A positive value is for the fraction of snowfall drifted away from the site and a negative value for capturing some drifting snow from surroundings. We estimated this parameter based on the vegetation types and their density (represented by the LAI in summer) (Table 3). Since this region is relatively flat, we did not consider the effects of topography on solar radiation.

2.2.6 Spatial modelling

To reduce the computation time, LAI was divided into 18 levels based on the effects of LAI on solar radiation (i.e., exp(-0.5LAI)). The latitude in the area was divided into five grads (0.2° difference between two adjacent grads). Together with the land-cover types (13 types), elevation levels (2 types), climate (20 classes), and wildfire years (13 types), the land pixels in the study area had 31 724 unique combinations of the input types, which was 0.2 % of the land pixels in this area (We ran the model only for these unique input types rather than running the model pixel by pixel). For each land-cover type, the model was run for all the ground-types under the three climate scenarios. Model computations took about three weeks using three personal computers.

3 Result and analysis

3.1 Permafrost distributions

Figure 5 shows the distributions of permafrost probability modelled for the 1950s (1950-1959), the 2000s (2000-2009) and the 2050s (2050-2059). These results show significant reductions in permafrost probability due to climate warming from the 1950s to the 2050s.

Permafrost is predicted to disappear completely in most of the area by the end of the 21st century. The spatial distribution of permafrost in this area was mainly related to land-cover types and associated ground conditions. For example, the non-permafrost area in the 2000s mainly occurred in rock outcrops, low vegetation, and deciduous forest (Land-cover types R, L and D, respectively), while sparse coniferous forest (types C4 and C5) and herb dominated areas and wetlands (types H and W) had high permafrost probability. Leaf area indices and fire disturbances also affected permafrost conditions, but their effects were mixed with that of land-cover types. Permafrost probability in the northeast corner of the study area was higher, probably due to the relatively cooler climate in this area. However, the overall effects of the climate gradient on spatial distribution of permafrost were not so obvious because of the strong effects of ground conditions and relatively small climate gradient in this area (Fig. 3f). For example, although the southern part is slightly warmer than the northern part, LAI is higher and soils contain more clay in the south, which compensated for the effects of warmer temperature on permafrost development.

Figure 6a shows the modelled temporal change of average permafrost probability (or permafrost extent) in this area from 1942 to 2100. On average, permafrost extent was reduced from 72.0 % in the 1950s to 52.0 % in the 2000s. The model predicted that permafrost extent would be reduced to 12.4 % in the 2050s and to 2.5 % in the 2090s. The difference in permafrost extent between the low and high warming scenarios was relatively small, usually less than 5 % (in permafrost extent).

Different land-cover types show different decreasing patterns in permafrost extent (Fig. 6b). The most rapid reduction in permafrost extent was in low vegetation or barren land (type L) due to their exposed land conditions. The reduction was rapid in deciduous forest area (type D) due to its shallow OLT. Spruce lichen bogs and wetlands (types C5 and W) were the last land-cover types experiencing permafrost reduction. With time, the reduction of permafrost for a land-cover type generally shows a slow, rapid and slow decline pattern. The initial slow reduction is due to the lower warming rate of climate (especially before the mid of the 1980s) and the time required to warm the ground to a critical level. The later slow reduction of permafrost is related to ground-types with deep organic layers and high LAI, which can protect permafrost from thawing (Shur and Jorgenson, 2007). Model results show that some forest areas could still maintain permafrost by the end of the 21st century mainly due to their deep OLT and high LAI, assuming they were not disturbed by wildfires during the 21st century.

3.2 The most likely permafrost conditions

Permafrost conditions under varying ground-types differ significantly due to the effects of OLT. Permafrost does not typically exist where OLT is very shallow. Therefore it is difficult to calculate the average permafrost conditions. A meaningful way is to present the most likely permafrost conditions, which is determined from the model results of the most likely ground-types under the medium warming climate scenario. The most likely permafrost extent averaged in this area (dashed curve in Fig. 6a) was slightly different from the average of all the ground-types under the three climate scenarios (solid curve in Fig. 6a). The average and the most likely spatial patterns were similar in the 1950s and 2000s (the most likely permafrost distribution only has two types, no permafrost or with permafrost, shown respectively as white or other colours in Fig. 7). However, the average and the most likely permafrost distributions were very different in the 2050s (comparing Figs. 5c and 7c) as permafrost was predicted to disappear in most areas under the most probable ground and climate conditions.

