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Assessment of Surface Collapse Risk Considering Forest Management Information in the Aso Region

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Abstract - Increased risk of sediment-related disasters, particularly surface collapse, has been observed in the Aso region of Kumamoto Prefecture due to climate change. Ecosystem-based disaster risk reduction (Eco-DRR) has gained attention as a method to mitigate such risks. Forests are known to increase soil strength through their root systems, reducing the risk of sediment disasters, particularly surface collapses. In this study, we aim to quantitatively assess, through statistical methods, the impact of forest conditions on the occurrence of surface collapses in the Aso region of Kumamoto Prefecture, considering important forest management indicators such as the relative spacing index, which represents the density of standing trees. In this study, to gain insights into disaster mitigation and prevention with consideration for ecosystems, we analysed surface collapses that occurred in the Aso area during the 2012 Northern Kyushu heavy rain event. We constructed and analysed a random forest model (RF) to assess the impact of various landslide factors, including the state of vegetation, on the occurrence of slope collapses. The results of the RF indicated that the most significant factor was the 1-h maximum rainfall, followed by geology, while the importance of average tree height and relative stem distance ratio was relatively small. A partial dependence plot for the relative stem distance ratio revealed that the lowest probability of landslide occurrence corresponded to a value of 23. This evaluation of the impact of the relative distance ratio, which indicates tree density, on surface collapses can provide valuable insights for future considerations in vegetation management to reduce the risk of surface collapses.

***Keywords*:** surface collapse, Ecosystem-based disaster risk reduction, ecosystem, random forest, vegetation

1. Introduction

In recent years, the risk of sediment disasters has increased owing to climate change. Even in the Aso region, there have been numerous reports of damage caused by sediment disasters. Forests are known to increase soil strength through their root systems, reducing the risk of sediment disasters, particularly surface collapses [1][2]. Therefore, in implementing ecosystem-based disaster risk reduction (Eco-DRR) mountainous regions of Japan, which are covered by vast forests, it is important to effectively utilize the disaster risk reduction functions of forests by managing them appropriately. Hence, in this study, we aim to quantitatively assess, through statistical methods, the impact of forest conditions on the occurrence of surface collapses in the Aso region of Kumamoto Prefecture, considering important forest management indicators such as the relative spacing index, which represents the density of standing trees.

2. Study Area Description

The Aso region is located in the central part of Kumamoto Prefecture in Japan, with an area of approximately 376 km2 (Fig.1). The Aso volcano, situated near the center of the study area, is a caldera measuring approximately 25 km north to south and 18 km east to west in the central part of Kyushu. The target disaster for this study is the 2012 Heavy Rainfall Disaster in Northern Kyushu. During this event, which occurred from July 11th to 14th, heavy rainfall exceeding 100 mm per hour and 800 mm in 24 h was observed in the northern part of Kyushu, primarily in Kumamoto, Oita, and Fukuoka prefectures, leading to floods and sediment disasters in various locations (Fig.2).

3. Methods

3.1 Extraction of surface collapse areas and creation of analysis units.

The extraction of surface collapse areas was conducted using the method proposed by Asada et al. [3]. A total of 1,347 surface collapse areas were identified (Fig. 3). For the creation of analysis units, slope units (referred to as SUs) were generated using GIS (Fig. 4). The surface collapse areas extracted were overlaid with the slope units, and the SUs were classified into two categories: those where surface collapses occurred and those where they did not.

