Author's response

Dear. Dr. Beer,

5   We are happy to provide the revised manuscript with markup showing changes to the original text. We have responded to all of the reviewer comments in the "Author Comments" posted in the discussion, and indicated the changes implemented as a result. We have also included the responses in this PDF, below. Most comments were addressed by minor additions to or editing of the manuscript text. The most major change was in response to comments by M. Allard that suggested our parameterization for colluvial sediments could be improved. In response to this, we altered the model parameters for colluvial

10   sediments, which caused minor changes to the segregated and wedge ice outputs.

Thank you,

H. Brendan O'Neill

Response to M. Allard

Dear Dr. Allard,

Thank you very much for the time and effort put into your review. We appreciate the thoughtful and constructive feedback. We have followed nearly all of your suggestions and responded to each comment individually below.

1. *P. 2, L15 " Holocene environmental changes results in reduce ice abundance where treeline advanced during warmer periods". This may not be correct or may need precision…*

   We have indicated on p4, L29 that the ice abundance for each map unit (i.e.) pixel is reported, so the relative abundance is now explicitly stated on a per-area basis.

2. *P 4, L5. Delete "data"*

   Deleted

3. *This methodological approach certainly leads to a great improvement in predictive mapping of ground ice occurence and abundance on the Canadian territory…*

   We have added text based on your suggestion. The text explains that the expert-system uses logical deduction and a set of conceptual models (rules), and have given a few examples of the rules.

4. *L9 not clear what is meant by "temporal criteria"*

   We have removed this sentence, as it was not necessary.

5. *L28-29, Formation of intra-sedimental massive ground ice. You could refer here to the therorical and modellin work of Konrad (1990) in the proceedinds of the 5th Canadian permafrost conference.*

   Thanks, we have added this reference to the section.

6. *P6, L.5, I appreciate the reference to the original (and often forgotten) Taber Paper on ice segregation*

   Cheers! Far too often the good fundamental papers don't get cited…

7. *L 10, Here I suggest adding aggradational ice at the base of active layer in areas where there is surface sedimentation (alluvium, colluvium, aeolian, organic).*

We have added this (now p6 line 15)

8. *P7, L3-4, I suggest to start the sentence by "Since most of the permafrost in surficial geological materials formed during and after the last glaciation, we model..."*
Good point, we have edited the sentence accordingly.

9. L 10. Precise: emerged (post-glacially uplifted) marine sediments

We have clarified that the sediments are emerged

10. *L11, again precise: "deposited in post-glacial seas"*
Added

11. *L16, I suggest adding a sentence: "Indeed, it can be assumed fine-grained matrix-rich tills are more prone for ice segregation than coarsed-matrix tills".*

We have added: It can be assumed that dominantly fine-grained matrix soils are more frost susceptible than coarse-grained deposits.

12. *L17 Precise: "each surficial geology unit"*

We have added "each surficial material unit"

13. *P8, L9, replace "since" by "but" or by "however"*
We have added "however"

14. *P9, L10, The ice volume is still very high in palsas, this is a decrease of permafrost area but not of % content in the remaining local permafrost. Avoid confusion between ice content in the permafrost in an area and ice content in a map area (see my first comment in the abstract)*

We have added a sentence to clarify this: It should be noted that these reductions reflect an overall decrease in ice abundance in the mapping units, though segregated ice content may remain high locally in remnant palsas and lithalsas.

15. *L14, I suggest replacing "melt" by "remnants of relict ice preserved: : :"*

==We have edited this sentence to indicate the model reflects the preservation of buried glacier ice.==

16. *L15, frost cracking takes place more in mid winter than in late winter*
    ==We have changed it to "mid to late winter" to be more inclusive.==

17. *P10, L 17-18 I cannot make sense of the sentence: "Finally, the present-day permafrost distribution is used to the differential melt of ice-wedges…" this needs more explanation.*

    ==We have added an additional sentence to clarify this==

18. *P 11. L 1, precise: the modelled distribution of segregated ice (your result is a predictive model)*

    ==We have added "modelled" to clarify this.==

19. *L4 replace "the" by "its"*
    ==Not sure where this is referring to – the only "the" on P11 L4 seems correct.==

20. *L7 should you not precise "Early Holocene" ?*

    ==We do not specify Early Holocene here because there are also small adjustments in the tree line later in the Holocene, though the most obvious changes were earlier.==

21. *P12, L2, add "in" glacial lake sediments*
    ==added==

22. *P13, L 16, spell out the Permafrost Map of Canada (PMC)*

    ==We have spelled it out in this paragraph to remind the reader of the acronym.==

23. *P14, L 26-27 be careful here, fine-grained slopewash material, weathered sedimentary rock and fine-grained regolith may contains significant segregated ice. I have even found segregated ice in sedimentary shales on an Arctic Island.*

    ==We have now split colluvial material into coarse/fine grained based on the underlying bedrock (see point 35). Fine-grained colluvium now has higher values for segregated ice and wedge ice grows more readily in the model. As for regolith/shales, we do not dispute that there are areas with ice in them. However, based on the average condition in these units, we must assign a reasonable relative value.==

Since on average these units are likely less frost-susceptible than marine, lacustrine, fine-grained tills deposits, we assign them a lower relative value.

24. P15, L3-4. I strongly support that the new model better represents distribution of segregated ice in Canada

Thanks, we are very glad of this!

25. L17 watch out. The model may fail in wet plains area, where surface drainage is poor, cracking frequent and water available each spring to feed the growth of ice veins and wedges.

Good to know – though the only published field evidence (that we could find) for the Great Plain of Koukdjuak indicated only small wedges. However, this point may be part of the reason the model seems to underestimate wedge ice in some areas Hudson Bay Lowlands (we have seen this in imagery). We have added a few sentences into the "conceptual validity" section on this point, and referenced this review.

26. L 19. Incipient

Thanks for noticing this!! Corrected

27. L20-25 again in the case of ice wedges: specify: abundance on ground ice in the model means spatial, i.e. amount by surface area, not at all locations.

We have now addressed this by indicating that abundance is amount per map unit.

28. P16, L12-13 "small units between two larger units were attached to similar adjacent units" incomprehensible technical jargon.

We have simplified this sentence to: "This reduction caused the removal of some small map units and a consequent loss of detail in the surficial geology dataset"

29. P17, L4 add "full" before complexity

Added, thanks

30. L10, add "overly" before simplified
Added

31. *L26-27 there is another issue with peatlands and permafrost in vast areas where palsas are found: often the minerotrophic peat has accumulated in non-permafrost conditions during warmer early Holocene climate interval. It froze into epigenetic permafrost during Late Holocene (Neoglacial and LIA) cold intervals.*

This is a good point. We mention that we cannot address the timing of peat accumulation in our model presently, and that the evolution of peatland terrain is a weakness in the model. I think this is something that could be considered for future improvements in the modelling, but at present is beyond the scope of the discussion to consider in detail.

32. *P18, L5 also on some Arctic Island, see Fortier and Allard, The Holocene, on Bylot Island.*

We have added reference to this paper in the paragraph

33. *P19, L4, replace "may " by shall*
We replaced with "will"

34. *L9 "updated paleoenvironmental information" : among these are treeline migrations during the Holocene which your model does not seem to consider. They are important for the current distribution of ice-rich permafrost in the discontinuous zone.*

Treeline migration is accounted for in the different biome distributions, i.e., the boundary between forest tundra and tundra. Though perhaps the treatment of this boundary could be improved in the model as it relates to ice-rich permafrost in the discontinuous zone.

35. *Table 1: I Think that low ice content in colluvial deposits is likely an erroneous interpretation. Fine grained ones can be rich in aggradation ice and wedge ice.*

We have considered this carefully. The initial rationale for low ice content in colluvial deposits was based on the legend description on Fulton's surficial geology map, which indicates that colluvial units are dominantly coarse grained. However, we fully agree that there are fine-grained ice rich colluvial deposits in places. Our solution has been to split the colluvial units based on the bedrock source, as we did for till. We have increased values for fine-grained colluvial units, which has resulted in higher segregated and wedge ice in areas of Yukon and some Arctic Islands. We think the depiction is more accurate now, and thank you for spurring this change.

36. *Figures: they are great.*

Thanks!

6

Response to M. Kanevskiy

Dear Dr. Kanevskiy,

Thank you very much for reviewing the paper and for the constructive comments and annotations on the PDF. We have implemented most of the suggested changes from the PDF and addressed all major comments below. We appreciate your time spent on the review, and your input has certainly improved the paper.

1. *I recommend to change the title because "a paleogeographic modelling" is only a part of your approach and does not reflect the entire process. Maybe just "a modelling approach"?*

   We have kept the title as is, as paleogeographic datasets are fundamental to all the models (e.g., the paleovegetation dataset, deglaciation, glacial lake and marine inundation). Many of the conceptual models that form the expert system are paleogeographic in nature.

2. *I recommend to clarify some terms and definitions. You often use the term "massive ice and icy sediments" (page 2, line 5; page 4, line 30; page 5 line 15, etc.) to describe tabular massive-ice bodies of either glacier or intrasedimental origin. This approach is common in the permafrost literature (e.g., Heginbottom et al., 1995; Brown et al., 1997; French, 2018) but the term "massive ice" itself is very general. This term covers many types of ground ice (including wedge ice) so I recommend to specify what particular type of massive ice you are talking about.*

   Yes, we also struggled with what to call this class of ice. The PMC refers to "massive ice" as "extensive sheets", but of course, buried glacial ice may be irregularly shaped, as can bodies produced by segregation/intrusion. We have decided to change the name of this ice class to "relict ice" (e.g., Kokelj et al. 2017), and have clarified in Sect. 2.1 that this ice is either buried glacier ice or intrasedimental ice formed by segregation/intrusion.

3. *The term "intrasedimental ice" is also very general (for example, see French, 2007, p. 182) but you apply it only to tabular massive ice bodies*

   We have removed the "tabular" qualifier so that other shapes of intrasedimental ice are not excluded.

4. *When you use the term "segregated ice" (e.g., page 6, line 5), it's better to specify that here you are talking not about massive ice bodies formed by segregated ice but about relatively thin lenses and layers that form cryostructures of the frozen soils*

We have added a sentence that we are not referring to larger intrasedimental ice bodies of segregation/injection origin.

5. Page 4, lines 9-11. I cannot see a big difference here: both maps (Heginbottom et al., 1995, and Brown et al., 1997) do not present numerical estimates for massive ice, pingos, and ice wedges using different symbols for their general distribution (abundant and sparse) instead

The legend of the Brown map does not indicate that the larger ice bodies are not included in the numeric estimates. Either way, perhaps this was the intent. We have removed the related sentences, as we have decided they add unnecessary confusion.

6. Page 4, lines 33-35. Increases in active layer thickness cannot reach 5 m (in such case, it's already permafrost degradation), so I recommend to talk about thermokarst and thaw subsidence to explain why these top 5 m of permafrost are so important.

True – we have changed the wording here to "thaw depth" instead of "active layer thickness".

7. 7. Page 5, lines 8-16. I recommend to rewrite this paragraph. When you describe formation of segregated ice…

We have reworked this paragraph to present aggradational ice/the intermediate layer up front, and simplified the text.

