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Author(s)	小林, 勇介
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学 位 論 文 内 容 の 要 約

博士（環境科学）　　　　氏 名 小林　勇介

学 位 論 文 題 名

Long-term three-dimensional analyses of trail degradation and proposal for a new partnership management framework in Daisetsuzan National Park, Japan

大雪山国立公園における登山道荒廃の長期 3 次元解析と新たなパートナーシップ管理フレームワークの提言

Chapter 1. Introduction

The growing popularity of recreational activities, associated with the transformation of society and lifestyles, has also affected mountainous areas. Hiking and trekking are among the major recreational activities undertaken in mountainous areas. Trails are the basic infrastructure for hiking and trekking. Trails have the role of guiding visitors to their destinations and protecting the surrounding environment. However, the concentration of use on mountain trails has led to the trail degradation. Trail degradation includes erosion, multiple tracks, widening, and exposure of tree roots. This type of degradation is a problem that not only degrades the landscape, but also threatens the safety of its users.

Since the 1970s, observations and documentation of trail degradation have been conducted in England, Sweden, and the United States. Particularly in the U.S., survey methods were developed to help managers make decisions. In particular, the cross-sectional method (CSA) is the leading survey method for trail studies. Other methods, such as the census method, survey the entire trail. Due to the nature of trails, surveys are extensive. Therefore, every survey method has its strengths and weaknesses. It is extremely difficult to measure the volume of trail erosion. The conventional two-dimensional cross-sectional area has been calculated for years, even today. However, Recent technological advancements of Structure from Motion (SfM) and Multi-View Stereo (MVS) photogrammetry have enabled the measurement of the eroded volume of trail surface. The three-dimensional recording of the entire trail area also reveals detailed topographic changes. This visualizes the relationship between erosion and deposition and topography. Spatial understanding of changes along the trail also helps inform management decisions.

The personnel and budget required for maintenance and management of national parks in Japan are not necessarily sufficient. As a result of the lack of proper management of degraded trails, leading to a vicious cycle of further degradation caused by heavy rains that have occurred in recent years. In light of this situation, Daisetsuzan National Park, located in the center of Hokkaido, has started repairing trails with the help of volunteer trekkers/hikers in 2017. However, due to the limited frequency of trail monitoring in Daisetsuzan National Park, the prioritization of trails for repair and the scientific basis for this prioritization are not adequate. In this study, long-term monitoring using three-dimensional measurement methods such as UAVs and pole photography was conducted from 2014 to 2022 in order to clarify changes and trends in trail degradation.

This study aimed to (1) create high-definition trail data using Structure from Motion and Multi-View Stereo photogrammetry, (2) use high-definition trail data to reveal trail surface changes based on three-dimensional analyses over long periods of time, for the first time in trail science, (3) discuss the effectiveness of the repair works, and (4) propose a new partnership management framework and measures in Daisetsuzan National Park, Japan. Although stakeholders have made significant efforts to manage eroded trails, their effectiveness has not been evaluated. In addition, the method employed in this study has not only academic value but also contributes to the future management of national parks.

Chapter 2. Materials and methods

2.1. Study area

Daisetsuzan National Park (DNP) was designated in 1934 as one of the oldest national parks in Japan. DNP has an area of 2,267.64 km2 and is the largest national park in the country. The approximate annual number of hikers/trekkers in the park was estimated to be 90,000±10,000 in 2019 and 100,000±10,000 in 2022 (unpublished data provided by the Ministry of the Environment). Thick snow covers ground surfaces from early October to the end of June. Therefore, almost all trekkers were concentrated during a short period from July to September. No mountain biking or horseback riding was allowed on the trails in the alpine zones of Japan's national parks. In this thesis, surveys were conducted at two locations in DNP. In Chapter 3, a monitoring survey was conducted at a site called Hokkai-daira to determine changes in the trail. In Chapter 4, the effects of trail maintenance were examined at a location called Kumo-daira.

Between 1991 and 2022, the mean monthly rainfall for June is 84.7 mm, 157.55 mm for July, 192.6 mm for August and 153.0 mm for September at the Sounkyo Meteorological Station in the summer during the study period. In terms of mean daily rainfall, this ranges from 3 mm to

6 mm (Japan Meteorological Agency, 2023).

The mean annual air temperature recorded at Hakuun Hut (2000 m a.s.l.) was -3.8°C, the lowest monthly air mean temperature in January was -21.3°C and the highest monthly mean air temperature in August was 13.9°C in 1985 (Sone and Takahashi, 1988). The area above 1,850 m is widely covered by periglacial landforms such as sorted polygons, sorted stripes, frost cracks, turf-banked terraces, earth hummocks, and palsas (Koaze, 1965; Sone and Takahashi, 1986; Takahashi and Sone, 1988). Permafrost also exists above 1,700 m (Fukuda and Kinoshita, 1974; Fukuda and Sone, 1992; Sone et al., 1988).

2.2. Study methods

In this study, a high-quality digital camera (RICOH GR) was attached to the DJI Phantom 2 from 2014 to 2016. An UAV flew 8 m above the ground to obtain detailed topographic information regarding the ground surface. To reinforce the weaknesses of UAVs, such as battery issues in cold climates and remote areas, as well as a camera-shaking issue due to strong winds, this study adopted pole photography for all surveys from 2017 onwards. RICOH GR2 was mounted on a 5- m long pole. The camera was operated using a smartphone via a Wi-Fi connection. Photographs were taken along both sides of each trail section from various angles, allowing an overlap of more than 80% of the consecutive photographs. Photographs were taken every year from September 2016 to August 2022, except in 2020, because of the spread of COVID-19. RICOH GR and GR2 have a large image sensor (APS-C) and camera weight of 245 to 251 g. It is suitable for attachment to Phantom 2 and a 5-m long pole for vertical photography.