Figure 7 shows the distribution of the most likely active-layer thicknesses in the 1950s, 2000s and 2050s. Active layer deepened from the 1950s to the 2000s, and permafrost in most areas was predicted to disappear in the 2050s. The red patches (deeper active layer) in the northeastern corner in Fig. 7b are due to the effects of wildfires, which consumed vegetation and some of the top organic matters. For the pixels with permafrost in all the years before 2012, the average active-layer thickness increased from 0.7 m in the 1940s to 1.4 m in the 2000s.

3.3 Result verification

Comment [ZY7]: revised based on the comment 8 from referee #2

According to the Canada permafrost map (Heginbottom et al., 1995), the study area is within the extensive discontinuous permafrost zone. Based on the 124 observation sites in this area, permafrost was detected at 87 sites. Frozen ground was not detected at the other 37 sites. The permafrost sites account for 70.2 % of the observation sites, which confirm that this area is within the extensive discontinuous permafrost zone (50 – 90 %). The modelled average permafrost extent in this area was 64.2 % during 1942-2012, well within the range of the extensive discontinuous zone. Based on the ground-types most closely matching local conditions, the model results show that permafrost occurred at 71 of 87 observed permafrost sites. For the other 37 sites where no frozen ground was detected in the field, the model results show that 21 sites did not have permafrost, six sites had permafrost but their thaw depths were deeper than the measurement depths, and the model results were incorrect for the other ten sites. Overall, the model correctly simulated permafrost occurrence for 82 % of the observed permafrost sites, and correctly simulated 73 % of the sites where frozen ground was not detected in the field either because thaw depths were deep, or permafrost did not exist. Coincidently, the modelled and observed total numbers of sites with permafrost (87 sites) were the same.

Figure 8a shows a comparison between the modelled and observed percentage of sites with permafrost at each land-cover type. The model results were close to the observations for most of the land-cover types except for the low vegetation sites (L). Permafrost was observed at three of the four low vegetation sites whereas the model did not indicate permafrost at these sites. Field data show that two sites are in disturbed areas with some peat layers added in the soil profile and another site is near the road with some embankment material on the surface. These modified conditions may have actually promoted permafrost development.

Wolfe et al. (2014) identified 955 lithalsas in our study area (Fig. 3b). By definition, permafrost exists at these locations. We calculated the average permafrost probability during 1978-1980, at which time the aerial photographs were acquired to identify the lithalsas. Eighteen locations were classified as water since they are very close to water bodies. The model results show that all the 937 non-water locations have a $\geq$ 14 % probability of permafrost occurrence. The probability of permafrost occurrence was $\geq$ 50 % at 838 locations, and was $\geq$ 90 % at 501 locations. The average probability was 76.9 % for all the locations. The lithalsa mounds are usually well drained due to their local topography and contain segregation ice. The modelled did not consider these factors therefore they might contribute to the underestimation of the probability of permafrost occurrence for these locations.

The modelled mean summer thaw depth for each land-cover type was comparable with the observations although the variation range was usually large among the sites (Fig. 8b). The modelled average thaw depth of all the sites with permafrost was 0.78 m, which was very close to the average of the observations (0.81 m). Figure 9 shows a scatter graph comparison for the 71 sites with permafrost. The magnitudes of the modelled summer thaw depths were similar to the observations for most of the sites although significant differences existed for some sites due to their specific soil, vegetation and hydrological conditions. The correlation coefficient is 0.365 (n = 71).

The modelled dynamics of snow depth, especially the timing of accumulation and disappearance of snow and the maximum snow depth, compared well with the observations at the Yellowknife climate station. The correlation coefficient is 0.892 for the 19794 observations from the 1955 to 2012. The modelled permafrost thickness for recent decades ranged from several metres to 130 m, which is comparable with the observations reported by Smith and Burgess (2002) and Roujanski et al. (2012). We also tested the model offline using observations in this area measured by Brown (1973), Karunaratne et al. (2008), and Roujanski et al. (2012). Based on their local ground and vegetation conditions, the model could capture their ground temperature regimes and permafrost conditions.

4 Discussion

This study proposes a new approach for mapping permafrost and change with climate considering uncertainties in ground conditions and climate projections. We apply this approach at 20 m resolution to a large area in northern Canada. The data requirement and the cost of computation are reasonable, and the mapped permafrost conditions are in reasonable agreement with field observations and other studies. Compared to previous mapping methods, several features of this approach are noteworthy.