8. Page 5, lines 17-21. I recommend to omit or simplify this paragraph: instead of talking about beds of intrasedimental ice, it's more important just to emphasize that here you are talking about relatively thin lenses of segregated ice that form various cryostructures and not about massive ice bodies formed by segregated ice.

We have simplified the paragraph, focusing on the difference in lens thickness and formation setting.

9. I recommend you not to use terms "extensive discontinuous" and "sporadic discontinuous zones." These terms were used in PMC (Heginbottom et al., 1995) but now synonymous terms "discontinuous" and "sporadic" are much more common. Anyway, you use both sets of terms in the same paper, and it doesn't look good – it's always better to be consistent.

We have corrected this issue and updated the nomenclature to "discontinuous" and "sporadic"

10. *In your manuscript, you do not describe yedoma in Canada…*

5

<mark>Since the model considers ice formed since 17 ka, we did not discuss Pleistocene syngenetic permafrost. However, you are right that these deposits are very important given the high ice content. We have added material to this section and suggested incorporating this into future modelling/mapping, as suggested.</mark>

New ground ice maps for Canada using a paleogeographic modelling approach

5 H. Brendan O'Neill[1], Stephen A. Wolfe[1], Caroline Duchesne[1]

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Abstract

Ground ice melt caused by climate-induced permafrost degradation may trigger significant ecological change, damage infrastructure, and alter biogeochemical cycles. The fundamental ground ice mapping for Canada is now >20 years old, and does not include significant new insights gained from recent field and remote sensing based studies. New modelling incorporating paleogeography is presented in this paper to depict the distribution of three ground ice types (relict ice, segregated ice, and wedge ice) in northern Canada. The modelling uses an expert-system approach in a geographic information system (GIS), founded in conceptual principles gained from empirically-based research, to predict ground ice abundance in near-surface permafrost. Datasets of surficial geology, deglaciation, paleovegetation, glacial lake and marine limits, and modern permafrost distribution allow representations in the models of paleoclimatic shifts, tree line migration, marine and glacial lake inundation, and terrestrial emergence, and their effect on ground ice abundance. The model outputs are generally consistent with field observations, indicating abundant relict ice in the western Arctic, where it has remained preserved since deglaciation in thick glacigenic sediments in continuous permafrost. Segregated ice is widely distributed in fine-grained deposits, occurring in highest abundance in glacial lake and marine sediments. The modelled abundance of wedge ice largely reflects the exposure time of terrain to low air temperatures in tundra environments following deglaciation or marine/glacial lake inundation, and is thus highest in the western Arctic. Holocene environmental changes result in reduced ice abundance where tree line advanced during warmer periods. Published observations of thaw slumps and massive ice exposures, segregated ice and associated landforms, and ice wedges allow a favourable preliminary assessment of the models, and the results are generally comparable with the previous ground ice mapping for Canada. However, the model outputs are more spatially explicit and better reflect observed ground ice conditions in many regions. Synthetic modelling products that incorporated the previous ground ice information may therefore include inaccuracies. The presented modelling approach is a significant advance in permafrost mapping, but additional field observations and volumetric ice estimates from more areas in Canada are required to improve calibration and validation of small-scale ground ice modelling. The ground ice maps from this paper are available in the supplement in GeoTIFF format.

25

1 Introduction

Ground ice is a key geomorphic agent in permafrost environments, and its formation is associated with characteristic landforms including ice-wedge polygons (Fraser et al., 2018; Lachenbruch, 1962), peat plateaus, palsas, and lithalsas (Laberge and Payette, 1995; Wolfe et al., 2014; Zoltai, 1972), earth hummocks (Kokelj et al., 2007b), involuted hills (Mackay and Dallimore, 1992), and pingos (Mackay, 1973). The degradation of ice-rich permafrost initiates geomorphic processes including thaw subsidence, slumping, active-layer detachment sliding, thaw lake development, and thermal erosion gullying (Kokelj and Jorgenson, 2013). These processes partly drive the evolution of permafrost terrain to produce the current landscape and ecological configuration, and may also damage infrastructure (Jorgenson et al., 2006; Liljedahl et al., 2016; Nelson et al., 2001; Raynolds et al., 2014). The nature and distribution of ground ice controls specific processes and the impacts of thaw on permafrost terrain. For example, melt of thick relict ice may result in the formation of deep thaw lakes in flat areas (Burn, 2002; Dallimore et al., 2000), and large retrogressive thaw slumps on hillslopes (Kokelj et al., 2017). Segregated ice melt may lead to shallow pond and thaw lake development (Hopkins, 1949), and smaller thaw slumps and active-layer detachment slides on hillslopes (Burn and Lewkowicz, 1990; Lewkowicz, 2007). Ice wedge melt may form thermokarst pits and troughs in flat terrain (Jorgenson et al., 2006; Kokelj and Jorgenson, 2013), and thermal erosion gullies on hillslopes (Fortier et al., 2007; Fraser et al., 2018).

The Permafrost map of Canada (PMC) compiled by Heginbottom et al. (1995) remains the primary source depicting ground ice information for the entire country. The ground ice mapping has proven of broad utility across disciplines and is used as input for other products including thermokarst and permafrost hazard potential mapping (e.g., Nelson et al., 2001; Olefeldt et al., 2016). However, the ground ice information is now over two decades old and does not include newer insights on ground ice conditions from field and remote sensing based studies. In addition, the map units are based on broad physiographic regions that include a variety of landscape types and surficial sediments, and thus the ground ice depiction lacks spatial detail. Given anticipated climate-driven permafrost thaw and the recent acceleration of thermokarst processes across circumpolar regions (Fraser et al., 2018; Jorgenson et al., 2006; Lantz and Kokelj, 2008; Liljedahl et al., 2016; Rudy et al., 2017), improving knowledge of ground ice conditions is of critical societal and environmental relevance. The broad aims of this paper are to (1) present a new paleogeographic approach to modelling the abundance of three ground ice types in permafrost, (2) present resulting ground ice maps for Canada, and (3) conduct a preliminary assessment of the model outputs. The specific modelling objectives are to (i) produce an improved depiction of ground ice conditions in Canada that incorporates knowledge gained from recent empirical studies, (ii) encourage the development of questions and hypotheses to guide new empirical ground ice investigations, and (iii) identify requirements to advance future modelling and mapping efforts.

2 Background

Ground ice information on the PMC includes qualitative estimates of the volumetric percentage of visible segregated and intrusive ice in the upper 10-20 m of permafrost (Heginbottom and Dubreuil, 1993). The relative abundance (abundant, sparse,

absent) of larger ice bodies is represented separately using symbols for massive ice, ice wedges, and pingos. The map polygons were based on 141 physiographic regions (Bostock, 1970), with some subdivided based on the distribution of permafrost, resulting in 171 map units (Heginbottom and Dubreuil, 1993). The mapping was developed using a database of available ground ice observations, mostly from western Canada. Gaps were filled by assessing available geological and environmental

5   conditions, and comparing them to adjacent units or others with similar attributes (Heginbottom and Dubreuil, 1993). Ground ice conditions were then assigned to units with similar physiographic attributes. Therefore, much of the mapping in the central and eastern Arctic represents extrapolations based on conditions in the western Arctic.

The ground ice information from the PMC was included on the Circum-Arctic Map of Permafrost and Ground-ice Conditions (Brown et al., 1997). While most of the original elements were maintained, some modifications were included in

10   the circum-Arctic representation. These included the differentiation of map polygons into areas with thin (<5-10 m) and thick (>5-10 m) overburden cover (Brown et al., 1997). In general, this distinction separated the sediment-poor Canadian Shield and areas of exposed weathered bedrock from areas underlain by sedimentary rock with more extensive and thick surficial deposits. The depicted ground ice contents are generally lower in regions with thin overburden (Brown et al., 1997), but the nature and origin of surficial deposits were not explicitly considered.

15   The modelling approach presented here builds on that of Jorgenson et al. (2008) for recent mapping in Alaska. The authors assessed excess ice content – the volumetric ice content in excess of soil pore space – in the top 5 m of permafrost from various ice types, based primarily on surficial geology and permafrost distribution. The ice contents generally correspond to soil texture, with fine-grained, frost-susceptible units assigned the highest values, and buried ice recognized in glacial deposits (Jorgenson et al., 2008). The influence of time and the mode of permafrost aggradation (epigenetic vs. syngenetic) on

20   segregated and wedge ice content were also considered by differentiating old and young glacial deposits, and by recognizing high ice contents in aggraded loess and re-transported colluvial sediments (Jorgenson et al., 2008). Our assessment similarly uses surficial geology as a base dataset. The 1:5,000,000 scale Surficial geology of Canada consists of 10,325 polygons with an average area of about 880 km^2 over Canada's landmass (Geological Survey of Canada, 2014). By comparison, the average area of the polygons on the Heginbottom et al. (1995) map is about 53,200 km^2. Thus, the surficial geology dataset is more

25   spatially detailed and may better represent variation in conditions that control ground ice than the modified physiographic map of Bostock (1970). Modern computing, GIS software, and available digital datasets facilitate this new approach (Heginbottom, 2002).

Three common forms of ground ice in permafrost are modelled: (1) relict ice, (2) segregated ice, and (3) wedge ice, each defined specifically in Sect. 2.1. Volumetric ice abundance in the top 5 m of permafrost is reported qualitatively for each

30   map unit (i.e., pixel). This depth is considered because wedge and segregated ice content is commonly highest within several metres below the permafrost table (Jorgenson et al., 2008; Pollard and French, 1980), and because increases in thaw depth caused by climate variation and surface disturbances are typically restricted within this range (Burn, 1998; Mackay, 1995). Pingos are not modelled, as they form due to local geologic and hydraulic conditions, are easily mapped from observations

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(Jones et al., 2012; Jorgenson et al., 2008; Mackay, 1963), and comprise a low proportion of near-surface ground ice volume even in areas where they are abundant (Pollard and French, 1980).

Rather than extrapolating field observations from northwestern Canada to similar physiographic units across the Arctic (Heginbottom et al., 1995), we model ground ice abundance using an expert-system approach built on principles developed from empirical studies relating environmental conditions to ground ice formation and preservation. The principles are formalized in a GIS using spatio-temporal datasets, and ground ice abundance for each ice type is calculated using map algebra (i.e., raster calculation). The models account for surficial geology, which regulates ground ice formation and preservation, and broad-scale Holocene environmental changes including deglaciation, glacial lake and marine inundation, and paleovegetation shifts that represent climate history. The expert-system is based in logical deduction, and uses numerous conceptual models (rules) that link Holocene environmental conditions and processes to ground ice abundance. These rules include, for example 1) regions covered by thick glacial sediments that have remained in tundra throughout the Holocene may include preserved glacial ice, 2) significant segregated ice has accumulated in regions with fine-grained sediments, 3) ice wedges form over time, and growth rates are most rapid in cold tundra environments, 4) ground ice thaws when terrain becomes inundated by the sea or by proglacial lakes. Many of the studies and datasets key to the model development were unavailable during production of the PMC, and thus the model outputs represent an updated understanding of ground ice conditions in Canada.

