Monitoring Campsite Soil Erosion by Structure-from-Motion Photogrammetry: A Case Study of Kuro-Dake Campsites in Daisetsuzan National Park, Japan

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Abstract
Camping in the mountain regions has several negative impacts, including soil erosion in the campsites. In many national parks, efforts to monitor and manage campsite soil erosion are insufficient or even lacking. Owing to the lack of implementation of formal management practices, the current and former Kuro-dake campsites in Daisetsuzan National Park (DNP) have suffered serious soil erosion. To gain more insights into campsite soil erosion, we investigated these two campsites by short-term monitoring through structure-from-motion (SfM) photogrammetry surveys with ground control points (GCPs). These surveys were conducted three times consecutively in the current (2017, 2018, and 2019) and former Kuro-dake campsites (2018, 2019, and 2020). Two sets of digital elevation models (DEMs) of the current and former campsites were produced with the resolutions of 0.015 and 0.025 m, respectively. We detected that the elevation changes exceeded by 0.03–0.04 m, using the DEMs of difference (DoDs) maps. Soil loss around the gullies was observed at each campsite. In the current campsite, soil losses of 2.20 and 0.30 m^3 were identified in the periods of 2017–2018 and 2018–2019, respectively. In the former campsite, soil losses of 1.55 and 22.27 m^3 were identified during 2018–2019 and 2019–2020, respectively. In addition, a large amount of exposed mineral soil with exposed rocks was observed at each campsite. Various erosion rates obtained in the short-term study indicated the importance of continuous monitoring. High-resolution and high-accuracy topographic products generated from the SfM photogrammetry survey enabled the detection of a small amount of campsite soil erosion and provided a new method to monitor campsite degradation. This study demonstrated that a simple closure of the former campsite in 1992 failed to reduce the impact of soil erosion. In the case of the current and former Kuro-dake campsites, burying the gullies with boulders and setting up boulders or wood fences at the termini of the gullies would be a potential solution to stop or mitigate further erosion. Thus, formal management including monitoring and maintenance of site conditions should be introduced to Kuro-dake as well as other unmanaged campsites in DNP.

Keywords: Soil erosion monitoring, campsite degradation, national park management, structure-from-motion photogrammetry, Daisetsuzan National Park, digital elevation model

1. Introduction

Camping is a popular recreational activity in terrestrial protected areas and other natural areas. However, human activities inevitably have various impacts on natural resources in and around campsites, including vegetation loss, soil compaction, and soil erosion (Hammitt et al., 2015). Consequently, a degraded environment negatively affects the recreational experience of a user (Daniels and Marion, 2006). Cole (1989) emphasized that monitoring campsite conditions plays an important role not only in avoiding negative impacts on campsites but also in confirming the effectiveness of practiced management actions. Providing users with high-quality recreational experiences while conserving the natural environment is an important goal for national-park managers. In mountain national parks, backcountry campsites not only provide over-night campers a solitude environment, but also are important accommodation facilities for trekkers and travelers. Managing the camping impacts is extremely challenging in mountain national parks with large-scale backcountry surroundings. As backcountry camping is gaining popularity, there is an urgent need to develop an array of science-directed monitoring and maintenance practices to ensure sustainable camping (Cole, 1989; Marion et al., 2018; Smith and Newsome, 2002).

Researchers in the field of recreation ecology have provided several methods to monitor short-term and long-term changes in the conditions of campsites. Condition class rating—initiated by Frissell (1978) and adapted by Cole (1993)—has been widely used as a quick method to document general campsite conditions. Multiple impacts (e.g., vegetation loss and mineral soil exposure) have been described to define the campsite characteristics in each class. However, this method cannot identify the trend of each specific type of impact. Multiple parameter ratings were developed to record the differences among campsites for each parameter and provide possibilities to track the changes over time (Cole, 1989; Cole and Hall, 1992; Marion, 1991). Since the 1990s, repeated multiple parameter ratings have been conducted in different backcountry areas to detect changes in specific camping impacts over different time intervals (Cole et al., 2008; Cole and Hall, 1992; Dixon, 2017; Dixon and Hawes, 2015; Marion and Cole, 1996). It has been pointed out that once a campsite is opened for use, it experiences rapid deterioration during the first few years when most vegetation cover loss occurs, accompanied by increasing mineral soil exposure and campsite expansion (Cole and Hall, 1992; Marion and Cole, 1996). To gain more insights into the actual changes in different parameters, repetitive ecological measurements of the parameters should be conducted both in campsites and control sites (Hammitt et al., 2015). However, because comprehensive measurements are time-consuming, they have been performed in only a limited number of studies (Cole, 2013; Eagleston and Marion, 2017).

Most early studies addressing the monitoring of campsite conditions have focused on detecting changes in ground surface cover using the established methodologies mentioned above. This is because campsite degradation remains at a rather low rate after the impact on vegetation cover reaches its maximum point (Cole and Hall, 1992). Most early long-term monitoring studies showed a consistent trend that site conditions tend to be stable in moderately or even in heavily impacted sites with extensive exposed mineral soil (Cole, 2013; Cole et al., 2008). However, a heavily compacted soil without the protection of vegetation cover is vulnerable to soil erosion (Marion, 2016), which can result in a trend of deterioration in heavily impacted sites in future. Some recent studies have provided evidence of soil erosion in campsites (Dixon and Hawes, 2015; Eagleston and Marion, 2017; Wang and Watanabe, 2019). Eagleston and Marion (2017) identified that soil erosion in old campsites in the boundary waters canoe area wilderness was the most important long-term impact. Wang and Watanabe (2019) reported that campsite soil erosion not only resulted in irreversible topographical changes to the ground surface but also influenced the spatial distribution of tents and the quality of the campers' experience. It is necessary to involve the measurement of soil erosion in the future monitoring of campsite conditions to direct decision-making of the managers.

Eagleston and Marion (2017) examined soil loss in campsites by comparing the current soil level around embedded rocks on site with that recorded in past photographs through visual observation. They estimated the volume of long-term soil loss by multiplying the mean incision depth around the campsite component by the size of the campsite. However, no actual measurements were performed to monitor topographical changes and soil loss volume in campsites.

Structure-from-motion (SfM) photogrammetry has been widely recognized as a cost-effective and easy-to-use method for generating high-resolution digital elevation models (DEMs). Photographs either taken by an unmanned aerial vehicle (UAV) or pole-mounted digital cameras can be processed for model generation using commercially available photogrammetry software, such as Agisoft PhotoScan Pro and Pix4Dmapper (Gonçalves et al., 2016; Nouwakpo et al., 2016; Vallet et al., 2011). Current photogrammetry software programs enable the generation of high-accuracy 3D models using SfM multi-view stereo (MVS) algorithms (Furukawa and Hernández, 2013; Westoby et al., 2012). The common workflow of DEM generation through SfM photogrammetry includes: 1) image alignment, 2) bundle adjustment, 3) dense point cloud generation, and 4) DEM generation (Smith et al., 2016; Westoby et al., 2012).

