ASSESSING THE SUSTAINABILITY OF THE KIAU NULUH – GURKHA HUT TRAIL, KINABALU PARK, SABAH, MALAYSIA

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ABSTRACT

Recreation trails are essential for promoting outdoor activities, ecological awareness, and sustainable tourism. This study comprehensively analyses the 14.2km Kiau Nuluh—Gurkha Hut Trail, a proposed trail to be developed northwest of Kinabalu Park. This study aims to assess the trail's characteristics and its sustainability for future use. One hundred forty-two samples were collected at 100m intervals using point sampling methodology, revealing key trail characteristics and sustainability ratings. Findings indicate that the trail predominantly ascending (88%) with sections at higher elevations exhibited narrower tread widths, lesser incisions, steeper trail grades and narrow slope alignment than those at lower elevations. Nearly 90% of the trail is deemed unsustainable, with higher elevations showing escalating unsustainable ratings, highlighting the need for realignment and sustainable trail management strategies. Recommendations include trail realignment according to the acceptable sustainability ratings, realigning the trail to the "side hill" or adhering to the contour lines, and using durable tread materials as one of the erosion control measures. The findings of this study provide baseline information for the future sustainable trail management of the Kiau Nuluh - Gurkha Hut Trail. The insights gained from this research will aid in developing strategies to maintain and improve the trail, ensuring its enjoyment for present and future generations while conserving the natural environment.

Keywords: *Recreation Trail Assessment and Trail Sustainability Ratings*

INTRODUCTION

Kinabalu Park is Malaysia's crown jewel, a revered UNESCO World Heritage Site and Global Geopark sprawling across 754 square kilometers and managed by Sabah Parks. The park holds a profound cultural significance for the people of Sabah, notably the indigenous Dusun community, which has inhabited the area for generations. This natural wonderland boasts diverse flora and fauna, verdant rainforests, cascading waterfalls, and breathtaking geological formations. The park spans three Sabah districts and is anchored by one main station: Kinabalu Park's headquarters, along with several substations, including Poring Hots Spring, Mesilau, Panalaban, Sayap, Nalapak, Monggis, and Serinsim. The hub of tourism activities primarily revolves around Kinabalu Park headquarters and Poring, situated in the southern part of the park, within Kundasang and in Ranau district, Sabah, Malaysia. The main attraction of Kinabalu Park is Gunung Kinabalu (Mount Kinabalu), towering 4,095 meters above sea level. Kinabalu Park's headquarters and Mesilau Substation are the primary gateways to Gunung Kinabalu. Access to the summit is currently centered at the Summit Trail started from Timpohon Gate, located in Kinabalu Park's headquarters, as the Summit Trail, which started from Tambang Gate, Mesilau substation, is presently closed for reconstruction. The mountain, limited to 163 daily visitors, has seen an average of 42,095 climbers annually over the past 22 years (Appendix 1).

As the primary trail, the Summit Trail from Timpohon Gate is constructed to cater to heavy foot traffic frequented by visitors, guides, porters, and park rangers. In addition, it is equipped with clear signage, resting points, and necessary facilities along the route, and visitors are required to stay overnight at Panalaban Hostel before the final ascent. As per the Recreation Opportunity Spectrum, the Timpohon Trail can be categorized as a semi-modern outdoor zone that strikes a balance between natural beauty and human-made conveniences, providing a comfortable and accessible environment for visitors and requiring fewer outdoor skills (Stankey, 1998; Wynveen et al., 2020) but with considerable levels of fitness due to the steepness of the trail, with an elevation gain of approximately 2,254m and maximum trail grade of 58.5%.

Plans for the Kiau Nuluh—Gurkha Hut Trail, this study's study site, have been proposed to diversify visitor experiences and promote ecotourism in the park's northwest. This new trail starts from Kiau Nuluh, a village in Kota Belud District, about 21.6km from Kinabalu Park's headquarters. According to the locals, this newly planned trail is a heritage trail, having historically been used by the indigenous Dusun community in the upper area (called Hill Dusun) to connect to the shore area in the north. However, other historical usage of the trail is not comprehensively recorded other than the locals who used it for hunting in the old days and the scientific expedition held by the Sabah Parks in 1981, 1990, and recently, in October 2023. Due to its rugged landscape, the Kiau Nuluh – Gurkha Hut Trail offered an adventure trekking experience requiring moderate to advanced outdoor skills. Before it can be opened to the public, a thorough trail inventory is vital to assess the existing conditions of the trail to ensure its sustainability. Therefore, this study aims to assess the trail's characteristics and sustainability to provide an outlook on its future use. The end goal of this study is to provide recommendations for future development and management of the Kiau Nuluh - Gurkha Hut Trail, Kinabalu Park, Sabah, Malaysia.

Recreation trail inventory and factors contributing to trail impacts

Recreation trails provide designated routes for leisure activities like hiking, biking, or walking in natural environments. Typically found in parks and recreational areas, these trails offer visitors opportunities for exercise and immersion in nature while fostering awareness and appreciation of the natural world. Trails are vulnerable to various impacts since they are the most frequented feature in park and recreation areas. Therefore, the trails need regular monitoring to ensure their sustainable use and protection of natural resources. Trail inventory offers a detailed description of the trail, often carried out based on the variables that explain the condition of the trails (e.g., trail width, tread incision, and trail canopy covers) or the factors that contribute to the trail degradation, such as the trail grade, trail slope alignment (TSA) and the tread surface conditions (Marion & Leung, 2001; Marion & Wimpey, 2017; Wimpey & Marion, 2010). These variables can assist management in pinpointing areas damaged by recreational use or areas prone to degradation and provide valuable insights for conservation efforts.

The trail width refers to the segment of the trail corridor that bears the primary load of recreational traffic, encompassing areas with bare substrate, trampled vegetation, or organic debris (Wimpey & Marion, 2010). Another term equivalently used is tread width, an area located on the trail's centre, commonly narrower, typically comprising exposed bare substrate or the flatter base of eroded trails (Wimpey & Marion, 2010). In a recreation trail, the width holds significant ecological implications. A trail twice as wide as necessary doubles the area subject to intensive trampling impacts (Wimpey & Marion, 2010). Moreover, excessive trail widths can lead to increased water runoff and erosion, habitat fragmentation, and the exposure of trail corridors to the sun, contributing to the growth of shade-intolerant native and non-native species (Kim et al., 2003). According to Hill and Pickering (2009), a trail with a width greater than 3m can be considered severely damaged. However, the optimum width of a trail should consider the intended use of the trail, especially at Kinabalu Park, where it is heavily used by various types of users, including porters, to carry the essentials and equipment for the use of tourism services such as the Panalaban Hostel. Tread incision refers to the depth of the trail that provides information on soil loss. The deeper the trail, the more soil has been lost on the trail surface, contributing to gully surface formation and tree root exposure. According to Hill and Pickering (2009), a tread incision exceeding 45cm indicates that the trail has been severely damaged. Canopy covers refer to the percentage of the forest canopy's covered trail area. Canopy covers can significantly affect recreation trail degradation, influencing soil erosion, vegetation growth, and overall trail conditions. Trees and vegetation can help stabilize soil, reduce erosion, and provide shade, improving trail conditions and user experience.

Regarding the factors contributing to trail degradation, improper trail construction exacerbates trail degradation. Recent research highlights that the trail grade (Meadema et al., 2020; Tomczyk et al., 2017) and trail slope alignment (TSA) (Marion & Wimpey, 2017) are the key factors contributing to trail degradation. Trail grade and TSA contribute to soil loss that helps the creation of gullies and exposed roots, while tread substrate such as organic soil contributes to muddy conditions on flat terrain along the trail (Marion & Wimpey, 2007; Olive & Marion, 2009; Wimpey & Marion, 2010). Moreover, eroded soil may accumulate on flat surfaces, leading to muddy terrain. These impacts contribute to a significant cumulative loss of vegetation (Ballantyne & Pickering, 2015; Pickering & Norman, 2017), mar the pristine landscape, diminish their aesthetic appeal, detract visitors from satisfaction in their activities and give rise to safety and legal concerns (D'Antonio et al., 2012; Marion & Leung, 2001; Peterson et al., 2018; Rodway-Dyer & Ellis, 2018; Verlič et al., 2015).

