

The Effect of Glacier Ablation on Vegetation Coverage

Chengjin Xu

Jinyu Avenue 3399 Jinan Foreign Language School, Jinan, Shandong, China.

ABSTRACT

The effects of climate change on glaciers, in terms of their scope and conditions, have become increasingly apparent, with serious consequences for various ecosystems, affecting hydrological and terrestrial factors. This paper reviews the existing literature on the complex interaction between glacier retreat and vegetation distribution. In the short term, glacier retreat may promote vegetation expansion by increasing water supply, while in the long term, drought may occur due to glacier depletion, adversely affecting vegetation growth. In addition, glacial meltwater is usually cooler, so the melting of glaciers will also affect the temperature of water resources, thus affecting the growth of vegetation to a large extent. On the one hand, glacier ablation results in the transfer of glaciated rocks and moraines from the glacier surface to the periglacial zone. The former is rich in organic matter and minerals, while the latter can provide parent rock, promote soil development, increase soil nutrients, and expand vegetation colonization. On the other hand, melting glaciers can cause soil erosion and soil depletion, which is not conducive to the growth of vegetation. Melting glaciers will lead to more surface runoff, which will affect soil erosion and even the formation of new terrain, all of which are associated with vegetation growth. The increasing concentration of carbon dioxide in the atmosphere has led to greening on a global scale, creating positive and negative feedback loops in different regions. Therefore, the glacier ablation and its pathways and sub-pathways are affected, so the glacier ablation seriously affects the vegetation distribution. Overall, the effects of glacial retreat on vegetation distribution are very complex. As glaciers continue to retreat globally, understanding these dynamics is critical to predicting future changes in vegetation distribution.

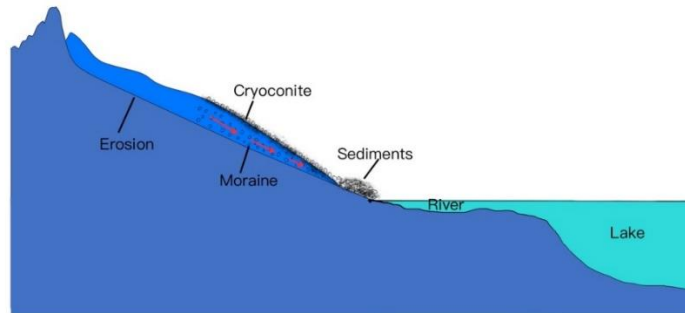
KEYWORDS

Climate change; Glacier ablation; Vegetation coverage.

1. INTRODUCTION

With the increasing frequency of human activities, our earth's climate is undergoing unprecedented changes[1]. As temperatures get hotter, glaciers around the world are melting, and this has clear implications for our ecosystems, one of which is its impact on plant distribution. This change is of great significance to us human beings, because the change of vegetation distribution will not only affect biodiversity and thus change the balance of the ecosystem, but also directly affect People's Daily life. For example, fluctuations in weather patterns can lead to more natural disasters, the impact of changing vegetation distribution on water resources can affect agricultural production, and it can affect air quality[2]. Therefore, it is very important to understand the current trend of vegetation distribution. Some scholars have been at the forefront of studying the changing trends of vegetation distribution in the current climate. But this paper will focus on a more specific area - the impact of glacial ablation on vegetation distribution.

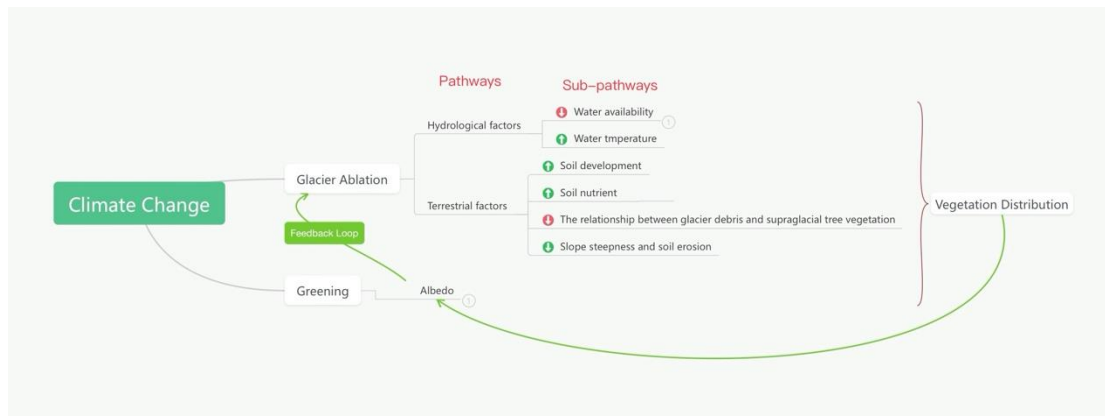
Fig 1: Simplified glacier dynamics schematic diagram



