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Interactive comment on “Permafrost soils and carbon cycling” by C. L. Ping et al.

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This manuscript provides a comprehensive and timely review of permafrost soils and carbon cycling. The authors summarize literature in a topic where recent decades has seen marked scientific progress and many new studies emerging. To review this field is challenging, but the authors are in a position to provide a valuable and authoritative overview. I view this manuscript as a welcome and strong addition to the topic of permafrost soils and carbon cycling. I recommend it for publication following minor reviews.

We thank the reviewer for his endorsement for our effort and his constructive comments

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which would help us to improve the manuscript.

I think this paper has the potential to become a future reference work on this topic, but I am concerned about a few points that need more attention. The larger issue that concerns me is that some sections of the review, and the cited literature, is overly focused on studies from the North American Arctic (specifically Alaska) while fewer studies from Eurasia are discussed. I feel that there is an imbalance here that should be adjusted if the review is to give an unbiased overall view of work on permafrost soils and carbon cycling. See specific comments and suggestions below.

We totally agree with the reviewer's comment on the imbalance of citations. We have incorporated the references the reviewer provided plus several additional Russian sources.

There are also several cases where I urge the authors to provide clearer formulations or definitions of statements that appear oversimplified or generalized. See specific comments below.

Specific comments: Page 710 lines 25-26: note that this figure cites the ice-free, soil-covered land areas. Water and rockland are excluded from this number.

We clarify this as suggested by the reviewer.

Page 711, lines 9-11. I would suggest the first batch of references are placed after the word thawing.

Revised as suggested.

Page 711 lines 19-20. Could the authors clarify if they would recommend a distinction between these two terms?

“Permafrost-affected soil” is a technical term whereas permafrost soil is a commonly used term. Page 712 line 9. This seems like an oversimplification. There are many occurrences of Gelisols in well-drained soils. The authors should clarify that poor

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drainage often favours near-surface permafrost but that well drained soils may also be Gelisols . We revised the sentence as: In this zone, Gelisols commonly form in lowlands with restricted drainage that favors near-surface permafrost but Gelisols also form in well-drained upland sites where the permafrost is deeper (Rieger et al., 1979; Ping et al., 2004; 2005a; Li et al., 2015).

Page 712 line 21: “There are two general types of permafrost: : :”. It would be helpful to define these two types directly in this introductory sentence

We revised as suggested to start the paragraph with the following introductory sentence:

There are two general types of permafrost. The most common one is the old permafrost, a remnant of the paleoclimate and the other type is of recently formed under contemporary climate conditions,.

Page 713 line 13 change to “is subject to change under contemporary: : :” Changed as suggested.

Page 713, lines 17-18: clarify that volumetric changes associated with the phasechange of water are important in this process of frost heaving

We clarify this by revising the paragraph in Section 2.3 Periglacial processes and patterned ground: “Frost heave results in volume change due to phase change of water from ice segregation and ice lens formation. It often results in the deformation of the ground surface. With horizontal expansion limited, there is often enough stress to produce crooked or tilted lenticular and reticulate structures (French and Shur, 2010). Differential frost heave eventually deforms originally flat horizons into warped or wavy horizons. When freezing occurs in saturated coarse grained soil, the cryostatic pressure pushes water out of soil, thus producing in features such as icing and frost blister (Tsytoovich, 1975).”

Page 714, lines 1-2. Three layers in a soil profile: Should not the fourth layer of true

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permafrost be included here? These often contain buried or palaeo-horizons as well. I realize you are citing another source here, but I think it is important to clarify that much of the deeper permafrost deposits have also undergone soil formation before being incorporated into permafrost.

We agree and we added a sentence after the first sentence: According to French and Shur (2010), Gubin and Lupachev (2008) a permafrost soil profile commonly has three layers referred to as active, transient, and intermediate layers. But considering the whole cryostratigraphy, there should be a fourth layer, the “true permafrost” which often contains the buried or paleo-genetic horizons (Hoefle and Ping, 1996; Schirrmeister et al., 2002; Kanevskiy et al., 2014).