Spatial resolutions of DEMs derived through SfM photogrammetry survey range from decimeter to sub-centimeter level, depending on the scale of the study (d'Oleire-Oltmanns et al., 2012; Eltner et al., 2013). Meinen and Robinson (2020) verified that involving well-distributed ground control points (GCPs) and oblique images in SfM photogrammetry surveys can increase the accuracy of the derived DEMs and orthomosaics. In previous studies, point clouds produced from SfM photogrammetry surveys were compared with the data derived from the terrestrial laser scanner (TLS). The results indicated that SfM photogrammetry survey can be an alternative method equivalent to traditional TLS to create high-quality surface models that can be applied in different terrains (James and Robson, 2012; Micheletti et al., 2015; Smith and Vericat, 2015). Marteau et al. (2017) also demonstrated that point clouds having low elevation errors (<0.02 m) can be generated from low-altitude (5 m) SfM surveys. Smith and Vericat (2015) further emphasized that the survey range should be controlled below 10–20 m while applying SfM surveys to monitor soil erosion.

Repeated SfM photogrammetry surveys with GCPs can detect topographical changes with an accuracy within 10 cm both horizontally and vertically (Ellett et al., 2019; Marteau et al., 2017). Such surveys have been widely applied to monitor geomorphic processes on Earth, such as mass movement on the debris-covered glacier surface, landslides, and quantification of soil erosion on different landforms and land scales (Carvalho et al., 2020; Ellett et al., 2019; Gillan et al., 2017; Guerin et al., 2020; Śledź et al., 2021; Westoby et al., 2020). At small scales, such as small plots (<3 × 1 m size), even changes at the sub-centimeter level can be detected (Balaguer-Puig et al., 2017; Eltner et al., 2017).

Highly compacted soil on trails and campsites is exposed to high risk of constant soil loss, especially in alpine areas where the environment is vulnerable. Previous studies also suggested that erosion (e.g., gully erosion) can accelerate in areas where vegetation was heavily cleared by human activities (Guerra et al., 2017; Poesen, 2018; Selby, 1993). Selby (1993) emphasized that controlling soil loss before gullies are formed is important, thus, indicating the importance of monitoring topographic changes from an early stage of ground degradation. As the application of SfM photogrammetry shows excellent performance in detecting comprehensive topographical changes, monitoring soil erosion in recreational sites (e.g., trail and campsite) using SfM photogrammetry has gradually attracted the attention of researchers (Ćwiąkała et al., 2018; Wang and Watanabe, 2019). Ćwiąkała et al. (2018) evaluated the erosion intensity on hiking trails in the Tatra National Park in Poland with the digital surface model (DSM) generated through a UAV-based SfM photogrammetry survey involving GCPs. Wang and

Watanabe (2019) identified gully erosion in an unmanaged campsite in Daisetsuzan National Park (DNP) in Japan and described the topographic features at the centimeter level by using a high-accuracy DEM derived from a close-range (object distance: approximately 5 m) pole-photogrammetry survey involving GCPs.

Generally, it is recommended that most backcountry campsites located in remote mountains in national parks and other protected areas should be maintained at small sizes to avoid extensive camping impacts (Marion, 2016). Glendell et al. (2017) suggested that utilizing high-resolution images (ground resolution: 0.6–1.1 cm) in small-scale SfM photogrammetry surveys can detect topographic changes of approximately 1 cm. This study provides a promising method for the actual measurement and monitoring of soil loss in campsites with the detection ability of a few centimeters, which, to our knowledge, has never been achieved by previous studies in this field.

This study aimed to detect topographical changes in ground surface and quantify the volume of soil erosion in current and former Kuro-dake campsites in the DNP by conducting repeated SfM photogrammetry surveys with GCPs. Although it is a localized study, the findings of the present study will promote an in-depth understanding of soil erosion development in campsites and will provide novel indicators for the future monitoring of campsite degradation worldwide.

2. Study area

The DNP, designated in 1934 by the Ministry of Health and Welfare of Japan (current responsible authority: Ministry of the Environment), is the largest national park in Japan. It covers an area of approximately 2267.64 km^2 in central Hokkaido (Fig. 1). A large number of mountains in DNP formed on the lava plateau after the eruptive activities occurred during the Quaternary period (Konoya et al., 1966), with several mountains rising 2000 m above sea level. The highest peak is the active volcano on Mt. Asahi-dake (2291 m). The area above 1500 m is an alpine zone characterized by dwarf *Pinus pumila* and a variety of alpine flora.

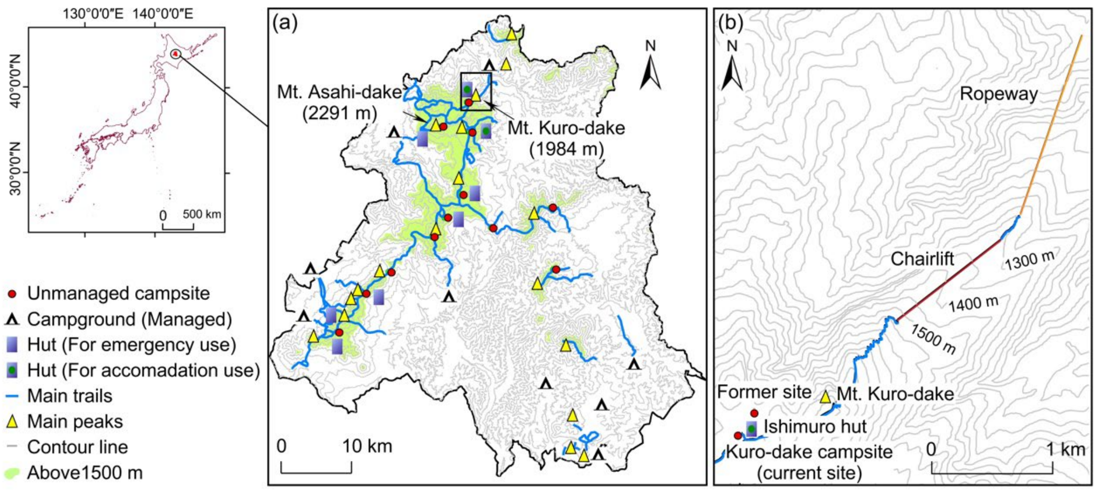

Fig. 1. Study site at Daisetsuzan National Park (DNP). (a) Topographic map of DNP (contour interval = 200 m), and (b) route to the current and former Kuro-dake campsites (contour interval = 50 m).

