

ASSESSMENT OF GLACIER MASS BALANCE IN THE HIMALAYAN-KARAKORAM REGION

NG, K. C.^{1*} – YAP, S. C.² – CHENG, K. M.³

¹ Faculty of Arts and Social Science, University of Malaya, Kuala Lumpur, Malaysia.

² Center for Housing Study, Building and Planning, Universiti Sains Malaysia, Penang, Malaysia.

³ De Institute of Creative Arts and Design, USCI University, Kuala Lumpur, Malaysia.

*Corresponding author
e-mail: kahchoon.15[at]gmail.com

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Abstract. Mountain glaciers are susceptible to climate change. Most high-elevation glaciers, including the Himalayan glaciers, have been receding at an unprecedented rate in recent decades. Moreover, most mountain glaciers are found in the Himalayan areas, but field sampling and research efforts are limited due to logistical and financial constraints. From 1997 to 1999, just 6.8 km² of the 33,000 km² were examined in the Himalayan region. Previous studies indicated that Himalayan glaciers have been melting at an alarming rate over the past few decades. The objective of this paper is to review glacier changes, with an emphasis on mass balance changes in the Himalayan-Karakoram ranges, using 15 ISI journal articles published between 2008 and 2017. The acquired data on glacier mass balance was used to create a glacier mass balance change map for quantification using ArcGIS software and Landsat map as base map. The majority of the glaciers in the study area melted at various rates, with the most extensive glacier loss occurring in the west Himalayan highlands and the lowest occurring in the Karakoram region. Therefore, additional scientific research have to be conducted, and significant actions have to be taken at many different levels to prevent the continued loss of glaciers in this area.

Keywords: Himalaya region, glacier mass balance, literature review, mapping, global warming

Introduction

Worldwide, glaciers are experiencing mass loss due to their susceptibility to changes in air temperature (Maurer et al., 2019; Bolch, et al., 2012) as a result of the anthropogenic processes, such as black carbon aerosol pollution and greenhouse gas emissions (Bryan and Alfonso, 2017; Solomon et al., 2009; Xu et al., 2009). Global warming has been linked to glacier mass loss and glacial lake outburst events, both of which have contributed to economic losses in the downstream communities (Immerzeel et al., 2010). In general, the volume and thickness of glaciers in Himalayan locations are governed by the amount of snow and rain that fall during a certain period (Kääb et al., 2007). Other climatic and geographic elements also influence glacier gains and losses in these cold climates, resulting in a variety of glacier hues, volumes, sizes, and structures (Lemke et al., 2007). Glacier mass balance is defined by the United States Geological Survey defines as an indication of glacier condition. The difference between snowfall in the winter and ice melt in the summer is referred to as the positive mass balance of glaciers, and it is commonly measure in metres water equivalent (m w.e.a-1). Traditional research methods for studying glacier changes involve ice drilling, field surveying, and measuring to gather and quantify glacier volume and mass balance information; however, this method is logistically costly, field-based, and labour

demanding (Pratap et al., 2016). The modern approach to analyzing glacier mass changes is to compare two satellite images to create a three-dimensional depiction of the glacier's current state (Bolch et al., 2012; Dyurgerov and Bahr, 1999). *Figure 1* presents the distribution of glaciers.