Page 717 section 2.4 Thermokarst. This section is rather brief and does not provide the same level of detailed discussion as did the previous section. Would the authors care to identify a previous review which gives detailed discussion of process understanding when it comes to formation of these mentioned forms of thermokarst?

We revised and expanded this discussion on thermokarst in 2.4 Thermokarst

Freezing of fine-grained soil attracts water to the freezing front from unfrozen soil below. Water content of frozen soil increases and ice occupies a pore space increases it and even forms lenses and layers of ice. Total amount of ice can greatly increase a volume of pores in soil prior freezing. Then thawing of the permafrost can cause the surface to settle or liquefy, and the amount of settlement is directly related to the amount and type of ice (Shur and Osterkamp, 2007). The irregular topography resulting from the melting of excess ground ice and subsequent ground collapse is called thermokarst. Czudek et al. (1970) identified two types of thermokarst. The first type is permafrost “back-wearing” which develops gullies, thermocirques, parallel retreating steep walls and eventually lower lowland. The second type is the more commonly discussed “down-wearing” due to permafrost thawing from above resulting in flat undissected relief, such as “alases”, a Russian term to describe the landform and processes

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of thermokarst formation. The patterns and amount of settlement or loss of surface material are related to complex interactions of slope position, soil texture, hydrology, and vegetation over time (Shur and Jorgenson, 2007). The highly variable terrain and permafrost factors have led to a wide variety of thermokarst landforms, that include degrading ice wedge troughs, thermokarst pits, thermokarst lakes, thermokarst bogs, thaw slumps, active-layer detachment slides, and thermal erosion gullies (Grosse et al. 2013; Kokelj and Jorgenson 2013; Jorgenson et al., 2013; Jensen et al., 2014).

Thermokarst is widespread throughout Arctic and boreal regions and has large implications for soil hydrology and C balance (Czudek et al., 1999; Schuur et al., 2008; Veremeeva and Gubin, 2009; Grosse et al., 2011). Thermokarst lakes often develop taliks underneath the deep water, where organic matter that has long been sequestered in permafrost and reworked by shoreline erosion can decompose and release greenhouse gasses (Walters et al. 2007, Grosse et al. 2013), but also provide good conditions for primary productivity and carbon gain (Walter-Anthony et al., 2014). Thermokarst bogs in the boreal region also develop thick taliks where previously frozen soils are susceptible to decomposition, but rapid sedge and Sphagnum colonization in the depressions add new peat and the net effect on carbon balance is uncertain (Sannel and Kuhry, 2011; Jorgenson et al., 2013). Degradation of ice wedges in the Arctic has increased, creating trough-like depressions that collect water and provide an anaerobic environment for new peat accumulation, while the adjacent polygon become better drained (Jorgenson et al., 2006). Thaw slumps and active-layer detachment slides are common on slopes where there is an ice-rich intermediate layer or where buried glacial ice is abundant (Kokelj and Jorgenson 2013). While the disturbance quickly removes surface organic layers and the material is exported to rivers and lakes, or is reburied in thick debris lobes, the newly exposed surface is susceptible to recovery and new organic matter accumulation (Pizano et al., 2013). Thermal erosion gullies often develop along thawing ice wedges, channelize surface water flow, and can lead to drying of adjacent soils (Godin, 2014).

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Page 717 lines 19-22. This section feels out of place here? I recommend it be moved, removed or rewritten.

We removed this section.

Page 718 line 6. By which mechanisms are anaerobic conditions favored by low temperatures? High moisture content is understandable and the link to anaerobic conditions is well known there, but I was unaware that there is a connection between temperature and oxygen demand. This statement should be clarified and supported with a reference.

We realized the way the sentence was written would mis-lead the audience. Thus we rewrote the sentence as:

The accumulation of soil organic matter (SOM) in the permafrost regions is enhanced by 2 factors; slow decomposition due to anaerobic conditions caused by high moisture content in the active layer and slow decomposition rate at low temperatures (Kaiser et al., 2007; Rodionov et al., 2007).

Page 718 line 15: This is again unclear to me. Should not saturated conditions promote anaerobic conditions that limit oxidation?