A steeper trail grade increases water velocity and heightens erosion risk. Guidelines and studies suggest that trail grades exceeding certain thresholds—such as 10% (Dissmeyer & Foster, 1980; Hooper, 1988), 11% (Olive & Marion, 2009), or 12% (Agate, 1996)—are prone to erosion. Trails with lower TSA (0-22^0), indicating poor alignment relative to landform contours, are particularly vulnerable to erosion (Wimpey & Marion, 2010; Wimpey & Marion, 2017). Trails constructed with low TSA pose challenges for installing drainage features, rendering them ineffective in diverting water from treads (Wimpey & Marion, 2010; Wimpey & Marion, 2017). Moreover, fall-aligned trails lack resistance to lateral visitor traffic, often leading to trail widening issues (Wimpey & Marion, 2017). According to the trail sustainability rating devised by Wimpey and Marion (2017), trails with a grade between 20% and TSA between 0 to 30 degrees should be avoided as such conditions would increase trail degradation. Olive and Marion (2009) also discovered that valley trails suffered significantly more erosion than those on mid-slopes and ridges, likely due to the trails in valley areas prone to periodic flooding, which erodes the trail surface, and are situated in lower watershed areas with higher water runoff volumes and rates. They suggest avoiding trail placement in floodplains altogether. For trails located in valleys, they propose positioning them above flood levels and designing them with side-hill alignments to improve water drainage. In a recent publication, Marion (2023) reviewed sustainable trail development and provided comprehensive information on the threshold for trail grade, TSA, and other important variables, such as tread surface conditions. Regarding the TSA and trail grade, a trail is proposed to be constructed based on the thresholds cited in Table 1.

Table 1. Trail sustainability ratings

TSA	Trail Grade			
	0-2%	3-10%	11-20%	>20%
0-30^0	3	5	7	7
31 – 60^0	3	1	5	6
61 – 90^0	3	1	5	6

Note. The colored area and number refer to the sustainability rating.

1 refers to High Sustainability. It characterizes an optimal trail grade and TSA of a highly sustainable trail that promotes quickly drained treads.

3 refers to Low Sustainability. It characterizes the trails as less susceptible to erosion but prone to muddiness and widening on a flatter surface.

5 refers to Moderately Unsustainable. It characterizes the two trail conditions. The first is the trails with TSA between 0 to 30^0 and trail grade 3-10%; they are difficult to drain and prone to soil loss and widening. The second is the trails with TSA above 30^0 and trail grade above 11-20%; they are susceptible to soil loss.

6 is the area not coded by Marion (2023). However, given the characteristics of the trails, the impacts should be between rating 5 and 7. In this study, this area is referred to as Unsustainable.

7 refers to Highly Unsustainable. Trails with TSA between 0 to 30^0 and trail grade above 10% are rugged to drain and highly susceptible to soil loss and widening. Trails with TSA between 0 to 30^0 and trail grade above 20% are highly susceptible to soil loss.

Source: Marrion (2023)

Another critical factor for trail sustainability is the tread surface (Marion, 2023). Sandy soils drain well but are easily displaced, while clay and silty soils resist water infiltration, increasing runoff and erosion (Parker, 2004. Loam soils offer an optimal mix of particle sizes, promoting drainage, structure, and binding (Marion, 2023). Organic soils, rich in decayed plant matter, erode quickly, retain water, and lead to muddy surfaces (Marion, 2023). Muddy surfaces are susceptible to impacts and often lead to trail widening as users (visitors) tend to avoid the muddy area and walk on the trail edge, which leads to the expansion of the trail width. In addition, studies show more significant soil loss on homogeneous clay soils compared to loams (Marion, 2023), and several studies indicate that the composition of angular rocks or crushed stone in substrates is more influential in influencing trail sustainability than soil texture differences (Meadema et al., 2020; Olive & Marion, 2009). For example, Olive and Marion

(2009) concluded that crushed stone significantly deterred soil loss on grades up to 12%, and heavily graveled trails substantially reduced soil loss on much steeper grades.

METHODOLOGY

Study area

The study took place on the newly proposed Kiau Nuluh - Gurkha Hut Trail, as depicted in Figure 1. This trail originates from Kiau Nuluh, a village situated in the western region of the park, in the Kota Belud District, approximately 21.6km from Kinabalu Park's headquarters. The trail began at 979m asl and traversed into various forest types, including upper dipterocarp forest (750 – 1,200m asl), montane forest (1,200 – 1,500m asl), montane-ericaceous forest (1,500 – 2,700m asl), ultramafic rock forest (2,700 – 3,000m asl), and ended at Gurkha Hut, an area in the granite rock forest (3,800m asl) and alpine forest (3,800 – 4,095m asl) region.

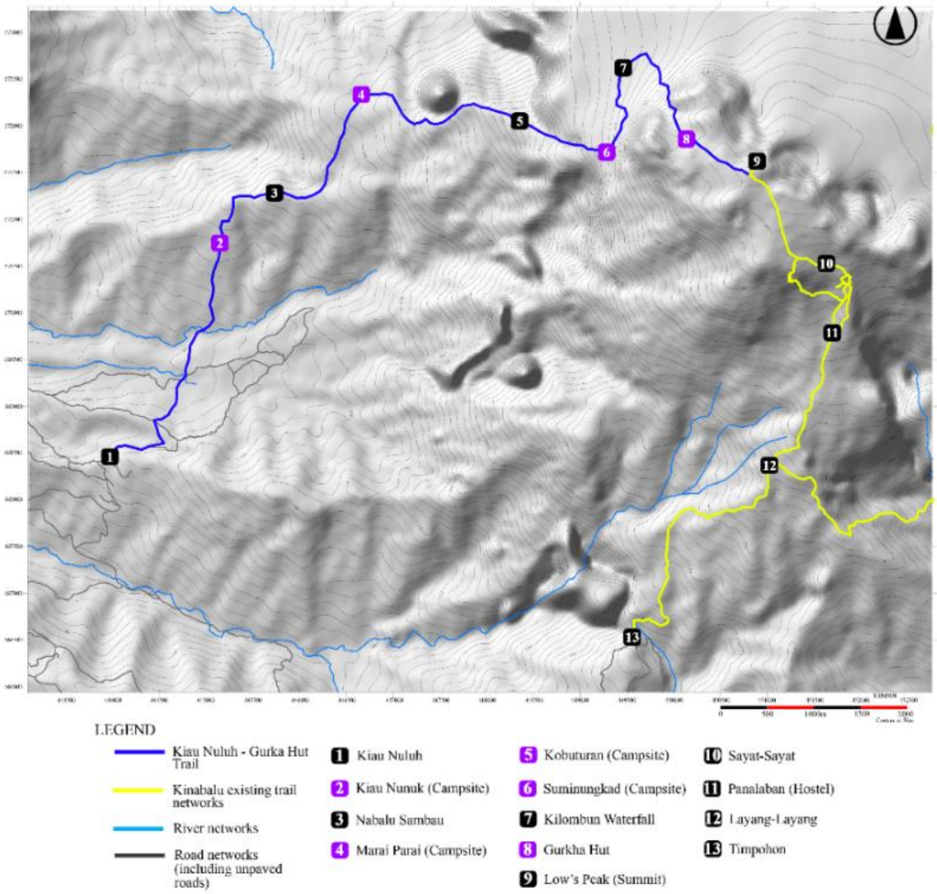

Figure 1. Route of the Kiau Nuluh – Gurka Hut Trail, Kinabalu Park.

The trail boasts several points of interest (POIs), as outlined in Table 2. Beginning at Kiau Nuluh, the trail traverses north, along the rural landscape to Nunuk Camp (1,206m asl), situated approximately 3.5km from the trailhead. Kiau Nunuk is a campsite constructed with several dorm-like accommodations, a communal area, a kitchen, and toilets that can accommodate about 60 people at one time. It is named after the *Ficus* sp. tree or Nunuk in the Dusun language and managed by the residents of Kg. Kiau Nuluh. Continuing up to 1.2km from the Nunuk

Camp is a community forest managed by the local community, and the area after that is marked as Kinabalu Park.

