Response to reviewer and editor comments

Submission bg-2019-50: “Reviews and syntheses: How do abiotic and biotic processes respond to climatic variations in the Nam Co catchment (Tibetan Plateau)?”

Dear Kirsten Thonicke,

thank you very much for handling our manuscript! We highly appreciated the critical but extremely constructive reviewer comments and their thoughtful suggestions. Based on these comments we carefully revised our manuscript. Below you will find our point-by-point response to the reviewer´s comments and suggestions. Further down, you will find a list of all relevant changes made in the manuscript, followed by the main text body with marked changes.

In the name of all co-authors,

Johannes Buckel and Felix Nieberding

Editor: Dr. Kirsten Thonicke

Comment 1:

Response to Reviewer 1: referencing "Third Pole". According to Kun Yan& Qin 2013 (https://journals.ametsoc.org/doi/full/10.1175/BAMS-D-12-00203.1#) the term was defined in this Nature Editorial in 2008: https://www.nature.com/news/2008/080723/full/454393a.html Please reconsider your response regarding the source of the term "Third Pole" and consider citing the Yan&Qin paper.

Author´s response: Thank you very much for your advice. Although it remains unclear, whether Qiu (2008) is really the first author to use this term, she definitively put together a sound overview and definition of the term. Hence, we included her as a source for the term “The Third Pole”.

Author´s changes in manuscript: We included Qiu (2008) as citation in the respective text passage. Furthermore, we adapted our response to Reviewer 1, Comment 2.

Reviewer 1 (Prof. Dr. Georg Miehe):

Comment 1:

P2 L7: "Why the NamCo should be a model system? Model for what? The lake is one of the three large lakes of the TP and like Yamco Yumco and Qinghai Lake, the lake had a drainage in humid phases - unlike most of the lakes west of the NC"

Author´s response: According to Li et al. (1981) and Zhu et al. (2002) the last humid phase, when lake levels of Nam Co were high enough (approx. up to 105-120 m higher than today) to overflow towards Siling Co (or Big Qiangtang lake) ended between 40 and 25 ka BP. This is well before the timeframe of the studies included in our review. As we are focusing on more recent studies, the Nam Co catchment can be used as a case study where many processes happening in larger and/or other areas may be observed on a local level.

Author´s changes in manuscript: We removed the word "model" and restructured the corresponding sentences throughout the manuscript to avoid misunderstanding of this term.
We added the sentence: "Large proportions of the inner TP are endorheic and therefore do not drain into the large river systems."
Furthermore, we included the following paragraph in chapter 3.1 to discuss the existence of a possible outflow of Nam Co: "There are at least seven different levels of continuous terraces around Nam Co, with the highest being over 30 meters above current lake level, corresponding well with the elevation of the natural spillway in the northeast of Nam Co. Several authors claim the existence of a much larger fluvial lake system called "Old Qiangtang Lake", which covered an area of about 30,000–50,000 km^2 or more (Li et al., 1981; Zhu et al., 2002). The connections provided by a large lake allowed the gene flow between drainages, which is reflected, for example, by the closely related clades of schizothoracine fish (Cyprinidae, Osteichthyes) from Nam Co and the surrounding lakes, compared with more distant parts of the TP (He et al., 2016). In contrast, due to a vector-mediated passive dispersal across large areas, other aquatic taxa, such as freshwater snails, seem to have been less influenced by drainage histories (Oheimb et al., 2011). Higher lake terraces are older, suggesting a long-term reduction in lake level (Zhu et al., 2002). This may be associated with an evolution from wet to dry phase, which Li et al. (1981) connects to the gradual uplift of the plateau from early Pleistocene to the Holocene. However, there is an alternative suggestion to this interpretation of a rather modern uplift proposed by Renner (2016) who states that large parts of the TP had already reached average heights of 4,000 m and more during the mid-Eocene (~40 Ma ago). Recent findings of palm leave fossils on the central part of the TP, dated to ca. 25.5 ± 0.5 million years, do not suggest a presence of such a high plateau before the Neogene (Su et al., 2019). Thus, although it is suggested that the final large lake phase took place during ca. 40-25 cal ka BP (Lehmkuhl et al., 2002; Zhu et al., 2002), the complex relationship between evolution of the TP and the development and the temporal existence of "Old Qiangtang Lake" are not completely resolved."

Comment 2:

P2 L24: "sorry: it is indeed annoying, but the citation sources could be necessary. Take care: Who first published "Third Pole"?"

Author´s response: To highlight the overall cold temperatures and the occurrence of the third largest ice-mass on earth (after the Arctic and Antarctic), the Tibetan Plateau is also called “The Third Pole”. We refer now to Qiu (2008) who put together a sound description on “The Third Pole”. Please also see Editor Comment 1.

Author´s changes in manuscript: We included Qiu (2008) as citation in the respective text passage.

Comment 3:

P2 L24: “the fact that this is often cited does not rise necessarily the value of this statement: could you please check the precipitation and hydrology data of the headwaters! the rivers get their main water in the outer slopes and NOT from the plateau.)PH D Hofer, Bern”

Author´s response: In our study, the Tibetan Plateau is defined as the geographical region including “the entire southwestern Chinese provinces of Tibet and Qinghai, parts of Gansu, Yunnan, Sichuan and neighboring countries” (P2 L25 f.). To highlight the role of the outer slopes to provide freshwater, we modified the sentence.

Author´s changes in manuscript: On P2 L27 now says: “The southern and eastern TP and the adjacent Himalaya regions form the headwaters of several major rivers […]”

Comment 4:

P2 L28: “please check the source of the Ganges”

Author´s response: Most of the tributaries to the Ganges originate in the Himalayas. The *author´s response* and *changes in manuscript* to the comment 3 also apply to this comment.

Author´s changes in manuscript: Regarding the source of the Ganges, please see Author´s changes concerning comment no. 3. Furthermore, we omitted to quote the “Amudarya” as it originates from the western TP, which is not anymore in compliance with the changes made above.

Comment 5:

P2 L28: “add "River"”

Author´s response: Thanks for your suggestion.

Author´s changes in manuscript: We added “River” so now it says “Yellow River”.

Comment 6:

P3 L11: “this is not a helpful generalization; probably not true for the eastern TP. Could you add sources for this”

Author´s response: Thank you very much for your hint. We agree with your concern and deleted this generalization as the eastern and central TP is modified and managed by humans for the past several thousands of years (see chapter 3.3).

Author´s changes in manuscript: We deleted: “and still relatively little human impact” on P3 L10 f..

Comment 7:

P3 L14: “currently. Please include Li et al. Proceed. Int. Symp. QTP Beijing, Vol 2”

Author´s response: Thank you very much for the suggestion. This adds to the comment 1 regarding the possible outflow of Nam Co towards Siling Co. We agree and restructured the sentence. We also refer to the inserted sentences in chapter 3.1.

Author´s changes in manuscript: The sentence now reads: **“**Currently, Lake Nam Co represents an endorheic system, acting as a sink for water, sediment and carbon fluxes. The existence of a former drainage (“Old Qiangtang Lake”) towards the northwestern Siling Co and further east, down from the TP is still under discussion (Li et al., 1981; Kong et al., 2011) (see chapter 3.1).”

Comment 8:

P5 L6: “is the weather station in the lake a small island ?”

Author´s response: Yes, there are two small islands in that area of the lake. One was equipped with an Automatic Weather Station (AWS) for approximately two years. Data collected by this AWS has not yet been published but the mean annual precipitation (see Fig. 4) was calculated and communicated orally by Dr. Binbin Wang, Institute of Tibetan Plateau Research, Beijing, who is in charge of the AWS.

Author´s changes in manuscript: No changes have been made in accordance to this comment.

Comment 9:

P5 L13: “What is the scientific value of the MAT ? ! Please check Körner Alpine Plant Life and Körner Alpine Treelines”

Author´s response: Mean annual air temperature (MAT) and mean annual precipitation (MAP) provide an overview about general climatic conditions at Nam Co. They provide a first glance if, for example, there is permafrost to be expected, or which type of vegetation can be anticipated. We agree, however, that these basic statistics do not provide a complete overview, especially as seasonality on the TP is high. We included a table (Table 1) with monthly mean, minimum and maximum air temperatures as well as monthly mean precipitation, averaged from 2006 to 2017, using meteorological data from NAMORS. The dataset was provided by the Institute of Tibetan Plateau Research and the calculations were performed by Felix Nieberding using the tidyverse package family in R on RStudio environment (Wickham, 2017; RStudio Team, 2018; R Core Team, 2019).

Author´s changes in manuscript: We added Table 1 which provides an overview of meteorological parameters throughout the year and cite Ma et al. (2009) for the equipment and maintenance of the sensors. Furthermore, the mean annual precipitation values, as well as the monsoon period were changed to correctly display the values calculated directly from the dataset.

Comment 10:

P5 L14: "please include data about the shifts of the monsoon onset - most important for the ecosystem!"

Author´s response: Depending on the location on the TP, strong interannual variability in onset and strength of monsoonal precipitation can be observed. To highlight the importance of precipitation for pasture greening, we included additional information in chapter 2.1.

Author´s changes in manuscript: In chapter 2.1 we added the sentence: "The onset and strength of monsoonal precipitation varies substantially between individual years and can be delayed by up to six weeks, depending on altitude and latitude on the TP (Miehe et al., 2019)."

Comment 11:

P9 L5: "this refers to Miehe et al. xxx"

Author´s response: We agree, thanks for your comment!

Author´s changes in manuscript: We added the corresponding citation: (Miehe et al., 2019)

Comment 12:

P9 L5: "You follow the Chinese claffification which is not in accordance to international standards. The fact that most publications use "Meadow" does not mean too much. According to the UNESCO Classification "meadow" is a mowed artifical grassland. Better to use "pasture""

Author´s response: Thank you very much for your advice! We agree, because the grasslands on the TP are primarily used for grazing by domestic animals such as yak, sheep and goat.

Author´s changes in manuscript: Throughout the whole document, we replaced "meadow" by "pasture".

Comment 13:

P9 L14: "please correct according to Noelling !"

Author´s response: We agree and added the corresponding citation.

Author´s changes in manuscript: We added the citation (Nölling, 2006) at P9 L11 in the text.

Comment 14:

P10 L4: "This sentence rise doubts if the authors have been in the area and it prooves that they are not at all familiar with vegetation ecology: Please check Zhang 1988 Vegetation of Xizang, Noelling. The NC catchment has open dwarf scrub of Juniperus pingii v wilsonii, on the southern slope as well; the only relics of trees are found in Nindung Xiang, described by sources cited in this paper - I am confused what has happened"

Author´s response: We agree with the reviewer´s demand to clarify our formulations. We rewrote the sentence to make clear that there are currently no trees in the Nam Co catchment.

Author´s changes in manuscript: The sentence now reads: **"**There is no evidence of tree species, except for the evergreen shrubs of *Juniperus pingii var. wilsonii*, which are mainly found on south-facing slopes in the northern Nam Co catchment, and shrubs of *Salix* spp.*,* which are present in the Niyaqu Valley in the eastern lake catchment (Li, 2018)."

Comment 15:

P10 L6: "this sentence is absolutely enigmatic or meaningless"

Author´s response: We agree, this sentence should be omitted.

Author´s changes in manuscript: We omitted the sentence and also P10 L10 f., as it holds no additional information.

Comment 16:

P10 L23: "please check if *K. tibetica* is really recorded in the NC area. It usually is in the NE plateau."

Author´s response: We double checked the occurrence of *K. tibetica* in the Nam Co area. Based on personal communications with Prof. Tsechoe Dorji, who has been working in the Nam Co area for the past decade, we are confident that *Kobresia tibetica* is also present there. Furthermore, the species is listed in Chen and Yang (2011). For the sake of completeness, we added *Kobresia schoenoides* to the list, as it is present in the Nam Co area as well.

Author´s changes in manuscript: The new sentence was changed to: "[…] or Kobresia *tibetica* (Yu et al., 2010) and *Kobresia schoenoides* (Nölling, 2006)."

Comment 17:

P10 L24: "possibly !!!!"

Author´s response: We did not include the word "possibly" because it does not fit the sentence. We agree that the influence of grazing on pasture degradation should be discussed. This is why we added a more in-depth discussion to highlight the dominating influence of environmental factors on pasture degradation, rather than just grazing (except for overgrazing in the vicinity of settlements and due to fencing of cattle).

Author´s changes in manuscript: Chapter 2.4 now contains several text passages dedicated to the topic of causes for pasture degradation. For detailed changes see comment 18.

Comment 18:

P10 L27 "please check Yun Wangs PhD in Halle. This is the most relevant source in this issue"

Author´s response: We read Wang's dissertation and also checked the respective publications.

Author´s changes in manuscript: Several changes were made in chapter 2.4 that includes the results of Wang and her co-authors. We also used more local studies related to the Nam Co catchment to verify the statements of Yun Wang et al.: "This effect, however, seems to be limited to the direct vicinity of herder´s settlements and camps (piosphere-centers), and many factors that are usually attributed to degradation rather proof to be environmentally controlled, especially in drier areas (Wang et al., 2018). Some researchers argue that climate change is the dominant or even sole driver of degradation (Wang et al., 2007), although the effects of rising temperatures and increasing precipitation appear to be an intensifier rather than the cause of degradation (Zhou et al., 2005; Harris, 2010). In turn, both Wang et al (2018) and Cao et al. (2019) point out that a multitude of effects might be in play, with a locally differing magnitude or even reversion, while usually moderate grazing was not to be found to cause degradation. Certainly, there are more factors than just grazing-pressure, and there might be site-specific effects leading to non-equilibrium behavior of the study object, be it pasture or steppe (Wang and Wesche, 2016). Plot-level experiments from the Nam Co area found warming to have significant effects on the shallow rooted *Kobresia pygmaea* by reducing the number of flowers and delaying its reproductive phenology. These changes were provoked by simulating increasing precipitation by means of snow addition (Dorji et al., 2013) and also by maintaining a moderate level of grazing combined with snow addition (Dorji et al., 2018). This underlines the importance of climate forcing on the terrestrial systems in the Nam Co catchment. Grazing should not be seen as a disturbance but as an integral part of a non-steady state but plagioclimax environment."

Comment 19:

P11 L3: "it is a well known fact of Chinese experts that the traditional management was sustainable and the trouble started with political interferences ignoring the grassland science of Chinese research stations"

Author´s response: We agree with the referee about this point. We modified the sentence to account for any ambiguities.

Author´s changes in manuscript: We deleted the first part of the sentence which now reads: "The Chinese government has favored policies such as sedentariness and fostered the construction of stationary settlements, which have, in turn, created hotspots of overgrazing (Miehe et al., 2008)."

Comment 20:

P11 L11: “this is a citation of Miehe et al. 2011 Applied Vegetation Science 14: 547-560”

Author´s response: We thank the reviewer for that comment! We added the citation

Author´s changes in manuscript: We added the citation (Miehe et al., 2011).

Comment 21:

P12 L4: “The correct naming is Juniperus pingii var. wilsonii. The elevational limits are not correct.. Please check with Google Earth. Please pass the whole manuscript to a vegetation ecologist: Please check with Wikipedia o other sources what "ruderal" means”

Author´s response: Thank you very much for your advice! We changed the name from *Juniperus pingii* to *Juniperus pingii* var. *wilsonii* throughout the entire manuscript. Furthermore, we adjusted the elevation limits in figure 4. Approximate biome elevations were taken from satellite imagery (Sentinel 2B) and herewith derived vegetation indices, field excursion and literature review (Wang and Yi, 2011; Ohtsuka et al., 2008).

Author´s changes in manuscript: See author’s response above.

Comment 22:

P14 L6: “The whole section could be improved to a valuable introduction if more sources would be involded, but it is the question if such a state of the art is necessary to point out the specific situation of NamCo”

Author´s response: The aim of this section is to provide a more general overview about the interdependencies of geodiversity and biodiversity on the TP by citing most relevant studies on this topic. To provide a valuable introduction, we carefully restructured the whole section and also pointed out the implications for the Nam Co catchment (see also comment no. 1).