Again this sentence is miss-leading. We changed the word “oxidized” to “decomposed”. Page 718, line 29 “upon in contact”. Rephrase We rephrased the sentence and also changed the reference: “When the concentration of SOM is high, the reduced Fe (Fe²⁺) in soil solution is rapidly oxidized when in contact with air and forms a poorly ordered Fe³⁺ oxide film on the surface of water and eventually precipitates as orange colored deposits called ferrihydrite (Schwertmann and Taylor, 1989).”

Page 718 line 26. Should not sub-Antarctic soils also be included here? Or perhaps just simplify to cold-region soils? Yes. We inserted “sub-Antarctic”.

Page 719, line 9-10.” SOM at the surface can be mixed with the surface few centimeters of mineral soil a: : :”. I do not follow the meaning of this sentence? We revised

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the sentence as: “Under snow cover, sublimation ice can build near the surface from water vapor in the soil surface atmosphere and resulted in needle ice. In this process small amount of surface-accumulated organic matter can be mixed with the top few centimeters of mineral soil promoting aggregation, disrupting root establishment and favoring biotic crust formation.(Michaelson et al., 2008; 2012).” Page 720, line 18. “: :in permafrost soils other processes, such as cryoturbation, deformation by massive ice growth, and intermittent burial and syngenetic permafrost growth, result in the storage of large quantities of this surface and near-surface produced SOM at depth.” I don’t agree with this statement. The mentioned processes result in a translocation of near-surface SOM to depth in the soil profile. The storage is a function of combined translocation and retarded decomposition/combustion in the subsoil We agree. To clarify the impact of cryoturbation on SOC accumulation we revised the statement as: “Cryoturbation does not cause direct input of OC to the soils, instead it displaces soil organic matter within the active layer of a soil profile and through time and changing conditions cryoturbated organic matter that is throughout the active layer can become encased in permafrost by processes associated with either intermittent burial or syngenetic permafrost growth (Kaiser et al., 2007; Ping et al., 1998; 2008b). The unique feature of most permafrost-affected soils is the storage of large quantities of this surface and near-surface produced SOM at depth, mainly in Turbels that account for 35% of the areas and 46% of the SOC stocks of all Gelisols (Hugelius et al., 2014). However, cryoturbation has no or only minor effect on OC storage in Histels, Orthels and vast areas of Histosols in the circumpolar region.”

Page 724 lines 12-13. “Thus, three different soil types develop across this microtoposequence: : : :”. I suggest you rephrase to: "three different main soil types have been observed to develop across polygons: : :". One cannot reasonably expect all the worlds polygons to exhibit this general pattern. We revised the sentence as suggested.

Page 724 lines 16-20. This describes one possible development but it is phrased as if it were the only possibility. There are many other potential developmental pathways for

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such polygon structures. In many circumstances, high-centre polygons can form due to peat accumulation in the polygon centre, without the ice-wedges degrading.

We amended the paragraph: However, with time, the ice wedges can degrade, forming deep troughs (Jorgenson et al., 2006). Polygon interiors then become high centered, surface cracking increases, and greater cryoturbation leads to formation of soils (Histoturbels) with greater accumulations of organic matter (Ping et al., 2008a; 2011; Zubrzycki et al., 2013).

Page 725, lines 8-9. Perhaps this oversimplified statement regarding thaw-lakes could be refined? Many parts of the Arctic and boreal regions do not contain thaw lakes. The occurrence of thaw lakes is strongly linked to the depositional origin of unconsolidated sediments and the occurrence of massive ground ice and previous climate cycles.