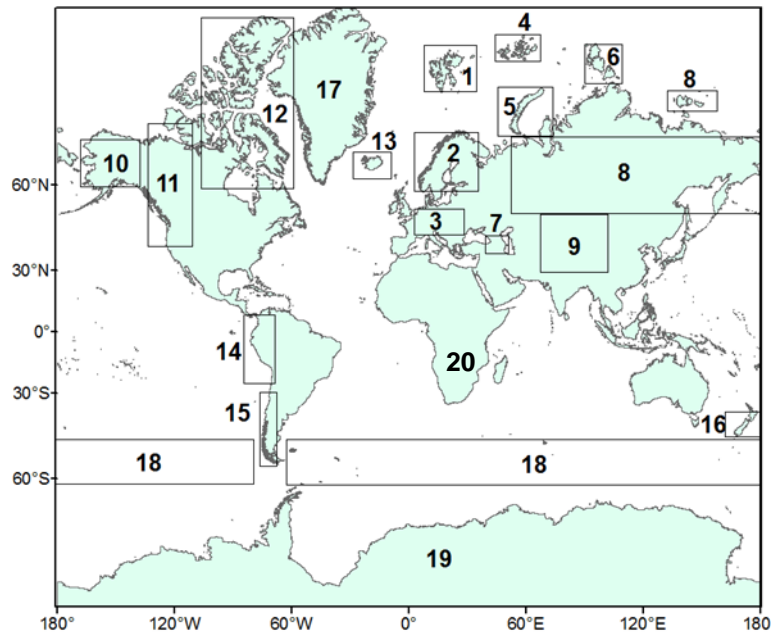


Figure 1. Glacier distribution around the world, with the Himalayan glaciers shown in red:
1.Svalbard; 2.Scandinavia; 3.Central Europe; 4.Franz Josef Land; 5.Novaya Zemlya;
6.Severnaya Zemlya; 7.Caucasus; 8.North and East Asia; 9.Central Asia (Himalaya); 10.Alaska
and NW. Canada; 11.W. Canada and W. U.S; 12.Arctic Canada; 13.Iceland; 14.South America
I; 15.South America II; 16.New Zealand; 17.Greenland; 18.Sub-Antarctic Islands;
19.Antarctica; 20. Africa's Kilimanjaro Mount.
Source: Radić and Hock (2010)

According to a research by Meier and Bahr (1996), worldwide glaciers cover roughly 10% of the total land area on all continents except Australia. However, only 3% of glacier coverage has been discovered in high-elevation places around the world. Glaciers can be found in the north and south polar zones, as well as various high-elevation mountain ranges such as the Himalayas, Africa's Kilimanjaro, Bolivia's Chacaltaya, and Iran's Zard Kud (Post and LaChapelle, 2000). These high-elevation mountains are crucial in delivering water to rivers and seas, which help to supply water to low-lying towns (Viviroli et al., 2007). According to Hong et al. (2016), glacier melting rate, topography, and atmospheric factors all influence the quantity of outflow and rainfall that reaches the downlands. Due to the unpredictability of melt outflow, towns were faced with two severe water supply scenarios: water shortages and glacial lake outburst floods, both of which caused substantial economic and social difficulties to the surrounding environment and neighbourhoods (Winkler et al., 2010).

Outside of the poles, the Himalayan regions are home to the majority of glaciers, although sampling and research efforts are limited, with only 6.8 km² of the 33,000 km² of total Himalayan glaciers examined in 1997-1999 (Berthier et al., 2007). Glaciers in the tropical highlands have received less attention from scientific communities than those in the polar areas and the European Alps glaciers, despite the fact that they have

also experienced recession due to the high susceptibility of glaciers to global warming (Maurer et al., 2019; Oerlemans, 2005). As a result, tropical mountain glacier health reports are uneven and limited when compared to other glacier locations (Hansen et al., 2005). As a result, this report offers a bibliographic analysis of glacier change between 1970 and 2017.

Study area

As seen in *Figure 2*, the Himalayan-Karakoram region stretches 2,400 kilometres horizontally across Pakistan, India, China, Nepal, and Bhutan (Ng, 2021). With 14 of the world's highest summits, these mountainous glaciers have an average height of 4,500 metres (Hewitt, 2005).