Continuing from the Kinabalu Park's border, the trail passes through a slightly narrow mountain pass to a place called Nabalu Sambau (1,470m asl) before traversing downhill and crossing over to the Marai Parai ridge located next to the Nabalu Sambau ridge. Marai Parai (1,669m asl), approximately 7km from the trailhead, features an open, slightly flat, muddy plain covered with sedges, shrubs, and pitcher plants. The terrain gradually steepens from Marai Parai to Suminungkad (3,072m asl), roughly 11.2km from the trailhead, located at the foot of Alexandra Wall, a prominent wall at the western peak of Gunung Kinabalu. The trail from Suminungkad to Gurkha Hut traveled to the west and perched on the Alexandra Wall ledge; from there, the landscape transitions from an ultramafic rock forest to an alpine forest. The trail crosses Kilombun Waterfall and enters the wall of Diwali Gorge en route to Gurkha Hut. The surveyed area concluded at Gurkha Hut, approximately 14.2km from Kg. Kiau Nuluh. Gurkha Hut (3,846m asl), erected by the Gurkha Army in 1981, lies in proximity to Oyayubi Iwu Peak, about 1.08km from Low's Peak (4,095 m asl), Gunung Kinabalu's highest peak.

Table 2. The cluster of points of interest in the study

POIs	Distance from trailhead (km)	Elevation (m asl)
Kg. Kiau Nuluh (Trailhead)	0	976
Nunuk Camp	3.5	1,206
Nabalu Sambau	5.1	1,470
Marai Parai	7.0	1,669
Suminungkad	11.2	3,072
Gurka Hut	14.2	3,846

Sampling, variables, measurements, and analysis

The point sampling employed with an interval of 100m in this study was adopted from Ballantyne and Pickering (2015). A total of 142 sampling points were established along the 14.2km trail. At each sampling point, a transect was established perpendicular to the trail tread, i.e., the area that has the most trampling effect characterized by the changes in vegetation height or when the vegetation cover is absent due to the disturbance to organic litter on the tread surface (Wimpey & Marion, 2010). The interval of each sampling point was determined via the 50m rope, and the area for sampling was marked at a 100m distance. The data was recorded via a rapid assessment protocol (Marion et al., 2006; Marion & Leung, 2011). Although the data via the point sampling method was usually recorded at a randomized start (Marion & Olive, 2009; Marion & Wimpey, 2017), however in this study, the data was recorded at the start of the trail since the study was designed to describe the characteristics of the trail that will be opened in the future. The variables used were based on the study by Wimpey and Marion (2010), as depicted in Table 3. Data was recorded using a standardized form, and the coordinates of each sampling point were recorded using GPS (GPS Garmin 64s). Spatial data were transferred from GPS into the Surfer 16 application from Global Mapper. Statistical data were transferred to Microsoft Excel and the statistical system SPSS 29 for further analysis. Data were analyzed using descriptive statistics, cross tab, and Welch F to describe the newly planned trail and to determine the area for improvement. The potential areas for impacts were determined based on the findings of Wimpey and Marion (2017).

Table 3. Variables used in the trail inventory.

Variables	Description	Variable type	Measurement
Tread width	The tread width is defined as the distance between disturbance-associated boundaries on the trail (Wimpey & Marion, 2010).	Continuous Condition class rating class (CCR): <250cm, 250 – 300cm, and >300cm. Categorical: 0-61cm, >61-92cm, >92-122cm, >122-152cm, >152cm and no indication of tread width.	The measurement was made using pocket measurement tape at the disturbance-associated boundaries on the trail. Tread width was then grouped based on two categories; CCR based Hill and Pickering (2009) and category based on Svajda et al. (2016).
Tread incision	The tread incision is defined as the vertical depth of the tread disturbance-associated boundaries on the trail (Svajda et al., 2016).	Continuous Condition class rating class: 0, >0-5cm, >5-30cm, >30-45cm and >45cm. Categorical: 0cm, >0-1.3cm, >1.3-2.5cm, >2.5-7.6cm, >7.6-12.7cm, >12.7cm and rocks.	Pocket measurement tape was placed horizontally on the tread boundary. Another pocket measurement tape was used to measure the vertical depth of the tread at five equally spaced points across the tread surface. The tread incision was calculated based on the average of the five equally spaced points. Tread incision was then grouped based on two categories; CCR based Hill and Pickering (2009) and category based on Svajda et al. (2016).
Soil compaction	Soil compaction refers to the level of compaction of the tread.	Continuous Categorical: 0-1.3kg/cm^2, >1.3-2.6kg/cm^2, and >2.6kg/cm^2.	Soil compaction was measured using a pocket penetrometer with a maximum capacity of 4kg/cm^2 at five equally spaced points across the trail surface (Ballantyne & Pickering, 2015). The soil compaction was then grouped based on equally spaced category.
Trail grade	Trail grade refers to the trail's slope measured in a fixed distance.	Continuous Categorical: 0-2%, >2-6%, >6-10%, >10-15%, >15-20%, >20-30%, and >30%.	The trail grade was determined via the clinometer measured in percentage by aligning the top of two poles of equal height 1.5m on either side of the survey point (Ballentyne & Pickering, 2015). The trail grade was then grouped based on the category adopted from Svajda et al. (2016).
TSA	TSA refers to the difference in compass bearing between the prevailing landform slope (aspect) and the trail's alignment angle at the sample point.	Continuous Categorical: 0-22^0, >22-45^0, >45-68^0, and >68 – 90^0.	Trail slope alignment refers to the minimal difference in bearings between the trail's alignment and the orientation of the predominant landform, falling within the range of 0° to 90°. Measurement of TSA was based on Wimpey and Marion

			(2017). TSA was then grouped based on the category adopted from Svajda et al. (2016).
Tread surface composition	Tread surface composition refers to the percentage of the tread width transect by tread surface categories.	Categorical: Bare soil, vegetation, organic litter, roots, rock, and muddy soil.	This variable was measured as a proportion of a linear transect oriented perpendicular to the trail at each sample point. For each category, the percentage of trail width was recorded to the nearest 5% (Wimpey & Marion, 2010). The following are the details of each category: i. Bare soil (%): Bare soil of all types except rocks and organic litter. ii. Organic litter (%): Organic litter and duff sufficient to cover the tread surface. iii. Roots (%): Exposed tree or shrub root. iv. Rocks (%): Naturally occurring rock surface (bedrock, rock, or gravel). v. Vegetation (%): Vegetation cover rooted within the tread boundary. Muddy soil (%): Seasonal or permanently wet and muddy soil.
Canopy cover	A visual estimation in each sampling point of the percentage canopy cover.	Categorical: 0% - 5%, 6% - 25%, 26% - 50%, 51% - 75%, 75% - 95%, and 95% - 100%.	Estimates were recorded as categories to the nearest 5%

RESULT

Trail description

The trail sections from Kiau Nuluh to Gurkha Hut covered 14.5 km distance, with 88% of the route ascending and 12% descending (Table 4). The tread width ranged from 15 to 353.1 cm, and the tread incision varied from 0 to 18.6 cm. The average width and incision of the whole section of the trail were 72.9 cm and 3.4 cm, respectively. The trail grade ranged from 0 to 180%, averaging 37.4%. The trail's TSA varied from 0 to 88 degrees, averaging 34.9 degrees. Soil compaction ranged between 0.45 and 2.2 kg/cm^2, with an average of 1.2 kg/cm^2.

Moving on to specific sections, Kiau Nuluh to Nunuk Camp spanned 3.5 km, with 68.7% ascending and 31.4% descending. The tread width varied from 40.6 to 353.1 cm, averaging 84.3 cm. The tread incision ranged from 0.20 to 8.9 cm, averaging 2.6 cm. The trail grade ranged from 0 to 55%, and TSA from 0 to 88 degrees. The average slope and TSA for this section of the trail were 25.1% and 36.5 degrees, respectively. Soil compaction ranged from 0.45 to 2.0 kg/cm^2, averaging 1.4 kg/cm^2. Nunuk Camp to Marai Parai covered 3.5 km, with 85.7% of the trail ascending and 14.3% descending. The tread width ranged from 45.7 to 182.9 cm, averaging 111.3 cm. The tread incision ranged from 0.6 to 18.6 cm. Slope varied from 0 to 78%, and TSA from 0 to 88 degrees, and the average slope and TSA were 31.6% and 35.5 degrees. Soil compaction ranged from 0.5 to 1.7 kg/cm^2, with an average of 1.1 kg/cm^2.