Author´s changes in manuscript: The restructured paragraph now reads: “Topography, geological context, climate and their complex interplay are key determinants for the distribution of organisms. In general, the ecoregion can serve as a proxy for community- and species-level biodiversity, which best describe communities of mammals, birds and plants (Smith et al., 2018). The TP forms a distinctive zoographical region, an “ecological island” (Deng et al., 2019), characterized by fauna that is adapted to high altitudes, drought, low temperatures and low oxygen levels (He et al., 2016). The TP is forming a unique high-altitude biogeographical biota by harboring also many unique lineages of other organisms, with higher endemism of low dispersal species (Yang et al., 2009; Clewing et al., 2016). As mountain building has been directly associated with the development of biodiversity (Hoorn et al., 2013; Antonelli et al., 2018), the biodiversity hotspots are located especially in the south and south-east of the TP. There is also a pattern of increasing biodiversity from west to east, which correlates positively with increasing precipitation. In contrast, the harsh central areas of the TP show much lower richness, but nevertheless harbor various endemics (Päckert et al., 2015). Throughout the geological formation of the TP, the mountainous south-eastern parts have been hypothesized to serve as center of species diversification (Mosbrugger et al., 2018), although the core TP region is also suggested to represent a center of origin (Deng et al., 2011). The TP has been a source area for several mammalian lineages (Out-of-Tibet hypothesis; Deng et al., 2011), including the snow leopard and the arctic fox (Wang et al., 2015), as well as birds, such as redstarts (Voelker et al., 2015), and plants, such as *Gentiana* (Favre et al., 2015). These mountainous areas may also have acted as refugia, which preserved unique lineages over long periods (López-Pujol et al., 2011; Lei et al., 2014). Whether some endemic taxa represent relics of a formerly more diverse clade or have never extensively diversified, remains unclear (Päckert et al., 2015). Besides being a center of origin, the TP may represent a center of accumulation as proposed by the examples of *Saxifraga* (Ebersbach et al., 2017), warblers (Johansson et al., 2007) and hynobiid salamander (Zhang et al., 2006). Overall, the regional biota of the TP is comprised mainly of Palearctic and Oriental species, Nearctic species from the Bering land bridge, as well as species from speciation *in situ*, and postglacial recolonization from adjacent areas. The evolution of biodiversity on the TP has been affected by the combination of geological and climatic changes over the time of the uplift phases (Mosbrugger et al., 2018). Although many studies have associated recent *in situ* radiations to different uplift phases of the TP, Renner (2016) pointed out that the evidence for recent rapid uplift (9–8 or 3.6–2.6 Ma) remains doubtful and controversial. As proposed by the "mountain-geobiodiversity" hypothesis, the evolution of biodiversity on the TP is a result of an increasing local geodiversity in combination with rapid climatic oscillations and steep ecological gradients (Mosbrugger et al., 2018)."

Comment 23:

P14 L10: "sorry there is far more than just fish !"

Author´s response: We are not sure to what the reviewer refers by this comment, but the citations in the text are not only fish related but also include results of research on birds, mammals (Yang et al., 2009) and snails (Clewing et al., 2016).

Author´s changes in manuscript: No changes.

Comment 24:

P14 L11: "please check the state of the art more careful !"

Author´s response: Associated with the comment no. 25. This part has been removed from the manuscript.

Author´s changes in manuscript: See comment no. 25.

Comment 25:

P14 L12: "I doubt if the environmental history of the NC has anything in common with the outer declivities like the Himalaya or the Hengduan Shan."

Author´s response: We agree with the reviewer´s comment. However, the aim of this section is to give a rather more general overview of the TP. Nevertheless, in order to avoid confusions, this sentence has been removed from the manuscript.

Author´s changes in manuscript: We have removed the following sentences, P17: "The TP, including Himalayas and Hengduan Mountains, harbor more than 12000 species of seed plants, 1000 species of terrestrial vertebrates and 800 species of birds (Zhang et al., 2016; Zheng and Zhao, 2017). The proportion of endemism among these plants and vertebrates is relatively high, about 38% and 20%, respectively, but only about 4% among breeding birds (Yang et al., 2009). The recorded species richness of fish exceeds the count of 150, with most common and abundant group being endemic schizothoracine (Zheng and Zhao, 2017). As the structure of soil microbial (including fungal) communities are affected by vegetation, climatic and soil parameters, the unique habitats of the TP potentially harbor many unique microbial lineages that are adapted to high altitude and cold environments (Huang et al., 2014)."

Comment 26:

P14 L13: "This is really misleading: the endemism of NC is another story and the sources about endemism have to be included"

Author´s response: Associated with the comment 25.

Author´s changes in manuscript: The sentences related to endemism percentages were removed from the manuscript.

Comment 27:

P14 L18 "the meaning of this sentence is that the cited sources are not relevant for the NC

Author´s response: Although the sentence is not only associated with the Nam Co catchment, as this entire short section, it is relevant for pointing out biodiversity hotspots on the TP.

Author´s changes in manuscript: No changes.

Comment 28:

P14 L21: "there are certainly no tropical forests on the TP since the late Pliocene !!"

Author´s response: While this is true, the authors meant the southern part of TP, the seasonal rainforests of the low altitudes in the eastern Himalayas, which are replaced by conifers at higher altitudes.

Author´s changes in manuscript: The following section has been removed in order to avoid confusion: "One of the driving factors is the strong altitudinal zonation, which creates habitat diversity and forms various ecosystems. On the TP, ecosystems are ranging from tropical rain forest over coniferous forest, shrubland, alpine meadow and alpine steppe to dry and desert steppe with increasing altitude."

Comment 29:

P15 L5: “if this chapter remains in place, please include Su et al. 2019, who gives a completely different record !”

Author´s response: We thank the reviewer for pointing out new research! However, the suggested reference does not include estimations about the onset of the uplift that we were pointing out to be ca. 50-55 Ma ago as based on Mosbrugger et al. (2018).

Author´s changes in manuscript: Because the onset of the Plateau uplift is still under debate, we removed “started ca. 55–50 Ma ago”. We furthermore included a short chapter in section 3.1, discussing the controversial arguments about the timing of the Plateau uplift (see comments no. 1 and no. 22).

Comment 30:

P15 L18: “why do you not cite Li et al. 1981 ?”

Author´s response: We thank the reviewer to point out that Li et al 1981 also noted that the drainage possibly changed during the Late Pleistocene.

Author´s changes in manuscript: We incorporated a paragraph about the shift of the drainage regime in chapter 3.1 (see comment no. 1).

Comment 31:

P17 L12: “Plant families are usually written in recte, only gebera and species in italics”

Author´s response: Thank you very much for your advice, we applied the scheme you proposed to the entire manuscript.

Author´s changes in manuscript: Throughout the manuscript, taxonomical family names are now written in normal letters, genus and species names in italics.

Comment 32:

P18 L16: “The phanerophytes of Juniperus and Salicx of the NC are throughout shrubs , not trees. What is your evidence that NC was ever forested ?”

Author´s response: Thank you for pointing this out. We explicitly state that there are no tree species in the catchment.

Author´s changes in manuscript: In chapter 2.4 we now write: **“**There is no evidence of tree species, and the only evergreen shrub species present are *Juniperus pingii var. wilsonii*, which is mainly found on the south-facing slopes of the northern Nam Co catchment, and *Salix* spp. in the Niyaqu Valley in the eastern lake catchment (Li, 2018).”

Comment 33:

P18 L24: “again: no evidence.”

Author´s response: We created a better link between chapters 2.4 and 3.3, where we discuss this hypothesis now with more distance and more critical. Our revised statements are now given in subjunctive, and we do point out that the hypothesis cannot be directly corroborated by the data currently accessible to us. However, we do state that we see a strong but not unambiguous hint for anthropogenic influence that might have led to severe changes of the landscape.

Author´s changes in manuscript: The end of chapter 3.3 now reads: “Furthermore, the occurrence of synanthropic taxa has been observed in the nearby Damxung valley since 8.5 cal ka BP (Schlütz et al., 2007). This corroborates the strong anthropogenic influence on the formation and restructuring of vegetation patterns in the area but leaves a time gap of almost 3 ka between the evidence from Damxung valley and Nam Co. Hence, further research is needed to address the question of onset of human activity and degree of landscape modification.”

Comment 34:

P18 L28: “ecosystems”

Author´s response: Thank you for your advice, we corrected this spelling error.

Author´s changes in manuscript: It now reads “ecosystems” instead of “Ecosystems”

Reviewer 2 (Anonymous Referee):

Comment 1:

P2 L28: "Please consider to write either Yellow river or, as with the other rivers the native name: Huang He."

Author´s response: Thank you very much for your helpful suggestion. We changed the name from "Yellow" to "Yellow River"

Author´s changes in manuscript: See author's response to this comment.

Comment 2:

P4 Fig. 1C: "Please provide for the salinity also the ppt value for ease of cross-comparison to other literature references."

Author´s response: Thank you very much, we agree with the reviewer´s suggestion.

Author´s changes in manuscript: The salinity is now provided in ppt to allow for easy comparison with other literature references.

Comment 3:

P8 L6: "It would be worth mentioning that ammonia oxidizing archaea are autotrophic microorganisms that contribute to CO2 fixation primarily in the aphotic zones of lakes and thus contribute to (dark) primary production - especially of deep and oligotrophic lakes. As an example, have a look at the following references: Callieri et al., 2014 (J. of Limnology), Callieri et al., 2016 (Aquatic Sciences), Herber et al., 2019 (Environ Microbiol)."

Author´s response: We appreciate your comment and added a paragraph to chapter 2.3 to emphasize and explain the archaea group and especially their role in fixing ammonium and CO_2. Moreover, we use the correct terminology that refers to lake systems.

Author´s changes in manuscript: In chapter 2.3 we added the following section: **"**Studies demonstrated that ammonia-oxidizing archaea (autotrophic microorganisms) are key contributors to ammonia oxidation in deep and oligotrophic lakes (Callieri et al., 2016). This has implications for CO_2 fixation in the hypolimnion or the benthic zone, where there is insufficient irradiance to support photosynthesis, implying that archaea would perform the final step in the decay of organic matter via methanogenesis, resulting in carbon dioxide accumulation (e.g. when they decrease during winter). Although nitrification does not directly change the inventory of inorganic Nitrogen in freshwater ecosystems, it constitutes the only known biological source of nitrate and as such represents a critical link between mineralization of organic N and its eventual loss as N_2 by denitrification or anaerobic ammonia oxidation to the atmosphere (Herber et al., 2019)."

Comment 4:

P13 L24: “Change “anaerobic” conditions to “anoxic” conditions. Anoxic refers to a physicochemical condition, anaerobic refers to the ability of an organisms to live w/o oxygen or its respective metabolism.”

Author´s response: Thank you for your suggestion! We changed the terminology in order to avoid ambiguities.

Author´s changes in manuscript: We changed the term from “anaerobic” to “anoxic”.

Comment 5:

P13 L25: “for methanogenic activity, which results in increasing CH4 emissions to the atmosphere”

Author´s response: We changed the text as proposed by the reviewer comment.

Author´s changes in manuscript: The sentence now reads: **“**Large amounts of SOC in combination with anoxic conditions are the main precursors for methanogen activity, which results in increasing CH_4 emissions to the atmosphere (Kato et al., 2013).”

Comment 6:

P14 L4: “It might be worth to include a short paragraph on N2O emission to the atmosphere from soils, if such literature exists for the TP. N2O is, in addition to CH4, a very potent greenhouse gas and may be released in areas of intense livestock farming.”

Author´s response: We agree with the importance of N2O emission to the atmosphere. Unfortunately, there is no study measuring N2O emissions in the Nam Co basin. But we added the topic to the manuscript based on the small number of experimental studies in other regions of the TP.

Author´s changes in manuscript: The following text was added to the chapter 2.5: “Overgrazing, along with the increase of burrowing pikas in the Tibetan grasslands may increase the Nitrous Oxide (N_2O) emissions (Zhou et al., 2018), an important greenhouse gas with 297-times larger warming potential compared to CO_2 (IPCC, 2013). Despite several studies focusing on greenhouse gas emissions on the TP, the magnitude of the N_2O emissions in different ecosystems has not yet been estimated. Experimental studies on the eastern TP demonstrated that the rate of N_2O emission may increase with increasing soil temperature and soil moisture under a future climate change scenario (Yan et al., 2018; Yingfang et al., 2018).”

Comment 7:

P19 L2: “anoxic conditions”

Author´s response: The sentence was deleted for consistency.

Author´s changes in manuscript: The sentence was deleted.

Relevant changes made in the manuscript:

P1, L2: Additional changes made by the authors: We wish to change the title of the manuscript to "Reviews and syntheses: How do abiotic and biotic processes respond to climatic variations in the Nam Co catchment (Tibetan Plateau)?". We feel that this better reflects the overall focus of the paper on the environmental processes in the Nam Co and especially its catchment.

P1, L3: Additional changes made by the authors: We shortened the description of the order in which the TransTiP Research Team members are listed.

P1, L4: Additional changes made by the authors: The co-affiliation of Sten Anslan with the Institute of Geosystems and Bioindication was missing.

P2, L3 f.: Additional changes made by the authors: We rephrased some words to enhance readability and consistency of the manuscript and corrected a small typos.

P2, L5: Additional changes made by the authors: We changed the term "climatic oscillation" to "climatic changes" to make clear, that the recent changes shall not be seen as natural or even regular variations, but are rather extraordinary, human induced events.

P2, L6 f.: Additional changes made by the authors: We restructured the sentence and wording to enhance readability and consistency of the manuscript. We deleted "have".

P2, L7: Additional changes made by the authors: We restructured the sentence and wording to enhance readability and consistency of the manuscript. We changed "focusing on" to "using".

P2, L7; P3, L26: Author´s response to Reviewer 1, Comment 1: We removed the word "model" and restructured the corresponding sentences throughout the manuscript to avoid misunderstanding of this term.

P2, L7 f: Additional changes made by the authors: Here, we wish to highlight, that not only global warming is an ongoing process, but also the observed deglaciation and enhanced freshwater input is still going on. Hence we rephrased the slightly.

P2, L10: Additional changes made by the authors: We restructured the sentence and wording to enhance readability and consistency of the manuscript. We changed "The enhanced" to "Increasing".

P2, L12: Additional changes made by the authors: Here, we wish to highlight, that the carbon fluxes are not only affected by global warming, but also to a great extend though the intensity of grazing. Hence, we added the term "additional" to the sentence.

P2, L16: Additional changes made by the authors: We restructured the sentence and wording to enhance readability and consistency of the manuscript. We deleted "have".

P2, L19 f.: Additional changes made by the authors: We restructured the sentence to highlight, that the processes observable at Lake Nam Co are potentially transferable to a larger area, such as the Tibetan Plateau or other high mountain environments.

P2, L23: Additional changes made by the authors: We restructured the sentence and wording to enhance readability and consistency of the manuscript. We changed “lake Nam Co” to “Lake Nam Co” throughout the manuscript.

P2, L26: Author´s response to Editor Comment 1 and Reviewer 1, Comment 2: We included Qiu (2008) as citation in the respective text passage.

P2, L28 f.: Author´s response to Reviewer 1, Comment 3 and Comment 4: In our study, the Tibetan Plateau is defined as the geographical region including “the entire southwestern Chinese provinces of Tibet and Qinghai, parts of Gansu, Yunnan, Sichuan and neighboring countries” (P2 L25 f.). To highlight the role of the outer slopes to provide freshwater, we modified the sentence. We omitted to quote the “Amudarya” as it originates from the western TP, which is not anymore in compliance with the changes made above.

P2 L30: Author´s response to Reviewer 1, Comment 5 and Reviewer 2, Comment 1: We changed the name from “Yellow” to “Yellow River”

P2 L31: Author´s response to Reviewer 1, Comment 1: We added the sentence: “Large proportions of the inner TP are endorheic and therefore do not drain into the large river systems.”

P3 L13: Author´s response to Reviewer 1, Comment 6: We deleted: “and still relatively little human impact”.

P3 L 17 ff.: Author´s response to Reviewer 1, Comment 7: We modified the sentence so now it reads: **“**Currently, Lake Nam Co represents an endorheic system, acting as a sink for water, sediment and carbon fluxes. The existence of a former drainage (“Old Qiangtang Lake”) towards the northwestern Siling Co and further east, down from the TP is still under discussion (Li et al., 1981; Kong et al., 2011) (see chapter 3.1).”

Figure 1: Author´s response to Reviewer 2, Comment 2: The salinity is now provided in ppt to allow for easy comparison with other literature references.

P6, L8 ff.: Author´s response to Reviewer 1, Comment 9: We added Table 1 which provides an overview of meteorological parameters throughout the year and cite Ma et al. (2009) for the equipment and maintenance of the sensors. Furthermore, the mean annual precipitation values, as well as the monsoon period were changed to correctly display the values calculated directly from the dataset.

P6, L23; P7, L2; P10, L8; P23, L28: Additional changes made by the authors: For consistency and because the “mountain” is already included in the Tibetan term “Nyainqêntanglha”, we decided to just call it “Nyainqêntanglha range” throughout the manuscript.

P9, L11 ff.: Author´s response to Reviewer 2, Comment 3: In chapter 2.3 we added the following section: **"**Studies demonstrated that ammonia-oxidizing archaea (autotrophic microorganisms) are key contributors to ammonia oxidation in deep and oligotrophic lakes (Callieri et al., 2016). This has implications for CO_2 fixation in the hypolimnion or the benthic zone, where there is insufficient irradiance to support photosynthesis, implying that archaea would perform the final step in the decay of organic matter via methanogenesis, resulting in carbon dioxide accumulation (e.g. when they decrease during winter). Although nitrification does not directly change the inventory of inorganic Nitrogen in freshwater ecosystems, it constitutes the only known biological source of nitrate and as such represents a critical link between mineralization of organic N and its eventual loss as N_2 by denitrification or anaerobic ammonia oxidation to the atmosphere (Herber et al., 2019)." Furthermore, we further distinguished the communities that are prone to water conductivity changes in the sentence before: "[…] archaea, bacteria, phytoplankton, and microinvertebrates.".