2.1. Ground ice types

2.1.1. Relict ice

Here, relict ice is considered as larger bodies or layers of ice preserved in permafrost under overburden by persistent cold-climate conditions. Relict ice may consist of either (1) buried glacier ice (French and Harry, 1988, 1990; Lorrain and Demeur, 1985; St-Onge and McMartin, 1995), or (2) intrasedimental ice formed by segregation, injection, or a combination thereof (Mackay and Dallimore, 1992; Rampton, 1988a). Buried glacier ice in Canada is predominantly found within large hummocky moraine belts and glaciofluvial deposits (Coulombe et al., 2019; Dyke and Savelle, 2000; French and Harry, 1990; Kokelj et al., 2017; Lakeman and England, 2012; Murton et al., 2005), and may consist of englacial or basal ice preserved by an overburden of ablation till or outwash (Evans, 2003). Intrasedimental ice has been identified in some regions of northern Canada (Dallimore and Wolfe, 1988; French and Harry, 1990; Fritz et al., 2011; Mackay and Dallimore, 1992; Murton, 2005; Pollard, 2000). This ice is considered to form by segregation and/or intrusion at the interface between layers of fine-grained and coarse-grained deposits during epigenetic permafrost growth (Mackay, 1971). The underlying unfrozen stratum supplies the water for ice growth. Isotopic evidence indicates that massive intrasedimental ice is commonly of glacial meltwater origin (Mackay and Dallimore, 1992). Thick ice growth may be facilitated by high pore water pressures that develop during freezing of saturated sands and gravels (pore water expulsion) or by glacial meltwater driven toward aggrading permafrost near an ice sheet margin (Konrad, 1990; Mackay and Dallimore, 1992; Rampton, 1988a). Debate remains over the origin (buried glacier

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ice vs. intrasedimental ice) of some ice-cored terrain in northern Canada due to the similar morphological appearance, associated surficial materials, and distribution near margins of the late-Wisconsinan Laurentide Ice Sheet (Evans, 2003). The relict ice model does not account for the localized hydraulic and stratigraphic conditions that may form intrasedimental ice, so the results should be considered representative of relict buried glacier ice, though intrasedimental ice may form locally within
5 the same glacigenic deposits (Murton et al., 2005).

2.1.2. Segregated ice

Segregated ice consists of discrete ice lenses or layers that form by migration of unfrozen pore water towards a freezing front (Taber, 1929). This segregated ice consists of relatively thin ice lenses and layers that form various cryostructures, and is thus differentiated from larger intrasedimental ice bodies formed by segregation and/or instrusion. Segregated ice is widely
10 distributed in fine-grained material in Canada, whereas large intrasedimental ice bodies formed in spatially and temporally restricted proglacial settings during recession of the Laurentide Ice Sheet (Rampton, 1988a), or smaller ice caps (Robinson and Pollard, 1998).

Segregated ice growth results in frost heaving, a displacement of the ground surface due to the volumetric increase of the soil as ice forms (Miller, 1972). Segregated ice forms during epigenetic (downward) permafrost growth, and due to annual
15 downward water migration from the active layer into permafrost (Cheng, 1983; Mackay, 1983). Gradual ice enrichment near the top of permafrost and a rising permafrost table due to climatic cooling, organic accumulation, or sedimentation in alluvial, eolian, or colluvial sediments forms aggradational ice, resulting in an upper ice-rich 'intermediate' layer found commonly in permafrost regions (French and Shur, 2010). Slow epigenetic freezing may form the segregated ice expressed as lithalsas, palsas, and peat plateaus (Allard et al., 1996; Calmels et al., 2008a; Laberge and Payette, 1995; Wolfe et al., 2014). Examples
20 of segregated ice enrichment include the ice visible in exposures above thaw unconformities (Burn, 1988; Kokelj and Burn, 2003), in near-surface sediments of drained-lake basins (Mackay and Burn, 2002a; Morse et al., 2009; O'Neill and Burn, 2012), in aggraded alluvial settings (Kokelj and Burn, 2005; Morse et al., 2009), and in loess sequences (Fortier et al., 2018; Fraser and Burn, 1997; Kotler and Burn, 2000). Segregated ice may be expressed as distinct cryofacies in polygenetic permafrost, where epigenetic permafrost growth is followed by surface sediment or organic matter accumulation and
25 subsequent syngenetic permafrost development (e.g., French and Shur, 2010; Gilbert et al., 2018).

2.1.3. Wedge ice

Wedge ice develops when low winter temperatures cause the ground to contract under stress and crack (Lachenbruch, 1962). Melt water later infills the cracks and freezes in permafrost, forming thin ice veins. Cracking in subsequent years occurs preferentially at existing ice veins because the tensile strength of the ice is lower than that of the surrounding frozen sediment
30 (Lachenbruch, 1962). Repeated cracking, water infilling, and refreezing causes the growth of an ice wedge over time. Ice wedge growth is thus controlled by winter temperature conditions and the time available for ice accumulation (Hamilton et al., 1983; Mackay and Burn, 2002b; Opel et al., 2018). Wedge ice may comprise a significant volume of the upper ground in

permafrost areas (Kanevskiy et al., 2013; Pollard and French, 1980; Ulrich et al., 2014), and the partial thaw of ice wedges can lead to ground subsidence that spurs marked ecological changes (Fraser et al., 2018; Jorgenson et al., 2006; Liljedahl et al., 2016).

3 Datasets and methods

Ground ice in permafrost today is the result of past geological and environmental processes affecting its formation, preservation, and decay (Gilbert et al., 2016). Since most permafrost in the surficial geological material formed during and after the last glaciation, we model ground ice evolution over the last 17 ka in Canada. Ground ice formed in unglaciated terrain prior to deglaciation is thus not considered. The 1:5,000,000 scale Surficial geology of Canada forms the basis of the three ground ice models (Geological Survey of Canada, 2014). Surficial geology units were modified using data from the Glacial map of Canada (Prest et al., 1968) and the bedrock Geological map of Canada (Wheeler et al., 1996) to better reflect physical conditions pertinent to ground ice formation. The distribution of hummocky terrain from the Glacial map of Canada was added to the surficial dataset, as these 'controlled moraine' deposits commonly host relict ground ice in permafrost regions (Dyke and Savelle, 2000; Evans, 2009; Kokelj et al., 2017), which are not adequately represented on the Surficial geology of Canada map. The surficial dataset was further modified by combining emerged nearshore and offshore glaciomarine and marine units deposited in post-glacial seas, respectively, as these typically include sediments with comparable soil textures in both depositional settings (Geological Survey of Canada, 2014), and thus have similar frost susceptibility.

Areas underlain by igneous, metamorphic, and volcanic bedrock were differentiated from those underlain by sedimentary bedrock using the Geological map of Canada (Wheeler et al., 1996). Till and colluvial units from the Surficial geology of Canada map were reclassified as either fine-grained (sedimentary bedrock derived) or coarse-grained (shield bedrock derived) units to reflect characteristic differences in matrix texture controlled by bedrock source (Fulton, 1989). It can be assumed that dominantly fine-grained matrix soils are more frost susceptible than coarse-grained deposits. These changes resulted in 29 surficial material units represented in our models (Fig. S1). Each surficial material unit was assessed in terms of general grain size characteristics and deposit type, which are pertinent to ground ice formation and permafrost preservation. For example, fine-grained offshore lacustrine and marine units are highly frost susceptible, favouring the formation of segregated ice (e.g., Chamberlain, 1981) and a protective surface organic layer (Tarnocai et al., 2011), whereas dominantly coarse-grained deposits are less frost susceptible and less likely to support permafrost in warmer climates (Jorgenson et al., 2008). Similar to the Brown et al. (1997) map, we consider overburden thickness in our assessment, based on surficial material units, i.e., sediment veneers vs. blankets (Fig. S1).

A time series of deglaciation and paleovegetation maps (Dyke et al., 2004) was used to iteratively modify ground ice abundance through 14 time steps from 14 ka BP to 1 ka BP (17.2 cal ka BP to 0.9 cal ka BP; Fig. S2). Four biome classes were considered to generalize climate and permafrost conditions during this period: i) herb tundra (very cold continuous permafrost); ii) shrub and alpine tundra (cold continuous permafrost); iii) forest tundra (warm extensive discontinuous permafrost); iv)

boreal forest and all other biomes (sporadic or isolated permafrost and seasonally frozen ground) (e.g., Burn and Kokelj, 2009; Heginbottom et al., 1995; Smith et al., 2010). The biome distributions control the rate of wedge ice accumulation and the melt of relict and segregated ice in the models due to transitions between tundra and forest during the Holocene (Fig. 1). The time series of ice sheet, glacial lake, and marine limit configurations on the paleovegetation maps are originally from deglaciation

5   maps for North America (Dyke et al., 2003), and are used to define the timing of subaerial exposure in the wedge ice model (Fig. 1). Maximum glacial lake and marine limits from the Glacial map of Canada (Prest et al., 1968) were used to represent Holocene thaw of relict ice due to submergence (Fig. 1). Justification for the inclusion of these processes and responses in the models is provided in Sections 3.1.–3.3. with reference to the pertinent literature. The contemporary permafrost distribution was used to modify ice abundance based on the likelihood of permafrost in different surficial material units (Heginbottom et

10   al., 1995).

The original vector datasets were converted to raster with 1 km^2 pixels. The spatial resolution was used to produce smooth cartographic boundaries, though the typical map unit of the underlying surficial geology dataset is much coarser in resolution, and the paleovegetation and deglacial limits are generalized (Fig. S2). Ground ice abundance in the top 5 m of permafrost is reported for each ice type qualitatively as 'high', 'medium', 'low', 'negligible' and 'none'. The 'none' class

15   represents no excess ground ice in non-permafrost areas, and a general absence in permafrost regions, however areas mapped as bedrock at the scale of the surficial geology dataset may include some sediment cover that hosts ground ice. The model uses ranked numeric values to account for ground ice abundance in the computational steps, but these do not represent absolute quantities or percentages.

3.1. Relict ice model

20   The relict ice model represents preserved buried glacial ice. An initial numeric abundance value is assigned to each surficial material unit in the GIS. Values are highest for thick, fine-grained hummocky till and moraine deposits, as these commonly include buried glacier ice (Evans, 2003; Kokelj et al., 2017), and are also associated with past ice margins where conditions may have been conducive to intrasedimental ice development (Mackay and Dallimore, 1992; Rampton, 1988a; Table S1). Glaciofluvial sediments are assigned a medium value, as glacier ice may be buried by outwash deposits (Coulombe et al.,

25   2018; Evans, 2003; Wolfe et al., 2017). Values are modified through the 14 time steps based on changes in biome distributions and marine and glacial lake inundation, representing melt due to large-scale Holocene environmental changes (Table S2). The partial melt of relict ice is assumed in the modern continuous permafrost zone when tundra transitions to forest tundra and/or boreal forest during the Holocene, as a warmer climate and wildfires near tree line cause increases in active-layer thickness that may partially thaw near-surface permafrost (Kokelj et al., 2017; Mackay, 1995; Murton, 2001). Marine and glacial lake

30   inundation reduce relict ice abundance to zero in the model (Table S2). Although marine settings may preserve ground ice in sub-zero saline waters, most submerged sediments would be subject to a range of water depths and temperatures that are more likely to melt relict ice than preserve it. Dyke and Savelle (2000) have indicated that moraine volumes are considerably reduced where they extend below marine or glacial lake inundation limits. This reduction indicates that inundation either prevented the

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formation of <u>relict</u> ice or caused it to melt rapidly (Evans, 2003). Finally, the modern-day permafrost distribution is applied and <u>relict</u> ice remains preserved in the continuous permafrost zone. <u>Relict</u> ice is considered to melt completely from the modern discontinuous permafrost zone in the model, where ground temperatures are relatively high and frequent forest fires cause significant increases in active-layer thickness (Burn, 1998; Viereck, 1983). The latitudinal decline of slump-affected terrain in
5   the western Arctic over the transition to discontinuous permafrost likely reflects this thaw of relict near-surface ground ice (Kokelj et al., 2017), and there have been no reported observations of <u>relict</u> ice at exposures in the discontinuous permafrost zone in Canada (Table S3). The resulting values represent the relative abundance of relict ice preserved in permafrost.