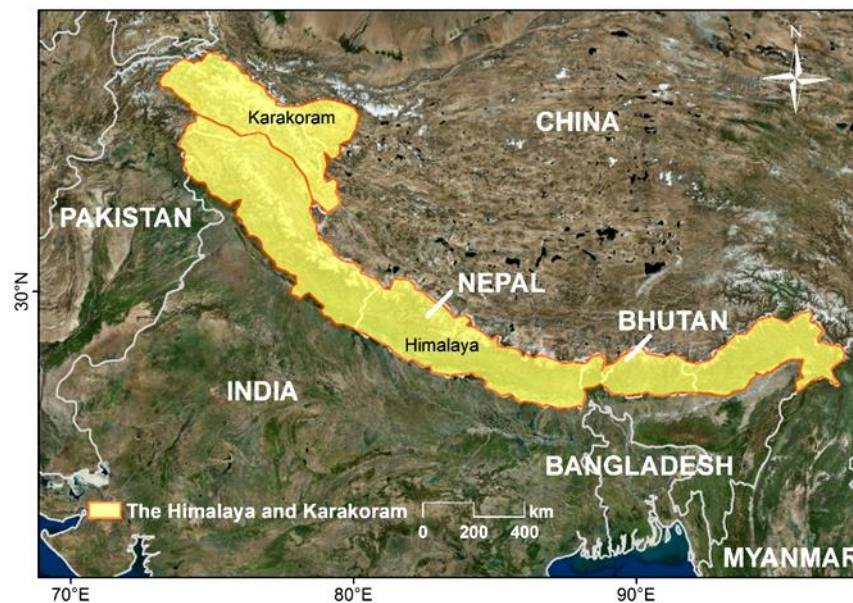


Figure 2. The Himalaya-Karakoram region's geographical location.

According to Bolch et al. (2012), Central Asia has a total of 2,300km³ glaciers spanning 40,800km². The geographical characteristics of these mountain glaciers range from ragged mountains in the north to low agricultural regions in the south Himalayas, with glaciers covering the majority of the high elevation areas (Yde and Paasche, 2010). This region also has a diverse climatic profile, ranging from alpine climate in the north to warm tropical climate in the south (Viviroli et al., 2007). Due to the natural formation of mountains by tectonic collision with the region's boundary, this region is also prone to earthquake and avalanche events, according to Coward and Butler (1985). The topography is geologically varied, and the mountain glaciers are geographically diverse (Bryan and Alfonso, 2017). The glaciers in the Langtang valley are made up of a variety of debris, ranging from microscopic silt to huge rocks, according to a field assessment undertaken by Pellicciotti et al. (2015). Additional forcing such as avalanches and rockfalls, in addition to natural decomposition of materials, contributed to the increasing debris thickness on glaciers (Fujita et al., 2017). As a result, there are various debris layers observable at the sites (Sakai et al., 2002).

The Indian summer monsoon and westerly winds dominate the climate (Pellicciotti et al., 2015). Despite the fact that the north-facing side is in the flood plain, the monsoon

season precipitation that begins in the south and travels north affects the south-facing terrains. Monsoonal glaciers are ablated and accumulated at the same time during the summer (Fujita et al., 2008). Because south-facing glacier slopes capture the bulk of precipitation and are more vulnerable to retreat than north-facing glacier slopes, this uneven mountain profile has led to local climatic variability (Barnard et al., 2006). Westerly weather systems, which develop over the Mediterranean Sea and bring snow and rain in the spring and winter, impact the western part of the site (Bookhagen and Burbank, 2010). Agriculture is the primary source of income and food for people living downstream (Singh and Bengtsson, 2004). The quantity of glacier melt in rivers that serves South Asia's increasing population is heavily dependent on food security. In the Indus Basin, roughly 144,900 ha of land is irrigated, 156,300 ha in the Ganges Basin, and 6000 ha in the Brahmaputra Basin (Immerzeel et al., 2010). Upstream of the Indus Basin, glacier melt accounts for nearly 40% of total stream flow (Nepal and Shrestha, 2015).

The westerly climate produces less rainfall than the monsoon period (Shrestha and Aryal, 2011). Substantial autumn and winter snowfalls are often associated with cyclonic storms and westerly instability, and snowfall can occur at high altitudes during any time of the year (Benn et al., 2012). Empirical long-term evidences of rainfall and mass balance at altitudes over 5000 m are severely lacking, but this data gap has gradually been filled using spatial information (Yamamoto et al., 2011; Bookhagen and Burbank, 2006). However, discrepancies persist between different remote sensing data packages, and estimating precipitation totals at high elevations remains difficult (Andermann et al., 2011).

Materials and Methods

Regardless of the study techniques used, a literature review of ISI scientific articles published between 1970 and 2017 was done to obtain glacier mass balance data in the Himalaya and Karakoram ranges. To guarantee that the study sites were appropriately specified, the coordinates of study sites were manually confirmed using a Landsat base map. Several studies, however, covered vast stretches, such as northern Bhutan (Gardelle et al., 2013), where the average mass balance could be difficult to portray as point values on the map. As a result, the coordinates of a single point within the stated region were used to represent the region on the map. A mass balance map was created using the collected glacier data loaded into ArcGIS software.