Marai Parai to Suminungkad was 4.2 km long, and 100% of this section ascended. The tread width ranged from 15 to 100 cm, with a tread incision of 0 to 4.0 cm. This section's average tread width and tread incision were 45.3 cm and 1.4 cm. Trail grades ranged from 3 to 103%, averaging 44.3%. TSA ranged from 0 to 86 degrees, with an average slope of 32.1 degrees. Soil compaction ranged from 0 to 1.8 kg/cm^2, averaging 1 kg/cm^2. Lastly, Suminungkad to Gurkha Hut covered 3.0 km, with a tread width ranging from 20 to 50 cm and an average of 30.9 cm. The tread incision was recorded at 0 to 3.2 cm, with an average of 1 cm. Slope varied from 5 to 180%, and TSA from 0 to 88 degrees, with average slope and TSA were 48.9% and 32.3 degrees. Soil compaction ranged from 1.7 to 2.2 kg/cm^2, with an average of 1.9 kg/cm^2. 96.7% of this section was ascending, with 3.3% descending.

Table 4. Descriptive statistics of the variables used to describe the trail characteristics

Trail section	Distance (km)	Direction	Tread width (cm)			Tread incision (cm)			Trail grade			TSA (degree)			Soil compaction (kg/cm²)		
			Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Kiau Nuluh – Gurkha Hut (The entire trail:14.2km)[1]	14.5	88% ascending 12% descending	15.0	353.1	72.3	.0	18.6	3.4	.0	180	37.4	.00	88	34.9	.45	2.2	1.2
Kiau Nuluh to Nunuk Camp section[2]	3.5	68.6% ascending 31.4% descending	40.6	353.1	84.3	.2	8.9	2.6	.0	55	25.1	0	88	36.5	.4	2	1.4
Nunuk Camp – Marai Parai section[3]	3.5	85.7% ascending 14.3% descending	45.7	182.9	111.3	.6	18.6	6.5	.0	78	31.6	0	88	35.5	.5	1.7	1.1
Marai Parai – Suminungkad section[4]	4.2	100% ascending	15	100	45.3	.0	4.0	1.4	3	103	44.3	0	86	32.1	.0	1.8	1.0
Suminungkad – Gurkha Hut section[5]	3.0	96.7% ascending 3.3% descending	20	50	30.9	.0	3.2	1.0	5	180	48.9	0	86	32.3	1.7	2.2	1.9

Note: [1] Tread width (n=126), Tread incision (n=113), Trail grade (n=142), TSA (n=142), and Soil compaction (n=112)
[2] Tread width (n=35), Tread incision (n=35), Trail grade (n=35), TSA (n=35), and Soil compaction (n=35)
[3] Tread width (n=35), Tread Incision (n=35), Trail grade (n=35), TSA (n=35), and Soil compaction (n=35)
[4] Tread width (n=42), Tread incision (n=37), Trail grade (n=42), TSA (n=42), and Soil compaction (n=37)
[5] Tread width (n=14), Tread incision (n=6), Trail grade (n=30), TSA (n=30), and Soil compaction (n=5)

The findings revealed that approximately 59.2% or 8.4km of the Kiau Nuluh – Gurkha Hut trail lay below 2000m above sea level (asl), while 20.4% or 2.9km of the route extended beyond 3000m asl. Analysis of tread width indicated that 55.6% fell within the 0-61cm category, with 54.9% of tread incisions measuring between 2.5cm and 12.7cm. Regarding TSA, the trail primarily featured slope alignments between 0-22 degrees (52.8%). The trail grade distribution indicated that 57.7% of the trail had grades between 31-100% and 15.5% between 21-30%. The predominant surface types along the 14.2km trail were organic litter (32.4%) and bare soil (31.7%), with rocks comprising 21.1% of the trail surface. Canopy cover mainly fell within the 0-5% and 25-50% categories, accounting for 35.2% and 33.8%, respectively. Soil compaction predominantly ranged from 0 - 1.3kg/cm^2 (50.7%), >1.3 – 2.6 kg/cm^2 (25.4%), and >2.6kg/cm2 (2.8%).

In the section from Kiau Nuluh to Nunuk Camp, 57.1% or around 2km out of 3.5km, this trail section was situated below 1000m asl. Tread width analysis indicated widths of 0-61cm (60%) and 93-122cm (28.6%), while tread incision predominantly fell within 0.0-1.3 cm (37.1%) and 2.5-7.6cm (31.4%). Slope alignment primarily ranged between 0-22 degrees (57.1%), and trail grades mainly were between 31-100% (42.9%) and 0-15% (34.3%). Bare soil constituted the primary surface type (85.7%), with canopy cover mainly falling within 25-50% and 76-95% categories, accounting for 37.1% and 40% of the trail section. Soil compaction ranged from 0-2.6kg/cm^2 (91.4%). From Nunuk Camp to Marai Parai, 74.3% or 2.6km of the 3.5km trail segment spanned 1000 to 1500m asl. Tread width varied between 123-152cm (34.3%) and 61-122cm (40%), with tread incisions mostly ranging between 2.5 – 7.6cm (42.9%). Slope alignment primarily occurred between 0-22 degrees (57.1%) and 68-90 degrees (34.3%), with trail grades predominantly between 21-30% (31.4%) and 31-100% (45.7%). Soil compaction was mainly within the 0-1.3kg/cm^2 (85.7%).

The section from Marai Parai to Suminungkad encompassed elevations ranging from 1500 to 3000m asl. Tread width predominantly fell within 0-61 cm (92.9%), with tread incisions mainly ranging from 13-2.5cm (35.7%) to 2.5 - 7.6cm (26.2%). Slope alignment was primarily between 0-22 degrees (50%) and 23-45 degrees (21.4%), with trail grades mostly between 31-100% (71.4%). Organic litter constituted the primary surface type (73.8%), and canopy cover ranged mainly within 25-50% (52.4%). Soil compaction mostly fell within the range of 0 – 1.3kg/cm^2 (71.4%). The final section, from Suminungkad to Gurka Hut, this trail section mainly traverses between 3000 to 3500m asl (66.7%). The tread width was indistinct due to rocky surfaces, with 53.3% of the section having no clear tread width. The incision was minimal, with 80% of this section displaying no incision. Slope alignment primarily ranged between 0 – 22 degrees (46.7%) and 68 – 90 degrees (30%), with a notable proportion between 23 – 45 degrees (16.67%). Trail grades predominantly fell within 31-100% (70%), with 83.3% comprising rock surfaces. Soil compaction ranged from 1.3- 2.6kg/cm^2 (16.7%) in areas where it could be measured.

Table 5. Detailed description of the Kiau Nuluh – Gurka Hut Trail and its trail sections