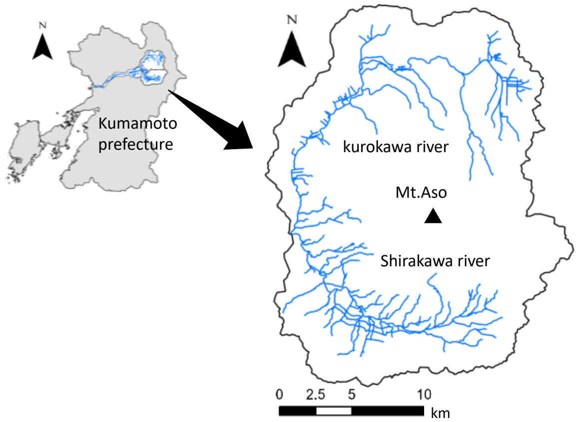

Fig. 1: Location of the study area

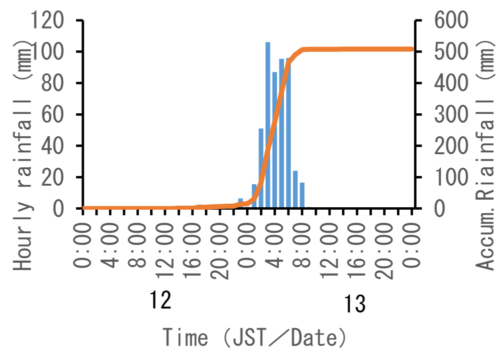

Fig. 2: Hourly rainfall and cumulative rainfall from July 11 to 12, 2012 at Aso Otohime Observatory, Kumamoto Prefecture

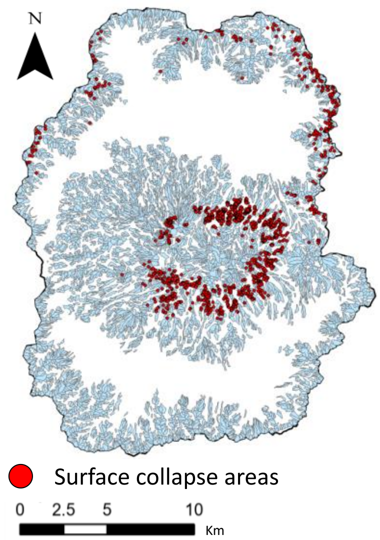

Fig. 3: Distribution of surface collapse areas

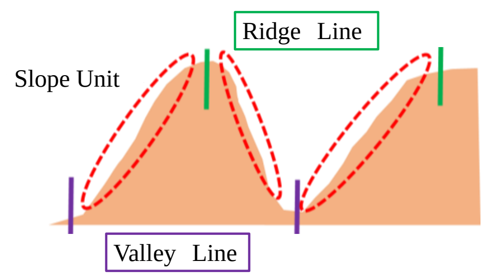

Fig. 4: Image of slope unit

3.2 Data Collection

We collected various data to assess the risk of surface collapse. We collected data on elevation [4], slope [5], aspect [6], relief [7], stream power index (SPI) [8] [9], topographic wetness index (TWI) [8] [9], surface geology [10], 1-h maximum rainfall [11], and forest management information such as tree height, tree density, and relative yield index. Elevation, slope, aspect, relief, SPI, and TWI were derived from a digital elevation model (DEM) based on pre-disaster LP data. The surface geology data were created by referring to the Aso Volcanic Geology Map by the National Institute of Advanced Industrial Science and Technology [12]. The 1-h maximum rainfall data were obtained using the 1-km mesh analysis precipitation data provided by the Japan Meteorological Agency [13]. Tree height and relative spacing ratio were generated from LP data. The relative spacing ratio, calculated from tree height and tree density, is an indicator representing the ratio of the average distance between trees to the average tree height of the canopy layer.