Results and Discussion

With a mass balance of -0.01 ± 0.11 m w.e.a-1, the Karakoram glaciers have a slight negative mass balance (*Figure 3*). This finding is consistent with prior research that found steady or even positive glacier mass balances in recent years (Rankl and Braun, 2016). For individual glacier, the Dunaigiri glacier experienced the greatest mass loss (-1.73 m w.e.a-1). In contrast, a significant mass growth has been observed on the Chukhung glacier ($+0.44 \pm 0.34$ m w.e.a-1) and Central Karakoram glaciers ($+0.11 \pm 0.22$ m w.e.a-1) (*Table 1*). The significant variations in glacier mass changes across four zones are due to a range of weather systems, terrain, and glacier dynamics (Bolch et al., 2011; Nuimura et al., 2012). The south-facing side of certain Himalaya glaciers receives more solar radiation (Sakai et al., 2002) and precipitation than the north-facing side

because the slopes of these glaciers are inclined toward the sun. As a result, glaciers on this side are directly exposed to sunlight for the most of the day (Zhang et al., 2015).

Table 1. Glacier name, latitude, longitude, glacier data source, period of the study, mass balance and source of ISI-cited publication on Himalayan-Karakoram glacier mass balance changes.

No.	Glacier name	Latitude	Longitude	Data	Period	Mass balance (m w.e.a ⁻¹)	Source
East Himalaya							
1	Bhutan (North)	27°28'N	90°28'E	SRTM, SPOT5	1999 – 2011	-0.22 ± 0.14	Gardelle et al., 2013
2	Changme Khangpu	27°58'N	88°39'E	Landsat	1979 – 1982	-0.16	Bolch et al., 2012
3	East Rathong	27°36'N	88°06'E	Landsat, Corona	1963 – 2011	-0.22	Agarwal and Tayal, 2015
					Mean	-0.20 ± 0.05	
Central Himalaya							
4	Ama Dablam	27°51'N	86°51'E	SRTM, SPOT5	1999 – 2011	-0.41 ± 0.21	Gardelle et al., 2013
5	Amphu Laptse	27°52'N	86°55'E	SRTM, SPOT5	1999 – 2011	-0.46 ± 0.34	Gardelle et al., 2013
6	AX010	27°49'N	87°01'E	Landsat ETM+	1978 – 2008	-0.75 ± 0.09	Bolch et al., 2012
7	Changri Shar/Nup	27°57'N	86°52'E	SRTM, SPOT5	1999 – 2011	-0.42 ± 0.17	Gardelle et al., 2013
8	Chukhung	27°54'N	86°52'E	SRTM, SPOT5	1999 – 2011	+0.44 ± 0.34	Gardelle et al., 2013
9	Dudh Koshi	27°57'N	86°43'E	Landsat, ASTER, Worldview	2000 – 2015	-0.58 ± 0.19	King et al., 2017
10	Duwo	27°54'N	86°45'E	SRTM, SPOT5	1999 – 2011	-0.16 ± 0.26	Gardelle et al., 2013
11	Everest	27°59'N	86°55'E	Landsat, ASTER, Worldview	2000 – 2015	-0.52 ± 0.22	King et al., 2017
12	Kangwure	28°23'N	85°44'E	Field measurement	1975 – 2008	-0.20 ± 0.08	Ma et al., 2010
13	Khumbu	28°03'N	86°45'E	SRTM, SPOT5	1999 – 2011	-0.51 ± 0.19	Gardelle et al., 2013
14	Lhotse	27°57'N	86°56'E	SRTM, SPOT5	1999 – 2011	-0.43 ± 0.18	Gardelle et al., 2013
15	Lhotse Nup	27°57'N	86°54'E	SRTM, SPOT5	1999 – 2011	-0.21 ± 0.27	Gardelle et al., 2013
16	Lhotse Shar/Imja	27°56'N	86°57'E	SRTM, SPOT5	1999 – 2011	-0.70 ± 0.52	Gardelle et al., 2013
17	Nuptse	27°57'N	86°53'E	SRTM, SPOT5	1999 – 2011	-0.37 ± 0.20	Gardelle et al., 2013
18	Rikha Samba	28°43'N	83°32'E	Landsat ETM+	1974 – 2010	-0.46 ± 0.07	Bolch et al., 2012
19	Tama Koshi	27°56'N	86°26'E	Landsat, ASTER, Worldview	2000 – 2015	-0.51 ± 0.22	King et al., 2017
20	Upper Langtang	28°19'N	85°39'E	SRTM, Hexagon	1974 – 2000	-0.32 ± 0.18	Pellicciotti et al., 2015
21	Yala	28°24'N	85°15'E	Landsat	1983 – 2009	-0.58 ± 0.08	Bolch et al., 2012
					Mean	-0.40 ± 0.21	
West Himalaya							
22	Baspa Basin	31°21'N	78°21'E	Landsat	2000 – 2011	-1.09 ± 0.32	Kumar et al., 2017
23	Chhota Shigri	32°21'N	76°40'E	Field measurement	2002 – 2010	-0.67 ± 0.40	Azam et al., 2012
24	Chorabari	30°44'N	79°03'E	Landsat	2004 – 2007	-0.74	Bolch et al., 2012
25	Dokriani	31°01'N	79°27'E	Landsat	1992 – 2000	-0.32	Bolch et al., 2012
26	Dunagiri	30°35'N	79°52'E	Landsat	1984 – 1990	-1.73	Pellicciotti et al., 2015
27	Gara*	31°26'N	78°46'E	SSC model	1900 – 2010	+0.70 ± 0.41 ~ -1.10 ± 0.41	Gaddam et al., 2017
28	Gor-Garang*	31°38'N	78°48'E	SSC model	1900 – 2010	+1.50 ± 0.60 ~ -1.60 ± 0.60	Gaddam et al., 2017
29	Hamtah	32°16'N	77°21'E	Landsat	2001 – 2006	-1.60	Bolch et al., 2008
30	Kolahoi	34°08'N	75°19'E	Landsat	1984	-0.26	Bolch et al., 2012
31	Lahaul/Spiti*	32°35'N	77°22'E	SRTM, SPOT 5	1999 – 2004	-0.70 ~ -0.85	Berthier et al., 2007
32	Lidder Valley*	32°00'N	76°54'E	Landsat, ASTER	1980 – 2013	-0.77 ~ -0.16	Murtaza and Romshoo, 2017