There are 12 unmanaged campsites, nine campgrounds (managed), and eight huts or shelters (six for emergency use only and two for accommodation use) in the DNP (Fig. 1a). Most unmanaged campsites are situated in a fragile alpine setting, whereas managed campgrounds are located in the subalpine zone. In Japan, a zoning management system with multiple land uses is adopted for national parks. Accordingly, lands are designated as national parks despite land ownership. The alpine lands where the 12 unmanaged campsites are located are owned by different organizations (such as the Forestry Agency and Hokkaido Government) instead of the Ministry of the Environment. Therefore, implementing managerial actions by national park managers is difficult. Contrastingly, landowners do not manage the campsites according to the management goals of the national parks. Consequently, the conditions of the unmanaged campsites are neither monitored nor maintained. As campgrounds in the subalpine zone are efficiently managed, soil erosion is not serious in most of these campgrounds. Owing to the limited capacity of huts, most overnight trekkers camp in unmanaged campsites. The camping season starts at the end of June and ends at the end of September. During the off-season period, these campsites are covered by thick snow for three-quarters of a year. Heavy precipitation and the continuous supply of snowmelt water in summer cause serious soil erosion in campsites and trails.

The surface materials in the alpine zone are formed from volcanic deposits (Konoya et al., 1966). The soil in the current and former campsites is derived from pyroclastic deposits and volcanic ash, which are vulnerable to soil erosion. The current and former Kuro-dake campsites are representative campsites that suffer serious soil erosion. The current campsite accompanied by the Ishimuro hut is the main accommodation facility located approximately 0.8 km southwest of the peak of Mt. Kuro-dake (Fig. 1b). Most visitors use ropeways and chairlifts to reach the peak of Mt. Kuro-dake. Easy access has made it one of the most frequently visited peaks in DNP. In the former Kuro-dake campsite lacking formal management and maintenance, soil erosion became increasingly serious, leading to the emergence of deep gullies across the campsite and its subsequent closure in 1992. The current Kuro-dake campsite was opened in the following year. Owing to constant unmanaged use, gully erosion was also observed at the current campsite.

3. Methods

3.1. Data acquisition

SfM photogrammetry surveys with GCPs were conducted in the current Kuro-dake campsite in 2017, 2018, and 2019 and in the former Kuro-dake campsite in 2018, 2019, and 2020. We conducted image acquisition by utilizing different combinations of platforms and cameras (Table 1).

Despite the use of different cameras for image acquisition, the ideal effective resolution (>16 MP) was ensured for all surveys, which are suggested for generating high-quality 3D point clouds (Mosbrucker et al., 2017). Camera features, such as autofocus, in-camera distortion correction, and noise reduction filters, were all disabled to avoid any modification of the captured objects, as suggested by Sanz-Ablanedo et al. (2012). Given the large area of the former Kuro-dake campsite (>1000 m^2), photographs were taken by a UAV at an object distance of more than 20 m (Table 1), except for the survey in 2020, when the weather was too windy to fly a UAV. In the case of the current Kuro-dake campsite, the mean object distances ranged from 6.4 to 12.3 m during the surveys. In the close-range (<10 m) surveys, a shutter speed faster than 1/1000 was used to avoid blur effects caused by camera motions. A suitable focal length of the lens was manually selected to ensure sharpness based on the optimal depth of the field. A ground sample (GS) distance of 0.07–0.60 cm was obtained in different surveys.

In this study, more than 80% forward overlaps and 60% side overlaps were ensured by confirming the image through smartphone application. In each survey, both nadir images with high overlaps and oblique images of the campsite surfaces were taken. This type of design can reduce the dome effect to increase the accuracy of the 3D model, which has already been validated in previous studies (James and Robson, 2014). Examples of camera positions are shown in Figure 2a.

We evenly distributed 7–13 GCPs across each campsite before image acquisition. Figure 2b shows an example of the distribution of GCP markers. Some of the GCPs were used as check points (ChPs) during 3D model generation (Table 1). A Trimble Geo 7X global navigation satellite system (GNSS) receiver was used to measure the location data of each GCP marker with an accuracy of 1–2 cm (Fig. 2c). The location data were acquired in the UTM Zone 54N and WGS 84 coordinate systems. To achieve better co-registration among the DEMs of different years, we selected some invariant points on some fixed stones and steel poles (Fig. 2d) across the campsites for co-registration. These co-registration points functioned as GCPs in the subsequent data processing. For instance, in the case of the current campsite, only the DEM of 2019 was generated using the in-situ measured location data of GCP markers. During the generation of the 2017 and 2018 DEMs, eight evenly distributed co-registration points with location data were abstracted from the orthomosaic raster of 2019 and used as GCPs.

Table 1 Characteristics of each structure-from-motion (SfM) survey.
[a] Ground control point.
[b] Check point.

Survey site	Survey date	Platform	Camera, Lens	Object distance (m)	Number of GCP[a]/ChP[b]
Current campsite	5/9/2017	Pole-mounted	RICOH GR II, GR Lens	9.5	5/3
	21/9/2018	Pole-mounted	RICOH GR II, GR Lens	6.4	5/3
	29/9/ 2019	UAV (DJI MAVIC 2 PRO)	Hasselblad, L1D-20c	12.3	7/6
Former campsite	21/9/ 2018	UAV (DJI MAVIC PRO)	RICOH GR, GR Lens	25.0	6/5
	28/9/ 2019	UAV (DJI MAVIC 2 PRO)	Hasselblad, L1D-20c	23.9	4/6
	25/9/ 2020	Pole-mounted	Sony α7 Ⅲ, FE 28-70 mm	3.5	4/3