Variables	Kiau Nuluh – Gurkha Hut (The entire trail, n=142)	Kiau Nuluh to Nunuk Camp (n=35)	Nunuk Camp – Marai Parai (n=35)	Marai Parai – Suminungkad (n=42)	Suminungkad – Gurkha Hut (n=30)
Tread width based on CCR (cm)	Freq (%)	Freq (%)	Freq (%)	Freq (%)	Freq (%)
<250 (Lightly damaged)	125 (88)	34 (97.1)	35 (100)	42 (100)	14 (46.7)
>250-300 (Moderately damaged)	-	-	-	-	-
>300 (Highly damaged)	1 (.7)	1 (2.9)	-	-	-
No clear width (rocks formation)	16 (11.3)	-	-	-	16 (53.3)
Tread width (cm)					
0 - 61	79 (55.6)	21 (60)	5 (14.3)	39 (92.9)	14 (46.7)
>61 - 92	10 (7)	1 (2.9)	7 (20)	2 (4.8)	-
>92 - 122	17 (12)	10 (28.6)	7 (20)	-	-
>122 - 152	13 (9.2)	-	12 (34.3)	1 (2.4)	-
> 152	7 (4.9)	3 (8.6)	4 (11.4)	-	-
No clear width (rocks formation)	16 (11.3)	-	-	-	16 (53.3)
Tread incision based on CCR (cm)					
0 (Minimal damaged)	8 (5.6)	-	-	5 (11.9)	3 (10)
>0 – 5 (Lightly damaged)	98 (69)	30 (85.7)	34 (97.1)	32 (76.2)	2 (6.7)
>5 – 30 (Moderately damaged)	6 (4.2)	5 (14.3)	1 (2.9)	-	-
>30 – 45 (Highly damaged)	-	-	-	-	-
>45 (Severely damaged)	-	-	-	-	-
Rocks	30 (21.1)	-	-	5 (11.9)	25 (83.3)
Tread incision (cm)					
0	9 (6.3)	1 (2.9)	-	5 (11.9)	3 (10)
>0 - 1.3	30 (21.1)	13 (37.1)	2 (5.7)	15 (35.7)	-
>1.3 - 2.5	25 (17.6)	7 (20)	6 (17.1)	11 (26.2)	1 (3.3)
>2.5 - 7.6	33 (23.2)	11 (31.4)	15 (42.9)	6 (14.3)	1 (3.3)
>7.6 - 12.7	12 (8.5)	3 (8.6)	9 (25.7)	-	-
> 12.7	3 (2.1)	-	3 (8.6)	-	-
Rocks	30 (21.1)	-	-	5 (11.9)	25 (83.3)
TSA (degree)					
0 - 22	75 (52.8)	20 (57.1)	20 (57.1)	21 (50)	14 (46.7)
>22 - 45	16 (11.3)	1 (2.9)	1 (2.9)	9 (21.4)	5 (16.67)
>45 - 68	10 (7)	1 (2.9)	2 (5.7)	5 (11.9)	2 (6.7)
>68 - 90	41 (28.9)	13 (37.1)	12 (34.3)	7 (16.7)	9 (30)
Tread surface condition	Freq (%)	Freq (%)	Freq (%)	Freq (%)	Freq (%)
Bare soil	45 (31.7)	30 (85.7)	10 (28.6)	2 (4.8)	3 (10)
Organic litter	46 (32.4)	1 (2.9)	12 (34.3)	31 (73.8)	2 (6.7)
Roots	6 (4.2)	2 (5.7)	3 (8.6)	1 (2.4)	-
Rocks	30 (21.1)	-	-	5 (11.9)	25 (83.3)
Muddy soil	15 (10.6)	2 (5.7)	10 (28.6)	3 (7.1)	-
Trail grade (%)					
0-2	6 (4.2)	5 (14.3)	1 (2.9)	-	-
>2-6	9 (6.3)	5 (14.3)	1 (2.9)	1 (2.4)	2 (6.7)
>6-10	8 (5.6)	-	5 (14.3)	2 (4.8)	1 (3.3)
>10-15	6 (4.2)	2 (5.7)	-	3 (7.1)	1 (3.3)
>15-20	9 (6.3)	5 (14.3)	1 (2.9)	2 (4.8)	1 (3.3)

>20-30	22 (15.5)	3 (8.6)	11 (31.4)	4 (9.5)	4 (13.3)
>30 and above	82 (57.7)	15 (42.9)	16 (45.7)	30 (71.4)	21 (70)
Canopy cover (%)					
0-5	50 (35.2)	8 (22.9)	6 (17.1)	8 (19)	28 (93.3)
5-25	22 (15.5)	-	9 (25.7)	12 (28.6)	1 (3.3)
25-50	48 (33.8)	13 (37.1)	12 (34.3)	22 (52.4)	1 (3.3)
75-95	22 (15.5)	14 (40)	8 (22.9)	-	-
95 -100	-	-	-	-	-
Soil compaction (kg/cm^2)					
>0-1.3	72 (50.7)	12 (34.3)	30 (85.7)	30 (71.4)	-
>1.3-2.6	36 (25.4)	20 (57.1)	5 (14.3)	6 (14.3)	5 (16.7)
>2.6	4 (2.8)	3 (8.6)	-	1 (2.4)	-
Rocks	30 (21.1)	-	-	5 (11.9)	25 (83.3)
Elevation (m asl)					
<1000	20 (14.1)	20 (57.1)	-	-	-
1000-1500	41 (28.9)	15 (42.9)	26 (74.3%)	-	-
1500-2000	23 (16.2)	-	9 (25.7)	14 (33.3%)	-
2000-2500	16 (11.3)	-	-	16 (38.1)	-
2500-3000	13 (9.2)	-	-	12 (28.6)	1 (3.3%_
3000-3500	20 (14.1)	-	-	-	20 (66.7%)
>3500	9 (6.3)	-	-	-	9 (30%)

Comparison analysis of each trail section

The comparative analysis unveiled significant variations in tread width, tread incision, trail grade, and soil compaction among the four trail sections (Table 6). Notably, the average tread width exhibited a considerable difference, as evidenced by *Welch's F* (3, 61.52) = 54.22, $p < .000$, $\omega^2 = .38$. The trend indicated that trail sections below 1600m asl boasted a higher average tread width (Nunuk Camp – Marai Parai: 111.3cm and Kiau Nuluh – Nunuk Camp: 84.3cm) compared to those above 1700m asl (Marai Parai – Suminungkad: 45.3cm and Suminungkad – Gurka Hut: 30.9cm). Similarly, tread incision showed significant differences across the four sections, illustrated by *Welch's F* (3, 23.14) = 13.51, $p < .000$, $\omega^2 = .33$. Consistent with tread width, trail sections below 1600m asl exhibited a higher average incision (Nunuk Camp – Marai Parai: 6.5cm and Kiau Nuluh – Nunuk Camp: 2.6cm) compared to those above 1,600m asl (Marai Parai – Suminungkad: 1.4cm and Suminungkad – Gurka Hut: 1.0cm).

Trail grades also demonstrated significant discrepancies across sections, indicated by *Welch's F* (3, 73.3) = 6.69, $p < .000$, $\omega^2 = .10$. Particularly, sections above 1600m asl exhibited higher trail grades (Suminungkad – Gurka Hut: trail grade of 48.9% and Marai Parai – Suminungkad: trail grade 44.3%) compared to those below 1600m asl (Nunuk Camp – Marai Parai: trail grade 31.6% and Kiau Nuluh – Nunuk Camp: trail grade of 25.1%). However, the analysis of the TSA indicated no significant slope alignment differences among the four trail sections, suggesting a consistent TSA distribution. The comparison of soil compaction levels across sections revealed significant distinctions, as evidenced by *Welch's F* (3, 19.49) = 24.45, $p < .000$, $\omega^2 = .33$. Particularly noteworthy was the significantly higher average soil compaction of the trail from Suminungkad to Gurkha Hut (1.9 kg/cm^2) compared to other sections. Additionally, the trail from Kiau Nuluh exhibited more compacted soil (1.4 kg/cm^2) than the trail from Nunuk Camp to Marai Parai (1.1 kg/cm^2) and Marai Parai to Suminungkad (1.0 kg/cm^2). The omega square (ω^2) ranged from .10 to .38, indicating a large difference in tread width, tread incision, trail grade, and soil compaction among the four trail sections according to Field's (2013) interpretation.

Table 6. Comparison analysis of each section of the trail

Variables	Trail sections				*Welch F*	ω^2
	1	2	3	4		
	Mean	Mean	Mean	Mean		
Tread width (cm)	84.3	111.3	45.3	30.9	54.22* $^{a, b, c, d, e}$	.38
Tread incision (cm)	2.6	6.5	1.4	1.0	13.51* $^{a, d, e,}$	.33
Trail grade (%)	25.1	31.6	44.3	48.9	6.69 *$^{b, c}$	.10
TSA (degree)	36.5	35.5	32.1	32.3	0.21	-.02
Soil compaction (kg/cm^2)	1.4	1.1	1.0	1.9	24.45*$^{a, b, c, e, f}$	.33

Note. Trail sections: 1 (Kiau Nuluh - Nunuk Camp section, n=35), 2 (Nunuk Camp – Marai Parai section, n=35), 3 (Marai Parai – Suminungkad section, n=42), and 4 (Suminungkad – Gurkha Hut section, n=14
*$p < .000$
Trail width: df= 3, 61.52, Incision: df=3, 23.14, Trail grade= 3, 73.3 and Compaction: df=3, 19.49
Like superscripts indicate significant difference: a= Significant between 1 and 2, b= Significant between 1 and 3, c=Significant between 1 and 4, d=Significant between 2 and 3, e=Significant between 2 and 4, f=Significant between 3 and 4.