First, compared to the traditional zonal permafrost mapping methods (Nikiforoff, 1928; Heginbottom et al., 1995; Brown et al., 1998), this new approach is more objective, replicable, and quantitative in integrating most of the related factors, and can be used to map permafrost at higher spatial resolution and to assess the impacts of climate change. Unlike the equilibrium models (Riseborough et al., 2008), our process-based modelling approach can quantify the transient responses of permafrost to changes in climate and ecosystems.

Comment [ZY8]: Added, explained in other revisions 2

Second, this approach integrates satellite remote sensing data, field observations, and a process-based model. Satellite data can greatly improve the spatial resolution of existing permafrost maps, and can provide various parameters including land-cover, LAI, wildfire, and topographic features. As current soil and surficial geological maps are coarse, the heterogeneous ground conditions are statistically represented based on field observations.

Third, the produced permafrost maps by this approach are more useful for land-use planners and decision-makers due to their higher spatial resolution and effectively incorporating incomplete and uncertain information about ground conditions and future climate projections. Previous studies usually presented different permafrost maps under assumed different ground conditions and climate change scenarios (e.g., Zhang, 2013; Zhang et al., 2008, 2013; Daanen et al., 2011). Such results are difficult to use due to their wide differences. This probability concept is similar to the traditional permafrost maps, but the new approach can develop permafrost maps with a much higher degree of precision and spatial resolution. Figure 10 shows the importance of spatial resolution for permafrost zones. At 20 km resolution, our results show the same permafrost zone as in the traditional permafrost map (extensive discontinuous). At finer resolutions, however, other permafrost zones appeared. In addition, this approach also provides most likely permafrost conditions, such as active-layer thickness and permafrost thickness.

Finally, this approach may serve as a practical way to map permafrost evolution at high spatial resolution for other regions. Satellite remote sensing data are routinely available across the globe. To consider the heterogeneity of ground conditions, we estimated their statistical distributions rather than mapping ground conditions explicitly, which is difficult at present. Organic layer thickness and other general ground conditions can be surveyed in the field and the data can be accumulated gradually as they do not change significantly with time without disturbances. In this study, we estimated the probability of ground-types based on OLT. With more field data available, other ground features can be included to better define ground-types. The spatial input data can be organized and used to run the model on multiple computers simultaneously, thus greatly reducing computation time for high resolution spatial modelling. In addition, this approach allows for changes or improvement in spatial resolution, new development in the model and remote sensing technology, and with the availability of more field observations.

Permafrost is a ground thermal condition influenced by many factors of geological, climatic, hydrological and ecological processes at different temporal and spatial scales (Jorgenson et al., 2010; Shur and Jorgenson, 2007; Bonnaventure and Lamoureux, 2013). Although our new mapping approach quantitatively integrated most of the factors based on energy and water dynamics, it has several limitations. First, the NEST model is one-dimensional and assumes each grid cell to be uniform without lateral heat exchange. Therefore the results cannot represent areas with strong lateral heat fluxes, such as areas between very different land-cover types, especially close to water bodies. And the model does not consider permafrost thaw due to lateral heat flow, which could be important for patchy permafrost. Second, we considered fire disturbances occurred in the past, but we did not consider future fires. Such a treatment might over-estimate future permafrost extent because high LAI and deep organic layer can effectively keep permafrost in disequilibrium from the warming of the atmospheric climate (Camill and Clark, 1998; Shur and Jorgenson, 2007). Ground subsidence and related hydrological changes could have significant impacts on permafrost degradation as well. And finally, this study did not consider changes in land-cover types and LAI with climate warming. Observations show that northern high latitudes are becoming greener and shrubbier with climate warming (e.g., Tape et al., 2006). These changes can be very important for the evolution of permafrost.

5 Conclusions

Spatially detailed information about permafrost evolution with climate warming is important for land-use planning and for environmental and ecological assessments. Although satellite remote sensing can provide detailed maps of vegetation and land-cover types, knowledge regarding soil and ground conditions are much coarser, which greatly limits our capacity to map permafrost at higher resolutions. The wide range of projected climate scenarios also brings in uncertainties for mapping permafrost change. Our proposed new approach incorporates these uncertainties for permafrost mapping by integrating remote sensing, field observations, and a process-based model. Land-cover types from satellite remote sensing are used to capture the general land features and to improve the spatial resolution of existing permafrost maps. Other vegetation features can also be derived from remote sensing imagery. The probability of different ground conditions within land-cover types is estimated from field observations. A process-based model is used to quantify the dynamics of permafrost for each ground-type under three representative climate scenarios of low, medium and high warming. From the model results, the probability of permafrost occurrence and the most likely permafrost conditions are determined. We apply this approach at 20 m resolution to a large area in Canada. The mapped permafrost conditions are in agreement with field observations and other studies. This demonstrates that the data requirements, model robustness and computation time are reasonable, and that this approach may serve as a practical means to map permafrost evolution at a high resolution in other regions.