P10, L6; P11, L7, L9 f., L20, L22, L23, L34; P12, L1, L4, L14, L17, L20; P22, L14: Author´s response to Reviewer 1, Comment 12: Throughout the whole document, we replaced "meadow" by "pasture".

P10, L7: Author´s response to Reviewer 1, Comment 10: We added the corresponding citation: (Miehe et al., 2019).

P10, L11: Author´s response to Reviewer 1, Comment 13: We added the corresponding citation: (Nölling, 2006).

P11, L13 ff.: Additional changes made by the authors: We added a short paragraph highlighting the relationship between the Kobreasia pastures, grazing intensity and soil properties: "The genesis of this felty root mat is attributed to Kobresia pygmaea, since this shallow rooting, small plant allocates most of its biomass belowground and is able to reproduce vegetative, making it well adapted to the high grazing pressure (Miehe et al., 2008). The curious dominance of K. pygmaea is often linked to grazing: (i) K. pygmaea replaces taller plants at sites where grazing pressure is increased experimentally. (ii) Several enclosures show that other grasses and shrubs gain in dominance after grazing competition ceased (Miehe et al., 2008). Hence, the felty root-mat can be seen as an effect of an anthropozoogenic plagioclimax."

P11, L 28 ff.: Author´s response to Reviewer 1, Comment 14: The sentence now reads: **"**There is no evidence of tree species, except for the evergreen shrubs of *Juniperus pingii var. wilsonii*, which are mainly found on south-facing slopes in the northern Nam Co catchment, and shrubs of *Salix* spp., which are present in the Niyaqu Valley in the eastern lake catchment (Li, 2018)."

P11, L 32 ff.; P12, L2 f.: Author´s response to Reviewer 1, Comment 15: We omitted the sentences.

P12, L16: Author´s response to Reviewer 1, Comment 16: The new sentence was changed to: "[…] or Kobresia *tibetica* (Yu et al., 2010) and *Kobresia schoenoides* (Nölling, 2006)."

P12, L17: Additional changes made by the authors: We slightly modified the sentence in order to highlight the ongoing scientific controversy concerning the origin and drivers of Tibetan alpine pasture degradation.

P12, L22 – P13, L8: Author´s response to Reviewer 1, Comment 18: Several changes were made in chapter 2.4 that includes the results of Wang and her co-authors. We also used more local studies related to the Nam Co catchment to verify the statements of Yun Wang et al.: "This effect, however, seems to be limited to the direct vicinity of herder´s settlements and camps (piosphere-centers), and many factors that are usually attributed to degradation rather proof to be environmentally controlled, especially in drier areas (Wang et al., 2018). Some researchers argue that climate change is the dominant or even sole driver of degradation (Wang et al., 2007), although the effects of rising temperatures and increasing precipitation appear to be an intensifier rather than the cause of degradation (Zhou et al., 2005; Harris, 2010). In turn, both Wang et al (2018) and Cao et al. (2019) point out that a multitude of effects might be in play, with a locally differing magnitude or even reversion, while usually moderate grazing was not to be found to cause degradation. Certainly, there are more factors than just grazing-pressure, and there might be site-specific effects leading to non-equilibrium behavior of the study object, be it pasture or steppe (Wang and Wesche, 2016). Plot-level experiments from the Nam Co area found warming to have significant effects on the shallow rooted *Kobresia pygmaea* by reducing the number of flowers and delaying its reproductive phenology. These changes were provoked by simulating increasing precipitation by means of snow addition (Dorji et al., 2013) and also by maintaining a moderate level of grazing combined with snow addition (Dorji et al., 2018). This underlines the importance of climate forcing on the terrestrial systems in the Nam Co catchment. Grazing should not be seen as a disturbance but as an integral part of a non-steady state but plagioclimax environment."

P13, L11 ff.: Author´s response to Reviewer 1, Comment 19: We deleted the first part of the sentence which now reads: "The Chinese government has favored policies such as sedentariness and fostered the construction of stationary settlements, which have, in turn, created hotspots of overgrazing (Miehe et al., 2008)."

P13, L20 f.: Author´s response to Reviewer 1, Comment 19: We added the citation (Miehe et al., 2011).

Figure 4: Author´s response Reviewer 1, Comment 21: We changed the name from *Juniperus pingii* to *Juniperus pingii* var. *wilsonii* throughout the entire manuscript. Furthermore, we adjusted the elevation limits in figure 4. Approximate biome elevations were taken from satellite imagery (Sentinel 2B) and herewith derived vegetation indices, field excursion and literature review (Wang and Yi, 2011; Ohtsuka et al., 2008). These changes were also stated in the figure description where we added the following sentence: "Approximate biome heights were gained from: satellite imagery (Sentinel 2B) and herewith derived vegetation indices, field excursion and literature review (Ohtsuka et al., 2008; Wang and Yi, 2011)."

P16, L26 f.: Author´s response to Reviewer 2, Comment 4 and Comment 5: We changed the term from "anaerobic" to "anoxic". The sentence now reads: **"**Large amounts of SOC in combination with anoxic conditions are the main precursors for methanogen activity, which results in increasing CH_4 emissions to the atmosphere (Kato et al., 2013)."

P17, L1 ff.: Author´s response to Reviewer 2, Comment 6: The following text was added to the chapter 2.5: "Overgrazing, along with the increase of burrowing pikas in the Tibetan grasslands may increase the Nitrous Oxide (N_2O) emissions (Zhou et al., 2018), an important greenhouse gas with 297-times larger warming potential compared to CO_2 (IPCC, 2013). Despite several studies focusing on greenhouse gas emissions on the TP, the magnitude of the N_2O emissions in different ecosystems has not yet been estimated. Experimental studies on the eastern TP demonstrated that the rate of N_2O emission may increase with increasing soil temperature and soil moisture under a future climate change scenario (Yan et al., 2018; Yingfang et al., 2018)."

P17, L13 – P20, L12: The whole section 3.1 was restructured according to Reviewer 1 comments 22 – 30, as well as comment 1:

P14, L16 – P19, L9: Author´s response to Reviewer 1, Comment 22: The restructured paragraph now reads: "Topography, geological context, climate and their complex interplay are key determinants for the distribution of organisms. In general, the ecoregion can serve as a proxy for community- and species-level biodiversity, which best describe communities of mammals, birds and plants (Smith et al., 2018). The TP forms a distinctive zoographical region, an "ecological island" (Deng et al., 2019), characterized by fauna that is adapted to high altitudes, drought, low temperatures and low oxygen levels (He et al., 2016). The TP is forming a unique high-altitude biogeographical biota by harboring also many unique lineages of other organisms, with higher endemism of low dispersal species (Yang et al., 2009; Clewing et al., 2016). As mountain building has been directly associated with the development of biodiversity (Hoorn et al., 2013; Antonelli et al., 2018), the biodiversity hotspots are located especially in the south and south-east of the TP. There is also a pattern of increasing biodiversity from west to east, which correlates positively with increasing precipitation. In contrast, the harsh central areas of the TP show much lower richness, but nevertheless harbor various endemics (Päckert et al., 2015). Throughout the geological formation of the TP, the mountainous south-eastern parts have been hypothesized to serve as center of species diversification (Mosbrugger et al., 2018), although the core TP region is also suggested to represent a center of origin (Deng et al., 2011). The TP has been a source area for several mammalian lineages (Out-of-Tibet hypothesis; Deng et al., 2011), including the snow leopard and the arctic fox (Wang et al., 2015), as well as birds, such as redstarts (Voelker et al., 2015), and plants, such as *Gentiana* (Favre et al., 2015). These mountainous areas may also have acted as refugia, which preserved unique lineages over long periods (López-Pujol et al., 2011; Lei et al., 2014). Whether some endemic taxa represent relics of a formerly more diverse clade or have never extensively diversified, remains unclear (Päckert et al., 2015). Besides being a center of origin, the TP may represent a center of accumulation as proposed by the examples of *Saxifraga* (Ebersbach et al., 2017), warblers (Johansson et al., 2007) and hynobiid salamander (Zhang et al., 2006). Overall, the regional biota of the TP is comprised mainly of Palearctic and Oriental species, Nearctic species from the Bering land bridge, as well as species from speciation *in situ*, and postglacial recolonization from adjacent areas. The evolution of biodiversity on the TP has been affected by the combination of geological and climatic changes over the time of the uplift phases (Mosbrugger et al., 2018). Although many studies have associated recent *in situ* radiations to different uplift phases of the TP, Renner (2016) pointed out that the evidence for recent rapid uplift (9–8 or 3.6–2.6 Ma) remains doubtful and controversial. As proposed by the "mountain-geobiodiversity" hypothesis, the evolution of biodiversity on the TP is a result of an increasing local geodiversity in combination with rapid climatic oscillations and steep ecological gradients (Mosbrugger et al., 2018)."

P19 L10 – P20, L2: Author´s response to Reviewer 1, Comment 22: “Topography, geological context, climate and their complex interplay are key determinants for the distribution of organisms. In general, the ecoregion can serve as a proxy for community- and species-level biodiversity, which best describe communities of mammals, birds and plants (Smith et al., 2018). The TP forms a distinctive zoographical region, an “ecological island” (Deng et al., 2019), characterized by fauna that is adapted to high altitudes, drought, low temperatures and low oxygen levels (He et al., 2016). The TP is forming a unique high-altitude biogeographical biota by harboring also many unique lineages of other organisms, with higher endemism of low dispersal species (Yang et al., 2009; Clewing et al., 2016). As mountain building has been directly associated with the development of biodiversity (Hoorn et al., 2013; Antonelli et al., 2018), the biodiversity hotspots are located especially in the south and south-east of the TP. There is also a pattern of increasing biodiversity from west to east, which correlates positively with increasing precipitation. In contrast, the harsh central areas of the TP show much lower richness, but nevertheless harbor various endemics (Päckert et al., 2015). Throughout the geological formation of the TP, the mountainous south-eastern parts have been hypothesized to serve as center of species diversification (Mosbrugger et al., 2018), although the core TP region is also suggested to represent a center of origin (Deng et al., 2011). The TP has been a source area for several mammalian lineages (Out-of-Tibet hypothesis; Deng et al., 2011), including the snow leopard and the arctic fox (Wang et al., 2015), as well as birds, such as redstarts (Voelker et al., 2015), and plants, such as *Gentiana* (Favre et al., 2015). These mountainous areas may also have acted as refugia, which preserved unique lineages over long periods (López-Pujol et al., 2011; Lei et al., 2014). Whether some endemic taxa represent relics of a formerly more diverse clade or have never extensively diversified, remains unclear (Päckert et al., 2015). Besides being a center of origin, the TP may represent a center of accumulation as proposed by the examples of *Saxifraga* (Ebersbach et al., 2017), warblers (Johansson et al., 2007) and hynobiid salamander (Zhang et al., 2006). Overall, the regional biota of the TP is comprised mainly of Palearctic and Oriental species, Nearctic species from the Bering land bridge, as well as species from speciation *in situ*, and postglacial recolonization from adjacent areas. The evolution of biodiversity on the TP has been affected by the combination of geological and climatic changes over the time of the uplift phases (Mosbrugger et al., 2018). Although many studies have associated recent *in situ* radiations to different uplift phases of the TP, Renner (2016) pointed out that the evidence for recent rapid uplift (9–8 or 3.6–2.6 Ma) remains doubtful and controversial. As proposed by the “mountain-geobiodiversity” hypothesis, the evolution of biodiversity on the TP is a result of an increasing local geodiversity in combination with rapid climatic oscillations and steep ecological gradients (Mosbrugger et al., 2018).”

P20, L3: Additional changes made by the authors: We modified the section header to “Holocene lake level changes […]” in order to highlight the geological timeframe covered by this section and, moreover by the whole paper.

This modification is related to **Reviewer 1, Comment 1:** According to Li et al. (1981) and Zhu et al. (2002) the last humid phase, when lake levels of Nam Co were high enough (approx. up to 105-120 m higher than today) to overflow towards Siling Co (or Big Qiangtang lake) ended between 40 and 25 ka BP. This is well before the timeframe of the studies included in our review. As we are focusing on more recent studies, the Nam Co catchment can be used as a case study where many processes happening in larger and/or other areas may be observed on a local level.

P22, L5 ff.: Author´s response to Reviewer 1, Comment 31: Throughout the manuscript, taxonomical family names are now written in normal letters, genus and species names in italics.

P22, L18 ff., L22, L27 – P23, L12; P23 L17 ff.: Author´s response to Reviewer 1, Comment 33: We created a better link between chapters 2.4 and 3.3, where we discuss this hypothesis now with more distance and more critical. Our revised statements are now given in subjunctive, and we do point out that the hypothesis cannot be directly corroborated by the data currently accessible to us. However, we do state that we see a strong but not unambiguous hint for anthropogenic influence that might have led to severe changes of the landscape.

We added the following Sentences: "This matter is closely related to the prior discussed onset of more intense human activity in the area, since parts of the discussion involve a human-made forest clearing in combination with a natural forest decline. As stated, there are only occurrences of shrubs (*Juniperus pingii var. wilsonii* and *Salix* (Nölling, 2006)) in the Nam Co area. No remains and yet no reliable evidence of a once tree-rich vegetation can be found in the Nam Co catchment. According to locals, there exist several caves with potentially (pre-) historic tree depictions of unknown age. Unfortunately, there is no verification of their existence, nor any dating approach. Since the area of Damxung still does feature larger occurences of *Juniperus pingii var. wilsonii* and, around 4250 m a.s.l., also tree stands of *Juniperus tibetica* in enclosed areas, there is the potential to discuss, that these species have been more numerous in this area (i.e. last-tooth-theory). Miehe et al. (2019) show locations of forest relicts and give a drought line of 200-250 mm precipitation and elevations between 3600 and 4000 m a.s.l. as the upper tree line. Questions arise, whether there has been an expansion of *J. tibetica* into the Nam Co catchment in earlier times, which would be feasible within certain limitations according to the presented thresholds. Charred micro remains as a potential sign of fire driven forest decline, are missing in one of the profiles of Adamczyk (2010) but can be found throughout the Holocene until 1 cal ka BP (Herrmann et al., 2010). The authors attribute the size and shape of the charcoal remains to local, small-scale burning of wood and leaves, not showing signs of larger forest clearings. In addition to the burning of *Juniperus* trees for religious reasons (Miehe et al., 2006), trees and shrubs may have been burned for heating or clearing of pastures by nomads."

The end of chapter 3.3 now reads: "Furthermore, the occurrence of synanthropic taxa has been observed in the nearby Damxung valley since 8.5 cal ka BP (Schlütz et al., 2007). This corroborates the strong anthropogenic influence on the formation and restructuring of vegetation patterns in the area but leaves a time gap of almost 3 ka between the evidence from Damxung valley and Nam Co. Hence, further research is needed to address the question of onset of human activity and degree of landscape modification."

P23, L26 ff., P24, L2 ff.: Author´s response to Reviewer 1, Comment 1: We removed the word "model" and restructured the sentences in order to enhance readability and text flow.

P23, L30 ff.: Author´s response to Reviewer 2, Comment 7: The sentence was deleted for consistency.

P24, L1: Additional changes made by the authors: We clarified the term "grassland" in order to clarify the differential response of wetlands and steppe-pasture ecosystems to global warming. In wetlands, methane emissions may increase whereas steppe and grassland ecosystems will likely see an increase in carbon dioxide emissions.

P24: Additional changes made by the authors: We restructured some sentences and wording to enhance readability and consistency of the manuscript.

L9: We changed “focusing” to “to achieve”.

L10, f.: We added suggestions how the open questions may be addressed in order to enhance the “perspectives” part of the conclusions. We added “[…] by in depth analysis of different biomes and in-situ observations”

L12: We changed “improved” to “advanced”.

L15: We changed “to be used” to “for application”

L19: We changed “of the catchment of Nam Co” to “of the Nam Co catchment”.

P24: Author contributions: We corrected an error: “AS conceived the idea and was responsible for funding acquisition.” Furthermore, we added the contributions for the Tables and corrected for some typos in order to comply with Copernicus publication guidelines.

P25: Acknowledgements: We restructured the acknowledgements in order to express our gratitude to the two reviewers and to comply with the publication guidelines of the funding agency of the TransTiP project.

P25: Data availability: We added the following declaration: Data availability: As this manuscript is reviewing existing literature findings, there was no data analyzed that is not already published in the studies we cite. The dataset from which Table 1 was generated was provided by the Institute of Tibetan Plateau Research and is publicly available under https://data.tpdc.ac.cn/en/data/4deeb2b4-4fc1-4c7c-b0c6-6263a547d53f/ (Wang and Wu, 2018) and https://data.tpdc.ac.cn/en/data/3767cacc-96e3-48b2-b66c-dac92800ca69/ (Wang, 2019)

Reviews and syntheses: How do abiotic and biotic processes respond to climatic variations ~~at~~ in the Nam Co catchment (Tibetan Plateau)?