2. METHODOLOGY (GAP: TO INTEGRATE GLOBAL DISCUSSION AND CASES ON THIS TOPIC)

The change in vegetation distribution will have a profound impact on human society; therefore, it is necessary to study its changing trend. This study analyzed the impact of glacier ablation on vegetation distribution through a literature review.

Figure 2: Evaluative Framework



The current literature has identified two major pathways through which glacier ablation affects vegetation distribution: hydrological and soil. Figure 2 presents the prominent sub-pathways agreed upon by current researchers. Based on the existing literature, this study qualitatively analyzes the impact of glacier ablation on vegetation distribution by considering the impact of glacier ablation on factors that can change vegetation distribution as the entry point. As a result, due to glacier ablation, water resources will increase, vegetation types may change, and vegetation coverage will increase, increasing net primary productivity. As increased water resources lead to increased surface runoff, soil erosion will increase and have different effects on different plants[3]. Furthermore, Topographic factors should also be taken into account, as retreating glaciers may shape new terrain and thus affect the distribution of vegetation[4, 5].

Chart 1: Pathways and Sub-pathways

Hydrological factors	Terrestrial Factors	Other factors
Water availability	Soil Nutrient	The dynamics in greening due to glacier ablation
Water temperature	Soil Development The relationship between glacier debris and supraglacial tree vegetation	
	Slope steepness and soil erosion	

3. LITERATURE REVIEW

3.1. Hydrological factors

3.1.1. Water availability

In the context of global warming, the melting of glaciers greatly affect hydrological conditions[1]. Young et al[1] found a single peak in summer runoff on the western Juneau Ice Sheet, which is consistent with Hill et al.[6], who used mathematical models to simulate freshwater discharge from 1980 to 2016 and predicted that the glacier melting rate would significantly increase by 2100, further increasing runoff. Furthermore, although the total runoff increased only slightly, glacial runoff and glacial ice loss showed strong increases, increasing by 3.0% and 9.6% per decade[7], respectively, this suggests that accelerated melting leads to an increase in glacier runoff. As runoff increases, more lakes and rivers begin to form, creating favorable conditions for this vegetation to colonize[8]. However, in the long term, the accelerated melting of glaciers will eventually lead to the depletion of water resources, because the accelerated melting of glaciers will lead to the gradual reduction of ground ice (ice in frozen ground) and surface runoff, both of which are important sources of water resources, and thus vegetation degradation and desertification downstream[9, 10]. According to the model established by MYRNA et al.[10] it is predicted that all glaciers in the Blackfoot-Jackson region will disappear by mid-century.

3.1.2. Water temperature

Glacier ablation contribute to runoff and lower water temperatures in rivers and lakes in short term by discharging large amount of low temperature runoff[9]. However, according to the research of Fellman, J. B. et al.[11], in the long run, with the continuous melting of glaciers, the cooling effect will gradually weaken, and the water temperature of the downstream will gradually rise. Studies have shown that for every 10 percent increase in glacier cover, the average summer river water temperature decreases by 1.1°C. This suggests that river water temperatures may increase in the future as glaciers melt due to climate warming[11]. Moore, R. D. et al.[12], also came to a similar conclusion. Based on multiple regression analysis, the scientists found that for every 10 percent reduction in glacier cover, the 7-day mean maximum water temperature (MWAT) rose by about 1.6°C[12].

