Review – Lake ecosystem tipping points

Dag Hessen et al. Earth System Dynamics Jan 5, 2024

General comments

I realize this review is over 5 single-spaced pages, but the vast majority of the comments are minor.

This paper is certainly of broad interest and is well-written but please see the detailed comments below. Some sections could be improved. For example, there are many extremely long, complex sentences that may be difficult to follow. I made some suggestions for many (but not all) of these.

After examining six potential drivers of lake tipping points, the authors found that only two potential drivers of tipping points (browning and eutrophication) fit their criteria and that these two are related or exacerbated by climate change. My main comment here is that this does not really fit the title of the paper "Lake ecosystem tipping points and climate feedbacks". Although they do mention that they focus on tipping points that are not necessarily driven by climate change per se (line 124) and acknowledge that climate can also be seen as separate driver (line 502), I wonder why the authors have not included situations where lakes that can cross tipping points that are mainly by triggered by accelerated warming… without needing additional stressors of eutrophication or browning (e.g. many High Arctic and very remote water bodies on granitic bedrock etc.). I certainly don't disagree that both browning and eutrophication are major drivers of regime shift changes in lakes and that climate change can help further push waterbodies towards a tipping point. However, and my main point here, waterbodies can also reach an ecological tipping point with accelerated warming and in the absence of these two drivers. The biggest take-away from this paper may appear to be that tipping points can only be crossed if lakes are affected by these two primary drivers (browning and eutrophication). Perhaps this needs to be better clarified and elaborated upon at the beginning of the paper (introduction) and again in discussion. I appreciate that Table 1 provides the "events" that trigger tipping points and the authors have examined all of these and that climate change is not considered an "event" here. Of course, recent accelerated warming is mainly anthropogenic and these feedbacks are important -- but I guess I am having some difficulty in seeing why climate is not considered as a main driver- particularly for lakes in remote regions (high latitude, parks etc.) where many studies have shown regime shifts in response to warming and in the absence of these two drivers. Maybe some further explanation is in order?

The section on disappearance of waterbodies (starting on line 324) seems to be solely focused on permafrost thaw as the component. As I detail below, when they talk about Smol and Douglas 2007 (lines 359-369-ish and again on lines 544-554-ish) and disappearing lakes– it seems they are incorrectly interpreting how these High Arctic waterbodies on granitic bedrock are disappearing. They intimate (unless I am misreading this section) that these small ponds

have disappeared because of *permafrost thaw and draining* (i.e. thermokarst lake). Contrary to what the authors indicate in this section, Smol and Douglas (2007) show that water levels in ponds such as those on Cape Herschel are not similarly influenced by permafrost drainage (as some subarctic waterbodies) and represent a more direct link to temperature, precipitation etc. They are excavated in granite and their disappearance was shown to be due to higher evaporation:precipitation. I provide some details below.

The authors argue that the disappearance of these waterbodies should not be considered "tipping points" per se but a binary shift (line 367). Could the authors elaborate on this point here?

The section on gradients or tipping points (line 559) is an important addition as it helps clarify the importance of abrupt changes, regardless of whether a set of criteria deems the change to qualify as a "tipping point" or not. The time perspective is important.

In the sections on TOC and browning etc – Well, clearly this is a paleolimnologist who is reviewing this paper(!), but the authors might consider the concept of "re-browning", as we have argued, given the perspective of several centuries of paleo inferences of DOC data. Perhaps lakes are returning to their natural "browner" conditions (i.e. re-browning).

If interested, some of these papers are:

Meyer-Jacob, C. et al. 2020. Re-browning of Sudbury (Ontario, Canada) lakes now approaches pre-acidification lake-water dissolved organic carbon levels. Science of the Total Environment 725: 138347.

Meyer-Jacob, C. et al. 2019. The browning and re-browning of lakes: Divergent lake-water organic carbon trends linked to acid deposition and climate change. Scientific Reports 9: 16676

The section on Salinization – I think is fine, but the authors could mention the threat of road salt seepage – which we know is changing lakes.