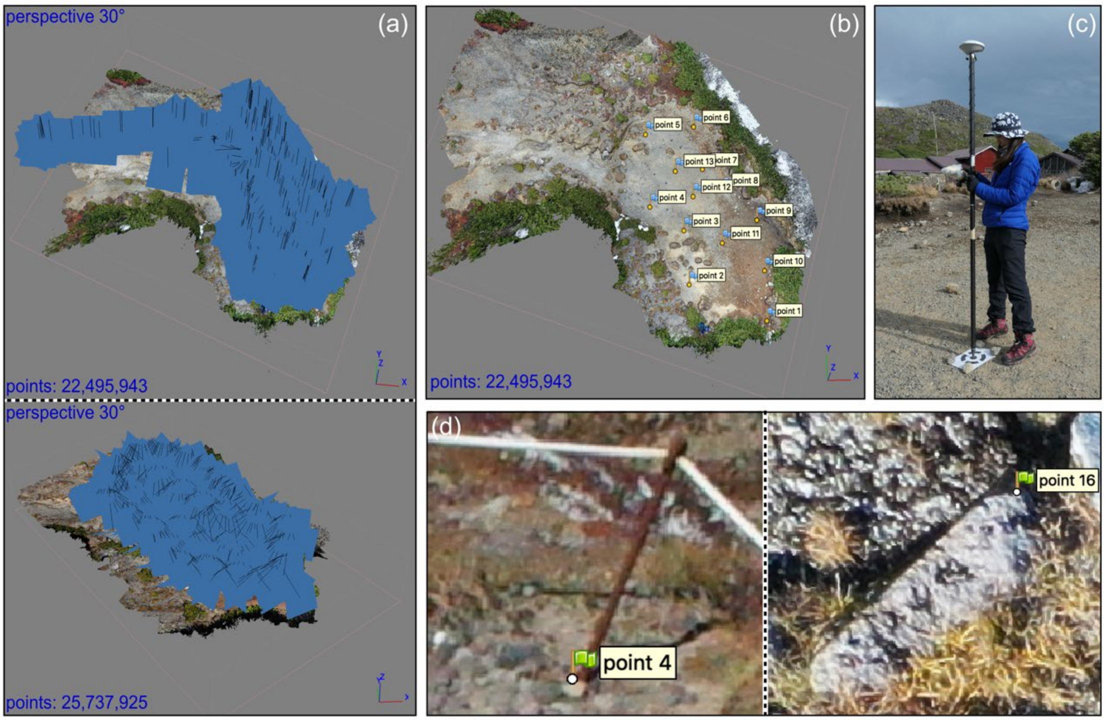

Fig. 2. Data acquisition for structure-from-motion (SfM) survey. (a) Examples of camera positions during the surveys in the current Kuro-dake campsite (top: 2019; bottom: 2018); (b) Distribution of ground control point (GCP) markers in the current Kuro-dake campsite, 2019; (c) Measuring the location data of GCP marker using Trimble Geo 7X GNSS; and (d) Examples of selected invariant points in the current (point 4) and former Kuro-dake campsites (point 16).

3.2. Data processing

3.2.1. Generation of DEMs and Orthomosaic maps

We followed the standard workflow described by Smith et al. (2016) to generate the DEMs of the current and former campsites. The photograph datasets were imported into *Metashape* Pro (v.1.6.1.10009). Before image alignment, we ran the "Estimating image quality" program for all photographs. A quality value ranging from 0 to 1 indicates the sharpness of the photograph. Only photographs with a quality value of more than 0.8 were used for processing. We also deleted some unnecessary photographs (e.g., repeated photographs taken) to reduce the processing pressure. After image selection, image alignment of medium quality was applied to generate a sparse point cloud with default settings on the key point limit (40 000) and tie point limit (4000). In addition, we deleted the points with a reprojection error higher than 1.0, to ensure high-quality point matches and to improve the accuracy of the following point georeference.

We manually identified the GCP markers in the corresponding photographs and adjusted them to correct the locations. We used the location data of the GCPs to orient the cameras and to georeference the generated sparse point cloud. A medium-quality dense point cloud was created in the mild depth-filtering mode. The MVS algorithm, which is available in *Metashape* Pro, enables the production of high-density point clouds and a high-accuracy DEM. We created DEMs in the same coordinate system as GCPs (UTM Zone 54N, WGS 84) by using the default interpolation method implemented in *Metashape* Pro. We conducted slope analysis and profile extraction with the DEMs to identify the topographic features of each campsite in ArcMap 10.8.1. The results were then used to gain a better understanding of the distribution of volumetric changes (erosion/deposition).

Furthermore, a high-resolution orthomosaic image was created for each survey. We identified the campsite boundary and exhibited the visual features of the ground surface where soil erosion was detected using orthomosaic images. When deciding the interest area of volumetric change detection, we excluded the area with some artificial items, such as a fixed wooden bench, two removable wooden benches (existing during the image acquisition in 2018 only), and a tent (existing during the image acquisition in 2017 only).

3.2.2. DEMs of Difference (DoDs)

One of the main applications of successive DEMs is to monitor topographic changes by producing a DoD map that explains the spatial distribution of elevation change over the study period. DoD maps have been widely used in studies that quantified soil erosion at different scales and different types of landforms (Ellett et al., 2019; Glendell et al., 2017). In this study, we produced two sets of DoD maps for each campsite over the corresponding study periods by subtracting the early DEM from the latter using the raster calculator in ArcMap 10.8.1.

Error analysis is an important step in identifying the level of changes that DoDs can explain. We used the root mean square error (RMSE) of the ChP residuals to indicate model accuracy. The model precision was represented by the standard deviation of the ChP residuals. In different surveys, three to six GCPs were used as ChPs (Table 1). A minimum level of detection (minLoD) was calculated and used to filter out uncertain topographical changes from each produced DoD. We adopted the same method as Marteau et al. (2017) to calculate the minLoD, which was deemed more reliable for detecting lower-magnitude topographical changes (Brasington et al., 2003; Wheaton et al., 2010). The minLoD was calculated using the following equation:

$$\min LoD = t\sqrt{\left(\varepsilon_{DEM_b}\right)^2 + \left(\varepsilon_{DEM_a}\right)^2} \qquad (1)$$

In this equation, ε_{DEM_a} and ε_{DEM_b} indicate the model precision of the later DEM (a: after) and the early DEM (b: before), respectively, which are represented by the standard deviation of the ChP residuals. We chose a t-score of 1.96 for 95% confidential intervals to calculate the minLoD. The t-score was calculated as described by Marteau et al. (2017). When the elevation change in a cell was smaller than minLoD, we considered it uncertain.

Volumetric changes were calculated by multiplying the average of certain negative/positive changes in elevations by the corresponding area, where negative values indicate erosion and positive values indicate deposition. Cells with elevation changes within minLoD were excluded from the calculation.

We did not calculate the traditional soil erosion rates in the form of eroded mass (Mg/ha/yr) as some previous studies showed (López-Vicente et al., 2013; Sack and da Luz, 2003). This is because the methodologies adopted were different. Nevertheless, establishing such a standardized comparison is important (Salesa and Cerdà, 2020) wherein the volumetric calculations adopted by our study will contribute to the research in this field.

4. Results

4.1. Accuracy and resolution of the DEMs

The main characteristics of the generated DEMs of the current and former Kuro-dake campsites, including model precision, model accuracy, and point density, are listed in Table 2. The precision of all models was high and never exceeded 0.02 m. The DEM of the current campsite in 2019 and that of the former campsite in 2018 were created as reference models with accuracies of 0.018 and 0.013 m, respectively, using the in-situ measured location data of GCPs. The DEMs of the current campsites in 2017 and 2018, and those of the former campsite in 2019 and 2020 were created with model accuracies ranging from 0.024 to 0.037 m. The point density of the models was between 1730 and 124 000 points/m^2. Even the lowest point density was comparable to the previous studies that utilized the SfM photogrammetry survey to generate high-quality DEMs (Marteau et al., 2017).

The resolution of the created DEMs in this study was between 0.007 and 0.010 m for the current campsite and between 0.002 and 0.024 m for the former campsite (Table 2). The number of images used to create the 3D model was between 323 and 520 for the current campsite and between 459 and 1556 for the former campsite.

Table 2 Characteristics of the generated digital elevation models (DEMs) of the current and former Kuro-dake campsites.