Low temperature will affect the physiological processes of plants such as water absorption and photosynthesis, thus inhibiting the growth and development of plants. Low temperature will cause the cell expansion rate to decrease, make the leaf cells smaller, reduce the single leaf area. Thus, it has a negative effect on the growth of vegetation[13].

Low temperature will hinder the respiration of the roots and affect the uptake of oxygen by the roots[14]. At the same time, low temperature will also affect the root's metabolism of ammonia ions, resulting in the accumulation of ammonia toxicity, thus inhibiting plant growth. Suffice to explain the effect of low temperature on nutrient absorption. Low temperature will also have a negative

impact on the ability of plants to absorb water,[15] so the reduction of water temperature is not conducive to vegetation growth. All these factors, Reduced Metabolic Rates and Impaired Root Functions could lead to Delayed Germination and Growth too[14], consequently decrease vegetation coverage.

On the contrary, in the long run, as the water temperature rises, the downstream conditions will gradually become suitable for vegetation colonization. The growth of vegetation will be ensured and the vegetation cover will increase.

3.2. Terrestrial Factors

3.2.1. Soil Nutrient

Glacial meltwater can carry nutrients and trace elements downstream, such as nitrogen, phosphorus, iron, and organic carbon, that can be absorbed by plants, which can provide nutrients for riverside and coastal ecosystems, promote vegetation colonization, and increase primary productivity[7, 16]. The source of these nutrients may be the physical and chemical weathering of the cryoconite hole sediments, as well as microbial activities, such as nitrogen fixation and biological leaching[17]. At the same time, meltwater from glaciers may also carry pollutants, such as mercury, which can affect vegetation and ecosystems[16].

3.2.2. Soil Development

The global (excluding Antarctica) cryoconite ecosystem is a significant source of organic carbon, which yields 100000 t C/yr of dissolved organic carbon[18, 19]. Cryoconite is also rich in microbes (such as cyanobacteria), which are important for primary succession[20].

In the context of global warming, glaciers are melting at an accelerated rate. According to Qin Ji et al.[21], Himalayan glaciers lost 11% of their total surface area between 1990 and 2015. As glaciers melt, cryoconite is washed into the pre-glacial zone by water flow. The microorganisms contained in cryoconites act as pioneer species, promoting the initial colonization of vegetation (such as mosses and lichens) and soil formation. The organic matter in cryoconite provides essential nutrients for soil development and accelerating this process[20]. During glacier melting, the irregular terrain of the glacier surface (such as crevasses and ice caves) gradually becomes exposed, forming an undulating landscape. Water is collected from low-lying areas, creating temporary lakes[22].

According to research by Navas et al.[23], in the presence of cryoconite, well-developed soil profiles can form within decades after glacier retreat, whereas this process would otherwise take hundreds of years. All of these factors create favorable conditions for vegetation colonization and increase vegetation coverage.

During the movement of the glacier, the surrounding rock debris was transported and accumulated to form a moraine[24]. The melting of glaciers exposes more moraines and accelerates the rate at which they are deposited. The discovery of a chronological sequence of recession in the Hailuoguo Glacier in China's Sichuan Province makes it an excellent site to study soil development and vegetation succession, He et al.[25]studied a series of moraine deposits exposed at different times during the melting process of glaciers. They found that moraine could provide rich parent rocks for soil development, which created favorable conditions for the rapid occupation of vegetation. In the context of accelerated glacier melting, moraines will be transported and accumulated faster, which means that soil development will be promoted, which will further promote the growth and succession of vegetation.

3.2.3. The relationship between glacier debris and supraglacial tree vegetation

There are two forms of glacier ablation: downwasting and backwasting, which will can influence the debris covered on the surface of the glacier and consequently influence the vegetation colonized[26]. When the downwasting of the glacier appears, like what happened southern ice cliff area of the Miage

Glacier[27], the debris will get thicker because of the collapse of the hillside. Some trees die when they are buried by debris, but the main cause of death from degrading is that trees slide down with the glacier and eventually die[26]. According to research, high temperatures will cause the thickness of debris cover on the surface of the glacier to increase exponentially, so the problem of increasing debris will become more and more serious, threatening the growth of vegetation[28]. On the other hand, backwasting process is more harmful to vegetation, and when backwasting process occurs, the lower part of the ice cliff melts at a greater rate than the upper part, which exposes the roots of the trees and leads to the death of the trees[26].