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Comment [ZY10]: Added

Comment [ZY11]: Replaced his 1984 paper

Comment [ZY12]: Added based on the comment 13 from referee #2

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Table 1 Land-cover types classified using SPOT satellite

Code	Name	Type description
D	Deciduous - medium to high density	Cold deciduous forest, closed tree canopy (crown closure 25-60%), small coniferous-herb understory.
M	Mixed - medium to high density	Mixed cold deciduous-needle leaved evergreen forest (crown closure 25-50%).
C1	Coniferous - high density	Sub-polar needle leaved evergreen forest (crown closure >75%).
C2	Coniferous - medium density	Sub-polar needle leaved evergreen forest, lichen-shrub understory.
C3	Coniferous - low to medium density	Sub-polar needle leaved evergreen forest, low-medium density, shrub-lichen understory.
C4	Sparse coniferous forest-shrub cover	Sparse needle leaved evergreen forest, herb-shrub cover understory.
C5	Spruce lichen bog	Wetland type feature that supports lichens and treed bogs.
W	Wetland or fen	Treed or herbaceous wetland with water table near or above the surface.
S	Erect shrubs	Tall shrubs or dense low shrubs.
SH	Shrub-herb mixture	Mixture of herbs and shrubs.
H	Herbs	Herb dominated (but not fens)
L	Low vegetation or lichen barren	Low- or non-vegetated area (but not roads or recently disturbed areas).
R	Rock outcrop	Rock outcrops with sparse vegetation.
U	Disturbed area	Recently disturbed areas (not modelled)
O	Roads	Roads (not modelled)
W	Water	Lakes, rivers, or ponds (not modeled)

Table 2 Probability parameters of organic layer thickness and the number of ground-types for each land-cover type estimated using field observations.

Type code	Observation sites	Probability parameters (cm)			R^2	Number of ground-types
		x_0	μ	s		
D	9	0.0	1.0	4.5	0.983	5
M	16	0.0	2.0	9.5	0.970	6
C1	15	0.0	10.8	2.5	0.963	5
C2	14	0.0	16.0	11.0	0.989	7
C3	7	0.0	13.0	9.5	0.949	6
C4	6	0.0	27.0	17.0	0.952	7
C5	20	20.1	80.0	26.0	0.980	8
W	25	5.2	31.0	16.0	0.970	7
S	19	2.7	10.0	8.0	0.956	7
SH	11	0.0	10.0	8.0	0.999	7
H	6	9.4	17.0	4.0	0.959	7
L	4	0.0	0.2	0.5	0.831	3
R	8	-	-	-	-	1

R^2 is the square of the correlation coefficient between the fitted and observed relative cumulative frequency.

Table 3. Hydrological parameters defined for different land-cover types

Type code	Ground inflow		Surface outflow		Ground outflow		Snow drifting parameter
	WT_{ig}	F_{ig}	WT_{os}	F_{os}	WT_{og}	F_{og}	
D	100	0.1	0	0.1	50	0.05	0
M	100	0.1	0	0.1	30	0.05	-0.03*L*
C1	−	−	10	0.1	30	0.05	-0.05*L*
C2	−	−	0	0.1	30	0.05	-0.03*L*
C3	−	−	0	0.1	30	0.05	0.00
C4	−	−	0	0.1	30	0.02	0.00
C5	60	0.1	0	0.1	20	0.05	0.00
W	20	0.05	-10	0.05	-	-	0.00
S	−	−	0	0.1	20	0.1	-0.10*L*
SH	−	−	0	0.1	15	0.1	-0.05*L*
H	−	−	0	0.1	5	0.1	0.00
L	−	−	0	0.1	20	0.1	0.1-0.1*L*
R	−	−	0	0.5	−	−	0.2-0.1*L*

WT_{ig} is the lowest water table (cm below the surface) for beginning lateral ground inflow. WT_{os} and WT_{og} are the highest water table (cm below the surface) for beginning lateral surface and ground outflows, respectively. F_{ig} is the rate of ground inflow (day^{-1}). F_{os} and F_{og} are the rates of surface and ground outflows, respectively (day^{-1}). Detailed description of these parameters can be found in Zhang et al. (2002, 2012).

− is assuming no lateral flows.

L is for leaf area indices in peak growing season.