Site	Model	3D Model precision (m)	3D Model accuracy (m)	Point density (p/m^2)	DEM resolution (m)	Number of images
Current campsite	Sept. 2017	0.015[a]	0.024[b]	10 500	0.010[c]	520
	Sept. 2018	0.013	0.029	23 100	0.007	468
	Sept. 2019	0.009	0.018	9470	0.010	323
Former campsite	Sept. 2018	0.005	0.013	1730	0.024	459
	Sept. 2019	0.017	0.037	2350	0.021	336
	Sept. 2020	0.010	0.032	124 000	0.002	1556

[a] Standard deviation of the check point (ChP) residuals.

[b] Root mean square error (RMSE) of ChP residuals.

[c] Original (highest) resolutions of the developed DEMs. DEMs of the same campsite were exported in a consistent resolution to create DoD maps (further details provided in the following section).

4.2. Topographic features of the ground surface in the campsites

The DEMs of the current and former campsites were exported at 0.015 and 0.025 m resolutions, respectively. These high-resolution DEMs enabled the detection of comprehensive topographic changes in campsites. Figure 3 shows examples of high-resolution topographic products of the two campsites. The gullies in the campsites, presenting a hillshade appearance, can be easily identified from the DEM maps. Two gullies ran through the current campsite in the northwest direction (Fig. 3a). Most parts of the campsite sloped slightly toward the northwest, where the surface slope was above 5°. The former campsite had six deep gullies (Fig. 3b), and the slope around the gully walls exceeded 30°. There is a limited flat area (slope < 5°) at the northern terminus of the former campsite.

Orthomosaic images produced from each survey were exported at the resolutions of 0.005 and 0.01 m for the current and former campsites, respectively. It clearly showed the appearance of the ground surface, which was characterized by extensive bare ground. Certain loose sediments accumulated at the lower flat area in both current and former campsites (Fig. 3a and 3b).

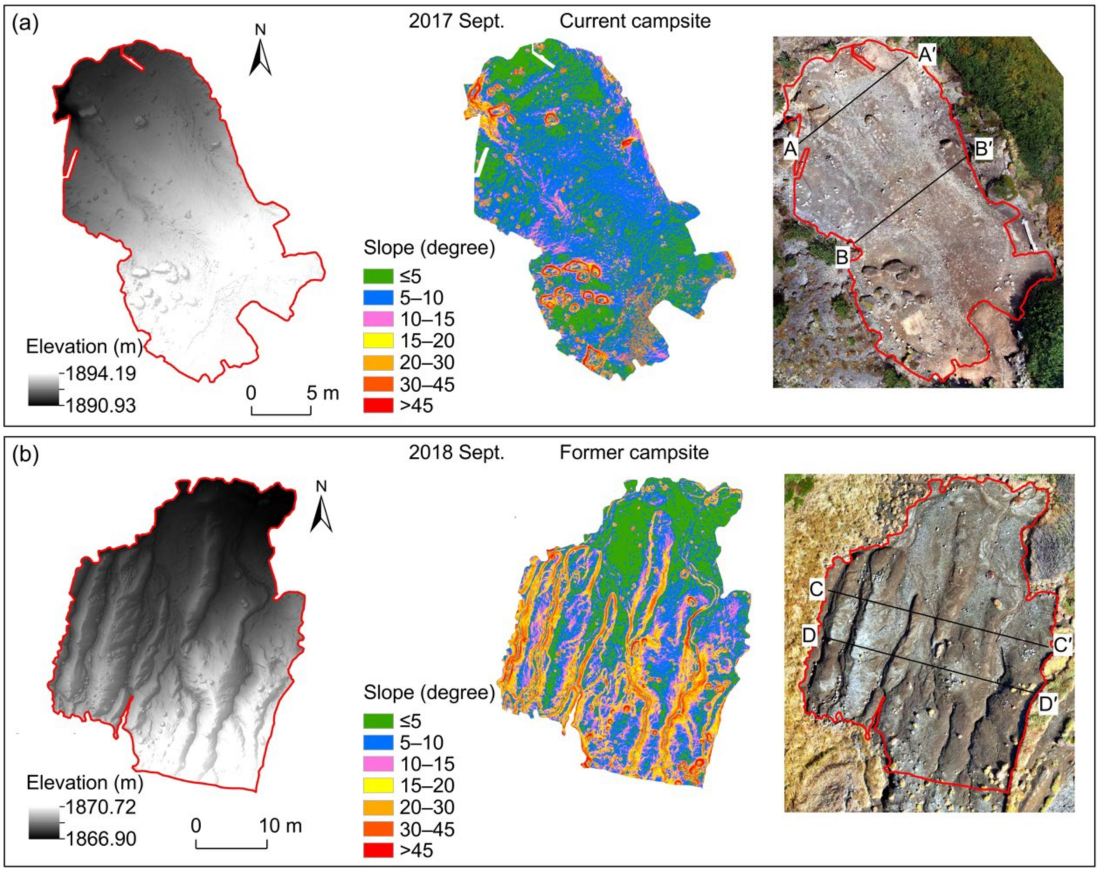

Fig. 3. Digital elevation model (DEM), slope maps, and orthomosaic images of the current and former Kuro-dake campsites created with the photographs taken in: (a) September 2017 and (b) September 2018. Site boundary of the current site was decided by excluding the area with artificial items existing in site during the surveys in 2017 and 2018. Note the difference in the scale of (a) and (b). See Fig. 5 for the locations of cross-sectional profiles.

4.3. Topographic changes in the campsites

The DEMs of the current and former campsites exported in 0.015 m and 0.025 m resolutions, respectively, were used to create DoD maps. The DoD maps created in this study achieved a detection ability of 0.03–0.04 m. Raster cells with elevation changes less than the detection ability were considered as “No detectable change” and were not colored in the maps (Fig. 4).

In the current campsite, the total erosion volume from 2017 to 2018 was approximately 2.52 m^3 (Table 3). The net volumetric change was −2.20 m^3 suggesting that erosion was dominant during the first study period (September 2017 to September 2018). From September

2017 to September 2018, localized vertical erosion was detected around the gully in the current Kuro-dake campsite (Fig. 4a). The maximum vertical erosion exceeded 0.15 m depth at the terminus of the gully running through the center of the campsite. During the second study period (September 2018 to September 2019), the gully remained stable without any significant elevational changes. The net volumetric change was −0.30 m^3, indicating a small amount of soil loss (Table 3).

In the former campsite, both erosion and deposition were assessed between September 2018 and September 2019 (Table 3 and Fig. 4c). The net volumetric change was −1.55 m^3, showing a small amount of soil loss (Table 3). From September 2019 to September 2020, large-scale erosion became dominant, especially in the central area. Notable erosion or deposition was not detected in the lower flat area (northern area). The maximum vertical erosion was 0.2–0.3 m deep (Fig. 4d). The total volume of erosion was 22.67 m^3 (Table 3).

Table 3 Volumetric changes in the ground surface in the current and former Kuro-dake campsites during each study period.