3.2.4. Slope steepness and soil erosion

Glacier retreat has varied effects on the slope steepness. As the glacier shrinks, the rocks at the bottom are exposed, and these exposed parts are usually steeper[4]. Moreover, melting glaciers also carry moraine, which flattens the terrain of the preglacial zone and makes room for vegetation growth; however, the areas upstream of the glacier become steeper, which increases the risk of soil erosion[5]. This makes it more difficult to colonize vegetation.

3.3. Other Factors

3.3.1. The dynamics in greening due to glacier ablation

Vegetation coverage on our planet has been increasing since 1981[29]. One of the main reasons is that the increasing concentration of Co₂ will thrive the growth of vegetation owing to the Co₂ fertilization-effect[30]. It is well known that changing the surface from ice to vegetation would reduce reflectivity and potentially warm the planet further, but this is not the case, and increased vegetation would act as a carbon sequester and thus slow down warming. However, this phenomenon varies depending on the vegetation type. At low and middle latitudes, the increase in vegetation slows the increase in temperature[31, 32] because both carbon sequestration and evapotranspiration are stronger in those regions, which means that the cooling they bring is more likely to offset the warming caused by the decrease in albedo. The picture becomes even more complicated when considering the vegetation that will colonize when the glaciers retreat. For high-latitude glaciers, such as those in Greenland or the Arctic, the greening caused by the retreat actually exacerbates the temperature increase because higher temperatures promote plant growth, and more plants mean lower albedo. This increases the absorption of solar radiation, which in turn creates a feedback loop that exacerbates the greening. For plants growing at higher elevations, such as the Tibetan Plateau, they can play a warming mitigation role, as well as plants at low and middle latitudes, because these are exposed to more radiation at the plateau, which promotes their evapotranspiration and offsets the warming effect of the lower albedo[33]. As a result, although the temperature is increasing, increased vegetation activity can restrain the temperature rise, and a negative feedback loop is formed[33]. In this case, both the rate of greening and glacier ablation are slowed down, thus affecting other channels through which the glaciers can impact vegetation distribution. In general, by using the land-atmosphere global climate model, it was found that the impact of global vegetation greening on temperature is cooling, which can offset approximately 12% of global warming[34], which means that the rate of greening and the rate of glacier ablation is slowing. However, the overall trend was unlikely to be altered.

4. CONCLUSION

In summary, there is a link between glacier ablation and changes in vegetation distribution in glacier-affected ecosystems. The interaction between them is very complex.

As glaciers continue to melt due to climate change, downstream hydrological conditions will be affected. Young, J. C. et al.[7] found that glacier ablation would significantly increase the runoff in the downstream area and accelerate the formation of lakes and rivers, and this process is gradually accelerating, thus providing a humid environment suitable for vegetation growth in the short term[7],

which is consistent with the results of Hill et al.[6], who found a significant increase in runoff using mathematical modeling[6]. The research of MYRNA H. P. et al.[10] shows that the above situation is not permanent, the glacier will disappear in a short period of time, and then the shortage of water resources will become a problem, which will have a devastating blow to the vegetation downstream. In addition, the melting of glaciers also has an impact on the temperature of downstream water resources, Fellman, J. B et al.[11] And Moore, R. D. et al.[12], found that although the decrease of water temperature in the short term is unfavorable to vegetation growth, with the continuous melting of glaciers, water temperature will gradually rise, creating favorable conditions for vegetation.

In addition to hydrology, Terrestrial Factors must also be considered. Melting glaciers carry organic matter and nutrients downstream[16], mainly from sediments in cryoconite holes[20]. These nutrients promote vegetation growth. Cryoconite also creates favorable conditions for soil development, as the organic matter and microorganisms it contains can promote soil development after it is carried downstream by glacial meltwater[21]. There is well-developed soil, the vegetation growth environment is guaranteed, and succession can be carried out smoothly[20]. According to Navas et al.[23], the rate of soil development in the presence of cryoconite is much faster than that in the absence of cryoconite, proving that cryoconite plays a key role in this process. Moraines can provide parent rocks for soil development during glacier melting, which also accelerates soil development, which promotes vegetation growth and succession[24, 25].

