Land Cover and Characteristics of Landslides Induced by the 2018 Mw 6.7 Eastern Iburi Earthquake, Hokkaido

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More than 6000 landslides over 400 km² were triggered by the Eastern Iburi Earthquake that occurred on September 6, 2018, in Iburi Sub-prefecture, Hokkaido. A large amount of sediment was transported downstream in gentle and hilly landscapes (< 500 m in elevation) by the landslides. The landslides occurred within two major land cover types: forested areas (FA) and logged areas (LA). Here, the characteristics of landslides within these different land cover types were evaluated based on GIS analysis and field investigation. A total of 1440 landslide scars were identified in an area of 18.9 km² consisting of 87% FA and 13% LA. The ranges of the slope gradient within the two land cover types were identical, from 30 to 40°. The mean landslide area in LA at 2306 m² (standard deviation [SD] : 1675 m²) tended to be greater than that in FA (mean : 1762 m² ; SD : 1749 m²). Based on the field investigation, the mean depth of landslides in FA (1.5 m) and LA (1.4 m) were similar, while the mean estimated volume of the landslides was 3610 m³ in FA and 6359 m³ in LA. The mean runout distance of landslides in LA was longer at 231 m (SD : 140 m) compared to that in FA at 146 m (SD : 140 m). The short runout distance in FA was possibly associated with a reduction in sediment momentum through the presence of wood pieces in FA. The findings of our study suggest that vegetation cover and the resultant differences in landslide size and runout distance are important factors for evaluating potential earthquake-related disasters, and future planning in forest management.

Key words : earthquake-triggered landslide, topographic characteristics, landslide mobility

1. INTRODUCTION

Earthquake-induced landslides are a major sediment disaster that can lead to significant fatalities and destruction of infrastructures [Owen et al., 2008]. Numerous studies have investigated the characteristics of earthquake-induced landslides worldwide. By studying the 2015 M. 7.8 Gorkha earthquake in Nepal, Roback et al. [2018] identified that slopes with gradients ranging from 40 to 50° and high-relief Himalayan mountainous topography (2500-5000 m a.s.l.) increased susceptibility to landslides. A high proportion of landslides occurred on hillslopes with gradients of 30-40° in the 2013 M. 5.9 Minxian earthquake in China [Tian et al., 2016]. In Japan, Koyanagi et al. [2020] demonstrated that landslides occurred on upwardly convex landforms in the 6.9 km² Tokosegawa watershed of the Mount Aso volcano region in the 2016 M. 7.0 Kumamoto earthquake.

The mobility of landslides is an important factor in their characterization. Guo et al. [2014] reported that the 46 landslides caused by the 2008 M. 7.9 Wenchuan earthquake traveled for 347-4170 m depending on the slope gradient. A rainfall-induced landslide in the 2014 Oso disaster in Washington, United States, was transported for approximately 1 km because of a high water content and liquefied conditions [Iverson et al., 2015]. Kharismalatri et al. [2017] showed that 33 deep-seated landslides traveled for 130-3310 m depending on the stream gradient and inflow angle.

Vegetation ground cover is another key factor for characterizing landslides and their mobilities in...
forested landscapes [Sidle and Ochiai, 2006]. In general, both the horizontal and vertical extents of tree root systems play an important role in stabilizing hillslopes by anchoring and binding [Schmidt et al., 2001; Cohen and Schwarz, 2017]. In the Kumamoto earthquake in Japan, Koyanagi et al. [2020] found that the landslide density of steep hillslopes (> 40°) in grassland tended to be high compared to the number of landslides observed on forested slopes due to the difference in root reinforcement. They also found that sediment supplied by landslides in forested areas accumulated in channels because the accumulation of wood in channels reduced the mobility of the sediment.

On September 6, 2018, the Mw 6.7 Eastern Iburi earthquake in Hokkaido, Japan, induced more than 6000 landslide scars over 400 km² of hilly topography (<500 m a.s.l.). Most of the landslides were categorized as shallow landslides, with a sliding surface to a depth of 1.5 m in the pumice layer [Yamagishi and Yamazaki, 2018]. Landslides occurred mostly in forested areas, although different areas, such as those with recent logging, were observed depending on management history. Therefore, the occurrence and size of landslides possibly differ depending on land cover conditions. The mobility of landslide materials may also differ by vegetation type.

Therefore, the objectives of this study were (1) to examine the characteristics of landslides induced by the 2018 Mw 6.7 Eastern Iburi earthquake occurring on different land cover types and (2) to evaluate the mobility of landslide materials within the different vegetation cover areas. We focused on the differences in vegetation cover between recently logged areas (<15 years) and mature forested areas.