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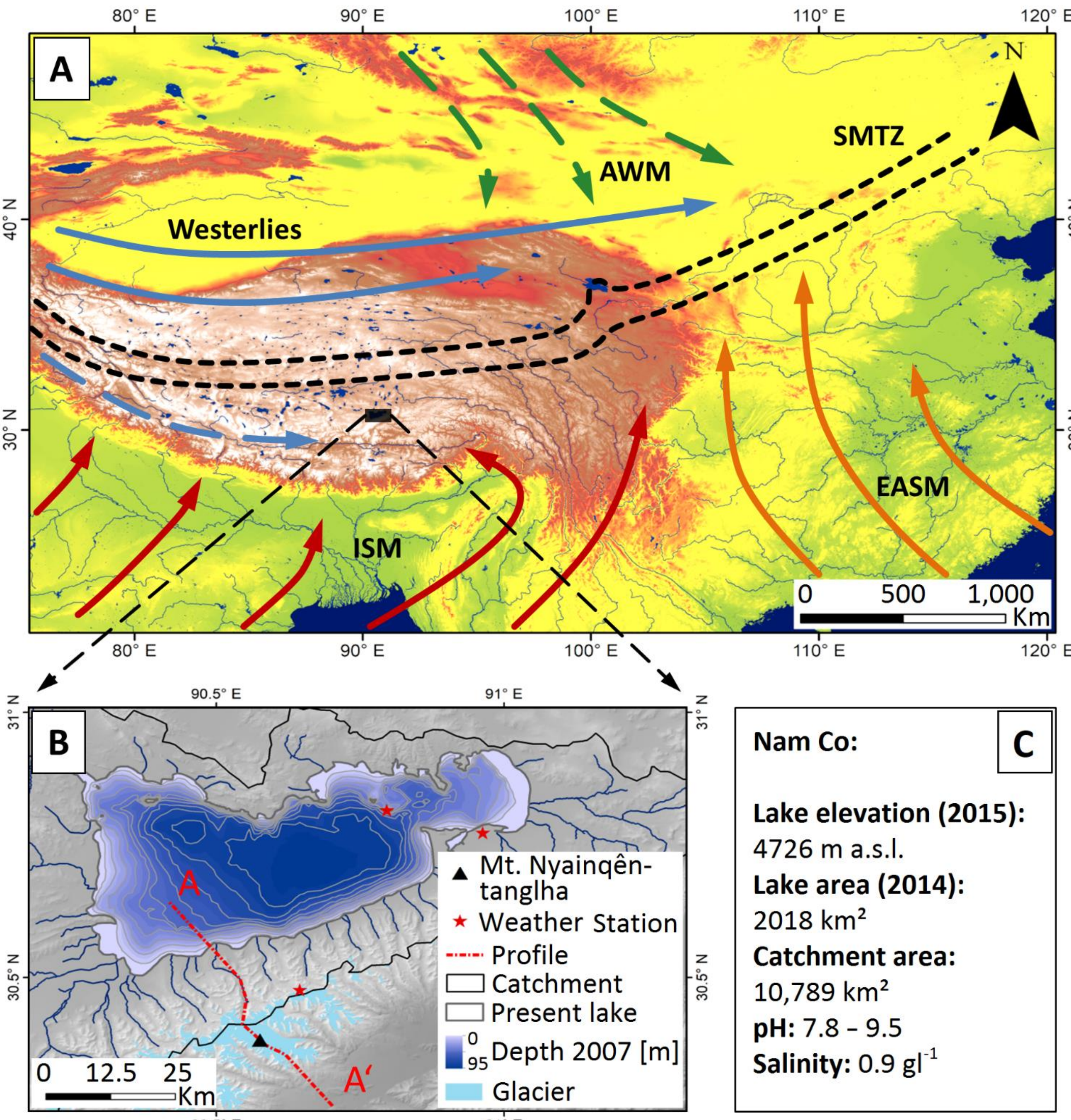
Abstract. The Tibetan Plateau (TP) is the largest alpine plateau on Earth and plays an important role in global climate dynamics. On the TP, climate change is happening particularly fast, with an increase in air temperature twice the global average. The particular sensitivity of this high mountain~~ous~~ environment allows ~~the~~ observation and tracking of abiotic and biotic feedback mechanisms. Closed lake systems, such as ~~the~~ Nam Co on the central TP, represent important natural laboratories for tracking past and recent climatic ~~oscillations~~changes, as well as geobiological processes and interactions within their respective catchments. This review gives an interdisciplinary overview of past and modern ~~and paleoenvironmental~~environmental changes, ~~focusing on~~using Nam Co as ~~model system~~a case study. In the catchment area, ~~the steep~~ongoing rise in air temperature force~~d~~s glaciers to melt, ~~leading~~contributing to a rise in lake level~~s~~ and changes in water chemistry. Some studies base their conclusions on inconsistent glacier inventories but an ever-increasing deglaciation and thus higher water availability have persisted over the last decades. ~~The enhanced~~Increasing water availability causes translocation of sediments, nutrients and dissolved organic matter to the lake, as well as higher carbon emissions to the atmosphere. The intensity of grazing has ~~a~~an additional and significant effect on CO_2 fluxes, with moderate grazing enhancing belowground allocation of carbon while adversely affecting the C-sink potential through reduction of above- and subsurface biomass at higher grazing intensities. Furthermore, increasing pressure from human activities and livestock grazing are enhancing grassland degradation processes, thus shaping biodiversity patterns in the lake and catchment. The environmental signal provided by taxon-specific analysis (e.g. diatoms and ostracods) in Nam Co ~~have~~ revealed profound climatic fluctuations between warmer/cooler and wetter/drier periods since the late Pleistocene and an increasing input of freshwater and nutrients from the catchment in recent years. Based on the reviewed literature, we outline perspectives to further understand the effects of global warming on geo- and biodiversity and their interplay ~~in the~~at Lake Nam Co, which acts as a case study for potentially TP-~~wide~~ or even worldwide processes that are currently shaping ~~the earth's future~~high mountain areas.

Key words: bioindicators, carbon cycle, climate change, climate reconstruction, deglaciation, geobiodiversity, lake level change, ~~lake~~ Lake Nam Co, paleo-environmental proxies, pasture degradation

1 Introduction

The Tibetan Plateau (TP), often referred to as "The Third Pole" and "The Water Tower of East Asia", is the highest and largest alpine plateau on earth (Qiu, 2008). With an area of about 2.5 million km² at an average altitude of > 4000 m above sea level (a.s.l.), it includes the entire southwestern Chinese provinces of Tibet and Qinghai, parts of Gansu, Yunnan, Sichuan and neighboring countries (Fig. 1). The southern and eastern plateau and the adjacent Himalayas regions are forming the headwaters of several major rivers (i.e., ~~Amudarya,~~ Brahmaputra, Ganges, Hexi, Indus, Mekong, Salween, Yangtze, and Yellow River), providing fresh water for ~1.65 billion people and to many ecosystems in greater Asia (Cuo and Zhang, 2017). Large proportions of the inner TP are endorheic and therefore do not drain into the large river systems. On the TP, the effects of climate change are expressed stronger than the global average, showing a steep rise in air temperature of about 0.3°C per decade since 1960 (Yao et al., 2007) and a moderate rise in precipitation during the last decades (Dong et al., 2018). The warming rate increases with altitude (Pepin et al., 2015) which is why the air temperature on the TP is soaring roughly twice the global average, thus substantially affecting the geo- and biodiversity. Glaciers and lakes are the dominant components for the Tibetan water sources, and their actual status and future development are strongly impacted by global warming. Since the 1990's, nearly all glaciers on the TP have exhibited retreat, causing a 5.5 % increase in river runoff from the Plateau (Yao et al., 2007). The consequences of deglaciation and permafrost degradation (Wu et al., 2010) are observable in higher water and sediment fluxes, relief changes and arising natural hazards (floods, rock falls, landslides, desertification, ecosystem degradation). Consequently, landscapes are continuously being rearranged which alters the spatial distribution and composition of the inhabiting species, many of which are endemic to the TP (Walther et al., 2002). Even conservative estimates predict substantial species extinction and considerable changes to the ecosystems (Chen et al., 2011; Bellard et al., 2012). The future trajectory of such complex processes is difficult to map accurately, thus it is important to monitor the current state as well as the evolution of this highly sensitive region. The large number of water bodies on the TP, its geological diversity, climatic setting as well as sensitivity to climate change~~, and still relatively little human impact~~ make it a unique natural laboratory, which could be used as an early warning system for other alpine environments. Many lakes on the TP are superficially closed systems, which is why they are particularly suitable as "thermometers" and "rain gauges" to measure the climatic, hydrological, geomorphological, pedological and ecological changes in their respective catchments. With an area of 2018 km², Nam Co is the second largest lake on the central TP. ~~As an endorheic system, it acts as a sink for water, sediment and carbon fluxes, making it an excellent model ecosystem.~~ Currently, Lake Nam Co represents an endorheic system, acting as a sink for water, sediment and carbon fluxes. The existence of a former drainage ("Old Qiangtang Lake") towards the northwestern Siling Co and further east, down from the TP is still under discussion (Li et al., 1981; Kong et al., 2011) (see Sec. 3.1). With good accessibility and infrastructure such as the Nam Co Monitoring and Research Station for Multisphere Interactions (NAMORS), the Nam Co catchment has become a frequent study location for monitoring and tracking of environmental changes over various timescales.

Here we present an interdisciplinary overview of how earth-surface fluxes have developed with changing environmental conditions and which consequences are to be expected for biodiversity, as well as for water, sediment and carbon fluxes within the ~~model ecosystem~~ study area of the Nam Co catchment on the central TP. In particular, this review considers past and modern geobiodiversity changes with focus on glacier retreat in relation to hydrological patterns and changes in lake water chemistry. The corresponding changes in terrestrial ecosystems concerning carbon cycle, greenhouse gas releases, as well as pasture degradation are discussed. We provide an overview of how the paleoenvironment on the Tibetan Plateau with respect to landscape evolution around Nam Co was shaped by geodiversity, lake level changes and Holocene vegetation cover. Lastly, based on the available studies, this review identifies the major research gaps that are awaiting further exploration and comparison with other high-altitude environments.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90° E
100° E
110° E
120° E
40° N
30° N
N
SMTZ
AWM
Westerlies
EASM
ISM
0 500 1,000
Km
B
90.5° E
91° E
31° N
30.5° N
A
A′
Mt. Nyainqên-tanglha
Weather Station
Profile
Catchment
Present lake
0
95
Depth 2007 [m]
Glacier
0 12.5 25
Km
C
Nam Co:
Lake elevation (2015):
4726 m a.s.l.
Lake area (2014):
2018 km²
Catchment area:
10,789 km²
pH: 7.8 – 9.5
Salinity: 0.9 gl-1

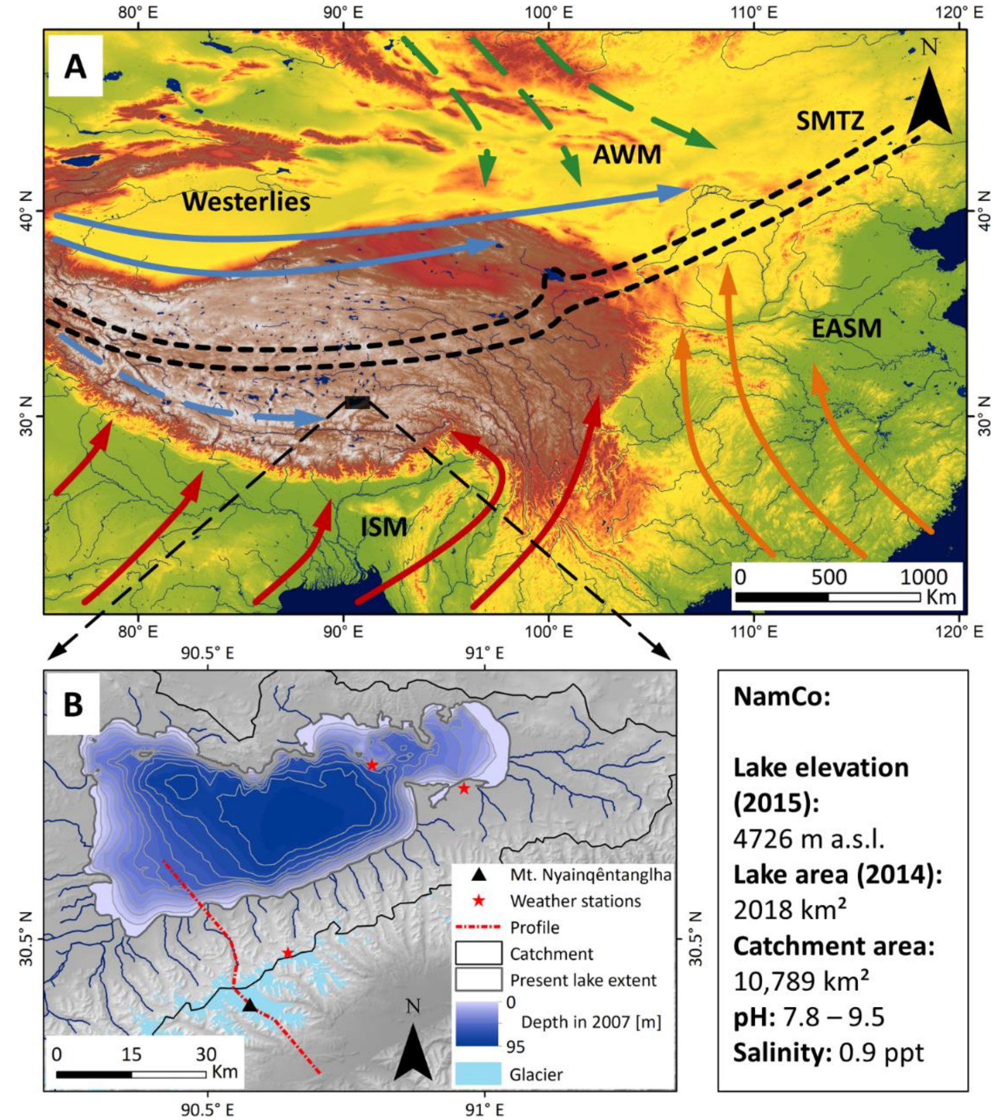


Figure 1. Major atmospheric systems governing the climate in China (A); Nam Co study site (B); and characteristics of Nam Co's catchment (C). A: Continuous arrows indicate systems active in summer. These are the Indian Summer Monsoon (ISM) in red, the East Asian Summer Monsoon (EASM) in orange and the Westerlies in blue. Dashed arrows represent systems active in winter. These are the Asian Winter Monsoon (AWM) in green and southern parts of the Westerlies in blue. The black dotted lines denote the Summer Monsoon Transition Zone (SMTZ) (after Wünnemann et al., 2018). Background elevation data according to SRTM DEM v4 (Jarvis et al., 2008). B: Nam Co catchment, including the current lake extent (based on Copernicus Sentinel data 2018, processed by ESA), its bathymetric depth in 2007 (Wang et al., 2009a), the outline of the catchment (after Keil et al., 2010), glaciers of the Nyainqêntanglha Range (GLIMS and NSDIC 2005, updated 2018) and rivers discharging into Nam Co (SRTM DEM v4; Jarvis et al., 2008). The red dotted line indicates the profile position of Figure 2. C: Characteristics of Nam Co: Lake elevation (Jiang et al., 2017), lake surface area (Zhang et al., 2017), catchment area, lake pH and salinity (Keil et al., 2010).

2 Environmental changes in lake Nam Co and its catchment

2.1 Climatic characteristics of the Nam Co basin

The prevailing climate at Nam Co is characterized by strong seasonality, with long, cold winters and short but moist summers. During winter, the Westerlies control the general circulation and lead to cold and dry weather, with daily temperature minima below -20 °C. In springtime, the TP heats up and allows the melt water to percolate to deeper soil layers. The drought situation increases gradually until the monsoon rains arrive, typically between May and June. During autumn, weather shifts again to clear, cold and dry conditions (Yao et al., 2013). The mean annual temperature measured at the NAMORS research station (Fig. 1) between 2006 and 2017 was -0.6 °C and the annual precipitation was between 291–568 mm (mean = ~~405~~406 mm), with the majority occurring during the monsoon season from May to ~~September .~~October (Tab. 1). The onset and strength of monsoonal precipitation varies substantially between individual years and can be delayed by up to six weeks, depending on the altitude and latitude on the TP (Miehe et al., 2019). ~~However, the precipitation~~ Precipitation rates are subject to spatial variations due to the > 7000 m high Nyainqêntanglha ~~mountain~~ range which represents the southern border of the lake catchment. This leads to considerably larger glacial areas in the southwestern part (~700 km^2) than in the northeastern part of the mountain range (~100 km²) (Bolch et al., 2010).