In the process of glacier melting, the impact of downwasting and backwasting on vegetation is also significant[28], and they both affect the growth of this cup. When downwasting occurs, the debris on the glacier surface buries vegetation and causes it to die, and this phenomenon becomes increasingly serious[30]. When backwasting occurs, the roots of the vegetation are exposed, causing it to die[28]. Retreating glaciers have exposed steeper terrain, such as valleys and ridges, where the slope is too steep for vegetation to occupy[4]. In addition, by changing the distribution and characteristics of sediment at the bottom and affecting hydrological processes at the glacier front, melting ice creates new geomorphic features, such as flatter areas, which provide space for vegetation growth[5].

REFERENCES

- [1] Calvin, K. et al. IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (Eds.)]. IPCC, Geneva, Switzerland. <https://www.ipcc.ch/report/ar6/syr/> (2023) doi:10.59327/IPCC/AR6-9789291691647.
- [2] The impact of plant stomatal control on mesoscale atmospheric circulations. *Agric. For. Meteorol.* 54, 353–372 (1991).
- [3] Relationship of Vegetation Distribution to Soil Properties in Kärkevagge, Swedish Lapland. [https://www.tandfonline.com/doi/full/10.1657/1523-0430\(2004\)036\[0021:ROVDTS\]2.0.CO;2](https://www.tandfonline.com/doi/full/10.1657/1523-0430(2004)036[0021:ROVDTS]2.0.CO;2).
- [4] Anderson, R. S. A model of ablation-dominated medial moraines and the generation of debris-mantled glacier snouts. *J. Glaciol.* 46, 459–469 (2000).
- [5] Zechmann J. M., Truffer M., Motyka R. J., Amundson J. M. & Larsen C. F. Sediment redistribution beneath the terminus of an advancing glacier, Taku Glacier (T'aakú Kwáan Sít'i), Alaska. *J. Glaciol.* 67, 204–218 (2021).
- [6] Spatial and temporal variability of freshwater discharge into the Gulf of Alaska - Hill - 2015 - *Journal of Geophysical Research: Oceans* - Wiley Online Library. <https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014JC010395>.
- [7] Young, J. C. et al. A Changing Hydrological Regime: Trends in Magnitude and Timing of Glacier Ice Melt and Glacier Runoff in a High Latitude Coastal Watershed. *Water Resour. Res.* 57, e2020WR027404 (2021).
- [8] Ziaja, W. Spitsbergen Landscape under 20th Century Climate Change: Sørkapp Land. *AMBIO J. Hum. Environ.* 33, 295–299 (2004).
- [9] HESS - Soil water sources and their implications for vegetation restoration in the Three-Rivers Headwater Region during different ablation periods. <https://hess.copernicus.org/articles/28/719/2024/>.
- [10] Modeled Climate-Induced Glacier Change in Glacier National Park, 1850–2100 | *BioScience* | Oxford Academic. <https://academic.oup.com/bioscience/article/53/2/131/254976>.