3.3 Statistical analysis

We used random forest (RF) model to evaluate the impact of factors, including vegetation, on surface collapses. RF is RF is an ensemble learning method that constructs numerous decision trees and makes a decision based on the majority of of these trees, smoothing out the overfitting of decision trees [14]. RF can be used for both classification and regression. In In this study, the RF model was constructed as regression. Using the constructed model, predictions are made on the out of bag (OOB) data, and the mean squared error (MSE) between the predicted values and actual measurements is computed [15]. The method used to calculate importance was the increase in mean squared error (IncMSE) approach, which estimates how much the MSE increases when making predictions without a particular explanatory variable [14]. RF constructs models with ntree and mtry as the hyperparameters, which were set via cross-validation. Ntree represents the number of decision trees to be created, while mtry indicates the number of explanatory variables used when generating decision trees. Using the constructed RF model, partial dependence plots related to the relative spacing ratio were created to understand the impact of the relative spacing ratio on surface collapse. To validate the accuracy of the constructed RF model, we calculated the area under the curve (AUC) using the receiver operating characteristic (ROC) curve. The AUC represents the area under the curve of the ROC curve. An AUC value of 0.7 or higher indicates good explanatory power of the model for the target variable, while a value below 0.5 indicates no explanatory power [16]. The analyses were conducted using R version 3.6.1.

4. Results

As a result of constructing the Random Forest model, the most significant factor was found to be the 1-h maximum rainfall in one hour, followed by geology. The importance of average tree height and relative spacing ratio was relatively small. The model exhibited a high accuracy with an accuracy rate of 0.84, a precision of 0.04, a sensitivity of 0.88, a specificity of 0.83, a cutoff value of 0.0066, and an AUC of 0.92, indicating that a very precise model was created. Additionally, the creation of partial dependence plots for the relative spacing ratio revealed that the value of the relative spacing ratio, which minimized the probability of collapse, was 23. When considering the interaction between the 1-h maximum rainfall and the relative spacing ratio in the partial dependence plots, it was clear that while the probability of collapse increases with higher maximum rainfall, setting the relative spacing ratio to 23 can reduce this probability. Furthermore, when considering the interaction between geology and the relative spacing ratio, the value of the relative spacing ratio that minimized the probability of collapse was 23 for all types of geology. However, the behaviour regarding the probability of collapse varied with each type of geology.

5. Discussion

The importance calculated by the RF model indicated that the 1-h maximum rainfall was the most significant factor, followed by geology. The disaster targeted in this study was heavy rainfall exceeding 100mm per hour, and the impact of this trigger was very significant, which is why its importance was high. Geology showed an importance level comparable to that of the 1-h maximum rainfall. The surface collapses that occurred in the study area were predominantly in volcanic ash layers [17]. Volcanic ash layers are extremely permeable, and it has been pointed out that collapses are likely to occur at the boundary with less permeable layers [18]. Therefore, it is believed that the importance of geology, which is closely related to rainfall, was high.

The relative spacing ratio is an index that represents the tree density, and as the tree density increases, the amount of root mass also increases. However, it has been reported that if the trees are too dense, the light inside the forest decreases, leading to a reduction in undergrowth vegetation [19]. Therefore, it is presumed that there is an optimal relative spacing ratio that minimizes the probability of collapse, and in this study, the probability of collapse was found to be the lowest when the relative spacing ratio was 23, falling below the cutoff value. In coniferous forests, a relative spacing ratio below 18 is considered overcrowded, and above 20 is considered sparse. The result of 23 obtained in this study suggests that thinning coniferous forests to allow light inside can help prevent surface collapses. However, since direct data on undergrowth vegetation was not incorporated into the analysis, future studies should consider the state of undergrowth vegetation and evaluate the relationship between the relative spacing ratio and undergrowth vegetation.

6. Conclusion

In this study, to gain insights into disaster mitigation and prevention with consideration for ecosystems, we analysed surface collapses that occurred in the Aso area during the 2012 Northern Kyushu heavy rain event. We constructed and analysed a Random Forest model to assess the impact of various landslide factors, including the state of vegetation, on occurrence of slope failures. The results of the Random Forest indicated that the most significant factor was the hourly rainfall, followed by geology, while the importance of average tree height and relative stem distance ratio was relatively small. A partial dependence plot for the relative stem distance ratio revealed that the lowest probability of landslide occurrence corresponded to a value of 23. This evaluation of the impact of the relative stem distance ratio, which indicates tree density, on surface collapses can provide valuable insights for future considerations in vegetation management to reduce the risk of surface collapses.

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