Table 1: Average daily air temperature (maximum, mean, minimum in °C) and average daily precipitation (sum in mm) from NAMORS from 2006 to 2017. Calculations were performed using the tidyverse package family in R on RStudio environment (Wickham, 2017; RStudio Team, 2018; R Core Team, 2019). Data provided by ITP Beijing, for details about sensor eqiupment see (Ma et al., 2009).

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ø / Σ**
T max	-0.7	-1.5	1.5	4.7	11.6	13.3	12.6	12.2	11.3	8.7	2.5	1.2	6.4
T mean	-10.8	-9.7	-5.7	-1.4	3.1	7.9	9.1	8.3	6.5	0.3	-6.5	-8.4	-0.6
T min	-21.5	-20.5	-14.3	-7.3	-4.5	1.1	5.2	3.2	-1.3	-14.7	-15.3	-19.1	-9.1
Precip.	4	1	3	13	23	41	85	117	81	34	5	1	406

2.2 Glacier retreat and hydrological patterns of Nam Co

The rise of satellites such as Envisat, CryoSat and ICESat and the increasingly wide-spread availability of their data, have enabled the accurate study of lake and glacier parameters as far back as the early 1970's (Wu and Zhu, 2008; Zhu et al., 2010b; Liao et al., 2013). The size of Nam Co as well as the extent and distribution of glaciers in the Nyainqêntanglha ~~mountain~~ range have been the subject of many publications over the recent years (Yao et al., 2007; Frauenfelder and Kääb, 2009; Bolch et al., 2010; Wang et al., 2013; Fig. 2; Table 1). Due to different data sources with varying resolutions as well as different mapping procedures, the estimated glacier area varies between different studies (Fig. 2; Table 1), as the delineation of debris- and snow-covered glaciers is rather subjective (Wu et al., 2016). This is especially true for the first glacier inventory (Li et al. 2003), which has been discussed in various studies due to inaccuracies and the quality of its base data (Frauenfelder and Kääb, 2009; Bolch et al., 2010). Nevertheless, recent studies show glacier shrinkage in the Nyainqêntanglha ~~mountain~~ range at a rate of 0.3–0.5 % yr^{-1} as measured since 1970 when the first satellite images were acquired (Fig. 2; Table 1). As a result of this glacier melting, the lake surface area has expanded from ca. 1930 km² to ca. 2018 km² at a rate of 2.1 km² yr^{-1} (Fig. 3A), and the lake level has risen at a rate of 0.3 m yr^{-1} until approximately 2009, and at lower rates since then (Fig. 3B). The initial rising trends of both lake level and surface area are mirrored by most lakes in the southern part of the TP, but the slowdown of this trend observed at lake Nam Co around 2009 seems unique (Jiang et al., 2017). This suggests that the lakes on the TP react to changing environmental parameters in a variety of different ways, and that geographical proximity among lakes does not necessarily produce similar reactions to change. The effects on freshwater input to the lake are discussed in the following section (2.3). Although changes in monsoonal precipitation and wind direction may influence glacial retreat rates (Wang et al., 2013), rising temperatures remain their primary cause (Ji et al., 2018). The total contribution of glacial melt water as surface runoff to this lake level increase has been estimated ranging from 10 % to 53 % (Zhu et al., 2010b; Lei et al., 2013; Wu et al., 2014; Li and Lin, 2017), with recent studies at the lower end of this spectrum. Increased precipitation is estimated to be responsible for 50–70 % of lake growth (Zhu et al., 2010b; Lei et al., 2013). Whether there is a change in evaporation remains unclear as studies for approximately the same time period have suggested both a slightly increasing and a slightly decreasing evaporation rate since the late 1970´s (Lazhu et al., 2016; Ma et al., 2016).

Table 2. Overview of glacier area changes (%) in the western Nyainqêntanglha range (changed after Wu et al., 2016).

Period	Region of the Nyainqêntanglha range	Glacier shrinkage (%)	Reference
1970–2000	Southeastern slope	-5.2	Shangguan et al. (2008)
1970–2000	Northwestern slope	-6.9	Shangguan et al. (2008)
1970–2000	Western	-5.7	Shangguan et al. (2008)
1977–2010	Western	-22.4 ± 2.9	Wang et al. (2013)
1970–2009	Western	-21.7 ± 3.4	Wu et al. (2016)
1970/80–2000	Southwestern	-19.8	Frauenfelder and Kääb (2009)
1970–2000	Nam Co Basin	-15.4	Wu & Zhu (2008)
1976–2001	Nam Co Basin	-6.8 ± 3.1	Bolch et al. (2010)
1976–2001	Southeastern slope	-5.8 ± 2.6	Bolch et al. (2010)
1976–2009	Detailed glaciers (Zhadang, Tangse No.2, Lalong, Xibu, Panu)	-9.9 ± 3.1	Bolch et al. (2010)

The rises in temperature and precipitation are also affecting permafrost soils that are extending over an area of ca. 1.4 million km^2 (Yang et al., 2004) on the TP. The permafrost layers can be described as relatively warm and thin, with temperatures mostly > -1.5 °C and < 100 m thickness (Wu et al., 2010). The mean annual soil temperature of permafrost in particular areas of the TP has increased by 0.1–0.3 ˚C between 1970–1990 (Cheng and Wu, 2007). Simulation studies have shown that along with climate warming, the permafrost extent may decrease by 9–19 % by 2049 and by 13–58 % by 2099 (Li and Cheng, 1999;

Nan, 2005). Although there is no clear estimate of permafrost extent in the Nam Co basin, Tian et al. (2009) reports a lower limit of permafrost at an elevation around 5300 m a.s.l. along the northern slopes of Mt. Nyainqêntanglha (7162 m). A frost lens was also encountered 9 m below surface (4738 m a.s.l.) while sampling an outcrop along the right bank of the Gangyasang Qu close to the northwestern lake shore in 2005 (Schütt et al., 2010). Thus, due to increasing temperatures, permafrost degradation may serve as an additional recharge factor to groundwater, resulting in increased subsurface inflow into the lakes. Focusing on lake Nam Co, the hydraulic interaction between lake and groundwater is still uncertain, as previous studies either neglected or ignored the influence of groundwater due to a lack of reliable data (Zhang et al., 2011). However, recent studies revealed a water imbalance, which was explained by lake water seepage with an estimated outflow of 1.9×10^9 m^3 and 1.5×10^9 m^3 during 1980–1984 and 1995–2009, respectively (Zhou et al., 2013; Du et al., 2018).

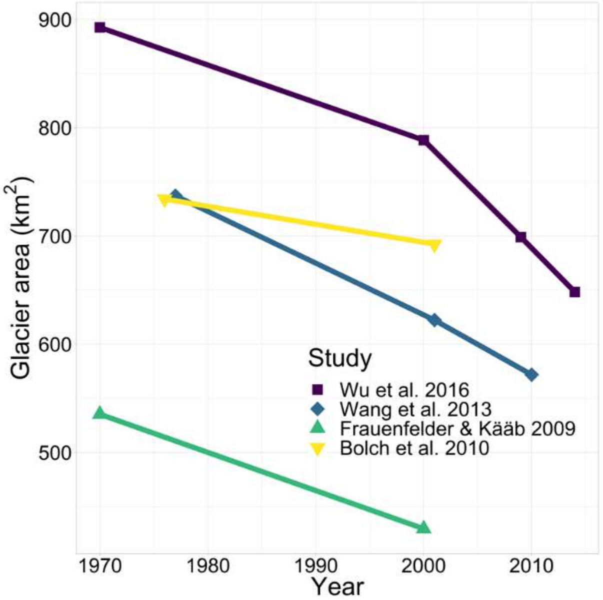


Figure 2. Glacier area reduction at south-western Nyainqêntanglha range since 1970 as evaluated in various studies.

2.3 Enhanced water availability controls changes in lake water chemistry

The maximum recorded depth of lake Nam Co is 122 m (Li et al., 2008a), with brackish water characterized by an alkaline pH of 7.8–9.5 and a conductivity of 1920 µS mm^{-1} (Keil et al., 2010). The chemical composition of a lake is essentially a function of its climate (which affects its hydrology) and the basin geology. Increased freshwater input from precipitation, melting glaciers and thawing permafrost alters the chemical composition of the lake water and enhances surface runoff, infiltration rates as well as subsurface flow. Together with the input of freshwater, streams transport dissolved organic matter (DOM) which is composed of a wide range of dissolved components and particles (≤ 0.45 µm), thus affecting the water chemistry in the lake (Spencer et al., 2014). Excessive landscape disturbance through removing vegetative cover causes higher rates of DOM leaching, more erosion and increasing water runoff velocity, resulting in additional input of minerals and nutrients into the lake. Since the process of DOM leaching and translocation itself is largely dependent on water and sediment cycles (Kaiser and Kalbitz, 2012), it represents both the seasonal and inter-annual variation in an ecosystem as well as its long-term trend. As the glaciers on the TP retreat, highly bioavailable DOM may provide additional nutrients to downstream environments and amplify the trend of eutrophication of lotic and lacustrine ecosystems. Furthermore, the rivers on the TP have been shown to transport dissolved organic carbon from thawing permafrost areas (Qu et al., 2017), which is likely rapidly degraded via microbial activity, resulting in CO_2 emissions, thus potentially producing a positive feedback on global warming. However, the research of DOM as an important allochthonous source of nutrients, and as a capture of bio- and geodiversity of its respective catchment area is largely lacking for High Asia. The concentration and ratios of different ions in the water have a regulatory impact on the structure of biotic communities (microbes, invertebrates and fish), that can best tolerate abiotic conditions (Wrozyna et al., 2012). In Nam Co, water conductivity has been regarded as the most important environmental factor for shaping communities such as ~~ammonia-oxidizing archaea, as well as phytoplankton~~ archaea, bacteria, phytoplankton, and microinvertebrates (Hu et al., 2010; Wang et al., 2011). ~~These organisms play essential roles in nitrogen cycling processes and the aquatic food-chain, respectively.~~ Studies demonstrated that ammonia-oxidizing archaea (autotrophic microorganisms) are key contributors to ammonia oxidation in deep and oligotrophic lakes (Callieri et al., 2016). This has implications for CO_2 fixation in the hypolimnion or the benthic zone, where there is insufficient irradiance to support photosynthesis, implying that archaea would perform the final step in the decay of organic matter via methanogenesis, resulting in carbon dioxide accumulation (e.g. when they decrease during winter). Although nitrification does not directly change the inventory of inorganic Nitrogen in freshwater ecosystems, it constitutes the only known biological source of nitrate and as such represents a critical link between mineralization of organic N and its eventual loss as N_2 by denitrification or anaerobic ammonia oxidation to the atmosphere (Herber et al., 2019). Ultimately, the changes in the communities of primary producers could alter the lake's trophic structure, which affects also the top predators of the ecosystem. The primary productivity, as an indicator of nutrient supply and a longer growing period associated with a shorter ice-cover duration, has increased markedly at Nam Co within the last 100 years (Lami et al., 2010). Wang et al. (2011) reported the increasing abundance of the diatom species *Stephanodiscus minutulus* during the last decades (ca. 1970–2001). This species is generally viewed as an indicator of water phosphorus enrichment, suggesting increasing inputs from the lake's catchment and stronger mixing in spring season. To predict future consequences of ongoing climate change, it is essential to understand the responses of biotic communities to hydrological variations. Thus, long-term monitoring is needed to adequately address the feedbacks of recent environmental changes, while climatic conditions of the past can be reconstructed through the study of organisms such as diatoms and ostracods that are sensitive to hydrologic and chemical variations (see section 3.2).

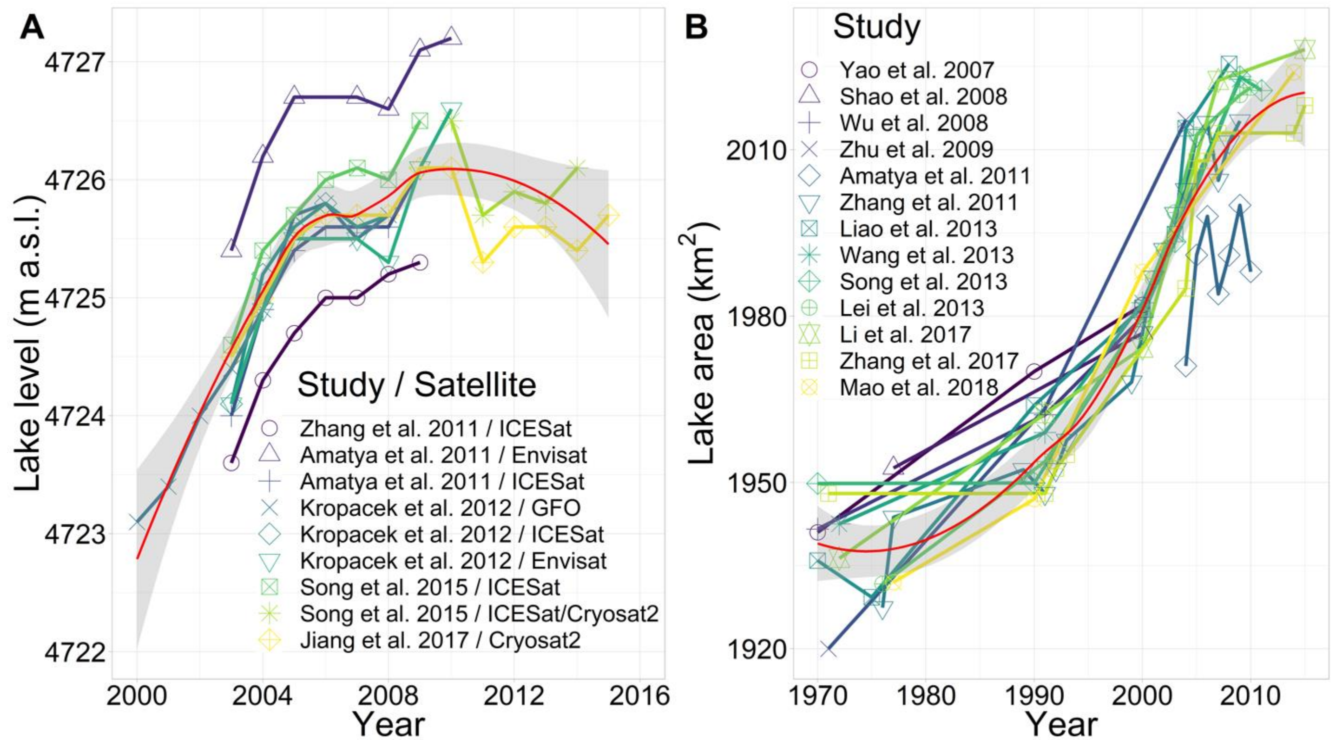


Figure 3. A) Lake level changes of Nam Co since 2000 (notable shift in the water balance in 2009); and B) changes of the lake surface area since 1970, as evaluated in previous studies. Overall increase rate of lake area is 2.1 km² yr^{-1}. Red lines denote LOESS curves with the 95 % confidence interval in gray.

2.4 Vegetation, soils and pasture degradation in the catchment

Lake Nam Co is located in the transitional zone between the central Tibetan *Kobresia pygmaea* ~~meadows~~ pastures and the north western alpine steppe ecosystem (Miehe et al., 2019) (Fig. 4). Situated on the northern slope of the Nyainqêntanglha ~~mountain~~ range, the vegetation pattern changes according to elevation, moisture availability and temperature. Grazing intensity and abundance of small rodents, such as the plateau pika (*Ochotona curzoniae*), may contribute to the shaping of the vegetation cover (Dorji et al., 2014; Miehe et al., 2014). The area close to the lake (< 4800 m) is covered mainly with alpine steppe vegetation consisting of *Artemisia, Stipa, Poa, Festuca* and *Carex* (Li, 2018; Nölling, 2006). Soils developed in the drier steppe areas consequentially tend to show lower organic carbon contents, naturally lowering their total C sink or source potential, as indicated by a study from Ohtsuka et al. (2008). Only one evaluable soil investigation exists from the area of Nam Co. Wang et al. (2009b) investigated two lake terrace sites, situated in the alpine steppe biome. According to their findings, the soils reflect the cold semiarid climate of the area, by showing low biologic activity, while the influence of physical weathering is dominant. The soils showed several decimeter thick layers of loess in which mainly the A-horizons were developed. Although only very sparse to moderate vegetation cover occurs, an almost 30 cm thick organic rich topsoil with granular structure was developed there (Wang et al., 2009b). Further organic-rich buried horizons were found and dated in both profiles, showing phases of climatic conditions enabling the buildup of organic material related to warm-wet periods in the past (before 2.4 and 1.6 cal ka BP) and interchanging with phases of erosion, leading to e.g.: sheet erosion, the formation of gullies and alluvial fans, supposedly during colder periods. These results fit well to climate reconstructions presented in part 3.3 of our review. In accordance with the World Reference Base for Soil Resources (WRB) classification, we propose that the soils described by Wang et al. (2009b) can be classified as Calcisols as there is evidence of carbonate translocation.