- [11] Fellman, J. B. et al. Stream temperature response to variable glacier coverage in coastal watersheds of Southeast Alaska. *Hydrol. Process.* 28, 2062–2073 (2014).
- [12] Moore, R. D. et al. Glacier change in western North America: influences on hydrology, geomorphic hazards and water quality. *Hydrol. Process.* 23, 42–61 (2009).
- [13] Hendrickson, T., Dunn, B. L., Goad, C., Hu, B. & Singh, H. Effects of Elevated Water Temperature on Growth of Basil Using Nutrient Film Technique. (2022) doi:10.21273/HORTSCI16690-22.
- [14] Fonseca de Lima, C. F., Kleine-Vehn, J., De Smet, I. & Feraru, E. Getting to the root of belowground high temperature responses in plants. *J. Exp. Bot.* 72, 7404–7413 (2021).
- [15] Hatfield, J. L. & Prueger, J. H. Temperature extremes: Effect on plant growth and development. *Weather Clim. Extrem.* 10, 4–10 (2015).
- [16] Icefield-to-Ocean Linkages across the Northern Pacific Coastal Temperate Rainforest Ecosystem | BioScience | Oxford Academic. <https://academic.oup.com/bioscience/article/65/5/499/324158>.
- [17] Grzesiak, J. et al. Microbial community changes along the Ecology Glacier ablation zone (King George Island, Antarctica). *Polar Biol.* 38, 2069–2083 (2015).
- [18] Zazovskaya, E. P. et al. Cryoconites as Factors of Soil Development in Conditions of Rapid Retreat of the Aldegonda Glacier, Western Svalbard. *Eurasian Soil Sci.* 55, 299–312 (2022).
- [19] Anesio A. M., Hodson A. J., Fritz A., Psenner R. & Sattler B. High microbial activity on glaciers: importance to the global carbon cycle.
- [20] Kaczmarek Ł., Jakubowska N., Celewicz-Gołdyn S. & Zawierucha K. The microorganisms of cryoconite holes (algae, Archaea, bacteria, cyanobacteria, fungi, and Protista): a review. *Polar Rec.* 52, 176–203 (2016).
- [21] Variations in glacier coverage in the Himalayas based on optical satellite data over the past 25 years. *CATENA* 214, 106240 (2022).
- [22] Gerdel, R. W. & Drouet, F. The Cryoconite of the Thule Area, Greenland. *Trans. Am. Microsc. Soc.* 79, 256–272 (1960).
- [23] Unveiling the provenance of sediments in the moraine complex of Aldegonda Glacier (Svalbard) after glacial retreat using radionuclides and elemental fingerprints. *Geomorphology* 367, 107304 (2020).
- [24] Soil development on moraines of Mendenhall Glacier, southeast Alaska. 1. The moraines and soil morphology. *Geoderma* 72, 1–17 (1996).
- [25] Soil development along primary succession sequences on moraines of Hailuoguo Glacier, Gongga Mountain, Sichuan, China. *CATENA* 72, 259–269 (2008).
- [26] The influence of glacier surface processes on the short-term evolution of supraglacial tree vegetation: The case study of the Miage Glacier, Italian Alps - Manuela Pelfini, Guglielmina Diolaiuti, Giovanni Leonelli, Mauro Bozzoni, Nicoletta Bressan, Daniele Brioschi, Anna Riccardi, 2012. <https://journals.sagepub.com/doi/abs/10.1177/0959683611434222>.
- [27] Diolaiuti, G. et al. Rates, processes and morphology of freshwater calving at Miage Glacier (Italian Alps). *Hydrol. Process.* 20, 2233–2244 (2006).
- [28] TC - Impact of varying debris cover thickness on ablation: a case study for Koxkar Glacier in the Tien Shan. <https://tc.copernicus.org/articles/8/377/2014/>.
- [29] Piao, S. et al. Characteristics, drivers and feedbacks of global greening. *Nat. Rev. Earth Environ.* 1, 14–27 (2020).
- [30] Farquhar, G. D. & Sharkey, T. D. Stomatal Conductance and Photosynthesis. *Annu. Rev. Plant Biol.* 33, 317–345 (1982).
- [31] Forzieri, G., Alkama, R., Miralles, D. G. & Cescatti, A. Satellites reveal contrasting responses of regional climate to the widespread greening of Earth. *Science* 356, 1180–1184 (2017).
- [32] Green, J. K. et al. Regionally strong feedbacks between the atmosphere and terrestrial biosphere. *Nat. Geosci.* 10, 410–414 (2017).
- [33] Shen, M. et al. Evaporative cooling over the Tibetan Plateau induced by vegetation growth. *Proc. Natl. Acad. Sci.* 112, 9299–9304 (2015).
- [34] Zeng, Z. et al. Climate mitigation from vegetation biophysical feedbacks during the past three decades. *Nat. Clim. Change* 7, 432–436 (2017).