33	Naradu*	31°41'N	77°52'E	SSC model	1900 – 2010	-0.2 ± 0.44 ~ -0.8 ± 0.44	Gaddam et al., 2017
34	Nehnar	32°33'N	77°08'E	Landsat	1975 – 1984	-0.54	Bolch et al., 2012
35	Shaune Garang*	32°11'N	77°22'E	SSC model	1900 – 2010	+0.80 ± 0.54 ~ -0.90 ± 0.54	Gaddam et al., 2017
36	Shishram	32°32'N	77°23'E	Landsat	1984	-0.29	Bolch et al., 2012
37	Siachen	35°25'N	77°04'E	Landsat, SRTM, Hexagon, Cartosat I, ASAR, ALOS PALSAR	1999 – 2007	-0.03 ± 0.21	Agarwal et al., 2016
38	Tipra Bank	30°40'N	79°43'E	Landsat	1981 – 1989	-0.29	Bolch et al., 2012
						Mean	-0.57 ± 0.17
<hr/>							
Karakoram							
39	Central Karakoram	35°56'N	75°29'E	SRTM, SPOT5	1999 – 2008	+0.11 ± 0.22	Gardelle et al., 2012
40	East Karakoram	35°28'N	77°30'E	SRTM, X-band SAR, InSAR	2000 – 2014	-0.10 ± 0.06	Lin et al., 2017
41	West Karakoram	36°24'N	73°36'E	SRTM, X-band SAR, InSAR	2000 – 2014	-0.02 ± 0.06	Lin et al., 2017
						Mean	-0.01 ± 0.11
						Overall mean	-0.31 ± 0.14

*Notes: The median of the mass balance range was taken into calculation, e.g. for Gara: $+0.70 \pm 0.41 \sim -1.10 \pm 0.41 = -0.04 \pm 0.41$