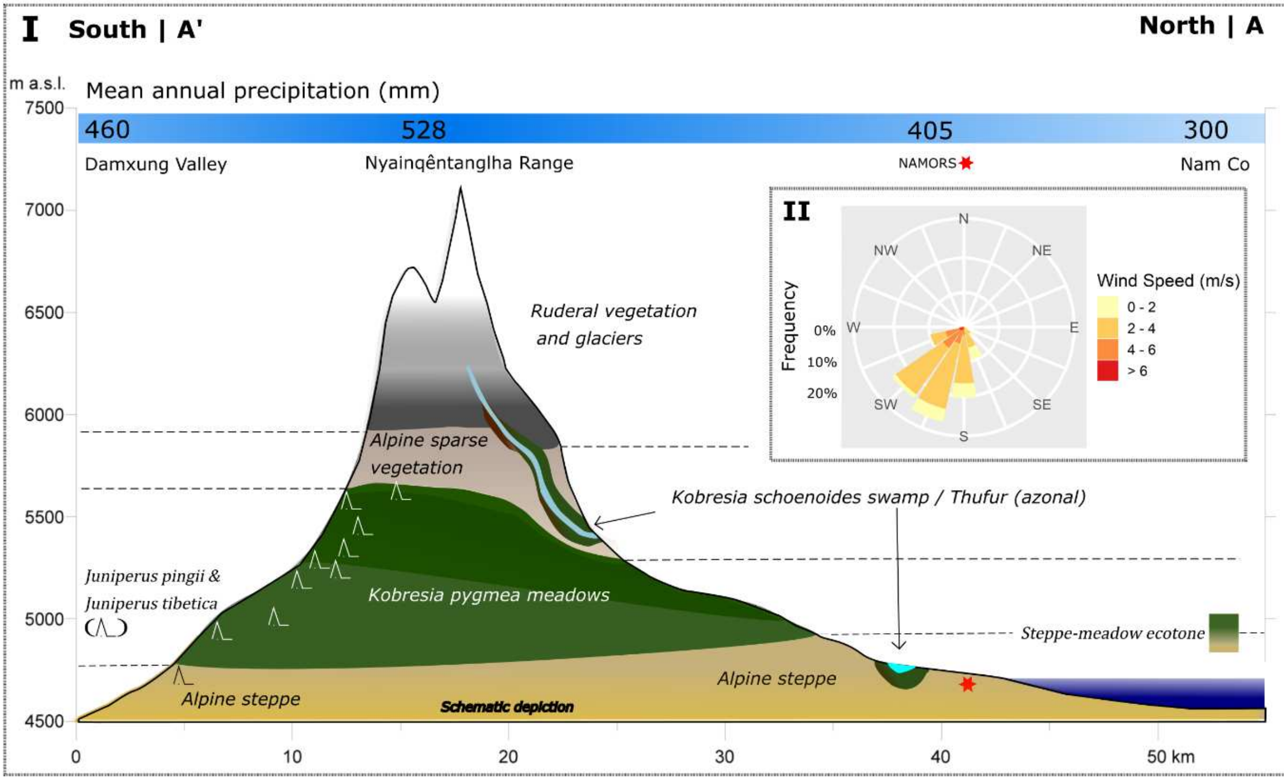
Higher up the slope (4800–5200 m), the alpine steppe is replaced by *Kobresia pygmea* ~~meadow~~ pasture. Wang et al. (2007) and Kaiser et al. (2008) investigated the relationship between plant communities and development of soil types on the High Asian Plateau and for ~~meadow~~ pasture soils in the wider area. Vegetation strongly controls the input of organic material into the soil, but beyond that also stabilizes fine materials (< 0.1 mm) and governs the degree of chemical weathering. The authors found soils with stronger signs of biologic activity and chemical weathering (e.g. Cambisols) associated with alpine ~~meadow~~ pasture sites. *Kobresia* root mats are usually developed in up to 40 cm thick loess layers and form a distinctive felty horizon which protects against erosion. The genesis of this felty root mat is attributed to *Kobresia pygmaea,* since this shallow rooting, small plant allocates most of its biomass belowground and is able to reproduce vegetative, making it well adapted to the high grazing pressure (Miehe et al., 2008). The curious dominance of *K. pygmaea* is often linked to grazing: (i) *K. pygmaea* replaces taller plants at sites where grazing pressure is increased experimentally. (ii) Several enclosures show that other grasses and shrubs gain in dominance after grazing competition ceased (Miehe et al., 2008). Hence, the felty root-mat can be seen as an effect of an anthropozoogenic plagioclimax. At higher elevation (5200–5900 m), only alpine sparse vegetation associated with initial soil processes occurs (Ohtsuka et al., 2008).

Where water availability is abundant, alpine ~~meadow~~ swamps with *Carex sagensis and Kobresia schoenoides* are formed, especially at source areas, along river banks and in waterlogged depressions, some of which can cover large areas (Li et al., 2011). Concerning soil development in alpine wetlands, the data base is sparse compared to the ~~meadow~~ alpine pasture and steppe biome. ~~However, it~~ It was pointed out for alpine ~~meadows~~ pastures, that a strong relationship exists between plant communities and (top)soil genesis. This relationship probably also holds true for alpine wetlands, with the exception, that the influences of water logging and seasonal fluctuations and frost-melt cycles in the water table are likely to have an effect on soils. This can be expressed in terms of formation of gleyic features, frost turbations, heaves or other azonal features related to the soil forming effects of water (Chesworth et al., 2008). It still needs to be clarified, how these water-logged areas effect the cycling and processing of organic matter and nutrients. ~~The only tree-like plants in the area are the evergreen shrubs of *Juniperus* spp., which are found on the south-facing slopes of the northern Nam Co catchment, and shrubs of *Salix* spp. in the Niyaqu Valley in the eastern lake catchment (Li, 2018).~~ There is no evidence of tree species, only the evergreen shrubs of *Juniperus pingii var. wilsonii*, which are mainly found on the south-facing slopes of the northern Nam Co catchment, and shrubs of *Salix* spp. in the Niyaqu Valley in the eastern lake catchment (Li, 2018). ~~The diversity of terrestrial flora varies within the vegetation zones and is reflected by their spatial distribution throughout the catchment, with higher diversity in the south-east of the Nam Co catchment (Li, 2018).~~ Alpine steppe comprises more plant species compared to ~~meadow~~ pasture and marsh ecosystems, which are predominantly covered with *Carex* spp. and *Kobresia spp.* (Miehe et al., 2011b). ~~The occurrence of different vegetation types in the form of a steppe-meadow ecotone along the high mountain slopes of the Nyainqêntanglha range further amplifies species diversity.~~

Alpine ~~meadows~~ pastures are often described as "golf-course-like" (Miehe et al., 2014) with the intention of illustrating their unique plane surface. However, small scale structures such as thufa or hummocks are also present. The origin of these structures around Nam Co remains unclear; however, frost heave and permafrost degradation processes are considered to play a major role (Adamczyk, 2010). The landscape, generally dominated by endemic *Kobresia pygmea* sedges, harbors only a few other species (Miehe et al., 2019), but the additional microhabitats provided by thufa and hummocks enable rarer and low-competitive species to settle in niches in these heterogeneous structures (Vivian-Smith, 1997). Compared to the surroundings, the microtopography of thufa possesses different degrees of wetness, exposition and insulation, depth of soil material and type of topsoil. Local studies of the Nam Co area state that slightly degraded bare soil patches and gullies are often areas where plants have the chance to evade the suppression of the closed *Kobresia pygmea* root mat (Schlütz et al., 2007; Dorji et al., 2014). Thus, the genesis of thufa and mild, limited degradation processes are likely to increase species richness and diversity by cracking open the closed root mat of alpine ~~meadows~~pastures. These structures can also be formed by grass species that grown in tussocks (i.e. clumps, bunches or tufts), such as the endemic species *Stipa purpurea* (Liu et al., 2009) or *Kobresia tibetica* (Yu et al., 2010) and *Kobresia schoenoides* (Nölling, 2006).

The often cited degradation ~~processes in the *Kobresia* meadows~~ of alpine pastures ~~are~~is likely initiated by natural polygonal cracking (Miehe et al., 2019), which can occur through drying (Velde, 1999), and then tend to be amplified by livestock trampling and plateau pikas using the cracks as highways (Liu et al., 2017b; Hopping et al., 2016). Overgrazing in alpine ~~meadows~~ pastures is one of the most frequently mentioned causes of pasture degradation (Unteregelsbacher et al., 2012; Harris, 2010; Miehe et al., 2008) as excessive trampling by livestock might aggravate the initial conditions of polygonal cracking (Miehe et al., 2019). ~~Some researchers argue that climate change is the dominant or even sole driver of degradation (Wang et al., 2007), though the effects of rising temperatures and increasing precipitation appear to be an intensifier rather than the cause of degradation (Zhou et al., 2005; Harris, 2010). In turn, the degradation of wide areas of alpine meadows is not without effect to pastoralists as severe degradation and sloughing off of the whole topsoil removes the basis for business and might lead to unknown consequences for the lake ecosystem.~~ This effect, however, seems to be limited to the direct vicinity of herder´s settlements and camps (piosphere-centers), and many factors that are usually attributed to degradation rather proof to be environmentally controlled, especially in drier areas (Wang et al., 2018b). Some researchers argue that climate change is the dominant or even sole driver of degradation (Wang et al., 2007), although the effects of rising temperatures and increasing precipitation appear to be an intensifier rather than the cause of degradation (Zhou et al., 2005; Harris, 2010). In turn, both Wang et al. (2018b) and Cao et al. (2019) point out that a multitude of effects might be in play, with a locally differing magnitude or even reversion, while usually moderate grazing was not to be found to cause degradation. Certainly, there are more factors than just grazing-pressure, and there might be site-specific effects leading to non-equilibrium behavior of the study object, be it pasture or steppe (Wang and Wesche, 2016). Plot-level experiments from the Nam Co area found warming to have significant effects on the shallow rooted *Kobresia pygmaea* by reducing the number of flowers and delaying its reproductive phenology. These changes were provoked by simulating increasing precipitation by means of snow addition (Dorji et al., 2013) and also by maintaining a moderate level of grazing combined with snow addition (Dorji et al., 2018). This underlines the importance of climate forcing on the terrestrial systems in the Nam Co catchment. Grazing should not be seen as a disturbance but as an integral part of a non-steady state but plagioclimax environment. Currently there are no estimates of the extent of degraded land at Nam Co, but the degradation of wide areas of alpine pastures is not without consequences for the pastoralist communities. The severe degradation and sloughing off of the whole topsoil remove the basis for business and might lead to unknown consequences for the lake ecosystem by means of enhancing or terminating nutrient exchanges. The economic rationale of herders might be to increase the numbers of livestock as this represents a form of social security (Simpson et al., 1994). The bottom line is that conflicts arise as less land is available for grazing (Hopping et al., 2016).

~~To reduce the ecological impact of poorly managed pastoralism, the~~ The Chinese government has favored policies such as sedentariness and fostered the construction of stationary settlements, which have, in turn, created hotspots of overgrazing (Miehe et al., 2008). In these hotspots, large portions of the topsoil are lost by erosion and denudation, leaving only an area of humic material or subsoil, thus being called “black beach” (Miehe et al., 2008) or “black-soil patch” (Liu et al., 2017a). The remaining landscapes are usually dry, poor in plant cover and prone to further degradation. Increasing areas of bare soil patches enhance evapotranspiration, causing earlier cloud cover formation especially before noon. This may, in turn, lead to reduced radiation and temperature at the surface, thus hampering photosynthesis and consequently overall carbon sequestration (Babel et al., 2014). However, the evolution of grasslands on the TP has been accompanied by herbivore communities, thus, the plants have developed coping mechanisms to persist under continuous grazing pressure (Miehe et al., 2011a). According to the intermediate disturbance hypothesis, species diversity is higher under moderate disturbances, which suggests the positive effect of intermediate level of grazing pressure. Indeed, a plant clipping experiment to simulate grazing demonstrated that under the effect of climate warming, the grazing activities mitigated the negative effects of rising temperature by maintaining a higher number of plants (Klein et al., 2008). Many studies hold the traditional nomadic practice to be a sustainable one (Miehe et al., 2008; Babel et al., 2014; Hafner et al., 2012), but the current policy of removing pastoralist lifestyles from certain regions could potentially reduce overall species richness.



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Mean annual precipitation (mm)
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Damxung Valley
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E
SW
SE
S
Frequency
0%
10%
20%
Wind Speed (m/s)
0 - 2
2 - 4
4 - 6
> 6
Ruderal vegetation
and glaciers
Alpine sparse
vegetation
Kobresia schoenoides swamp / Thufur (azonal)
Juniperus pingii &
Juniperus tibetica
Kobresia pygmea meadows
Steppe-meadow ecotone
Alpine steppe
Alpine steppe
Schematic depiction
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7000
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10
20
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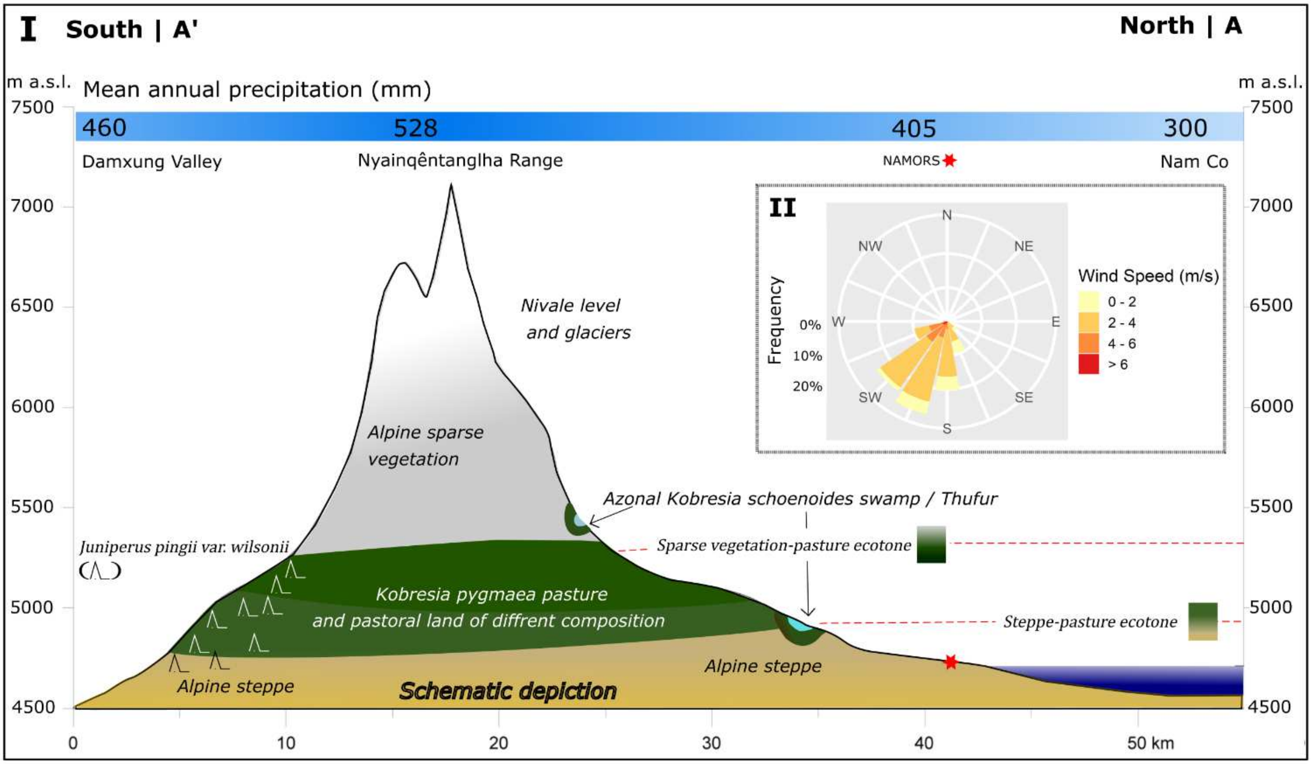

Figure 4. I: Cross-section from Damxung valley to lake Nam Co study area (A'-A) as shown in Fig. 1 (B). Schematic ~~D~~depiction of altitudinal dependent biomes and azonal landforms, changes in chroma denote height-dependent biome shifts. Approximate biome heights were gained from: satellite imagery (Sentinel 2B) and herewith derived vegetation indices, field excursion and literature review (Ohtsuka et al., 2008; Wang and Yi, 2011). II: Frequency, direction and velocity of mean daily wind measurements at the NAMORS (30°46'22'' N, 90°57'47'' E) between 2005–2015.