3.2. Segregated ice model

An initial segregated ice value is assigned to each surficial material (Table S4), representing the frost susceptibility based on
10   general soil texture (Chamberlain, 1981). <u>F</u>rost susceptibility was assessed for each surficial material unit using legend descriptions from the Surficial geology of Canada map, descriptions in other source material (e.g., Fulton, 1989), and expert knowledge of the surficial geology of northern Canada (Table 1). Smith and Burgess (2004) similarly assigned frost susceptibility values to surficial material units in an assessment of the physical response of permafrost terrain to climate warming. The segregated ice values may decline following biome transitions from tundra to boreal forest, reflecting the partial
15   melt of near-surface ground ice during Holocene warm periods (Burn, 1988; Table S5). The values also decrease in discontinuous permafrost zones (Table S6), representing the decrease in areal extent of permafrost and preferential thaw in coarse-grained units. <u>It should be noted that these reductions reflect an overall decrease in ice abundance in the mapping units, though segregated ice content may remain high locally in remnant palsas and lithalsas.</u>

3.3. Wedge ice model

20   Ice wedge cracking typically occurs when <u>ground</u> temperatures fall below -10 to -15 °C, usually in <u>mid to</u> late winter (Allard and Kasper, 1998; Fortier and Allard, 2005; Kokelj et al., 2007a; O'Neill and Christiansen, 2018). Snow cover and winter air temperatures critically control these ground thermal conditions (Lachenbruch, 1962; Mackay, 1974, 1992). Both winter air temperatures and snow depths generally decrease northward from boreal forest to tundra (Atlas of Canada, 2010; Palmer et al., 2012). In tundra, snow cover properties are dominantly controlled by vegetation characteristics and site-scale topography
25   (Essery and Pomeroy, 2004). Shrubs trap windblown snow, protecting it from densification and sublimation, which promotes thicker snow cover and warmer ground temperatures than in barren tundra (Liston et al., 2002; Sturm et al., 2001). The northward decrease in air temperature and snow depth result in an associated decline in ground temperatures (Burn and Kokelj, 2009; Smith et al., 2010).

      There are few long-term records of ice-wedge cracking in Canada, but these generally indicate decreasing cracking
30   frequency moving from tundra to forest environments in response to warmer ground temperatures (Kokelj et al., 2014). Observations by J. Ross Mackay provide a wealth of information from the western Canadian Arctic (Burn, 2015), and results from monitoring on Bylot Island, Nunavut, are also instructive (Fortier and Allard, 2005). In herb tundra on Bylot Island,

cracking monitored at two ice wedges occurred in 4 (67%) and 5 (83%) out of six winters, with both wedges cracking in three winters (Fortier and Allard, 2005). In low shrub tundra at Garry Island, Northwest Territories, cracking frequency at one site over 12 years was 8-42% and at another 22-75% over 20 years. Ice-wedge cracking frequency in 1968-1973 at 10 sites decreased linearly with snow depth (Mackay, 1974, Fig. 19). At the Illisarvik drained lake basin on Richards Island, Northwest Territories, ice wedge development was rapid on the initially-barren drained lake bottom (Mackay, 1986). Cracking frequencies decreased as vegetation established and snow cover increased, and all cracking ceased when snow depths reached about 0.6 m (Mackay, 1986; Mackay and Burn, 2002b). Near the tree line at Inuvik, Northwest Territories, no cracking was recorded at twelve locations in forest in 1980-1988 (Mackay, 1992). The growth of spruce trees in many of the troughs attested to infrequent recent cracking. Similarly, ice-wedge cracking is inactive in white spruce forests in eastern Mackenzie Delta (Kokelj et al., 2007a). Infrequent cracking during cold years led to the formation of thin ice veins in the boreal forest in central Yukon Territory since the 1950s (Burn, 1990). In Alaska, ice wedges are typically weakly active or inactive in forested areas of the discontinuous permafrost zone (Jorgenson et al., 2008). However, it is unlikely that significant wedge ice accumulates in the northern boreal forest, since the recurrence interval of fires is commonly <150 years (Johnson, 1979; Larsen, 1997; Payette et al., 1989; Viereck, 1983). These environmental conditions cause the size of ice wedges and the density of polygonal terrain to decrease southward across the tundra-forest transition (Kokelj et al., 2014).

Wedge ice abundance is modelled over the 14 time steps. Ice accumulates over time as terrain becomes exposed following deglaciation or lake/marine recession. Based on available empirical data on ice wedge cracking and broad patterns of vegetation, snow cover, and ground temperature, we assume the rate of wedge ice growth is greatest in herb tundra, moderate in shrub and alpine tundra, and low in forest tundra (Table S7). Wedge ice accumulation is considered most rapid within herb tundra in thick, fine-grained sediments, where cold winter air temperatures and thin snow cover are conducive to frequent and deep thermal contraction cracking (Lachenbruch, 1962). Wedge ice remains preserved but ceases to accumulate in areas that transition from tundra to boreal forest biomes, as ground thermal conditions in forest are typically not favourable for ice-wedge cracking (Burn, 1990; Kokelj et al., 2007a, 2014; Table S7). Finally, the current permafrost distribution from Heginbottom et al. (1995) is used to model the differential melt of ice wedges in discontinuous permafrost depending on the surficial material (Table S8). For example, wedge ice is assumed to melt from coarse-grained glaciofluvial deposits in the discontinuous, sporadic, and isolated permafrost zones, as these materials are subject to deep thaw following forest fires and are unlikely to contain permafrost in warmer climates. The resulting accumulated numeric values are reclassified as high, medium, low, and negligible abundance using the quantile method (Table S9).

4 Results

Modelled relict ice abundance mainly reflects the distribution of thick glacigenic sediments in regions that have remained in herb and shrub tundra environments since deglaciation, and occur in the modern continuous permafrost zone (Fig. 2). High abundance occurs in four main areas 1) western Arctic islands, including Banks and Victoria islands, 2) the western Arctic

mainland, 3) the central Canadian Shield, and 4) northwest Baffin Island. Areas of high relict ice abundance constitute about 2% of the continuous permafrost zone in Canada and areas of medium abundance about 9%.

Modelled segregated ice is widely distributed owing to the ubiquity of fine-grained surficial materials in northern Canada. High abundance occurs in areas covered by marine or lacustrine sediments that are in tundra of the continuous

5 permafrost zone (Fig. 3). Areas of high abundance occupy about 3% of the continuous and 4% of the discontinuous permafrost zones, respectively. Areas of medium segregated ice abundance are widespread, occupying about 25% of the continuous and 17% of the discontinuous permafrost zones, respectively. These areas largely reflect the distribution of till derived from sedimentary bedrock, particularly in northwestern Canada, which may include a significant fine-grained fraction. Paleovegetation distribution also influences modelled segregated ice, particularly in the Mackenzie Valley of the western

10 Arctic where Holocene tree line advance causes a modelled reduction in ice abundance.

Modelled wedge ice abundance largely reflects exposure time of unconsolidated sediments to cold climatic conditions. The pattern of deglaciation and Holocene environmental history thus strongly control the modelled wedge ice distribution. Abundance is high where herb and shrub tundra have persisted for long periods (ca. 13 ka), including the western Arctic islands and some areas of the western Arctic mainland and coast (Fig. 4). As with segregated ice, a corridor of negligible

15 wedge ice abundance in the western Arctic is associated with Holocene tree line advance. Areas of high and medium wedge ice abundance comprise about 2% and 10% of the modern continuous permafrost zone, respectively. Wedge ice abundance is generally low and negligible in the discontinuous and isolated permafrost zones, reflecting the limited time that tundra conditions persisted following deglaciation in more southerly regions.

4.1. Model evaluation

20 The model validation process may include a number of techniques, but 'validation' ultimately depends whether the model behaviour seems reasonable to knowledgeable people given the stated model objectives and performance criteria (Riseborough et al., 2008; Rykiel, 1996). Our modelling objectives were to produce an updated depiction of ground ice in Canada, encourage questions that guide new ground ice investigations, and identify requirements to advance future modelling efforts. Systematic observations of different ground ice forms are still lacking from many areas, making quantitative validation techniques in most

25 areas impossible. Therefore, we present comparisons between the model outputs, available field observations, and the ground ice mapping of Heginbottom et al. (1995). As more data become available or are compiled, continued scrutiny of the methodology, parameterization, and outputs will permit improvements through an iterative modelling approach (e.g., Overton, 1977), contributing to an improved understanding and depiction of ground ice in permafrost in North America.

4.1.1. Relict ice

30 Areas with high modelled relict ice abundance correspond well with the distribution of large thaw slumps, which typically develop in areas underlain by thick layers of relict ice (Kokelj et al., 2017), helping validate the model in northwest Canada (Fig. 5). The model reproduces relict ice observed directly or interpreted from thaw slump mapping on Banks Island, Victoria

Island, the western Arctic mainland, the central Canadian Shield, and Ellesmere Island (Fig. 5b; see Fig. S3 for specific locations mentioned throughout the text). Areas of high ice abundance are associated with hummocky till and moraine deposits that have remained in tundra and continuous permafrost during the Holocene. Field observations of relict ice from the discontinuous permafrost zone are lacking, as is indirect evidence in the form of large thaw slumps (Fig. 5b). The model also depicts relict ice in medium and lower abundance in other glacigenic terrain of the continuous permafrost zone that was not inundated during the Holocene. It is difficult to evaluate results in many of these areas due to the lack of field evidence. Nonetheless, it seems reasonable that relict ice may remain preserved in other till and glaciofluvial deposits.

4.1.2. Segregated ice

Areas with high modelled segregated ice abundance occur in raised marine and in glacial lake sediments, and correspond to observations of widespread shallow thaw lakes, lithalsas, palsas, and peat plateaus (Fig. 6). High segregated ice abundance is modelled in Old Crow Flats in Northern Yukon where there are about 2700 shallow thermokarst lakes with an average depth of <2 m (Turner et al., 2014). In epigenetic permafrost, segregated and wedge ice is concentrated in the upper sediments, which explains the shallow thaw lake depths (Matthews et al., 1990; Roy-Leveillée and Burn, 2015, 2017). High segregated ice abundance is modelled in Hudson Bay Lowlands and is evident in the form of widespread palsas and peat plateaus in the uplifted fine-grained marine sediments (Kuhry, 2008; Payette, 2004). High abundance is also modelled around Umiujaq on eastern Hudson Bay, where both palsas and lithalsas are common (Allard and Seguin, 1987; Calmels et al., 2008b). Southwestern Baffin Island also includes high segregated ice abundance where shallow (< 2 m) thaw lakes and drained lake basins are widespread on the Great Plain of the Koukdjuak (Martini and Morrison, 2014).