We expanded the discussion on thaw lakes: Thaw lakes and drained thaw-lake basins are prevalent on flat landscapes in the Arctic and boreal regions where ground ice is sufficiently abundant to allow the surface to thaw, collapse, and be filled with water to form shallow (<2 m) and deep (>2 m) lakes. Thaw lakes are most abundant on ice-rich, fine-grained deposits, such as abandoned floodplains, colluvial lower slopes and basins, peatlands, and lowland loess deposits (Veremeeva and Gubin, 2009; Grosse et al., 2013; Jorgenson, 2013). The age of thaw lakes can be extremely variable with some thaw lakes in Yedoma persisting since the late Pleistocene (Grosse et al. 2013, Kanevskiy et al. 2014), while others are newly formed. Veremeeva and Gubin (2009) identified 2 stages of active thaw-lake formation in Northern Russia; one during Early Holocene around 9 to 8 kyr BP and the second one during Late Holocene, at 5 to 4 kyr BP. In addition, not all lakes in permafrost regions are thaw lakes and can simply be abandoned channel lakes, inter-dunal lakes, or impoundments in depression in undulating surficial deposits (Jorgenson et al. 2007). In many Arctic coastal plain regions, there are overlapping lakes and lake basins, which have been attributed to a “thaw-lake cycle” that can be as short as 3000 years in northern Alaska (Hinkel, 2003). Jorgenson et al. (2007) argue that ice aggradation and degradation takes longer and that, while

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secondary thaw lakes are common, the process is less cyclical and more evolutionary, depending on changing surficial deposits, ground ice conditions, and land use. In some cases, soils formed in drained-lake basins reflect multiple thaw episodes, as evidenced by the presence of multi-layered organic-mineral horizons with cryoturbated organic matter to depths of 2-4 m (Ping et al., 2014, Kanevskiy et al., 2014) (Fig. 5). Thaw lakes can also form in landscapes where there are no ice-wedges. Commonly occurring thaw lakes associated with degradation of palsas and peat plateaus in sub-arctic peatlands such as those observed in the northern boreal region of Alaska (Brown and Kreig, 1983). As a consequence of the thaw-lake dynamics, large soil C stocks can accumulate, as high as 90 kg C m² in profiles up to 3 m deep (Ping et al., 2011). Much of the organic matter in the central portions of drained-lake basins derive from limnic sediments comprised of algal material and detrital peat eroded from the collapsing lake shores (Jorgenson et al., 2013).

Page 725 lines 9-10. This general statement regarding ice-wedges and thaw lakes applies only to some type of thaw lakes but is not applicable in all cases. Thaw lakes can also form in landscapes where there are no ice-wedges. Commonly occurring thaw lakes associated with degradation of palsas and peat plateaus in sub-arctic peatlands is one example of this.

Our revision stated above contains comments related to lines 8 – 16 on Page 725.

Page 725 lines 10-11. The statement about a cycle of 3000 are local/regional estimates for Alaskan thaw lakes that does not apply to other regions and this must be clarified. This cyclicity is likely to be very different depending on lithologies, permafrost initial conditions, climate and land use (applies to the Siberian landscapes where human land use is important for alas landscapes) Please see our revision above..

Page 725 lines 15-16. “accumulate, as high as 90 kgCm⁻² from 0–3m deep..”. Rephrase this sentence. We rephrased the sentence. Please see the three previous replies to comments from line 8 to 16.

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Page 725 lines 27-28. “and froze once air temperatures dropped below zero.: : :”. This statement is an oversimplification which should be taken out or elaborated. Presumably they froze when the ground temp dropped below zero, not the air temperature. Do the authors mean that permafrost aggraded as mean annual air temperatures dropped below zero? Much of the yedoma has been shown to accumulate under syngenetic conditions when permafrost was already present so presumably it was deposited into an environment that already experienced sub-zero temperatures for most of the year.

We revised the sentence to clarify the genetic environment of Yedoma: Yedoma deposits are polygenic; accumulations of water- related as well as eolian origin, that settled in the interglacial periods under syngenetic conditions when permafrost was already present or in an environment that already experienced sub-zero temperatures for most of the year (Kanevskiy et al., 2011; Schirrmeyer et al., 2002, 2011; Strauss et al., 2012).

Page 726 lines 12-13. This statement of alas meaning peat-filled depression is not correct. Most Yakutian alases are characterized by grass growing in mineral soils rather than deep peat. While there are many different developmental stages and some alases form deep peat deposits, it is not correct to state that they are all filled with deep peat. The word alas is also not exclusive to peat-filled thermokarst depressions but refers to characteristic thermokarst depressions with steep slopes and flat floors. See e.g. work by Czudek et al. (1970), Veremeeva and Gubin (2009) or Morgenstern et al. (2013).