2.5 Effects on carbon cycling in alpine ecosystems

Changes in temperature and moisture have a significant effect on the biotic community structure with feedbacks on ecosystem productivity. Alpine meadows respond with increased plant productivity to warming, while productivity may be hampered in alpine steppe ecosystems (Ganjurjav et al., 2016). As soil moisture governs the community response to warming, negative effects of warming on the plant productivity likely occur due to limited water availability (Ganjurjav et al., 2016). Warming was also reported to have a negative effect on plant species diversity in both alpine meadow and steppe ecosystems(Klein et al., 2008; Ganjurjav et al., 2016). Possible explanations for a decline in plant species diversity include changes in small mammal activity, storage of belowground nutrient resources as well as water stress and microclimate in general (soil temperature and moisture) (Ganjurjav et al., 2016; Klein et al., 2008, 2004). Thus, climate change may reduce the habitat quality for the local populations of grazers and reduce well-being of the pastoralists by diminishing abundance of palatable and medicinal plant groups. The changes in the plant productivity levels as well as community changes affect the local carbon cycle. Alpine grassland root mats on the TP are estimated to store up to 10 kg of carbon (C) per square-meter (Li et al., 2008b), summing up to roughly 2.5 % of the global terrestrial carbon stocks (Wang et al., 2002). At Nam Co, the top soils contain an almost 30 cm thick organic rich layer (Wang et al., 2009b), thus representing considerable soil organic carbon (SOC) stocks. Due to higher plant productivity, alpine meadows in general represent a CO_2 sink, however, the interannual and seasonal uptake is highly variable (Kato et al., 2004; Kato et al., 2006; Gu et al., 2003). Like plant productivity, the CO_2 uptake depends on water availability and temperature which exhibit a diurnal, seasonal, and annual fluctuation. The overall great importance of water availability and temperature on ecosystem-atmosphere CO_2 exchange in the central Tibetan alpine *Kobresia* meadows was demonstrated in several studies through Eddy Covariance measurements (Zhang et al., 2018), chamber measurements (Zhang et al., 2018; Zhao et al., 2017), decomposition of cellulose cotton strips (Ohtsuka et al., 2008) and altitudinal transplantation experiments (Zhao et al., 2018). Similarly, carbon fluxes in alpine steppe are driven by precipitation and temperature on a daily to seasonal and annual time scale. The inter-annual flux variability follows the varying monsoonal precipitation, showing stronger tendencies to function as a C sink in wetter years and as a source in drier years (Wang et al., 2018; Zhu et al., 2015b). Soils that develop in the drier steppe areas tend to show lower organic carbon contents, therefore lowering the total C sink and source potential (Ohtsuka et al., 2008). Although the production of plant biomass may be hampered in steppes, the ecosystem may still act as a carbon sink through microbial CO_2 fixing activities as shown by a recent study on the TP that reported relatively high CO_2 fixation capacity (29 mg kg^{-1} soil d^{-1}, Zhao et al., 2018). Interestingly, this study also found that alpine steppe soils demonstrated significantly higher microbial CO_2 fixation capacity compared to meadow soils (29 *vs*. 18 mg kg^{-1} soil d^{-1}, respectively).

As a result of increasing precipitation and glacier runoff, wetlands in the Nam Co area are expanding, thus increasing emissions of CH_4, which is 28 times more climate active than CO_2 (Intergovernmental Panel on Climate Change, 2014). A study conducted in the alpine wetlands around Nam Co reported, that CH_4 emissions have increased exponentially with increasing precipitation, especially when soil moisture exceeded 80 % (Wei et al., 2015). However, there was a large difference between swamp meadows and swamps (67 and 1444 µg CH_4 m^{-2} h^{-1}, respectively). Swamps are permanently inundated, while swamp meadows are usually seasonally inundated. Furthermore, SOC stocks are higher in swamps compared to swamp meadows (Wei et al., 2015). ~~The large~~Large amounts of SOC in combination with ~~anaerobic~~ anoxic conditions are the main precursors for methanogens activity ~~that stimulate~~, which results in increasing CH_4 emissions to the atmosphere (Kato et al., 2013). Thus, the saturated soils with high SOC content produce higher CH_4 emissions (Deng et al., 2013). Observations from 2008 to 2013 at Nam Co have shown, that alpine steppe and alpine meadows show annual uptake rates of 72 and 59 µg CH_4 m^{-2} h^{-1}, respectively (Wei et al., 2015); however, the corresponding emission rates are much higher. Generally, it is expected that the alpine wetland acts as a CH_4 source while the aerated soils of alpine steppe and alpine meadow act mainly as a CH_4 sink.

As the grasslands on the TP are widely used for yak and sheep grazing, carbon cycling is influenced particularly through human activities and the degree of degradation. The intensity of grazing has a significant effect on CO_2 fluxes, with moderate grazing enhancing belowground allocation of carbon (Hafner et al., 2012), while adversely affecting the C-sink potential through reduction of above- and belowground biomass at higher grazing intensities (Babel et al., 2014). Overgrazing, along with the increase of burrowing pikas in the Tibetan grasslands may increase the Nitrous Oxide (N_2O) emissions (Zhou et al., 2018), an important greenhouse gas with 297-times larger warming potential compared to CO_2 (IPCC, 2013). Despite several studies focusing on greenhouse gas emissions on the TP, the magnitude of the N_2O emissions in different ecosystems has not yet been estimated. Experimental studies on the eastern TP demonstrated that the rate of N_2O emission may increase with increasing soil temperature and soil moisture under a future climate change scenario (Yan et al., 2018; Yingfang et al., 2018). Expanding wetland areas provide anoxic conditions for the release of methane and, due to the greater temperature sensitivity of permafrost areas, subsurface SOC is at high risk of loss, which may decrease the carbon sequestration potential in the region (Li et al., 2018). Besides carbon cycling through decomposition processes, responses to changing temperature and precipitation depend on the composition of decomposer communities (Glassman et al., 2018). Thus, the conclusive effects and feedback mechanisms (i.e. positive *vs.* negative loop) on warming are complex and not always clear.

3 Paleoenvironments on the Tibetan Plateau and landscape evolution at Nam Co

3.1 Geodiversity and evolution of biodiversity

~~Topography, geological context, climate and their complex interplay are key determinants for the distribution of organisms. In general, the ecoregion can serve as a proxy for community- and species-level biodiversity, which best describe communities of mammals, birds and plants (Smith et al., 2018). The TP forms a distinctive zoographical region, characterized by fauna that is adapted to high altitudes, drought, low temperatures and low oxygen levels (He et al., 2016). Certainly, the TP harbors also many unique lineages of other organisms, with higher endemism of low dispersal species (Yang et al., 2009; Clewing et al., 2016). The TP, including Himalayas and Hengduan Mountains, harbor more than 12000 species of seed plants, 1000 species of terrestrial vertebrates and 800 species of birds (Zhang et al., 2016; Zheng and Zhao, 2017). The proportion of endemism among these plants and vertebrates is relatively high, about 38% and 20%, respectively, but only about 4% among breeding birds (Yang et al., 2009). The recorded species richness of fish exceeds the count of 150, with most common and abundant group being endemic schizothoracine (Zheng and Zhao, 2017). As the structure of soil microbial (including fungal) communities are affected by vegetation, climatic and soil parameters, the unique habitats of the TP potentially harbor many unique microbial lineages that are adapted to high altitude and cold environments (Huang et al., 2014). Mountain building has been directly associated with the development of biodiversity (Hoorn et al., 2013; Antonelli et al., 2018), and the biodiversity hotspots are located especially in the south and south-east of the TP. One of the driving factors is the strong altitudinal zonation, which creates habitat diversity and forms various ecosystems. On the TP, ecosystems are ranging from tropical rain forest over coniferous forest, shrubland, alpine meadows and alpine steppe to dry and desert steppe. There is also a pattern of increasing biodiversity from west to east, which correlates positively with increasing precipitation. In contrast, the harsh central areas of the TP show much lower richness, but nevertheless harbor various endemics (Päckert et al., 2015). Throughout the geological~~

~~formation of the TP, the mountainous south-eastern parts have been hypothesized to serve as center of species diversification (Mosbrugger et al., 2018), although the core TP region is also suggested to represent a center of origin (Deng et al., 2011). The TP has been a source area for several mammalian lineages (Out-of-Tibet hypothesis; Deng et al., 2011), including the snow leopard and the arctic fox (Wang et al., 2015), as well as birds, such as redstarts (Voelker et al., 2015), and plants, such as *Gentiana* (Favre et al., 2015). These mountainous areas may also have acted as refugia, which preserved unique lineages over long periods (López-Pujol et al., 2011; Lei et al., 2014). Whether some endemic taxa represent relics of a formerly more diverse clade or have never extensively diversified, remains unclear (Päckert et al., 2015). Besides being a center of origin, the TP may represent a center of accumulation as proposed by the examples of *Saxifraga* (Ebersbach et al., 2017), warblers (Johansson et al., 2007) and hynobiid salamander (Zhang et al., 2006). Overall, the regional biota of the TP is comprised mainly of Palearctic and Oriental species, Nearctic species from the Bering land bridge, as well as species from speciation *in situ*, and postglacial recolonization from adjacent areas. The evolution of biodiversity on the TP has been affected by the combination of geological and climatic changes over the time of the uplift phases (started ca. 55–50 Ma ago; Mosbrugger et al., 2018). High mountain ranges, such as the Himalayas, represent a great distribution barrier for biota (Oheimb et al., 2013). Although many studies have associated recent *in situ* radiations to different uplift phases of the TP, Renner (2016) pointed out that the evidence for recent rapid uplift (9–8 or 3.6–2.6 Ma) remains doubtful and controversial. As proposed by the "mountain-geobiodiversity" hypothesis, the evolution of biodiversity on the TP is a result of an increasing local geodiversity in combination with rapid climatic oscillations and steep ecological gradients (Mosbrugger et al., 2018).~~

Topography, geological context, climate and their complex interplay are key determinants for the distribution of organisms. In general, the ecoregion can serve as a proxy for community- and species-level biodiversity, which best describe communities of mammals, birds and plants (Smith et al., 2018). The TP forms a distinctive zoographical region, an "ecological island" (Deng et al., 2019), characterized by fauna that is adapted to high altitudes, drought, low temperatures and low oxygen levels (He et al., 2016). The TP is forming a unique high-altitude biogeographical biota by harboring also many unique lineages of other organisms, with higher endemism of low dispersal species (Yang et al., 2009; Clewing et al., 2016). As mountain building has been directly associated with the development of biodiversity (Hoorn et al., 2013; Antonelli et al., 2018), the biodiversity hotspots are located especially in the south and south-east of the TP. There is also a pattern of increasing biodiversity from west to east, which correlates positively with increasing precipitation. In contrast, the harsh central areas of the TP show much lower richness, but nevertheless harbor various endemics (Päckert et al., 2015). Throughout the geological formation of the TP, the mountainous south-eastern parts have been hypothesized to serve as center of species diversification (Mosbrugger et al., 2018), although the core TP region is also suggested to represent a center of origin (Deng et al., 2011). The TP has been a source area for several mammalian lineages (Out-of-Tibet hypothesis; Deng et al., 2011), including the snow leopard and the arctic fox (Wang et al., 2015), as well as birds, such as redstarts (Voelker et al., 2015), and plants, such as *Gentiana* (Favre et al., 2015). These mountainous areas may also have acted as refugia, which preserved unique lineages over long periods (López-Pujol et al., 2011; Lei et al., 2014). Whether some endemic taxa represent relics of a formerly more diverse clade or have never extensively diversified, remains unclear (Päckert et al., 2015). Besides being a center of origin, the TP may represent a center of accumulation as proposed by the examples of *Saxifraga* (Ebersbach et al., 2017), warblers (Johansson et al., 2007) and hynobiid salamander (Zhang et al., 2006). Overall, the regional biota of the TP is comprised mainly of Palearctic and Oriental species, Nearctic species from the Bering land bridge, as well as species from speciation *in situ*, and postglacial recolonization from adjacent areas. The evolution of biodiversity on the TP has been affected by the combination of geological and climatic changes over the time of the uplift phases (Mosbrugger et al., 2018). Although many studies have associated recent *in situ* radiations to different uplift phases of the TP, Renner (2016) pointed out that the evidence for recent rapid uplift (9–8 or 3.6–2.6 Ma) remains doubtful and controversial. As proposed by the “mountain-geobiodiversity” hypothesis, the evolution of biodiversity on the TP is a result of an increasing local geodiversity in combination with rapid climatic oscillations and steep ecological gradients (Mosbrugger et al., 2018).

The combination of geological, climatic and ecological changes has left its footprint in the history of Nam Co. ~~It has been inferred that during some phases of the Mid-Late Pleistocene, Nam Co was connected to several other neighboring lakes and covered an area of about 30,000–50,000 km~~$\cancel{^2}$~~ or more (Zhu et al., 2002). The connections allowed the gene flow between drainages, which is reflected, for example, by the closely related clades of schizothoracine fish (Cyprinidae, Osteichthyes) from Nam Co and the surrounding lakes, compared with more distant parts of the TP (He et al., 2016). In contrast, due to a vector-mediated passive dispersal across large areas, other aquatic taxa such as freshwater snails seem to be less influenced by drainage histories (Oheimb et al., 2011). Findings from lake terraces suggest lake shrinkage starting during the Late Pleistocene (Zhu et al., 2002). There are at least seven different levels of continuous terraces around Nam Co, with the highest being over 30 meters above current lake level. Higher terraces are older, suggesting a long-term reduction in lake level, with the last large lake phase likely taking place during ca. 40–25 cal ka BP (Lehmkuhl et al., 2002; Zhu et al., 2002). With the generally drying climate since the onset of the Holocene, Nam Co gradually shrank and evolved into the present state (Fig. 5; modern lake area is 2018 km~~$\cancel{^2}$~~).~~ There are at least seven different levels of continuous terraces around Nam Co, with the highest being over 30 meters above current lake level, corresponding well with the elevation of the natural spillway in the northeast of Nam Co. Several authors claim the existence of a much larger fluvial lake system called “Old Qiangtang Lake”, which covered an area of about 30,000–50,000 km2 or more (Li et al., 1981; Zhu et al., 2002). The connections provided by a large lake allowed the gene flow between drainages, which is reflected, for example, by the closely related clades of schizothoracine fish (Cyprinidae, Osteichthyes) from Nam Co and the surrounding lakes, compared with more distant parts of the TP (He et al., 2016). In contrast, due to a vector-mediated passive dispersal across large areas, other aquatic taxa, such as freshwater snails, seem to have been less influenced by drainage histories (Oheimb et al., 2011). Higher lake terraces are older, suggesting a long-term reduction in lake level (Zhu et al., 2002). This may be associated with an evolution from wet to dry phase, which Li et al. (1981) connects to the gradual uplift of the plateau from early Pleistocene to the Holocene. However, there is an alternative suggestion to this interpretation of a rather modern uplift proposed by Renner (2016) who states that large parts of the TP had already reached average heights of 4,000 m and more during the mid-Eocene (~40 Ma ago). Recent findings of palm leave fossils on the central part of the TP, dated to ca. 25.5 ± 0.5 million years, do not suggest a presence of such a high plateau before the Neogene (Su et al., 2019). Thus, although it is suggested that the final large lake phase took place during ca. 40-25 cal ka BP (Lehmkuhl et al., 2002; Zhu et al., 2002), the complex relationship between evolution of the TP and the development and the temporal existence of "Old Qiangtang Lake" are not completely resolved.

3.2 ~~Paleo-~~Holocoene lake level changes and climate reconstruction based on aquatic bioindicators

Lake sediments contain important indicators, or proxies, that can be used to reconstruct limnological and (hydro-) climatic conditions over long time periods (Zhu et al., 2010a; Wrozyna et al., 2010). Widely used environmental indicators include communities of diatoms (Bacillariophyceae) and ostracods (Crustacea: Ostracoda) as they are abundant and usually preserve well in sediments (Kasper et al., 2013). For example, the investigations of Quaternary ostracods, modern assemblages, and stable isotopes from Nam Co and nearby water bodies represent the most detailed application of ostracod analysis in the south-central region of the TP (Mischke, 2012). Different approaches (stratigraphy, paleoecology, etc.) detected several climatic fluctuations between warmer/cooler and wetter/drier periods (Fig. 5). In general, higher lake levels based on aquatic fauna suggest a more humid environment during the early and middle Holocene, which displayed a shift pattern compared to the northern TP (Wünnemann et al., 2018). Together with the indicator species approach, and the application of transfer functions for Nam Co sediments different stages can be recognized. Stage I (8.4–6.8 cal ka BP): climate changed from warm-humid to cold-arid with water depth being much lower than today (Zhu et al., 2010a). Stage II (6.8–2.9 cal ka BP): environmental conditions returned to warm and humid (Zhu et al., 2010a). During 4–2 cal ka BP, lake water depth initially remained much shallower than today but then gradually increased due to high rates of precipitation (Frenzel et al., 2010). The presence of the diatom taxa *Stephanodiscus* in this stage indicated stronger monsoon activity and higher availability of nutrients (Kasper et al., 2013). Finally, stage III (2.9 cal ka BP to present): the climate again became warm-humid, with a cold-dry event between 1.7 and 1.5 cal ka BP (Zhu et al., 2010a). Between 2 and 1.2 cal ka BP, benthic diatoms, inferred a lower water level and drier climate (Kasper et al., 2013). Subsequently, wetter conditions and an increase in lake level was detected (1.2 cal ka BP until 250 cal BP), possibly corresponding to the Medieval Warm Period (MWP), with high planktonic diatom species and high ostracods diversity (Kasper et al., 2013). During the late Holocene, the minimum water level occurred throughout the Little Ice Age (LIA) (~1490 and 1760 AD) (Frenzel et al., 2010). However, the lake level increased towards the present, which is plausibly linked to the melting of the glacier due to the current warming.