High segregated ice abundance modelled on small parts of the Fosheim Peninsula on Ellesmere Island correspond to areas covered by fine-grained, ice-rich deposits (Pollard, 1991). Massive intrasedimental ice may underlie these deposits, and is considered to have formed by segregation during permafrost aggradation into sands and silt overlying unfrozen coarse strata with highly pressurized groundwater (Pollard, 2000; Robinson and Pollard, 1998). These specific formation conditions following marine emergence are not considered in either the relict or segregated ice model, but the general near-surface ice conditions are nonetheless represented by the high modelled segregated ice abundance. Medium segregated ice abundance is modelled over much of the western Arctic mainland, Banks, and Victoria islands in till derived from sedimentary bedrock. These areas also include abundant shallow thaw lakes (Burn, 2002; Dallimore et al., 2000) and thaw slumps (e.g., Lantz and Kokelj, 2008). Further south in the discontinuous permafrost zone, small thaw slumps and active layer detachment slides occur in the Mackenzie Valley where segregated ice abundance is largely modelled as low or medium (e.g., Couture and Riopel, 2008).

4.1.3. Wedge ice

The modelled distribution of wedge ice generally corresponds to field and remote sensing observations of ice wedges and polygonal terrain. The size of ice wedges and the density of polygonal terrain decreases southward across the tundra-forest

transition in the western Arctic (Kokelj et al., 2014), and the wedge ice model reproduces this general pattern as an increase from negligible to high wedge ice abundance (Fig. 7). Areas of modelled negligible wedge ice abundance in forest-tundra generally correspond to small ice wedges observed only in organic soils. Low wedge ice abundance corresponds to small-to-moderate sized ice wedges observed in both mineral and organic soils in shrub tundra (Kokelj et al., 2014). Areas of medium ice wedge abundance correspond to medium-to-large ice wedges observed further north in dwarf-shrub tundra (Fig 7). Pollard and French (1980) estimated that wedge ice on Richards Island constitutes about 12% of the upper 4.5 m of permafrost, where the modelled abundance is medium to high (Fig. 7a).

High wedge ice abundance is modelled over large areas of Banks and Victoria Island (Fig. 4). Evidence of abundant large ice wedges is available from imagery and from field investigations on Banks Island. Ice wedges may exceed 3 m in width and 10 m in depth, and comprise up to 15% of the volume of upper ground (French, 1974). The formation of large ice wedges in this environment occurs due to the persistence of an Arctic climate for millennia. In addition, wedge growth may be facilitated where it occurs in relict ice, which has a high thermal contraction coefficient, promoting wide and deep thermal contraction cracking (Lachenbruch, 1962). A recent image analysis of Banks Island highlighted the widespread degradation of large ice wedges and the resulting broad-scale increase in ponding in flatter terrain (Fraser et al., 2018).

Recent estimates on Fosheim Peninsula indicate that ice-wedge polygons cover about 50% of the terrain, and that wedge ice occupies between 1.4 to 5.9% volume of the upper 5.9 m of permafrost (Bernard-Grand'Maison and Pollard, 2018). In this region, wedge ice abundance is modelled mostly as low, with some small areas of medium abundance (Fig. 4). The modelled wedge ice abundance and field/imagery derived wedge volume estimates are thus generally consistent for Banks Island, Richards Island, and Fosheim Peninsula.

4.2. Comparison with previous mapping

The broad patterns of modelled relict, segregated, and wedge ice abundance are similar to those mapped by Heginbottom et al. (1995) on the Permafrost Map of Canada (PMC), but the modelled results are more spatially explicit and portray ground ice conditions more accurately in many regions. The modelled ground ice abundance was compared to the PMC by standardizing the legends and producing a difference map using a raster combination (Table 2; Fig. 8). The ice class on the PMC that includes "segregated ice, intrusive ice, reticulate ice veins, ice crystals and ice coatings on soil particles" was considered analogous to the modelled segregated ice in this paper, since reticulate veins and ice coatings on soil particles also form by segregation, and intrusive ice forms only under localized conditions. Massive ice on the PMC is considered analogous to modelled relict ice, and is referred to as such in the comparison. The comparison for each ice type is not exhaustive, but rather focuses on regions with significantly different assessed ice abundance: i.e., (1) where our models indicate high ground ice abundance and the PMC indicates low or none; (2) where the PMC indicates high ground ice abundance and our models indicate low or none (see Table 2; Fig. 8).

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4.2.1. Relict ice

Both representations generally depict abundant ice on the western Arctic mainland and Banks and Victoria islands, but the model output is more spatially defined and more accurately reflects current knowledge of the distribution of relict ice (Fig. 2, 8a). For example, no relict ice is modelled on southeastern Victoria Island, where marine inundation is considered to have melted relict ice (Fig. 2, 8d). This interpretation is supported by the lack of large thaw slumps mapped in the region (Fig 5b; Kokelj et al., 2017). The PMC indicates abundant relict ice over most of the Canadian Arctic Archipelago islands northeast of Banks and Victoria islands (Fig. 8a, d). In contrast, the model indicates that relict ice is absent on most of these islands, as the surficial materials are regolith or colluvium and are thus unlikely to include large preserved ice bodies. In addition, many of the islands were partially or fully inundated following deglaciation. On the Great Plain of the Koukdjouk, western Baffin Island, the PMC indicates abundant relict ice. However, the region was also marine inundated, and the shallow depths and consistent shape of the lake basins there indicate thaw of uniformly distributed segregated ice restricted to upper sediments rather than of thicker relict ice bodies (Martini and Morrison, 2014). In the Peel Plateau region, areas of high and medium modelled relict ice abundance occur where widespread exposures have been observed directly and mapped using remotely-sensed imagery (Kokelj et al., 2015; Lacelle et al., 2015). In contrast, the PMC indicates that relict ice is absent or sparse in this region (Fig. 8a, d). The model indicates an absence of relict ice in Old Crow Flats, whereas the PMC indicates that it is abundant (Fig. 8d). The region includes abundant ice wedges, a thin layer of near-surface segregated ice, and resulting shallow thermokarst lakes (Labrecque et al., 2009; Roy-Leveillée and Burn, 2017), but evidence of relict ice is lacking. The past submergence of the area by glacial Lake Old Crow and associated deposition of thick glaciolacustrine sediments precludes the preservation of relict ice, so the modelled output is more appropriate. In the northern Mackenzie Valley region, the relict ice abundance is higher on the PMC than the model output (Fig 8d). Low, negligible, and no relict ice is indicated by the model due to the presence of different till units (hummocky, blanket, veneer), and reductions in modelled abundance due to Holocene tree line advance in the region. The large physiographic unit with abundant ice on the PMC extends south to areas with little evidence in the form of large thaw slumps (Fig. 5b). In these examples the modelled distribution of relict ground ice is in better agreement with available empirical data and more spatially discrete than the portrayal on the PMC. Further empirical investigations are required to assess the model outputs in some areas, such as on Brodeur Peninsula on northwest Baffin Island and on the central Canadian Shield, where the modelled abundance is higher than on the PMC (Fig. 8d).

4.2.2. Segregated ice

The distribution of segregated ice is also broadly similar on the PMC and model output, with relatively high abundance portrayed over much of the western Arctic mainland and islands (Fig. 3, 8b). However, some key differences are evident (Figure 8e). For example, ice content is considered low-medium in Hudson Bay Lowlands on the PMC, whereas the model output indicates high abundance in the extensive fine-grained marine sediments (Fig. 8e). Smith and Burgess (2004) similarly mapped this region as having high thaw sensitivity due to high ground ice content. Given the abundance of peat plateaus and

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palsas in this region and the evident landscape change that has occurred due to recent ground ice melt (Payette, 2004), the high modelled segregated ice abundance is more appropriate. The PMC indicates a higher abundance of segregated ice than the model in some areas on eastern and high Arctic islands (Fig. 8e). However, many of these areas are covered by weathered regolith or bedrock, which are not highly frost susceptible and thus likely contain little excess ice. The modelled abundance is

5   higher than the PMC in some areas mapped as fine-grained colluvium, notably on parts of Axel Heiberg and Melville Islands. High segregated ice abundance is indicated on the northeast Tuktoyaktuk coastlands on the PMC, whereas the model indicates a general absence (Fig 8e). The surficial materials in this area are largely eolian sand and sandy outwash that contain little segregated ice (Rampton, 1988b). Some small areas with frost susceptible lacustrine deposits are also present (Rampton, 1988b), but not mapped at the scale of surficial geology dataset used in the model. The PMC indicates high segregated ice

10 abundance in the Mackenzie Valley area south of tree line, where the modelled abundance is reduced to represent periodic thaw and loss of ice from the upper permafrost (Burn, 1988; Shur et al., 2005). This modelled pattern requires further investigation. The model indicates high or medium segregated ice abundance in many areas of the central Canadian Shield that include frost-susceptible sediments, whereas the PMC indicates low-medium or low ice content in the encompassing physiographic regions (Fig. 8e). The difference map in Figure 8e highlights how the surficial geology basemap leads to a more

15 detailed depiction of segregated ground ice that accounts for the heterogeneity in frost susceptibility of surficial materials. The model depiction is an improvement in several regions, but further evaluation using field datasets is required in some areas to better assess the outputs.

4.2.3. Wedge ice

Broad patterns of wedge ice abundance are similar on the model output and the PMC, with areas of high abundance

20 concentrated in the western Arctic (Fig. 4, 8c). However, the PMC indicates more wedge ice on many of the islands of the central and northern Canadian Arctic Archipelago (Fig. 8f). The modelled abundance on these islands is generally low or negligible because the substrate is dominantly coarse-grained and thin regolith, which does not favour ice wedge development. Small areas of medium and high abundance are modelled near some coasts in fine-grained till and marine deposits, and in fine-grained colluvium in areas with sedimentary bedrock. The lower modelled abundance on most of the islands is a more

25 reasonable depiction, particularly considering the lack of polygonal terrain visible in imagery compared to Banks Island, where large ice wedges are widely distributed and the modelled abundance is high (Fraser et al., 2018). Abundant ice wedges are indicated on the PMC on southwest Baffin Island on the Great Plain of the Koukdjuak (Fig. 8c). In contrast, our model results indicate only negligible to low wedge ice abundance in the area (Fig. 4), partly because the plain has only been terrestrially exposed for ca. 4 ka. The modelled abundance better represents field conditions, as only small incipient ice wedges occur on

30 the plain (Martini and Morrison, 2014). In the northern Mackenzie Valley and Mackenzie Delta regions, modelled wedge ice abundance is lower than indicated on the PMC due to the modelled decrease of wedge ice across the tundra-forest transition (Fig. 4, 8f). As indicated in Sect. 4.1.3., this pattern reproduces the observed southward decrease in polygonal terrain density and wedge width on the western Arctic mainland (Kokelj et al., 2014). Modelled wedge ice abundance is high or medium in

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the Peel Plateau region, but sparse or absent on the PMC. In this case, field observations suggest that the PMC better represents wedge ice conditions, as the distribution of polygonal ground on Peel Plateau is limited to small peatlands that occupy a small proportion of the overall landscape (S.V. Kokelj, personal communication, 2018). Sect. 5.1.2. discusses why the model likely over represents wedge ice in the region.