SfM analysis was conducted using images taken by UAVs and poles. The digital elevation model (DEM) created was used to examine changes in the trail over time.

In order to predict the depth which will erosion in future, this study utilized a hand-held dynamic cone penetrometer, PANDA2, originally designed to measure soil compaction. This method is ideal to be applied to national parks because of a non-destructive way of the trail surface. The sounding was carried out at 16 sites. A 1-m to 2-m metal rod was driven into the ground with a hammer. The resistance value at this time was used to determine whether or not erosion can occur in future. A threshold was set at 5000 psi, and the depth at which erosion can occur was defined as the depth at which 5000 psi was reached.

Chapter 3. Changes of trail degradations in *Hokkai-daira*

The survey was conducted by dividing the trail into 10 sections that pass through a flat area formed by lava flows and pyroclastic deposits called the Hokkai-daira, located at an elevation of around 2,060 meters.

The first survey was conducted in 2014. In the first survey in 2014, a large amount of degradation (>200 m^3) was already observed in survey sections on the southeast-facing slope where clayey soil was developed. Total erosion from trail establishment to 2014 or 2016 shows the largest erosion on the direct ascending trail along the fall line located on the southeast-facing slope. PANDA 2 results suggested the potential for additional vertical erosion of more than 1 m in Hokkai-daira.

On the other hand, during the eight years of long-term monitoring from 2014 to 2022, erosion of more than 10 m^3 was observed in study sections covered by pyroclastic flow deposits on the northwest-facing slope, showing a larger amount of erosion than in study sections located on the southeast-facing slope. The difference in erosion was related to snow cover. The fact that there was almost no snow cover in the northwestern direction suggested the influence of water from underground sources. Especially immediately after heavy rainfall, water flow was constant and accelerated the erosion. This indicates that each study section responded differently to heavy rainfall events with daily precipitation exceeding 80 mm that occurred in 2016, 2018, and 2022. The results indicate that identifying changes in erosion rates is important in determining which trails should be repaired.

Based on 6 or 8 years of monitoring, trail alignment, surface materials, and hydrologic conditions such as snow cover are important for trail erosion. This indicates that trail erosion is a very localized phenomenon. In addition, the three-dimensionaly brings a new interpretation to trail science, which has shown mixed results in the past. Repeated monitoring by three-dimensional method and data storage, as this chapter has done, is an effective method for trail management.

In Chapter 3, three-dimensional data were used to obtain values related to the width and depth of the trail and to identify changes in the cross-sectional shape. From the knowledge of fluvial geomorphology, the flow of surface water over the trail can be inferred. This will be useful for trail maintenance.

Chapter 4. Evaluations of trail repair works in DNP

The Japanese Ministry of the Environment and local governments manage mountain trails in national parks; however, there is no official management or construction organization owing to a lack of personnel and budget. Most trail repairs are voluntarily conducted by mountain lodge owners and local mountaineering associations. However, traditional voluntary trail management has faced difficulties owing to the aging of technical staff and volunteers in recent decades and the deterioration of business conditions caused by COVID-19 over the past few years (Aikoh, 2021; Yasuhara and Aikoh, 2022). Therefore, more trekkers/hikers are invited as volunteers to maintain and manage trails and be involved in repair work in Japan's mountain national parks, including DNP. Trekkers/hikers are highly motivated to participate in repair work because they can contribute to nature conservation through their work. Such initiatives have the potential to spread to more protected areas and other mountain trails in Japan (Watanabe et al., 2004) as well as other parts of the world.

This chapter focuses on trail repair and examines its effectiveness by using the three-dimensional approach validated in Chapter 3. Although many monitoring studies of trail erosion have been conducted, this chapter is the first attempt to adopt a combined approach of long-term monitoring over a six-year period and an in-situ observation study on the effectiveness of repair works.

A six-year long-term monitoring of trail repairs in Kumono-daira was carried out. The water and sediment control techniques implemented in DNP, involving the use of palm fiber bags, have proven to be effective in protecting side slopes from heavy rainfall and preventing sediment flow. This method will be successful in national parks with trails located in remote, cold, or alpine areas. However, it was noticed that sediment from the upstream area continued to accumulate despite these measures, resulting in the storage capacity being filled after three years. This emphasizes the critical importance of regular maintenance and monitoring for trail upkeep.

Chapter 5. General Discussion for future management of DNP's trails

In the sensitive environment of Daisetsuzan National Park, repair work needs to be conducted carefully, and long-term monitoring is essential. However, it is not practical to cover the entire 300 km of trails due to the lack of specialized staff and budget.

Therefore, as in the case of repair work, the participation of volunteer trekkers/hikers may play a significant role in acquiring basic data that is essential for decision-making in trail maintenance and management.

In this study, UAVs and pole photos were used, but Apple's iPhone is equipped with Lidar, which makes it relatively easy to acquire similar three-dimensional data. By establishing a data platform and feedback system, it is possible to provide value in the form of trail maintenance and management, and ultimately contribute to the preservation of the natural environment. Long-term monitoring using three-dimensional data and the cooperation of volunteer hikers/trekkers are essential to enhance the value of national parks and to ensure sustainable use of trails. To this end, it is desirable to have a system that allows for integrated management of human resources and monitoring data. Integrated management would also allow for quicker response to trail repairs immediately after heavy rains.

Three-dimensional visualization facilitates scientific evaluation and decision-making. Additionally, by involving hikers and individuals from diverse backgrounds, sustainable data acquisition and trail repairs can be carried out. These efforts are effective not only for trails in Japan, but also for trails worldwide. DNP's initiatives will serve as a leading role model for the international community.

The establishment of the Daisetsuzan Foundation is necessary to ensure comprehensive and efficient maintenance management.

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