Table 1

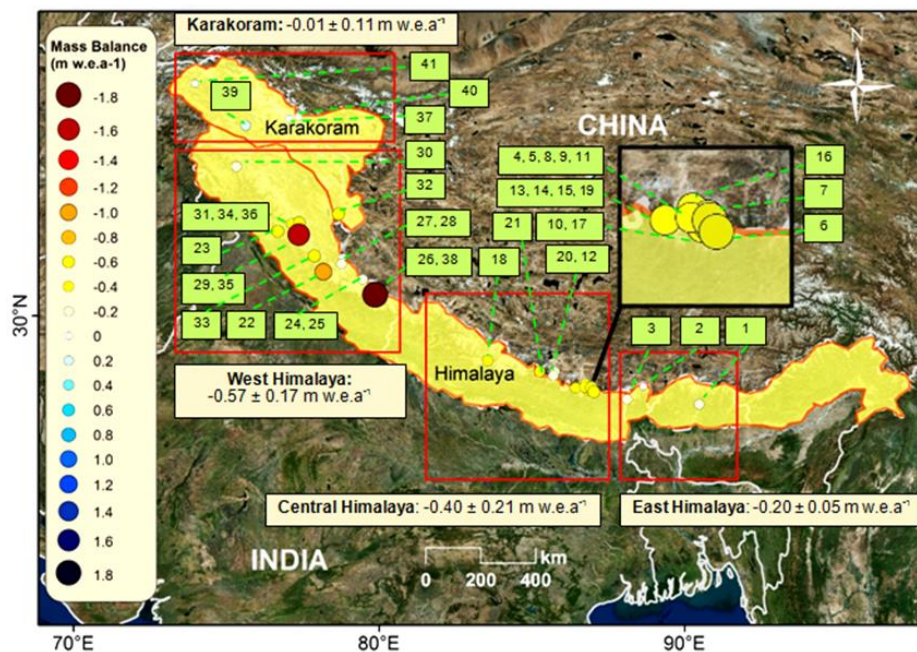


Figure 3. Mass balance of the Himalayan glaciers based on the data in Table 1.

Based on Table 1, a literature survey of 41 glaciers indicated that the average mass balance for the entire Himalaya-Karakoram region was -0.31 ± 0.14 w.e.a-1. About 95% of the glaciers experienced different degrees of mass loss, with the West Himalaya had the highest negative mass balance (-0.57 ± 0.17 m w.e.a-1), followed by the Central Himalaya (-0.40 ± 0.21 m w.e.a-1) and East Himalaya (-0.20 ± 0.05 m w.e.a-1).

Remote sensing technologies were used in around 90% of the research based on this literature study. Because of the scarcity of high-quality satellite imagery that meets their research aims, the remaining 10% of the studies relied on modelling and fieldwork instead of remote sensing approaches (Yeh et al., 2020). The frequent cloud cover and seasonal snows have a significant impact on image quality (Ronco and Michele, 2014). Inadequate and biased Himalayan glacier data has affected the accuracy of glacier information supplied to the public (Maurer et al., 2019). For example, some inaccurate glacier prediction claims in the 2007 Intergovernmental Panel on Climate Change (IPCC) report (Cogley et al., 2010) revealed a lack of reliable facts and scientific understanding in glacier research. Furthermore, the shortage of long-term and thorough studies on glacier changes has made it difficult to understand the recent pattern of glacier modification (Dyurgerov and Bahr, 1999). As a result, research activities in mountain glacier inventory are actively urged in order to assure high-quality and precise data for glacier preservation and assessment (Bolch et al., 2012).

In this study, we suggest that people should be aware of environmental issues and the melting mountain glaciers, mainly due to anthropogenic pressures on natural resources, such as environmental pollution due to construction (Ng and Yap, 2016). Additionally, the governments of the neighbouring nations and international environmental

organisations should play a substantial role in educating and informing the citizens about the effects of global warming and mountain glacier retreat driven by economic development are important, and economy, technology, social aspects, and governance are the potential factors that lead to a greener and smart-oriented nations (Cheng et al., 2022). Additional in-depth studies should be conducted to provide the general public more knowledge about global warming due to human activities

Conclusion

The purpose of this study is to assess the change in glacial mass balance of Himalayan glaciers using secondary data. According to regional mapping based on a review of literature, 95 percent of the glaciers surveyed suffered varied degrees of retreat between 1970 and 2017 result of a combination of natural and anthropogenic development processes. For future plan, there is a need for more long-term and comprehensive glacier recession information to enhance the accuracy of glacier impact assessment and greater efforts of different levels are also essential to prevent glaciers from further melting due to global warming.

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Conflict of interest

The author confirms that there is no conflict of interest with any parties involved with this study.

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