5   These comparisons highlight the limitations of representing ground ice conditions in large physiographic units that may include a range of surficial materials and landscape histories. Overall, the model outputs offer an improved representation of known ground ice conditions by accounting for specific surficial materials and considering the effects of broad-scale environmental processes. The apparent inaccuracies on the PMC in many areas necessarily impact the output of other broad-scale landscape assessments that use the ground ice distribution as input parameters, such as mapping of thermokarst

10   landscapes and permafrost hazard potential (e.g., Nelson et al., 2001; Olefeldt et al., 2016).

5 Discussion

5.1. Limitations

The presented models include several limitations and assumptions that originate from (1) input data validity, (2) conceptual validity, and (3) the calibration of input values (Rykiel, 1996). Nonetheless, the resulting ground ice distributions appear

15   reasonable, recreating broad patterns from previous mapping, and improving the depiction in many regions.

5.1.1. Input data validity

One of the main challenges of representing complex phenomena over large areas is the precision and accuracy of the source information. The surficial material dataset used in the models, though more spatially detailed than physiographic units used in previous mapping (Brown et al., 1997; Heginbottom et al., 1995) lacks precision and accuracy in some areas. The mapping by

20   Fulton (1995) synthesized maps that were typically 1:50,000 to 1:250,000 scale. The map units for the national representation were compiled at 1:1,000,000 scale and then photographically reduced to 1:5,000,000 scale (Fulton, 1995). This reduction caused the removal of some small map units and a loss of detail in the surficial geology dataset (Fulton, 1995). In addition, many areas of Canada and particularly the Arctic remained unmapped at the time of compilation. In these areas, Fulton (1995) relied on available literature and assessments by experts to delineate surficial units. These deficiencies caused inaccuracy in

25   the modelled results in some areas. For example, lithalsas are abundant in glaciolacustrine sediments along the northern shore of Great Slave Lake near Yellowknife, Northwest Territories (Wolfe et al., 2014). Segregated ice is modelled as either absent or negligible in much of this area because surficial materials are mapped as bedrock and till veneer. More recent mapping has properly identified the widespread glaciolacustrine sediments that host the many ice-cored features in the region (Stevens et al., 2017; Wolfe et al., 2014). Therefore, the model output could be improved by including updated surficial geology mapping.

30   These data are becoming available in a consistent digital format through new mapping and conversions of existing maps by the Geological Survey of Canada (Deblonde et al., 2018).

The generalized paleogeographic datasets, although fundamental to the model, are inherently limited and subject to scrutiny regarding the timing and spatial extent of the last glaciation, deglacial limits, lake and sea levels, and biome distributions. For example, the paleovegetation dataset of Dyke et al. (2004) has several limitations that affect model results. The biome distributions are based on a relatively large dataset of pollen sites, plant and terrestrial mammal macrofossils across northern North America (n = 4659), but these observations are most limited in modern herb, shrub, and forest tundra environments. Therefore, the interpretation of biomes and their limits are approximations, particularly in northern regions. Second, the biome distributions reflect climatic factors such as growing season length and the mean temperature of the warmest month, which are not direct analogues of ground thermal conditions. Climatic and vegetation conditions may vary significantly within each of the defined biomes, affecting ground thermal conditions controlling, for example, wedge ice development or the preservation of relict ice.

5.1.2. Conceptual validity

Conceptual validity refers to the justifiability of underlying theories and assumptions in the model that represent the system behaviour (Rykiel, 1996). For each model, the cause-effect relations and assumptions are explained in the methods section and supplementary material. Necessary assumptions in the expert system do not fully capture the full complexity of conditions known to influence ground ice growth and decay. For example, the relict ice model does not deal with ice melt over time in tundra environments of the continuous permafrost zone resulting from erosional processes. Melt of relict ice may occur irrespective of climatic amelioration due to colluvial, fluvial, or coastal erosion processes, which are controlled by topography, site-scale conditions, and energy and mass transfers that are not represented in the models.

For the wedge ice model, complex relations between air temperature, snow and vegetation conditions, and ground temperature were overly simplified under the broad assumption that ice-wedge cracking frequency increases as air temperature and snow cover decrease from forest to herb tundra (e.g., Kokelj et al., 2014). Regional deviations in air temperature and snow accumulation controlled by synoptic weather patterns and orography were not considered, which may influence wedge ice abundance. For example, the model indicates areas of high wedge ice abundance on Peel Plateau, Northwest Territories, in fine-grained glacigenic sediments that have remained in herb and shrub tundra biomes for much of the Holocene. However, polygonal terrain is sparse in the region. Ice wedge development may be limited on Peel Plateau because winter ground temperatures in the uplands are relatively high, owing to strong winter air temperature inversions and relatively thick snow cover compared to shrub tundra north of latitudinal tree line (O'Neill et al., 2015), and these specific regional conditions are not captured in the model. The model indicates negligible wedge ice abundance in some areas of Hudson Bay Lowlands where dense polygonal networks are visible in satellite imagery. These areas emerged in the mid to late Holocene and include forest tundra vegetation, which both lead to low accumulated wedge ice values in the model. In reality, frequent ice wedge cracking and rapid wedge growth may be facilitated in these plains where the organic cover is thick and there is ample water supply to effectively feed ice vein growth (Allard, 2018).

Finally, the models do not account for the difference in ground ice accumulation due to the mode of permafrost aggradation, i.e., epigenetic or syngenetic. Syngenetic permafrost, which forms contemporaneously with aggrading sediment or organic cover, is commonly more enriched with ground ice than epigenetic permafrost (French and Shur, 2010). In Canada, this has implications to ground ice formation and preservation, particularly where surface organic matter has accumulated during the Holocene. The thermal properties of peat favour aggradation of the permafrost table and the development of thick layers of segregated ice (Burn, 2004; Zoltai and Tarnocai, 1971). In addition, the presence of a surface organic layer may preserve permafrost and underlying inactive ice wedges in environments that no longer support ice-wedge cracking (Shur and Jorgenson, 2007). National-scale datasets of contemporary peatland distribution and thickness are available (Tarnocai et al., 2011), but they do not depict the timing of peat initiation or accumulation over time. Therefore, we do not explicitly consider the important influence of peat accumulation in our models. However, peat accumulation is strongly associated with the hydraulic conductivity of the mineral substrate. Clays and silts have significantly lower hydraulic conductivity than coarser-grained materials, so peat forms preferentially over fine-grained deposits (Tarnocai et al., 2011). Thus, the higher ground ice values assigned to fine-grained lacustrine, marine, and sedimentary bedrock-derived till units indirectly account for the influence of surface organic matter on ice content and the preservation of permafrost. In addition, thick and widespread organic deposits are included in the surficial geology dataset. Nonetheless, the accumulation of peat may be better incorporated in future modelling.

Aggrading fine-grained sediments may also include layers of ice-rich, syngenetic permafrost (Fortier and Allard, 2004; Kanevskiy et al., 2011). Thick Pleistocene loess deposits, sometimes termed 'yedoma', occur in the Klondike region and southwest Yukon, preserving syngenetic wedges and segregated ice (Fortier et al., 2018; Fraser and Burn, 1997; Kotler and Burn, 2000). The ice in these deposits formed prior to 17 ka and may extend to >20 m depth, and is thus not represented by the modelling. Though the distribution of yedoma in Canada is limited to areas of Yukon, the very ice-rich nature of the deposits makes them important to consider in a landscape change context. These deposits could be identified on future ground ice mapping products. Other deposit types, such as alluvial fans, are not differentiated at the scale of the surficial geology dataset, so syngenetic ground ice accumulation at depth in these settings is not represented in the models.

5.1.3. Input value calibration

Calibration includes the adjustment of model parameters to improve agreement between model outputs and observations. The development of the models was an iterative process that included multistage assessments of outputs and small adjustments as knowledge of the mapped surficial material units, paleovegetation distributions, and current ground ice conditions was gained. The assignment of values for surficial material units benefitted from conversations with experts on the surficial geology of northern Canada (D.E. Kerr, personal communication, 2017 & 2018), and examination of map legends from larger-scale surficial geology maps. Volumetric estimates of ground ice, themselves derived by upscaling from relatively little quantitative field data, are available from only a few areas in Canada, including Richards Island, Banks Island, and Fosheim Peninsula (Bernard-Grand'Maison and Pollard, 2018; Couture and Pollard, 1998; French, 1974; Pollard and French, 1980). Therefore,

there is insufficient field data to meaningfully calibrate model parameters and quantitatively validate the outputs. It is for this reason that we maintain qualitative descriptors for the ground ice abundance rather than numeric estimates in the map legends.

5.2. Directions for ground ice modelling and mapping

5   Detection and mapping of ground ice over large areas remains challenging. Ground ice volume measurements are required from more areas in Canada to improve validation of small-scale models. Direct observations are only possible at limited exposures and by coring, both of which are logistically demanding. Indirect ground-based geophysical methods such as ground penetrating radar and electrical resistivity tomography can be used to detect ice bodies, but are only applicable in site-scale investigations (Hinkel et al., 2001; Kneisel et al., 2008). Complementary geophysical techniques may allow differentiation and

10   mapping of relict ice, wedge ice, and icy sediments (De Pascale et al., 2008), but accurate volumetric determinations are not yet possible. Because of their distinct polygonal surface expression, volume estimates of ice wedges can be derived using high-resolution imagery (Bernard-Grand'Maison and Pollard, 2018; Ulrich et al., 2014), but their accuracy ultimately depends on field measurements of ice wedge widths and depths. Air and spaceborne optical, LiDAR, and D-InSAR techniques allow characterization of thermokarst terrain and processes, offering indirect insights into ground ice conditions (Kääb, 2008; Kokelj

15   and Jorgenson, 2013). Despite these significant recent advances in geophysical and remote sensing techniques in permafrost regions, the lack of assembled data on ground ice and volumetric estimates from different areas in Canada remains a key challenge in assessing the validity of small-scale ground ice models. The compilation of existing ground ice information and new field data from poorly characterized areas will improve calibration and validation of future model outputs.

Combining outputs produced using multiple techniques and perspectives will lead to further improvements to ground

20   ice modelling (e.g., Silver, 2012). For example, pingos identified using remote-sensing techniques could be added as a point data layer. The depiction of deeper ground ice could be improved by accounting for stratigraphic configurations as opposed to surficial cover only, and occurrences of ice-rich syngenetic deposits. Further modelling efforts will benefit from emerging updated surficial geology mapping in a consistent digital format. The paleogeographic approach presented here may also be improved by incorporating revised glacial boundaries and other updated paleoenvironmental information (e.g., Lakeman and

25   England, 2013). Alternate or updated information on permafrost distribution (e.g., Gruber, 2012) could also be utilized, and patterns of ground ice loss could be investigated with projections of future permafrost loss (Chadburn et al., 2017).