In the context of this paper, the section on the spread of invasive species seems out of place – why include this if the authors deemed this not to be a candidate for tipping points? It is short and, in my opinion, not very informative.

Detailed Comments

Perhaps of relevance to this paper is a J. Paleolimnology review paper on regime shifts in lakes in response to climate change and anthropogenic activities (Randsalu-Wendrup et al. 2016). https://link.springer.com/article/10.1007/s10933-016-9884-4

Line 32: as noted later, maybe add "or higher precipitation to evaporation ratios" after "shifts"

Line 34: remove "on"

Line 37 – for parallel structure, should be "increase" nt "increased"

Line 39: Several of these processes can feature potential tipping point~~s~~ thresholds, which further warming will likely make easier to ~~reach~~ surpass.

Line 56: is "populous" the correct word here?

Line 57 and elsewhere – usually convention is now sub-Arctic – with Arctic always uppercase

Line 58-59: oddly worded. Perhaps change to

Widespread loss of waterbodies, from Arctic or sub-arctic ponds to wetlands or bogs might qualify as one type of tipping point, but are not self-propelled by internal feedbacks *per* se,~~themselves~~ but rather ~~than~~ by permafrost thaw (Smol and Douglas 2007).

Also, in this instance our 2007 PNAS paper is not appropriate for permafrost thaw, as these Cape Herschel ponds were excavated in granite and the loss of water was higher evap:precip ratios. Although we published papers and reviews discussing loss of ecosystems with permafrost thaw, the Smol and Douglas 2007 PNAS paper is on ponds excavated in granite bedrock (so they are like bathtubs in the bedrock – not permafrost) – chosen as not directly influenced by permafrost thaw but increased evaporation. We had pondwater conductivity measures going back to 1983 – so we could show it was evaporation. So, these ecosystems are disappearing due to evaporation, not permafrost thaw.

So it would be correct to say by higher evaporation to precipitation ratios (Smol and Doulgas 2007) as well as permafrost thaw (many papers can be cited here….. Chapter 7 of my new book Smol, J.P. 2023. *Lakes in the Anthropocene: Reflections on tracking ecosystem change in the Arctic.* Excellence in Ecology Book Series, International Ecology Institute (ECI), Oldendorf/Luhe, Germany. 13 chapters. 438 pp. – has many examples. One common one is: Smith, L. C., Sheng, Y., MacDonald, G. M., and Hinzman, L.D. 2005. Disappearing Arctic lakes. Science 308: 1429,

Line 134: add "a" before "tipping point"
Line 142: hysteresis should be plural "hystereses"
Line 148: remove "if not"; change "impacts" to "stressors"; remove "s" from "waters"

Line 153: change “among” to “as well as”
Line 155: change “pointed” to “identified”
Line 160: figure caption within the brackets: I found this hard to follow. Should “drive” here not be “driven”? “(...a tipping point-driven self-sustaining change)”?
Lines 165-169: this is an overly complex sentence that is hard to follow. Could you simplify/clarify?
Hysteresis can be strengthened by eutrophication-driven biological changes ~~in biota, such as changes~~ in fish composition and size structure ~~with~~ that have cascading effects on zooplankton and phytoplankton as well as strong impacts ~~if~~ on fish-mediated nutrient cycling (Brabrand et al. 1990). This in turn, ~~also strengthen hysteresis and~~ will maintain a system with deepwater anoxia and high nutrient load, supporting the release of GHGs (Fig. 2).
Line 175: Replace “speed” with “an acceleration”
Line 176: increases thermal stability and the duration and strength of stratification
Line 177: Minor, but there is a newer Woolway et al review that might be appropriate here: Woolway et al. 2022. Lakes in hot water: the impacts of a changing climate on aquatic ecosystems. BioScience 72: 1050-1061
Line 187: add a hyphen to “eutrophication-induced”
Lines 186-190: This is a very long and complex sentence – perhaps split in two.
Line 201 (and elsewhere): Yang et al. (2015) is missing from the reference list.
Lines 210-212: Why only shallow lakes?
Line 213: what is meant by “coherent tipping”? Do you mean coherent “threshold exceedance”?
Lines 215-218: This sentence was long and complicated and I found it difficult to follow. How about:
However, given the dearth of studies that generate bi-directional carbon flux data to assess the balance between emission and burial in lakes, it remains unknown whether the effect of ~~any of eutrophication's~~ climate feedback ~~effect~~ can be buffered by the projected eutrophication-driven increases in lake carbon burial (Anderson et al.2020). ~~remains uncertain, and there is a dearth of studies that generate bi-directional carbon flux data to assess the balance between emission and burial in lakes.~~
Line 221: Consider starting a new sentence after (Grasset et al. 2020).
Line 236: There are several other studies relevant to treeline shifts and DOC or TOC including:

Pienitz, R. et al. 1999. Paleolimnological reconstruction of Holocene climatic trends from two boreal treeline lakes, Northwest Territories, Canada. *Arct, Antarct., and Alpine Res.* 31:82-93. https://doi.org/10.1080/15230430.1999.12003283

Rühland, K.M et al. Limnological characteristics of 56 lakes in the Central Canadian Arctic Treeline Region. J. Limnol. 62:9-27.

Lines 247-250: can you provide a reference for this. Also, the closed bracket is missing at end of sentence.
Line 309: delete “as of”
Lines 310-312: This sentence was difficult to understand as written. How about changing to:

Given that high concentrations of DOM and deep-water anoxia are common, most ~~Most~~ boreal lakes are net heterotrophic and thus conduits of CO2, and often ~~also~~ CH4.~~, due to high concentrations of DOM and common deep-water of sediment anoxia~~

Lines 313-315: This long sentence would be clearer if split into two.

If it eventually leads to oxygen depletion and cascading feedbacks then it would qualify as a tipping point. ~~, yet with~~ However, there would be a time delay between the two events, ~~and where~~ with the latter ~~is~~ being the critical tipping event.

Line 327: should this not be "drought" rather than "draught"?

Line 329: usually High Arctic is capitalized (but perhaps depends on the journal).

Line 330: delete "and" before "onset" and replace with "further promoting the onset of permafrost thaw..."

Line 331: delete "both" – the sentence starts with "Both"

Line 339: change "share" to "sheer"

Line 344: as noted above the Smol & Douglas paper is on evaporation – so I would change the sentence to: While the main problem is loss of water bodies affected by warming-induced increased evaporation rates (Smol and Douglas, 2007) and permafrost thaw (maybe cite Smith et al., 2005 here) ….

Line 345-347: In addition to "collapsing palsas and thermokarst areas" another climate-mediated phenomenon related to permafrost thaw is retrogressive thaw slumps that increase inorganic sediments to freshwater systems and affect biodiversity (Thienpont et al. 2013. Freshwater Biology; Heino et al. 2020).

Lines 351-353: The sudden introduction of "bird induced eutrophication" is a bit odd. Can you introduce/connect this better to the rest of this section – it seems to come out of nowhere. Also bird-induced here should be hyphenated.

Line 361: North America should not be hyphenated.

Line 372: delete extra period after reference.

Line 461: change "is" to "as"

Line 497: add an "s" to "regime shifts"

Line 522 on: You might consider discussing "re-browning" here as well.

Near lines 572 to 575: There is also the Smol et al 2005 PNAS compilation across the circum-polar Arctic that perhaps you meant to cite here? It is in the reference list, but not actually cited in text as far as I can see… Also, the newer Kahlert et al. (2022) paper would be appropriate here: Kahlert, M. et al. 2022. Biodiversity patterns of Arctic diatom assemblages in lakes and streams: Current reference conditions and historical context for biomonitoring. Freshwater Biology 67: 116-140.

Interesting paper.