Regarding the tread surface condition, the surfaces were categorized into four groups: bare soil and roots, organic litter, muddy soils, and rocks. Analysis using the Likelihood Ratio test revealed a significant association between the types of tread surface conditions across the four trail sections, indicated by $G^2 = 162.53$, $p < .00$ (Table 7). Nevertheless, the Suminungkad –

Gurkha Hut section exhibited a higher prevalence of rock surfaces than the others. Similarly, examination through the Chi-square test demonstrated a moderate and significant association between the canopy cover categories across the four trail sections, with X^2 = 90.54, p< .00 (Table 8). However, the data trends in Table 8 revealed that the sections along the Suminungkad – Gurkha Hut trail were characterized by more open canopy cover than the other trail sections.

Table 7. Likelihood Ratio test for the tread surface condition of the four trail sections

Trail sections	Tread surface condition				Likelihood Ratio	Cramer's V
	Bare soil and roots	Organic litter	Muddy soil	Rocks		
Kiau Nuluh – Nunuk Camp	32	1	2	0	162.53**	.63[a]
Nunuk Camp – Marai Parai	13	12	10	0		
Marai Parai - Suminungkad	3	31	3	5		
Suminungkad – Gurkha Hut	3	2	0	25		

Note. **indicates p<.00
[a] indicates approximate p<.00
4 cells (25%) have expected count less than 5. The minimum expected count is 3.17.
df=9

Table 8. Chi-square test for the canopy covers of the four trail sections

Trail section	Canopy cover				Chi-square test	Cramer's V
	0-5%	5-25%	25-50%	75-95%		
Kiau Nuluh – Nunuk Camp	8	0	13	14	90.54**	.46[a]
Nunuk Camp – Marai Parai	6	9	12	8		
Marai Parai - Suminungkad	8	12	2	0		
Suminungkad – Gurkha Hut	28	1	1	0		

Note. **indicates p<.00.
[a] indicates approximate p<.00.
2 cells (12.5%) have expected count less than 5. The minimum expected count is 4.65.
df=9

Kiau Nuluh – Gurkha Hut Trail Sustainability Ratings

The trail's sustainability rating was evaluated using Marion's (2023) trail sustainability rating. The TSA and trail grade were grouped together into sustainability ratings of highly sustainable, low sustainability, moderately sustainable, unsustainable, and highly sustainable. In addition, the information on tread surface was provided to provide a comprehensive description of the tread surface for each trail section together with its sustainability ratings. Table 9 outlines the sustainability ratings for various sections and tread surfaces of the Kiau Nuluh – Gurkha Hut trail. Across the entire 14.2km trail, 8.5% can be classified as highly sustainable, 4.9% as low sustainability, 7.7% as moderately sustainable, 27.5% as unsustainable, and 51.4% as highly unsustainable. The predominant tread surfaces were bare soil, organic litter, and roots, accounting for 52% of the trail, with muddy soil comprising 23%. For the Kiau Nuluh to Nunuk Camp section (3.5km), 14.3% was rated highly sustainable, 14.3% as low sustainability, 8.6% as moderately sustainable, 11.4% as unsustainable, and 51.4% as highly unsustainable. Most of this section featured bare soil, organic litter, and roots (94.3%), with a smaller portion covered by muddy soil (5.7%).

In the Nunuk Camp to Marai Parai section (3.5km), 8.6% was highly sustainable, 5.7% low sustainability, 5.7% moderately sustainable, 34.4% unsustainable, and 48.6% highly unsustainable. Most of this section's tread surface consisted of bare soil, organic litter, and roots (71.4%), while 28.6% was muddy soil. The Marai Parai – Suminungkad section (4.2km) recorded 4.8% as highly sustainable, 4.8% as moderately sustainable, 35.7% as unsustainable, and 54.8% as highly unsustainable. Approximately 81% of this section featured bare soil, organic litter, and roots, with 7.1% muddy soil and 11.9% rocks. Lastly, the Suminungkad – Gurkha Hut section (3km) had 6.7% rated highly sustainable, 13.3% moderately sustainable, 30% unsustainable, and 50% highly unsustainable. Rocks were the predominant tread surface in this section (86.7%), with 13.3% covered by bare soil, organic litter, or roots.

Table 9. Kiau Nuluh - Gurkha Hut Trail Sustainability Rating

Trail section/Tread surface	Trail sustainability rating					Total
	1 Freq (%)	2 Freq (%)	3 Freq (%)	4 Freq (%)	5 Freq (%)	Freq (%)
Kiau Nuluh – Gurkha Hut (The entire trail: 14.2km)						
Bare soil, organic litter, and roots	8	7	6	23	52	96 (67.6)
Muddy soil	1	0	1	8	5	15 (10.6)
Rocks	3	0	4	8	16	31 (21.8)
Total	12 (8.5)	7 (4.9)	11 (7.7)	39 (27.5)	73 (51.4)	142
Kiau Nuluh to Nunuk Camp section (3.5km)						
Bare soil, organic litter, and roots	5	5	3	4	16	33 (94.3)
Muddy soil	-	-	-	-	2	2 (5.7)
Rocks	-	-	-	-	-	-
Total	5 (14.3)	5 (14.3)	3 (8.6)	4 (11.4)	18 (51.4)	35
Nunuk Camp – Marai Parai section (3.5km)						
Bare soil, organic litter, and roots	2	2	1	6	14	25 (71.4)
Muddy soil	1	-	1	5	3	10 (28.6)
Rocks	-	-	-	-	-	-
Total	3 (8.6)	2 (5.7)	2 (5.7)	11 (31.4)	17 (48.6)	35
Marai Parai – Suminungkad section (4.2km)						
Bare soil, organic litter, and roots	1	-	1	11	21	34 (81)
Muddy soil	-	-	-	3	-	3 (7.1)
Rocks	1	-	1	1	2	5 (11.9)

Total	2 (4.8)	-	2 (4.8)	15 (35.7)	23 (54.8)	42
Suminungkad – Gurkha Hut section (3.0km)						
Bare soil, organic litter, and roots	-	-	1	2	1	4 (13.3)
Muddy soil	-	-	-	-	-	-
Rocks	2	-	3	7	14	26 (86.7)
Total	2 (6.7)	-	4 (13.3)	9 (30)	15 (50)	30

Note. 1=Highly Sustainable, 2= Low Sustainability, 3= Moderately Sustainable, 4= Unsustainable and 5= Highly Unsustainable.

Further examination of the topographic features, utilizing Digital Elevation Model (DEM) data with a resolution of 30 meters obtained from the Shuttle Radar Topography Mission (STRM), has yielded significant insights into the 7,389.32 hectares surrounding the Kiau Nuluh – Gurkha Hut Trail (refer to Figure 2). The analysis reveals that 72.34% or 5,345.17 hectares of the area is characterized by slope gradients ranging between 30% and 90% (approximately 16.7 degrees and 41.99 degrees), with less than one percent of the slope grade falling below 10%. This observation illuminates why more than 70% of the assessed trail segments are classified as unsustainable according to Marion's (2023) trail sustainability rating. Additionally, a notable portion of the trail traverses the ridgelines, as evidenced by the contour lines, potentially representing the most accessible areas within the rugged terrain of Kinabalu Park's northwest region.