The results contribute an improvement in small-scale permafrost mapping for Canada, which has remained unchanged for over two decades. The mapping is of practical relevance given recent widespread circumpolar landscape changes that have already been observed in association with ground ice melt (Fraser et al., 2018; Jorgenson et al., 2006, 2015; Kanevskiy et al.,

30   2011; Liljedahl et al., 2016; Rudy et al., 2017). Improved ground ice data layers are valuable for broad-scale Earth System modelling, and other derived synthetic mapping products. In addition, the modelling approach may also enable depictions of ground ice in past periglacial environments of North America, and thus indicate where features such as ice-wedge casts may occur today (Gao, 2005; Morgan, 1972). The discrepancies highlighted between mapping in this paper and by Heginbottom et

al. (1995) underscore the need for caution when interpreting outputs from previous models that have used the ground ice information as input parameters.

The modelling approach presented here is flexible and updateable, and the Geological Survey of Canada plans to make the most up-to-date iteration of ground ice maps for Canada available on GEOSCAN (geoscan.nrcan.gc.ca/). The ground ice maps and derived surficial material data from this paper are available in the supplement in GeoTIFF format. We look forward to further improving the mapping through future collaborations with, and feedback from, the Canadian permafrost community.

6 Conclusions

New modelling using a paleogeographic approach depicts the abundance of relict ice, segregated ice, and wedge ice in permafrost in Canada. The predictions are broadly consistent with observations from empirical studies. Relict ice is modelled in high abundance over 2% of the continuous permafrost zone, and is restricted to thick glacigenic sediment that has remained in cold tundra environments during the Holocene. High segregated ice abundance is modelled over 3% of the continuous and 4% of the discontinuous permafrost zone in fine-grained marine and glacial lake sediments. High wedge ice abundance is modelled over 2% of the continuous permafrost zone, mainly on Banks and Victoria islands and the western Arctic coast. The distribution of high wedge ice abundance reflects the time available for ice-wedge cracking in tundra environments since terrain exposure following glaciation or submergence. The presented model outputs offer improved spatial detail and seemingly improved accuracy in several areas compared to previous ground ice mapping of Canada. This has potential implications to the validity of models that have used the Heginbottom et al. (1995) and Brown et al. (1997) ground ice mapping as input parameters. This study has identified the need for further compilation of ground ice information for the purposes of calibrating and validating small-scale ground ice models.

7 Data availability

The datasets used in this paper are referenced and available online. Model outputs and the derived surficial material dataset are available in the supplement.

8 Author contribution

SAW conceived the modelling approach. SAW, HBO, and CD contributed to modifications to the models. HBO and SAW prepared the manuscript. CD operationalized the models in the geographic information system. CD and HBO produced cartographic outputs. All authors contributed edits to the manuscript. HBO revised the manuscript following review.

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Table 1. Examples of surficial material units, soil texture, and resulting assessment of frost susceptibility.

Surficial material	Soil texture	Frost susceptibility
Mo: Marine offshore	Dominantly silt and clay (Geological Survey of Canada, 2014)	High
A: Alluvial undifferentiated	Silt, sand, clay, and gravel (Geological Survey of Canada, 2014)	Medium
CC: Colluvial undifferentiated (coarse)	Blocks, rubble with sand, and silt with minor clay (Geological Survey of Canada, 2014)	Low
Wv: Weathered regolith veneer	Rubble to blocky felsenmeer (Geological Survey of Canada, 2014)	Negligible

Table 2. Raster reclassification used to produce the ground ice abundance difference map between the Permafrost map of Canada (PMC) (Heginbottom et al., 1995) and the models (M).

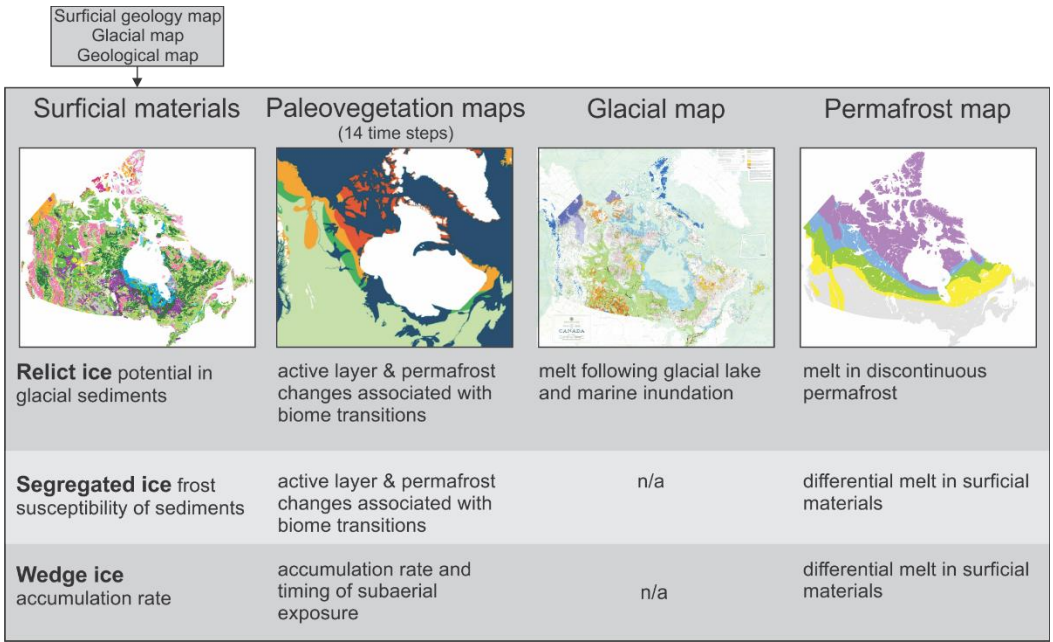| Reclassified value	Original map legend		
	PMC massive, wedge	PMC segregated	M (All ice types)
High (2)	Abundant	High, Med-high, Med	High, Medium
Low (1)	Sparse	Low-Med, Low	Low, Negligible
None (0)	Absent	Nil-Low, None	None

Figure 1. General model framework indicating datasets used and processes represented for the three ground ice types. See text for descriptions of each dataset.
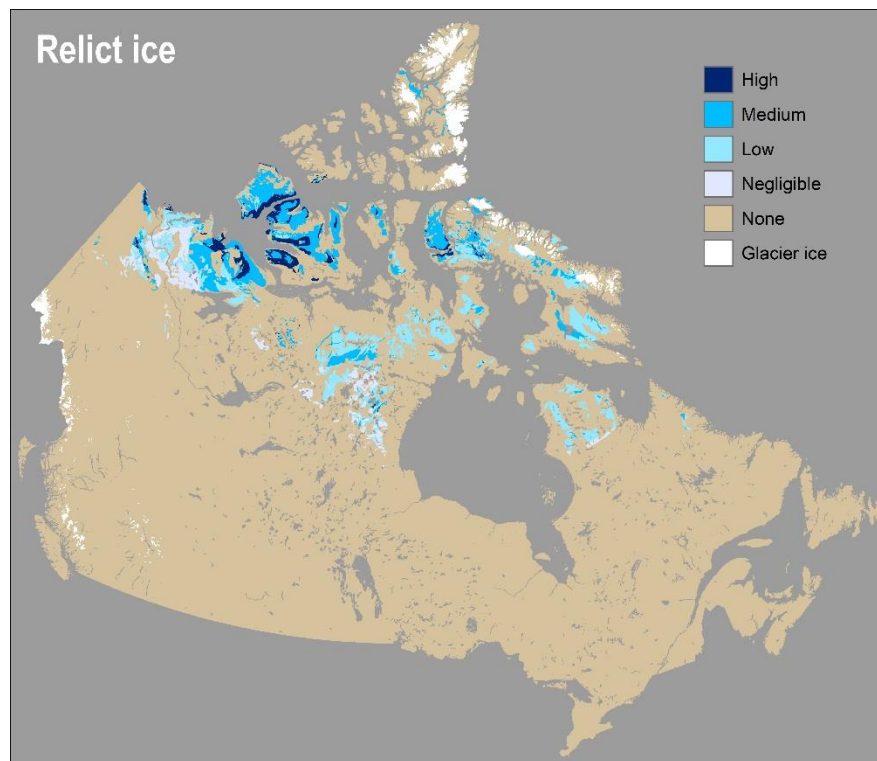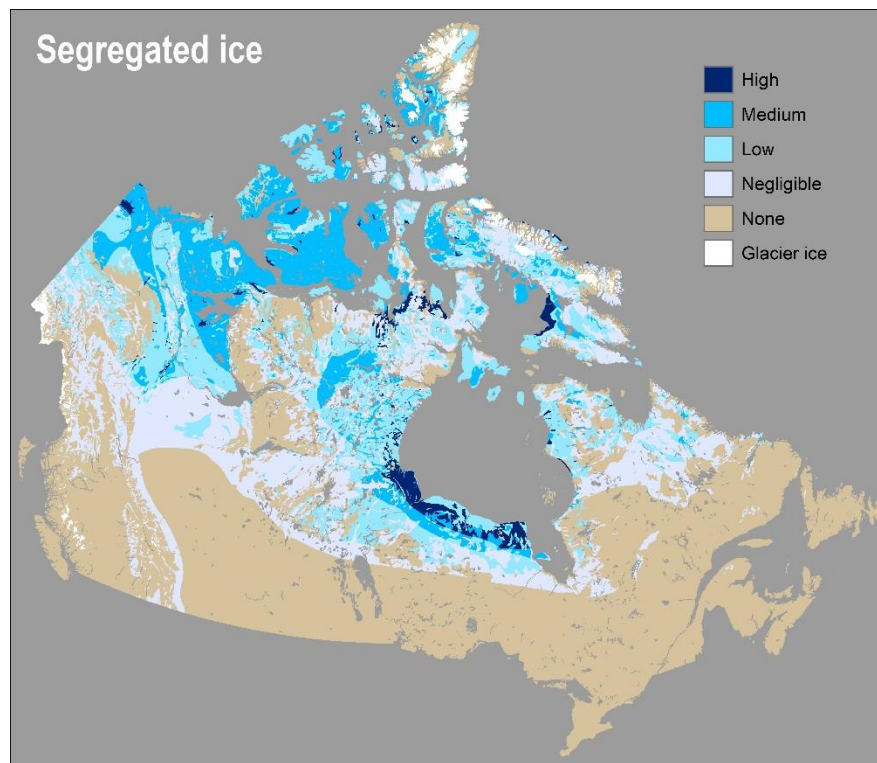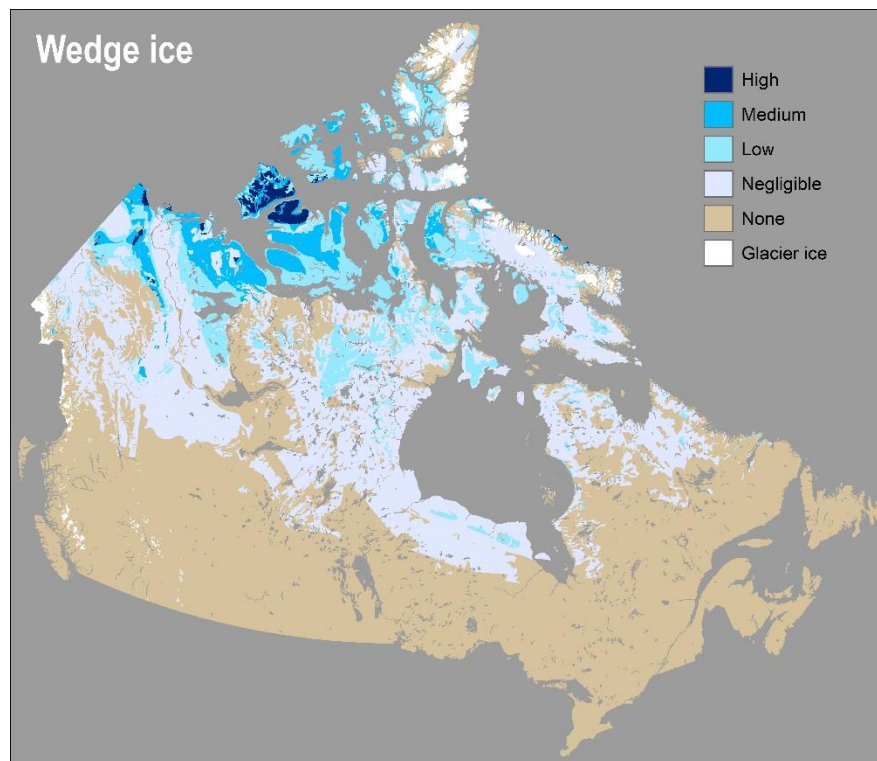
Figure 2. Modelled relict ice abundance.