Site	Study period	Erosion		Deposition		Net volumetric change (m^3)
		Area (m^2)	Volume (m^3)	Area (m^2)	Volume (m^3)	
Current campsite	Sept. 2017–Sept. 2018	38.80	−2.52	5.70	0.32	−2.20
	Sept. 2018–Sept. 2019	16.45	−0.67	6.95	0.37	−0.30
Former campsite	Sept. 2018–Sept. 2019	50.14	−3.06	25.52	1.51	−1.55
	Sept. 2019–Sept. 2020	369.86	−22.67	6.95	0.40	−22.27

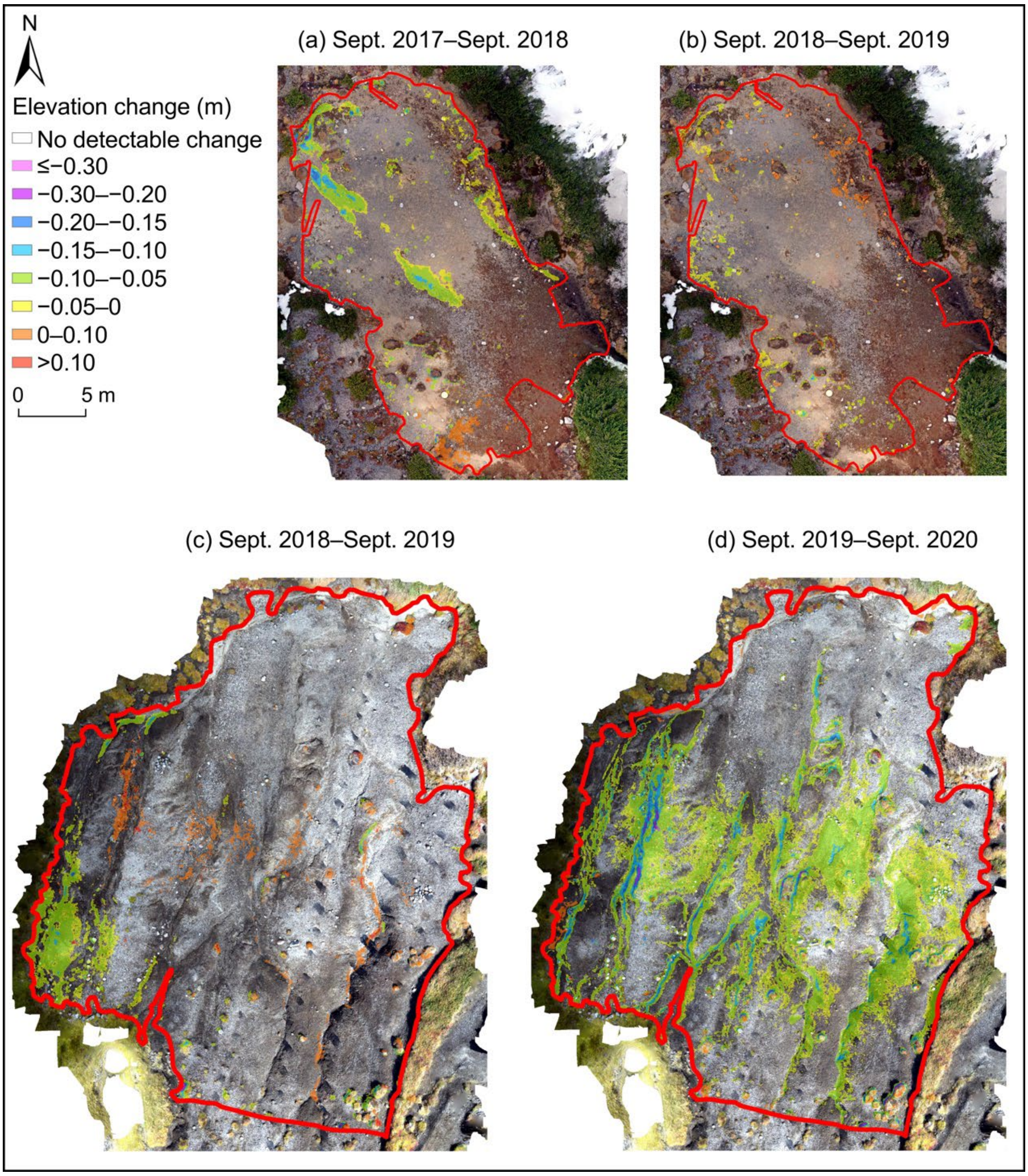

Fig. 4. DEMs of Difference (DoD) maps of the current and former Kuro-dake campsites. (a) and (b): Current campsite. The orthomosaic image of 2019 was used as a base map. (c) and (d): Former site. The orthomosaic image of 2020 was used as a base map.

Figure 5 shows the profiles of the ground surface in the current and former campsites. From 2017 to 2018, the gullies in the current campsite developed both vertically and horizontally (Fig. 5a and 5b). Erosion was observed not only on the gully walls but also at the bottom of the gullies. Gullies in the former campsite were much deeper (Fig. 5c and 5d), and considerable erosion was observed on the gully walls (Fig. 5c). The bottom of these deep gullies remained stable during the short study period.