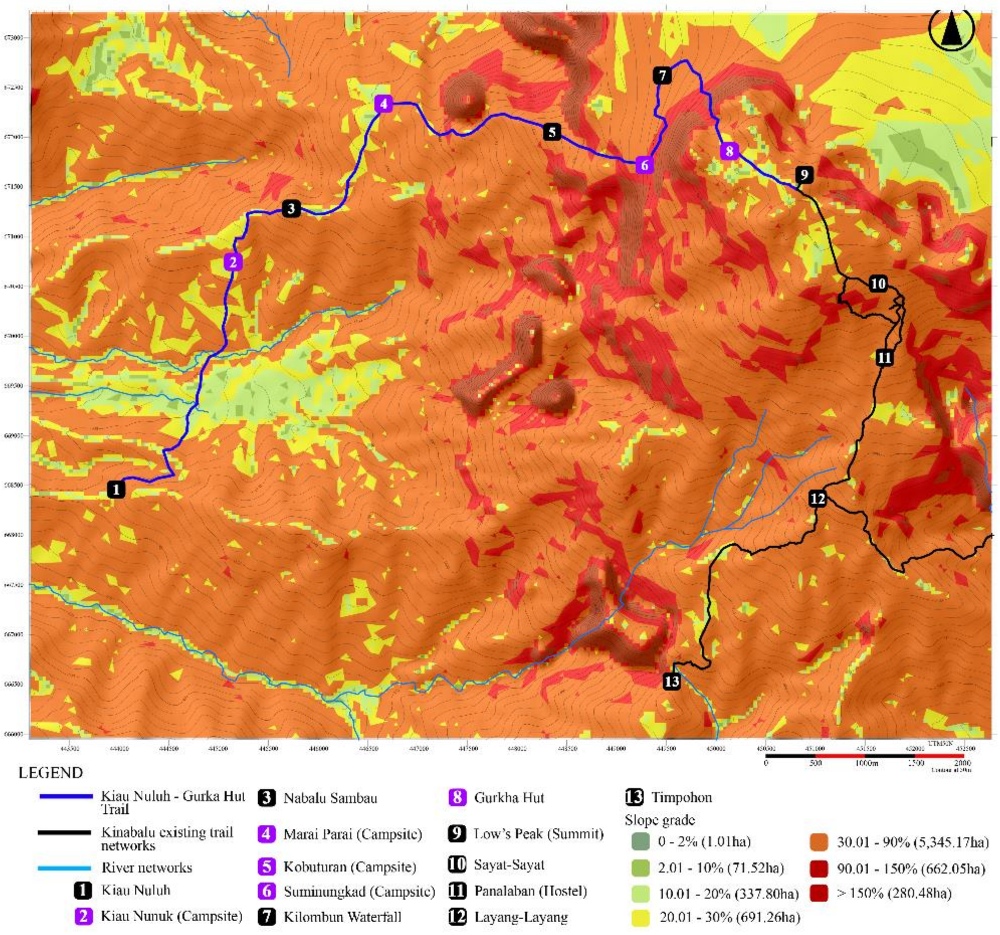

Figure 2. Slope grade analysis of the Kiau Nuluh – Gurkha Hut Trail, Kinabalu Park.

DISCUSSION

This study comprehensively examines the 14.2km Kiau Nuluh—Gurkha Hut Trail, a trail proposed to be officially established northwest of Kinabalu Park. Utilizing a point-sampling methodology at 100m intervals, the research generated 142 samples representing various topographic elevations along the trail, ranging from 976m at the trailhead to 3,846m at Gurkha Hut. The findings revealed that 59.2% (8.4km) of the Kiau Nuluh – Gurkha Hut trail traverses under 2,000m asl, 20.5% (2.91km) between 2,000m asl and 3,000m asl, and 20.4% (2.9km) of the trail situated above 3,000m asl. In addition, 88% of the trail route was ascending (12.5 km), while 12% was descending (1.7 km). Most trails exhibited a tread width of 0-61 cm (55.6%), with 54.3% showing tread incisions between 2.5cm and 12.7cm. Organic litter (32.4%) and bare soil (31.7%) were the predominant surface types, with rocks constituting 21.1% of the trail surface, primarily at elevations 3,000m above sea level and higher. Soil compaction ranged from 0.1 to 1.69 kg/cm^2 (71.8%). Most of the route was covered by at most 50% tree canopy (84.5%), reflecting the characteristic vertical crown of the forest canopy in the Gunung Kinabalu montane region (Aiba et al., 2004). Compared to CCR (Hill & Pickering, 2009), most of the trail route falls within the minimally damaged category, with a few areas that can be considered as lightly damaged, particularly near the trailhead marked by the tread width over 300cm and the presence of root exposure at a few areas along the trail.

The soil compaction in the Kiau Nuluh - Nunuk Camp section was greater than the Nunuk Camp – Marai Parai and Marai Parai – Suminungkad sections, can be attributed to its status as an established trail. Unlike the higher elevation sections, which have seen minimal use since the 1990s, this trail segment was regularly utilized by local villagers for accessing their rubber plantations, paddy fields, and vegetable gardens situated along the mid-section of the trail. Additionally, Nunuk Camp and its adjacent areas have been designated as a community forest managed by the villagers of Kiau Nuluh. The establishment of the camp in 2017 marked the community's foray into ecotourism, with a recorded visitation count of 1,007 visitors since its inception. The presence of muddy surfaces covering 28.6% of the trail segment from Nunuk Camp to Marai Parai poses a significant threat to trail sustainability due to poor drainage. These flat areas are prone to waterlogging and expansion since future users may bypass the muddy patches by trampling the trail's edges (Leung & Marion, 1996), and this was already observed in this study where the tread width of this trail section was notably wider than others. This trampling accelerates vegetation loss and could lead to the creation of multiple trails or undesignated trail over time (Leung & Marion, 1999; Nepal & Nepal, 2004; Wimpey & Marion, 2010). Muddy trail surfaces also pose safety hazards for users, increasing the risk of slips, falls, and travel difficulties while potentially reducing user satisfaction (Sam Shor et al., 2021). Moreover, sections of the trail passing through the valley of Sg. Kinotoki, particularly from Nunuk Camp to Marai Parai, are particularly vulnerable to accelerated erosion compared to mid-slope and ridge sections. This heightened erosion risk is linked to the valley's susceptibility to periodic flooding, which contributes to trail surface erosion (Olive & Marion, 2009).

The Kiau Nuluh – Gurkha Hut trail primarily featured slope alignments ranging from 0 to 22 degrees, constituting 52.8% of the trail's overall layout. Analysis of grade distribution revealed that a significant portion of the trail, approximately 57.7% or 8.19 km, exhibited grades exceeding 30%, with an additional 15.5% or 2.2 km falling within the 21-30% grade range. Notably, the maximum recorded grade reached 180% (approximately 61 degrees), with an average grade of 37.4% (approximately 20 degrees). The comparative analysis demonstrated that trail sections at higher elevations tended to have steeper grades, with over 70% exceeding a 30% grade, indicating an increase in steepness with elevation gain. Analysis of the TSA revealed consistent slope alignments throughout the trail sections. Based on Marion's (2023) trail sustainability ratings, findings indicated that 78.9% or 11.2 km of the 14.2km trail received unsustainably to highly unsustainable ratings, characterized by a TSA below 30 degrees and a trail grade exceeding 20%. Further investigation revealed that as elevation increased along the trail, the proportion of unsustainable to highly unsustainable ratings escalated. Specifically, from Kiau Nuluh to Nunuk Camp, the percentage of unsustainable to highly unsustainable ratings stood at 62.8%, rising to 80% from Nunuk Camp to Marai Parai, 90.5% from Marai Parai to Suminungkad, and 80% from Suminungkad to Gurkha Hut. These findings suggested that the Kiau Nuluh – Gurkha Hut Trail is susceptible to accelerated degradation in the future, as such characteristics posed challenges for drainage, heightening the risk of water runoff, soil erosion, muddiness, and trail widening (Meadema et al., 2020; Marion, 2023; Marion & Wimpey, 2017). Moreover, trails that aligned closer to their fall line indicated by the low TSA were more difficult to maintain due to their increased vulnerability to erosion and the need for more extensive drainage systems (Marion, 2023).

The Suminungkad – Gurkha Hut section, situated between 3,000 to 3,846m above sea level, predominantly featured a trail tread covered by rocks (83.3%) with 16.7% bare soils and organic litter. A comparative analysis highlighted that this section's 16.7% bare soil and organic litter tread surface exhibited higher compaction levels compared to other trail segments. These areas are characterized by ultramafic and granite forest vegetation. The vegetation in ultramafic forests typically thrives on modest thickness of ultramafic soil (Kelpertzis et al., 2013; Marescotti et al., 2019), while granite forests grow on weathering granite bedrocks (Ashton, 2003). These geological features could potentially influence the observed level of soil compaction in these areas. Moreover, 80% of the trail from Suminungkad to Gurkha Hut was classified as unsustainable to highly unsustainable. The thin layer of organic litter and bare soil covering the ultramafic soil in this trail section may be experiencing accelerated loss due to the narrow trail fall line. Additionally, 80% of the tread in the Suminungkad – Gurkha Hut section was covered by rocky surfaces, where the steeper grade and narrow trail slope angle may contribute to increased water runoff, especially during tropical thunderstorms, thereby heightening hiking risks for users in the future. Furthermore, the trail tread's exposure to raindrops, with most areas covered by 50% canopy cover, increases the rate of surface runoff, leading to erosion and soil loss (Elliot & Rhee, 2022; Dunkerley, 2020; Hartano et al., 2003; Wallin & Harden, 1996). This exposure contributes to the degradation of the trail in the future, emphasizing the need for effective erosion control measures and sustainable trail management practices.