Although a large number of studies describe profound hydrological changes and general climate fluctuations, there are several uncertainties regarding taxonomy, resolution and proxy sensitivities. For example, modern ostracod data detects several morphological variations, characterized by different nodding or shell sizes, which could lead to an erroneous ecological interpretation and later, vague paleoenvironmental conclusions in relation to salinity changes (Fürstenberg et al., 2015). In paleo-studies, different sedimentation rates and uncertainties in the core chronologies also cause a lack of correspondence between signals detected by different proxies (Wang et al., 2012). For this reason, it is surrogate to understand the precise causal relationships between a complex environmental gradient (e.g. water depth, water chemistry, temperature, etc.) and the response of bioindicators. Although ecological information is still poorly known for many species, ostracod and diatom assemblages represent reliable proxies to trace the climatic history of Nam Co.

Further emphasis should be placed on combining morphology and DNA analysis to corroborate the classification of the species already described. Furthermore, experiments with living individuals should be performed under controlled environmental variables to allow the setup of a transfer function that could be used to evaluate quantitative data for paleoreconstructions.

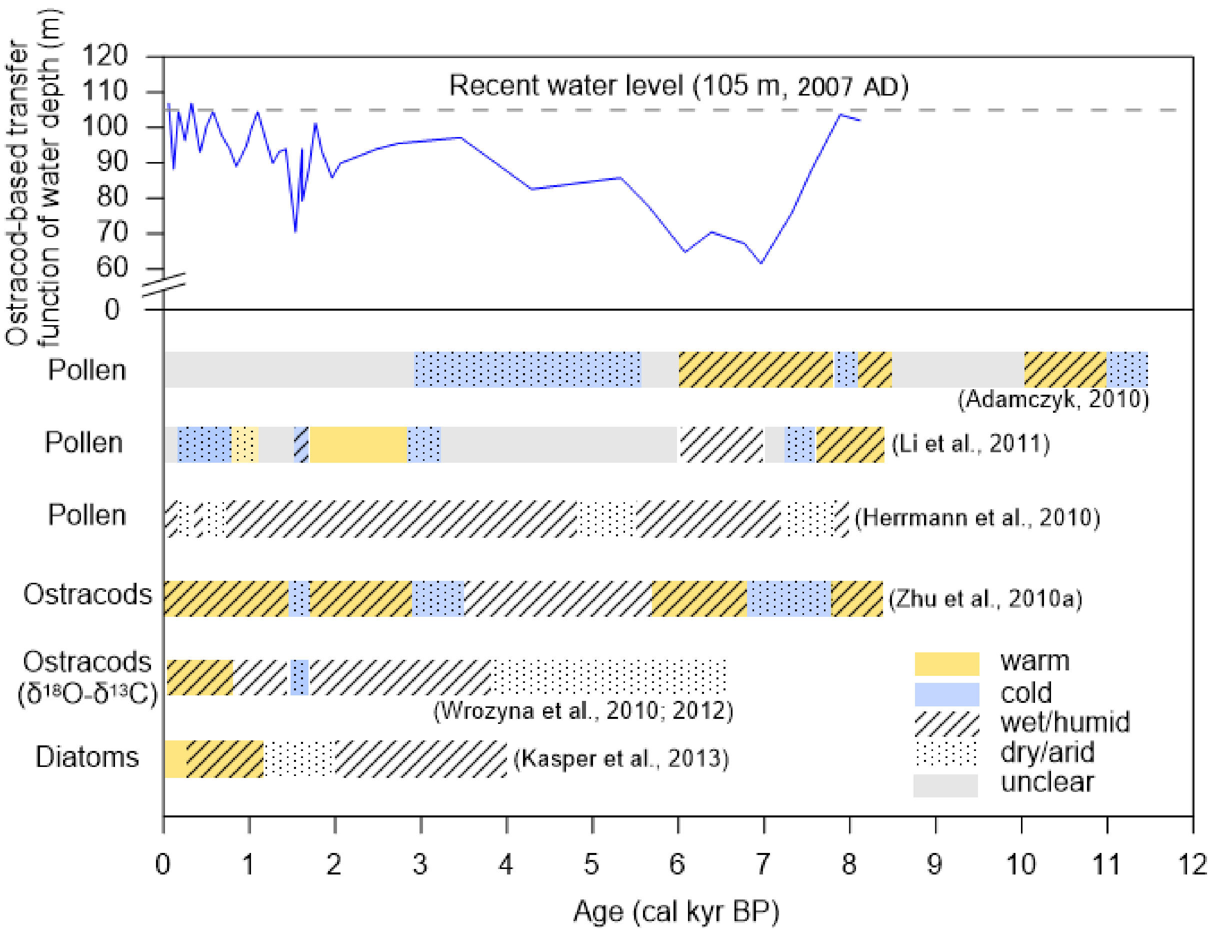

Figure 5. Comparisons of the reconstructed climate conditions based on fossils of pollen (Li et al., 2011; Adamczyk, 2010; Herrmann et al., 2010), Ostracods (Zhu et al., 2010a), Ostracod δ18O (Wrozyna et al., 2012; Wrozyna et al., 2010) and diatoms (Kasper et al., 2013) from sediment cores in, and at the shoreline of lake Nam Co. Ostracod-based water-depth transfer function (Zhu et al., 2010a); blue line) was used to indicate long-term hydrological changes and all reconstructed water-depth values were adjusted to the maximum water level of the lake according to the 45 m difference between this study site (60 m) and deepest site (105 m) of lake Nam Co. Main species also shown in different periods.

3.3 Holocene vegetation cover and climate reconstruction based on pollen records

The comparison of modern pollen assemblages with those from sediment cores allows the reconstruction of floristic diversity and distribution across various time scales. Vegetation patterns contribute to reconstruct past climate and also with assessing the degree of local human influence. Modern vegetation belts around Nam Co reveal that alpine steppe is containing mostly species of *Artemisia* (~~*Asteraceae*~~Asteraceae) and ~~*Poaceae*~~Poaceae, while alpine meadows and swamps are dominated by ~~*Cyperaceae*~~Cyperaceae (Li et al., 2011). The sedimentary pollen ratio of *Artemisia* to ~~*Cyperaceae*~~Cyperaceae (A/Cy) can, within certain limitations, be used to reconstruct past climates (Li et al., 2011; Li, 2018; Zhu et al., 2015a) provided that vegetation belts move with altitude during climate change. For example, when the climate is warmer and drier, alpine steppe reaches higher up the mountain, displacing alpine meadow into areas further away from the lake, leading to a higher input of *Artemisia* pollen into the nearby lake and consequently a higher A/Cy pollen ratio in the sediments. However, the A/Cy pollen ratio and abundance of tree-pollen originating from a short distance can be altered by human-driven change of plant composition, hence the beginning of pastoral economy might limit the explanatory power of pollen records (Adamczyk, 2010; Miehe et al., 2014). Pollen composition inferred from sediment cores reveals a downward shift of the altitudinal vegetation belts since 8.4 ka BP (Li et al., 2011). A major extension of alpine ~~meadow~~ pasture and alpine sparse vegetation closer to the lake shore during the late Holocene is corroborated by a pollen-based climate reconstruction from a peat core near Nam Co (Herrmann et al., 2010) and two other pollen records from the eastern lake shore (Adamczyk, 2010). They found a trend of increasing temperatures from the late glacial until the early Holocene, accompanied by an extension of alpine steppe, tree and shrub vegetation. Already in this period, synanthrope taxa pollen are increasing in the data used by Adamczyk (2010) with the only small occurrence of e.g. *Plantago lanceolata* in the whole profile. This very early signal shows, that still much room exists for studies of pollen archives around Lake Nam Co with today much doubt persisting. Climate fluctuated between dry and humid from 8.5 to 4.8 ka BP, with an intense cold regression between 8.1to 7.8 ka BP. The onset of human activity at Lake Nam Co is dated to 5.6 ka BP according to synanthrope taxa proxies (Li et al., 2011; Herrmann et al., 2010). Between 4.8 and 0.7 ka BP, a relatively stable climate with predominantly humid conditions developed (Fig. 5), the vegetation pattern already showed trends of a human-made steppe biome, potentially a plagioclimax (Adamczyk, 2010). Since 0.7 ka BP, drier conditions prevailed.

Whether and to what extent the central Tibetan Plateau was forested, and what caused the forest decline is the subject of ongoing discussion (Miehe et al., 2006; Miehe et al., 2019). ~~Besides some *Juniperus pingii* and *Salix* occurrences (Nölling, 2006) there are no remains of this once potentially tree-rich vegetation in the Nam Co catchment.~~ This matter is closely related to the prior discussed onset of more intense human activity in the area, since parts of the discussion involve a human-made forest clearing in combination with a natural forest decline. As stated, there are only occurrences of shrubs (*Juniperus pingii var. wilsonii* and *Salix* (Nölling, 2006)) in the Nam Co area. No remains and yet no reliable evidence of a once tree-rich vegetation can be found in the Nam Co catchment. According to locals, there exist several caves with potentially (pre-) historic tree depictions of unknown age. Unfortunately, there is no verification of their existence, nor any dating approach. Since the area of Damxung still does feature larger occurences of *Juniperus pingii var. wilsonii* and, around 4250 m a.s.l., also tree stands of *Juniperus tibetica* in enclosed areas, there is the potential to discuss, that these species have been more numerous in this area (i.e. last-tooth-theory). Miehe et al. (2019) show locations of forest relicts and give a drought line of 200-250 mm precipitation and elevations between 3600 and 4000 m a.s.l. as the upper tree line. Questions arise, whether there has been an expansion of *J. tibetica* into the Nam Co catchment in earlier times, which would be feasible within certain limitations according to the presented thresholds. ~~Charred micro remains, however, can be found throughout the Holocene until 1 cal ka BP (Herrmann et al., 2010).~~ Charred micro remains as a potential sign of fire driven forest decline, are missing in one of the profiles of Adamczyk (2010) but can be found throughout the Holocene until 1 cal ka BP (Herrmann et al., 2010). The authors attribute the size and shape of the charcoal remains to local, small-scale burning of wood and leaves, not showing signs of larger forest clearings. In addition to the burning of *Juniperus* trees for religious reasons (Miehe et al., 2006), trees and shrubs may have been burned for heating or clearing of pastures by nomads. ~~The~~ Following the presumptuous argumentation of some authors, the trees were previously able to spread again due to sufficient precipitation provided by the summer monsoon. Furthermore, the occurrence of synanthropic taxa has been observed in the nearby Damxung valley since 8.5 cal ka BP, corroborating the strong anthropogenic influence on the formation and restructuring of the vegetation patterns in the area (Schlütz et al., 2007). The decrease of summer precipitation and temperature, ~~very likely~~ in conjunction with ongoing human activity ultimately led to the total disappearance of trees and the formation of the alpine grasslands and steppe as we know them today (see section 2.4). Furthermore, the occurrence of synanthropic taxa has been observed in the nearby Damxung valley since 8.5 cal ka BP (Schlütz et al., 2007). This corroborates the strong anthropogenic influence on the formation and restructuring of vegetation patterns in the area but leaves a time gap of almost 3 ka between the evidence from Damxung valley and Nam Co. Hence, further research is needed to address the question of onset of human activity and degree of landscape modification.

4. Conclusions and perspectives

This literature review summarizes the manifold environmental changes affecting abiotic and biotic processes in the area caused by past and ongoing climate change. ~~The~~ Ecosystems ~~of~~ on the Tibetan Plateau experience an increase in air temperature roughly twice the global average. ~~Based on the model system of the Nam Co catchment in central Tibet, this literature review describes the manifold environmental changes affecting abiotic and biotic processes in the area. The air temperature increase~~ This has accelerated deglaciation of the Nyainqêntanglha ~~mountain~~ range during the last decades, leading to substantial inflow of freshwater and various solutes resulting from weathering to the lake. The combined effects of overgrazing by livestock and warming accelerated degradation processes of the alpine grasslands further increase surface runoff in the catchment. ~~Further down the slope, increasing glacier runoff leads to an enlargement of the wetland extent, thus augmenting anaerobic conditions leading to enhanced release of methane.~~ Moreover, warmer and wetter climate as well as pasture degradation may turn alpine

~~grassland~~ wetlands and steppe-pasture ecosystems into an overall source of methane and carbon dioxide, respectively. Based on the reviewed literature focusing on the ~~model~~ catchment of Nam Co, we outline ~~future~~ perspectives to ~~further~~ improve the understanding ~~about~~ of the close connections between geo- and biodiversity. (1) Permafrost areas act as buffers of the water budget, and influence the behavior of geomorphological processes and periglacial landforms. Although a significant warming and consequent decay of permafrost have been reported throughout the TP in recent decades, studies on permafrost in the Nam Co catchment and in the immediate Nyainqêntanglha range are missing. (2) The rising lake level trend, starting in late 1970, had a point of reflection around 2009, which indicates changes of variable precipitation and evaporation trends, reduced water inflow from already melted glaciers and additional ground water seepage out of the lake. Therefore, long term monitoring is necessary to calibrate and validate models properly, ~~focusing~~ to achieve on a more accurate climate prognosis. (3) To improve climate modelling approaches, the dynamics of DOM, CO_2 and CH_4 fluxes need further clarification by in-depth analysis of the different biomes and in-situ observations. (4) The development of molecular methods for biomonitoring and water quality assessment has ~~improved~~ advanced greatly during last decade with the aim to provide clear monitoring standards. These offer time- and cost-effective approaches for complementary studies to tackle community shifts of various water quality indicator organisms. (5) Alongside the 'traditional' paleobioindicator analysis, DNA based taxa identification methods hold also a great potential ~~to be used~~for application in paleoecological studies to provide improved taxa differentiating accuracy. Various biological and geochemical proxies in Nam Co sediments have enabled the tracking of historical events and the reconstruction of past environments, which provide information about the magnitudes and directions of past climate change and thus a key to assess future changes. Both the formation of high elevation environments and pronounced past climate oscillations have contributed to the development of biota on the TP. Interdisciplinary research of the Nam Co catchment ~~of Nam Co~~ has provided vast insights into how warming trends may affect ecosystems from microbes to the top of the food chain. Recognizing the impacts of a warming climate is the base for establishing effective climate change adaptation strategies and actions in the TP region and in alpine regions in general.

Team list:

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Author contributions:

SA, MAR, JB, PEG, JK, WK, LK, PM, FN, ER, HT, TVT, YW contributed equally to the content of the Manuscript. ~~SA~~AS conceived the idea and was responsible for funding acquisition. SA, JB, PM, FN structured the main text body; The following authors were in charge of the corresponding sections: JB, ER, TVT: *Glacier retreat and hydrological patterns of Nam Co*; PEG, LK: *Enhanced water availability controls changes in lake water chemistry*; PM, FN: *Vegetation, soils and pasture degradation in the catchment* & *Effects on carbon cycling in alpine ecosystems* & *Holocene vegetation cover and climate reconstruction based on pollen records*; SA, PEG, WK: *Geodiversity and evolution of biodiversity* & *Paleo-lake level changes and climate reconstruction*; The tables and figures were prepared as follows: ER: ~~fig.~~ Fig. 1, JB and FN: Tab.1, Tab. 2, ~~fig.~~ Fig. 2 and ~~fig.~~ Fig. 3, PM: ~~fig.~~ Fig. 4, WK: ~~fig.~~Fig. 5.

Competing interests:

The authors declare that they have no conflict of interest.

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Data availability:

As this manuscript is reviewing existing literature findings, there was no data analyzed that is not already published in the studies we cite. The dataset from which Table 1 was generated was provided by the Institute of Tibetan Plateau Research and is publicly available under https://data.tpdc.ac.cn/en/data/4deeb2b4-4fc1-4c7c-b0c6-6263a547d53f/ (Wang and Wu, 2018) and https://data.tpdc.ac.cn/en/data/3767cacc-96e3-48b2-b66c-dac92800ca69/ (Wang, 2019)

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