In response to Reviewer 3’s comment on Yedoma we revised the statement on organic soils in alases: Some thermokarst lakes eventually turn into drained basins, or “alases”, a Yakutian term for thermokarst basin and its formation passes through a sequence of landforms and soil types; lakes, swamp, wet meadow and grassland (Czudek et al., 1970; Rodionov et al., 2007; Desyakin, 2010). In the intermediate stage, permafrost organic soils (Histels) were found in alas at Duvaany Yar, the extensively studied Yedoma formation along the Kolyma River upstream from Cherskiy (Smith et al., 1995), and northern Alaska (Kanevskiy et al., 2011).

We will revised this statement with consideration of the new references provided by the Reviewer.

Page 726, line 25-26: If this aims to be an exhaustive list of important studies regarding the influence of permafrost on soil OC storage I am concerned that it is biased towards Alaskan studies without giving due credit to other work. I would argue that the work of Tarnocai and Lacelle (1996) should be viewed as pioneering when it comes to soil C stocks in North America (and indeed the whole Arctic). Hugelius et al. (2010) also provide a SOC inventory from a poorly studied part of Canada.

It is also surprising that the authors limit themselves to naming only one study from Eurasia. Eurasian studies on permafrost and OC stock interactions by: Becker et al., (1999), Kuhry et al. (2002), Mahzitova et al. (2003), Rodinov et al. (2007), Gundelwein et al. (2007), Hugelius and Kuhry (2009), Klaminder et al., 2009, Hugelius et al. (2011), Schirrmeister et al., 2011, Hugelius (2012), Zubrzycki et al. (2013) could be mentioned in this context. I am aware that I mention many of my own papers and I am not suggesting that you necessarily have to cite these. I just wish to point out some parts of a significant body of literature that may have been overlooked which the authors could familiarize themselves with to provide a more balanced circum-Arctic review. We revised this section with the added references.

Page 727 line 11. The proper reference here would be Hugelius et al 2013 a and b. Corrected as suggested.

Page 727 line 14. Note that the final, accepted, version of this paper has slightly different SOC stock numbers following adjustments of the methodology. We corrected according to Hugelius (2014).

Page 727 lines 19-20. Note that these pedon numbers only apply to deeper soils. For 0-1 m depth the database is ca 1700 pedons adapted from Tarnocai et al., 2009. See Hugelius et al., 2014 for details. We revised the sentence: In the NCSCD database, the C data of the 0-1m depth was represented by 1700 pedons whereas the deeper

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soils were represented by a total of only 341 Gelisol pedons and 177 pedons of non-permafrost soils (Hugelius et al., 2014).

Page 729 lines 2-5. Here I would wish to point to the study by Hugelius et al., 2011, who used the highest resolution upscaling to date of any permafrost SOC study (2m resolution) and discusses local scale heterogeneity versus regional scale upscaling. Hugelius (2012) provide in depth discussion regarding the topic of upscaling accuracy and spatial resolution in upscaling. We overlooked these 2 references. We revised this part as:

“In addition to these pedon-scaled studies, there are explicit efforts to account for and incorporate local-scale spatial heterogeneity into sampling designs and up-scaling approaches in the estimation of soil OC stocks at landscape or regional scales (Horwath et al., 2008; Zubrzycki et al., 2013). Hugelius et al (2011) used the highest resolution upscaling to date of any permafrost SOC study (2m resolution) to discuss local scale heterogeneity versus regional scale upscaling. Hugelius (2012) also provided in depth discussion regarding the topic of upscaling accuracy and spatial resolution in upscaling.

Page 731. Lines 27-28. Please note the interesting study by Kaiser et al. (2007) which examines mineralization in cryoturbated soil horizons.

We included Kaiser et al (2007) in the reference. And cited their results.

References Thank you for providing these references. We have considered and include all of them.

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