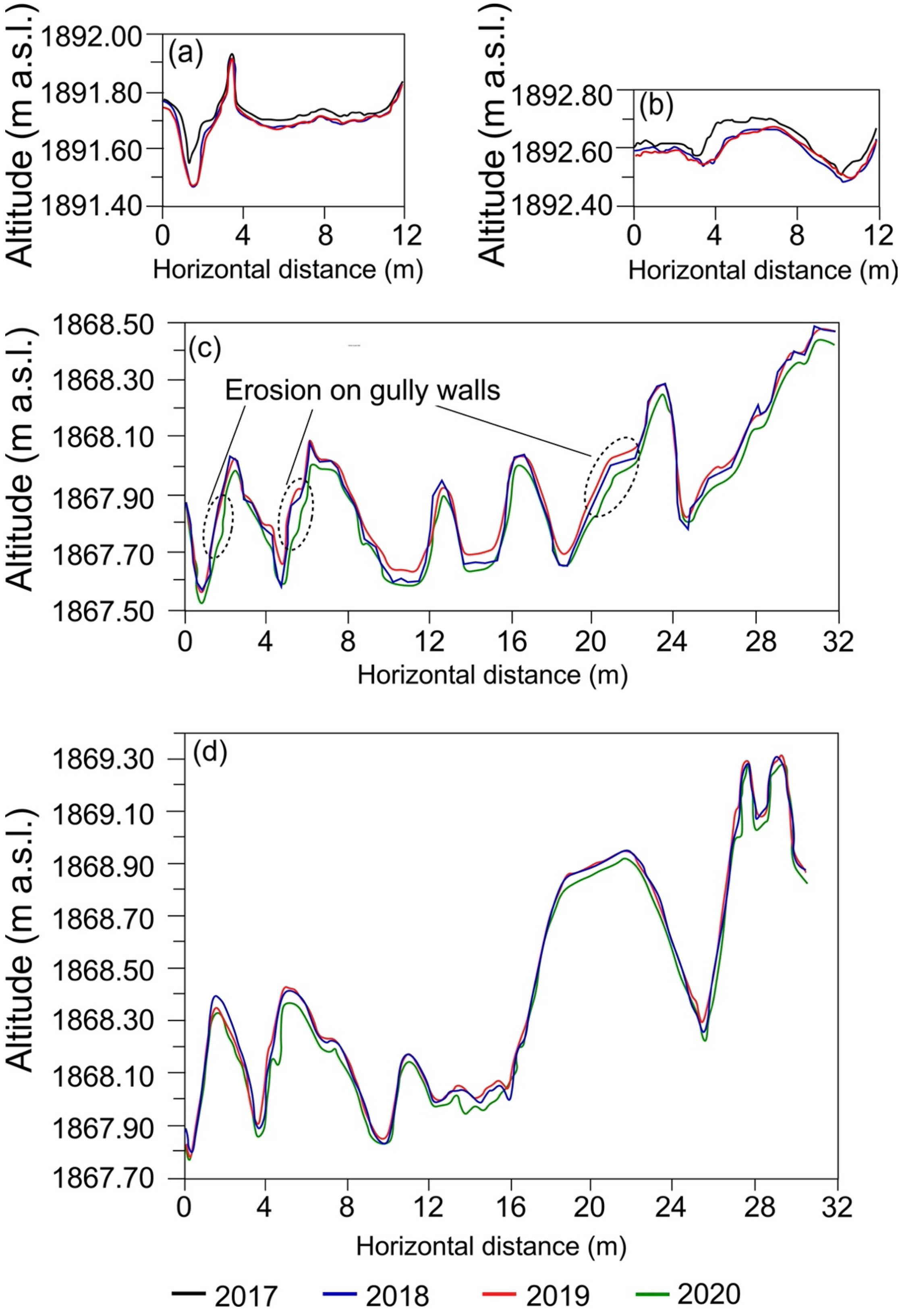

Fig. 5. Changes in the cross-sectional profiles of the ground surface in the current and former Kuro-dake campsites. (a), (b), (c), and (d) correspond to A–A′, B–B′, C–C′, and D–D′ in Fig. 3.

5. Discussion

5.1. Advances in the monitoring of campsite degradation

Our study identified gully erosion of different magnitudes in the current and former Kuro-dake campsites. The shallow gullies in the current campsite represented slight soil erosion at an early stage, which was easily overlooked by park managers. In the former campsite, however, as erosion continued, the shallow gullies deepened, attaining a depth of nearly 1 m (Fig. 5c).

We found that soil erosion in the campsites developed slowly in some years, accompanied by a small amount of soil loss during the short-term period (Table 3). To understand the minor changes that occurred in the campsites during the erosion process, high-resolution and high-accuracy topographic products are required. The high-accuracy DEMs of campsites produced by the SfM photogrammetry survey in this study enabled the detection of vertical changes that exceeded 0.03–0.04 m in the campsites. To the best of our knowledge, the volume of soil loss in the campsites was successfully quantified for the first time. The results of this study not only provide a new method for exploring campsite degradation, but also provide information regarding a new monitoring and management tool. The method used in this study can be widely applied in other protected areas across the world to monitor campsite soil loss with necessary devices (e.g., UAV/pole-mounted cameras and GNSS).

It is highly recommended to set up fixed GCPs around the campsite when planning to utilize repeated SfM photogrammetry surveys to monitor soil erosion. The absence of fixed GCPs can lead to inconsistent quality of georeferencing between different DEMs and influence the quality of change detection (Glendell et al., 2017). We overcame this problem by utilizing fixed steel poles and stones around the campsites as "fixed GCPs," although it was time-consuming. We ensured that the selected fixed objects were remarkable and had sufficient projections in the captured photographs. We believe that utilizing in-situ measured location data of fixed GCPs for georeferencing can help detect topographic changes at the sub-centimeter level, as achieved in a previous study (Eltner et al., 2015).

5.2. Suggestions for campsite management in the future

A deep gully had developed at the lowest corner of the current campsite (Fig. 5a). As gully erosion will extend, the shallow gully at the higher area (Fig. 5b) will soon develop that would be as deep as the lower area. Without management, the current campsite will finally turn into the same condition as the former campsite, where multiple deep gullies exist (Fig. 5c and 5d). To avoid this, park managers must stop or mitigate further erosion in the current campsite before the development of multiple deep gullies. Setting up boulders or wooden fences at the gully terminus is suggested as a specific management action. Active site maintenance is necessary to achieve the sustainable use of the current campsite. Wang and Watanabe (2020) reported that more than half of the campers agreed to introduce tent platforms or tent pads to the current Kuro-dake campsite, indicating that it can be a potential solution to improve the degraded camping environment caused by soil erosion.

Our results demonstrated that site closure cannot effectively minimize the camping impacts where gully erosion has already emerged in the past. Significant soil loss still occurs in and around gullies. In addition, considerable elevation changes (>10 cm) were identified not only around the gullies but also in the areas without gullies (Fig. 4d), indicating the development of new gullies, which was confirmed by comparing the 2019 orthomosaic image with the 2020 image (see Supplementary 1). New gullies can be further developed during the erosion process, suggesting that it is necessary to fill the gullies and conduct rehabilitation in the former campsite as well as other sites in the park when they are closed.

To mitigate the camping impacts completely, vegetation and soil recovery should be promoted in closed sites that are heavily impacted. Cole and Spildie (2007) verified that transplanting native species and amending soil with organics and compost significantly promoted soil and vegetation recovery in closed sites during a 10-year treatment. They estimated that 50% of the vegetation cover by closure alone will recover in approximately 1000 years. However, a combination of several restoration treatments, including scarification, establishing a mulch mat, amending soil with organics and compost, seeding, and transplanting, can shorten this recovery process to approximately 30 years or even less. In the former Kuro-dake campsite, where gully erosion continues, gully development should be controlled initially. Furthermore, decreasing the water flows and transplanting vegetation can be effective in protecting the bases of gully walls (Guerra et al., 2017; Poesen, 2018; Selby, 1993). Cole and Spildie (2007) and Guerra et al. (2017) suggested that mulch mats and geotextiles can be used to reduce erosion, which is important for recovering degraded soil. Scarification accompanied with soil amendments or even transplanting could also increase vegetation cover, which can in turn rehabilitate the eroded ground surface in campsites. However, the suitability of amending soil and transplanting native species in alpine settings needs to be further discussed.

5.3. Management actions to improve gully terrain in the Kuro-dake campsite

Although the erosion volume varied during the short-term monitoring periods, continuous soil loss was observed in the current campsite. The highest soil loss was contributed by gully erosion (Fig. 4a). Without implementing suitable control actions, the gully heads can progressively increase upstream (Ionita et al., 2021; Selby, 1993). The topographic map of 2019 revealed that the gully in the current campsite extended from the deep gully on slope "E" in the northwest to the current campsite (Fig. 6). Hence, terminating the connection between the campsite and slope can be a key management action to reduce further soil loss.