Implications and suggestions

Natural trail systems serve as crucial infrastructure for accessing remote protected natural areas. Maintaining their condition and usability is a primary concern for land managers, who must navigate the delicate balance between facilitating recreational access, preserving the environment, and meeting visitors' expectations for high-quality experiences. Poorly designed trails deteriorate quickly, harm the local environment, and are more challenging to maintain. Thus, establishing sustainable trails is crucial, requiring meticulous design and construction to minimize their impact on hydrology, aiming to reduce surface water runoff diversion and concentration. The trail must effectively accommodate anticipated levels of use while ensuring the protection of both visitor enjoyment and the integrity of natural resources. This study thoroughly analyses the 14.2km Kiau Nuluh - Gurkha Hut Trail, shedding light on its characteristics and sustainability ratings. From this assessment, several implications and recommendations emerge.

The results of this study raise significant concerns, indicating that nearly 90% of the Kiau Nuluh - Gurkha Hut Trail is deemed unsustainable, with the proportion of unsustainable ratings escalating at higher elevations. Such a prevalent occurrence of unsustainable ratings poses a substantial risk of trail degradation and potential harm to the surrounding natural environment once the trail is opened to the public. To tackle this issue, urgent action is required to realign the trail to attain more sustainable ratings, particularly in segments where the trail grade exceeds 20% and minimize the TSA to below 10% (Marion, 2023). Furthermore, multiple studies in trail science suggest that minimizing tread impacts can be achieved by deviating the TSA from the fall line by more than 22°, preferably exceeding 45° whenever feasible (Marion & Wimpey, 2017; Meadema et al., 2020; Wimpey & Marion, 2010). This approach can be implemented in higher elevation areas with narrower ridge widths, providing limited space for constructing higher TSAs.

One potential approach to achieve the preferable sustainability rating is to closely realign the trail with contour lines where the ridge width permits trail construction along these lines. Trails constructed in harmony with the contour of the surrounding terrain, commonly referred to as "side-hill" trails, consistently exhibit one lower side slope and typically demand less maintenance (Marion et al., 2022; Wimpey & Marion, 2017). This design facilitates more efficient water drainage from out-sloped treads or drainage features and offers greater ease in shedding water from their treads (Marion & Wimpey, 2017). In situations where tread shapes become concave or raised berms form on the lower side, trail maintainers can typically excavate to facilitate water drainage by out-sloping treads to the downhill side by 2-3% for hiking trails (Marion & Wimpey, 2017), thereby mitigating soil erosion and preventing muddiness. Furthermore, the sloping terrain adjacent to side-hill trails naturally channels user traffic onto the tread, effectively curbing trail widening and preserving the trail's integrity (Marion & Wimpey, 2017).

Another method involves adhering to the "Half Rule" (Webber, 2007) during trail construction. Unlike the TSA, which focuses on the difference between trail bearing and the fall line, the Half Rule centers on the trail grade, aiming for it to be half or 0.5 of the landform grades. For instance, on a landform with a 30% grade, the trail grade ideally should be 15%, effectively preventing trails from aligning closely with the fall line. Marion (2023) introduced trail sustainability ratings based on the ratio of landform grade to trail grade. A ratio of less than .31 indicates a sustainable trail. At the same time, moderate sustainability falls within the range of .31 to .4. Trails are deemed unsustainable when the ratio of trail grade to landform grade falls between .41 and .5. However, as illustrated in Figure 2, the higher elevation sections of the Kiau Nuluh – Gurkha Hut Trail are predominantly characterized by grades of 30% and above, presenting challenges in achieving preferable sustainable ratings. Nonetheless, these challenges can be mitigated if tread substrates incorporate substantial rock with highly effective drainage features (Marion, 2023).

Therefore, another approach is to increase the trail durability by hardening the tread surface. Research demonstrates that the material used significantly influences sustainability, with rock proving more resilient than soil (Meadema et al., 2020; Olive & Marion, 2009). Sandy soils drain well but are prone to erosion, while clay and silty soils resist water infiltration, leading to runoff and erosion (Parker, 2004). Organic soils are susceptible to erosion, water retention, and widening of trails and loam, with their balanced particle sizes, providing optimal drainage and stability. Studies indicate that trails with higher rock content experience less soil loss, particularly on steep grades (Olive & Marion, 2009). In addition, hardening the trail with crushed rocks could lessen the impacts of the raindrops and water runoff, especially since most of the Kiau Nuluh – Gurkha Hut Trail was only covered by at most 50% forest canopy. However, rock surfaces such as crushed stone require frequent maintenance while effectively preventing soil loss (Marion & Wimpey, 2017). Another approach is to install artificial substrates or harden the tread surface by installing a boardwalk. However, such installations are usually being constructed in the area adjacent to the urban environment where the presence of unnatural materials is more tolerable by the users (Marion, 2023).

Nevertheless, it is imperative that the authority of Kinabalu Park assess the experience opportunities desired by users in the area where such information would guide the authority in choosing the appropriate hardening technique for the Kiau Nuluh – Gurkha Hut Trail. Exploring user perceptions and preferences regarding trail surfaces and their tolerance for artificial materials in trail construction would provide valuable input for future trail design and management strategies. In addition, future studies could explore several avenues to enhance the sustainability of natural trail systems. Investigating the long-term effects of realigning trails to achieve more sustainable ratings, particularly in challenging terrain, would provide valuable insights. Additionally, experimental research is needed to isolate and understand the relative impact of soil texture and rock content on trail sustainability, informing better trail construction practices. Additionally, examining the ecological impacts of trail hardening techniques, particularly in sensitive natural environments, would help guide sustainable trail management practices.

CONCLUSION

In conclusion, this study offers a comprehensive examination of the 14.2km Kiau Nuluh—Gurkha Hut Trail, providing insights into its topographic characteristics and sustainability ratings. The findings underscore the urgent need for trail realignment to achieve more sustainable ratings, particularly in segments with steep grades exceeding 20%. Implementing trail design strategies such as adhering to contour lines and applying the "Half Rule" during construction can mitigate sustainability challenges, along with incorporating durable materials like rock to harden trail surfaces. Furthermore, user preferences should inform decision-making regarding trail hardening techniques, emphasizing the importance of assessing experience opportunities desired by trail users. Future studies should explore the long-term effects of trail realignment and investigate the ecological impacts of trail hardening techniques to enhance the sustainability of natural trail systems. Such research will guide effective trail management practices and ensure the preservation of natural resources while meeting recreational needs.

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APPENDIX

Appendix 1: Visitor Statistics to Kinabalu Park from year 2000 - 2022

Year	Malaysian	International	Total
2000	26,667	15,931	42,598
2001	22,712	15,780	38,492
2002	22,495	16,799	39,294
2003	25,968	15,016	40,984
2004	23,509	19,923	43,432
2005	20,816	22,338	43,154
2006	16,910	22,388	39,298
2007	18,993	21,397	40,390
2008	21,341	26,507	47,848
2009	19,363	28,201	47,564
2010	19,870	27,737	47,607
2011	23,352	28,248	51,600
2012	25,670	28,183	53,853
2013	26,845	28,528	55,373
2014	30,151	28,277	58,428
2015	19,426	13,988	33,414
2016	17,357	20,508	37,865
2017	21,205	20,129	41,334
2018	20,509	19,579	40,088
2019	24,173	19,654	43,827
2020	15,428	3,658	19,086
2021	13,765	210	13,975
2022	41,531	7,149	48,680
Mean	22,524.20	19,570.80	42,095