Figure 3. Modelled segregated ice abundance.

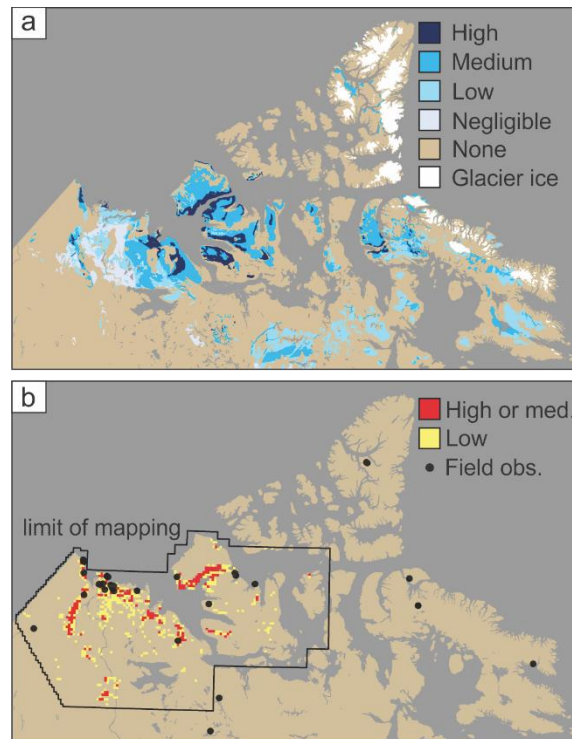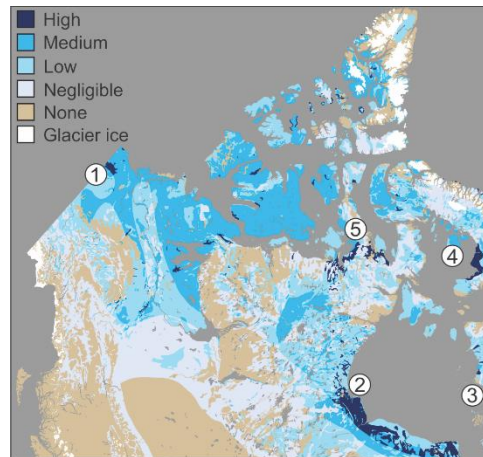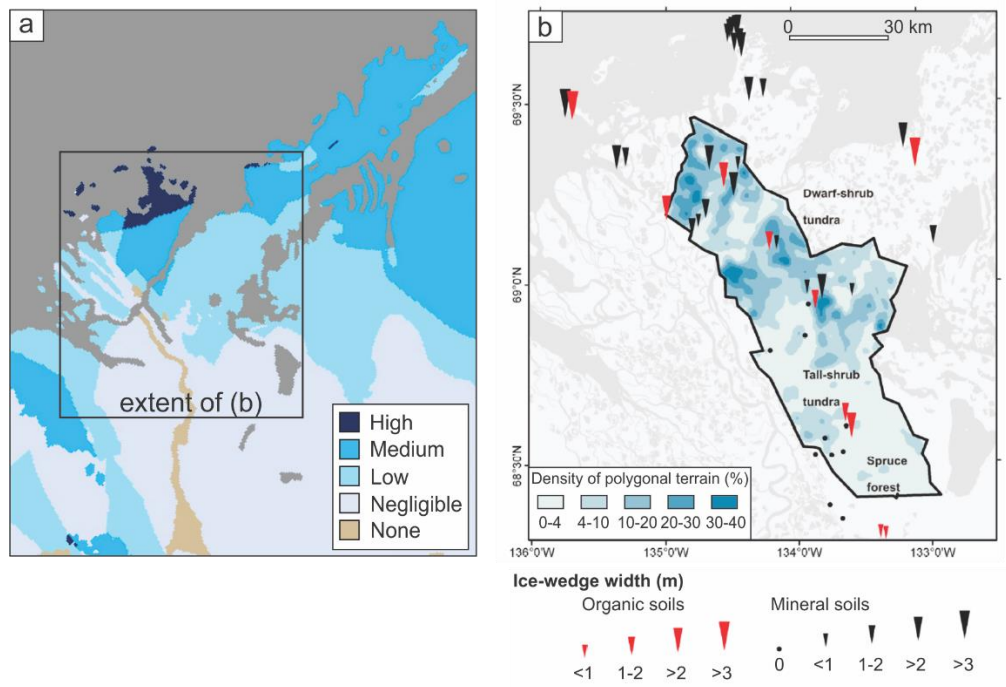**Figure 4. Modelled wedge ice abundance.**

Figure 5. a) Modelled abundance of <u>relict </u>ice and; b) abundance of large (>1 ha) thaw slumps in northwest Canada (Kokelj et al., 2017; Segal et al., 2016), and field observations of <u>relict </u>ice from the literature (Table S3).

Figure 6. Modelled abundance of segregated ice. Old Crow Basin [1] is characterized by widespread excess-ice in fine-grained lacustrine sediments and an abundance of shallow thermokarst lakes. Within the Hudson Bay Lowlands [2], areas with high segregated ice abundance include extensive raised peat plateaus. Lithalsas are widespread in raised marine sediments at Umiujaq [3]. The Great Plain of the Koukdjuak [4] and southern Boothia Peninsula [5] also include fine-grained uplifted marine sediments, and shallow thaw lakes are abundant in both regions.

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Figure 7. Comparison of (a) modelled wedge ice abundance to (b) wedge widths and the density of polygonal terrain in the western Canadian Arctic (modified from Kokelj et al., 2014, Fig. 6).
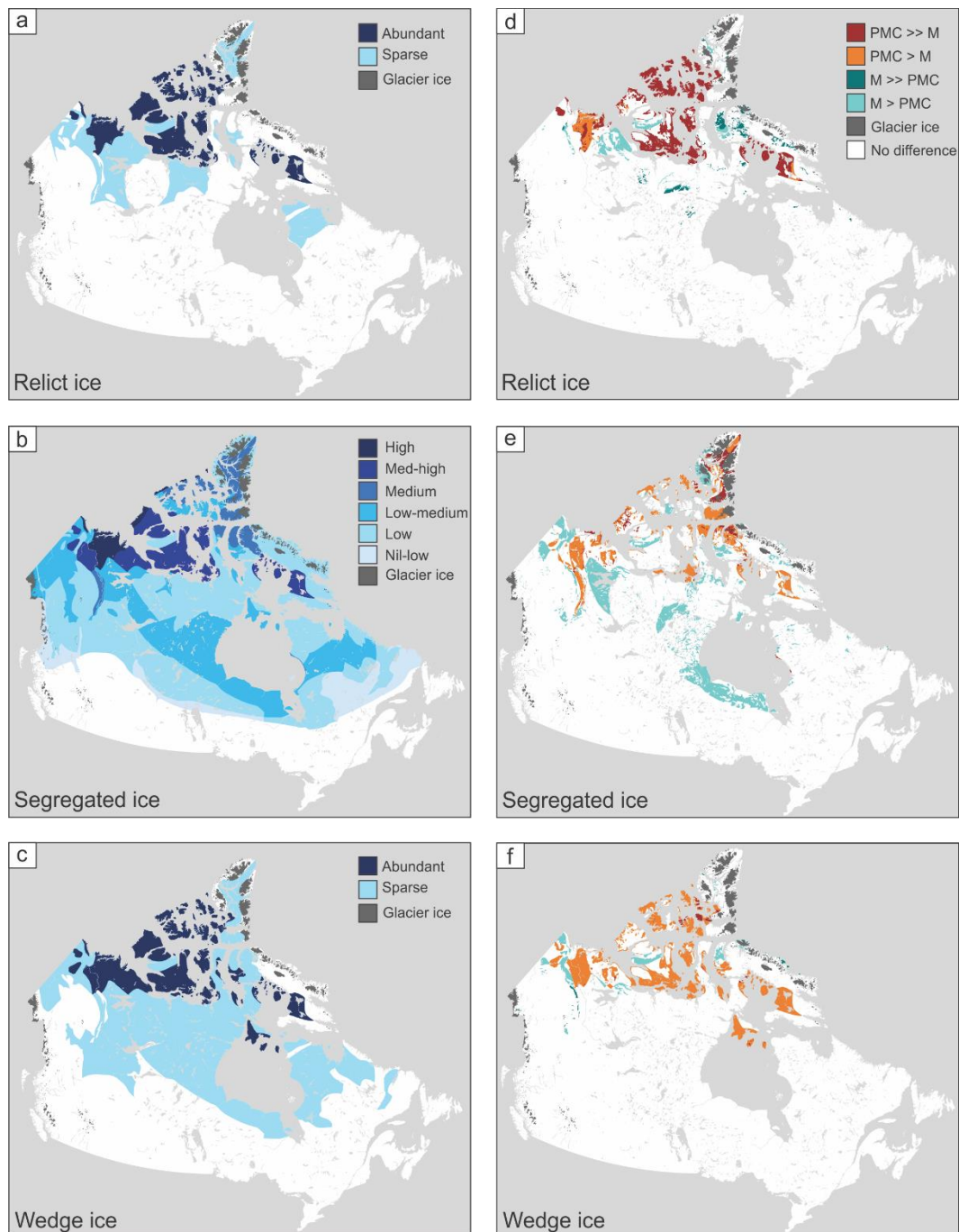
Figure 8. The Permafrost map of Canada (PMC) depictions of (a) relict ('massive') ice, (b) segregated ice, and (c) wedge ice (modified from Heginbottom et al., 1995). (d) to (f) present; comparisons between the PMC and the models (M). PMC >> M indicates, for example, that the reclassified relative ground ice abundance on the PMC is 'high' and the modelled abundance is 'none'. M > PMC indicates the reclassified ground ice abundance is 'high' on the model output and 'low' on the PMC. See Table 2 and text.

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