Figure 6 presents a recommendation to terminate further gully development by setting up boulder filling at the cross-section F–F′. Additionally, the deep gully at the lower part "G" can be filled with sand and small rocks or boulders to create steps between the campsite and the slope "E" (Fig. 6). This design can help to reduce erosion while simultaneously provide flat and comfortable surfaces for camping. It is similar to a design in which side-hill campsite is constructed on a sloping terrain and boulders are used to construct retaining walls downslope (Daniels and Marion, 2006; Marion et al., 2018).

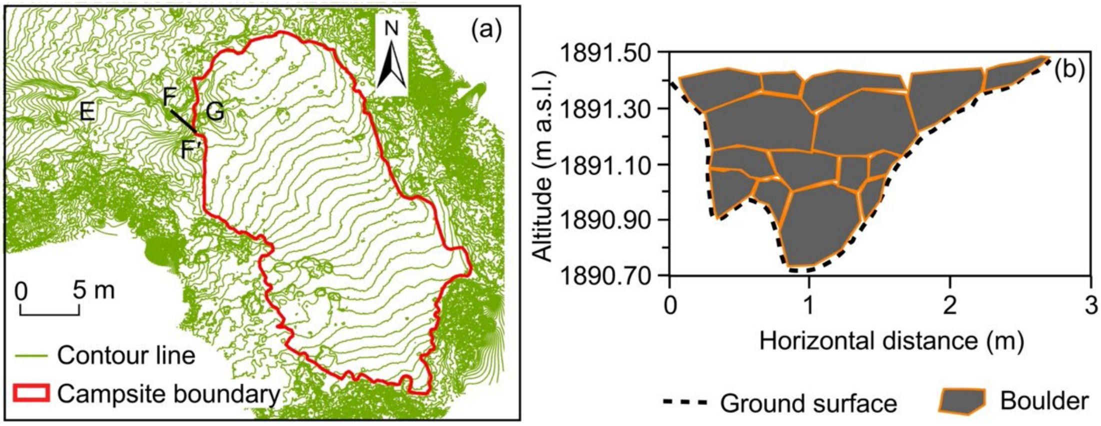

Fig. 6. Example of a design of the campsite in which the connection between gully in the campsite and downward slope "E" is terminated using boulders. (a): Topographic map of the current Kuro-dake campsite in 2019 (contour interval = 10 cm) highlights the location of slope "E" with the deep gully and the cross-section F–F′, which represents a proposed site to be filled by boulders, (b): Illustration depicting the set-up of boulders at F–F′ (The profile was created based on digital elevation model (DEM) of 2019). G: Existing gully.

6. Conclusions

We verified that SfM photogrammetry could be used to monitor soil erosion in campsites with detection ability of a few centimeters. We succeeded in detecting the smallest vertical change of 0.03–0.04 m and the smallest volumetric changes (erosion) of −0.30 m^3 with 95% confidence.

Efforts should be made to stop or mitigate further soil erosion in both current and former Kuro-dake campsites. Burying the gullies with boulders and setting up boulders or wooden fences at the termini of the gullies can be a potential solution to stop or mitigate further erosion. Once eroded, it is not recommended to leave both the current and closed sites unattended. Rehabilitation efforts need to be taken into consideration to avoid the development of new gullies in closed sites. For this purpose, formal management should be introduced to all currently unmanaged campsites in DNP.

Soil erosion monitoring by SfM photogrammetry will provide a better understanding of the campsite degradation trend to national-park managers, which is important for future decision-making regarding campsite management and maintenance. In addition, further studies are needed to explore effective management actions to reduce campsite soil erosion and hence, improve site sustainability. The SfM photogrammetry survey is a potential approach for assessing its effectiveness.

Credit author statement

Ting Wang: conceptualization, methodology, formal analysis, writing – original draft, writing – review and editing, visualization. Teiji Watanabe: conceptualization, methodology, formal analysis, writing – original draft, writing – review and editing, visualization, supervision, project administration, funding acquisition.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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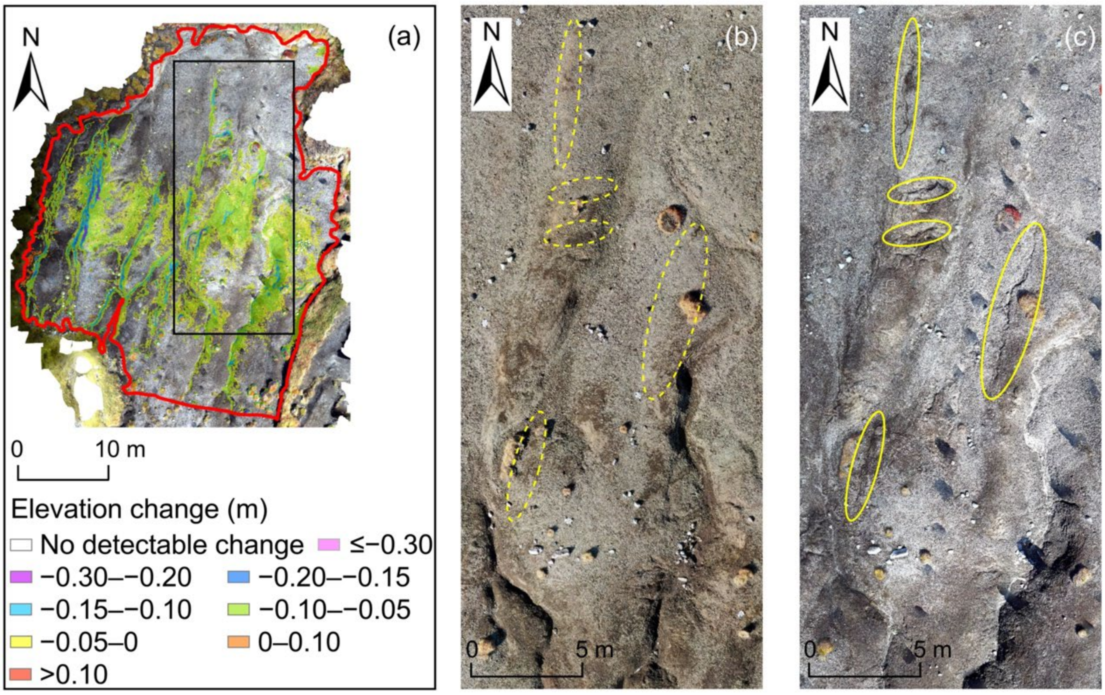
Supplementary material



Supplementary 1. Newly developed gullies on the former Kuro-dake campsite during 2019–2020. (a): the location of the orthomosaic images showing in (b) and (c), (b): orthomosaic image of 2019, and (c): orthomosaic image of 2020. Broken-line circles: absent with gullies in 2019. Solid-line circles: newly developed gullies by 2020. Base map: Digital elevation model of difference (DoD) map of the former Kuro-dake campsite (2019–2020).