2. RESEARCH AREA

This study was conducted in a total study area of 18.9 km² consisting of 18 sub-watersheds ranging in area from $4 \times 10^{-7}$ km² to 2.5 km². The study area is located 10 km northwest of the epicenter of the Eastern Iburi earthquake, specifically in the northern part of Apporo Dam in Tomisato area, Iburi Sub-prefecture, Hokkaido (Fig. 1). We selected this area because of wide ranges of elevation from 36 to 400 m for examining landslides. The mean annual precipitation is 997 mm and the mean air temperature is 6.7° (AMeDAS Atsuma, 1976-2019 data). The dominant vegetation cover in this area is secondary deciduous forest (e.g., Betula platyphylla, Quercus mongolica) and mixed-conifer forest or conifer plantation such as larch (Larix kaempferi) and Todo fir (Abies sachalinensis), considered as Forested Areas (FA). The dominant understory vegetation is Sasa dwarf bamboo (Sasa kurilensis) that mostly was found in the Logged Areas (LA), located in the southern part of our study area. The underlying geology in this area is Neogene sedimentary rock covered by various pyroclastic deposits such as tephra and andosol.

The soil profile in our study areas varied depending on the thickness of pyroclastic fall deposits. The most recent pyroclastic fall deposits found in our study
location (southern area) are from Mount Tarumae and are named Ta-b (1667 CE), Ta-c (2.5 ka), and Ta-d (9.2 ka) (Fig. 2a and 2b). We also found pyroclastic deposits consisting of Ta-d and Eniwa (20 ka) in the northern part of our study area (Fig. 2c and 2d). Based on field observations, all landslides in the study area are considered as shallow landslides with depths of 1.5 m collapsed over the pumice layers of Ta-d. Sediments and woody debris from hillslopes were transported in channels (Fig. 3a). Some of the materials appeared to be liquefied and accumulated in downstream channels (Fig. 3b). Mobilized sediment was also transported toward agricultural areas (Fig. 3c) and caused damage to properties.

3. METHODS

This study consisted of GIS analysis and field investigation. We used DEM derived from Light Detection and Ranging (LiDAR) data with a resolution of 0.5 m and orthophoto imaging with a resolution of 0.2 m taken on September 11, 2018. Based on shaded relief and orthophoto visualization, we delineated areas into landslide scars, transport, and deposit zones based on the method proposed by Burns and Madin [2009]. The topography of landslide scars was identified based on concave topographic characteristics using the 0.5 m DEM data. Other topographic characteristics such as elevation, slope gradient, and the length and width of landslide scars were also measured. Minimum Bounding Geometry tools were applied to estimate the width and length of landslide scars [Tian et al., 2016].

The land cover of forested areas (FA) and logged areas (LA) were distinguished by visual interpretation using an orthophotograph. FA was demarcated by dark green vegetation cover (Fig. 1a) and LA was identified by the light green color (Fig. 1b) corresponding to the understory vegetation (Sasa dwarf bamboo) after clear-cutting, with clear skid trails. The total areas of FA and LA were 16.4 and 2.5 km², respectively.

Among the landslides identified from the GIS analysis, we selected 25 (15 in FA and 10 in LA) for field investigation. The landslides for investigation were chosen based on equal quartile distributions of landslide areas. The length and width of the landslide scars were measured using a portable laser distance meter, and the depth of landslide scar was measured at three locations (upper, left, and right sides) of each landslide scar using a 2-m rod. Then, the mean depth of the landslides was calculated. We also identified three depths of major root networks in each landslide scar and estimated the mean root depth. Because Ta-d with a reddish color is one of the key soil layers [Kameda et al., 2020; Li et al., 2020], the depth of the Ta-d was also measured in the field.

We calculated the area of a landslide through a rectangular shape multiplication of the width and length of the landslide estimated from the field investigation. Individual landslide volumes were estimated by multiplying the landslide rectangular area by the depth of the landslide scar. We then developed a relationship between the landslide area and the
where $A_i$ is based on GIS analysis and $V_i$ is based on the field investigation.

The runout distance of the landslides was measured when the transport material could be clearly distinguished [Lin et al., 2013]. The runout distance of the landslides is defined as the length of the traveled-landslide materials from the topmost point of the landslide scar to the end of the landslide toe (Fig. 4) [Devoli et al., 2009]. We applied the Minimum Bounding Geometry tool to assess the landslide runout distance.

We performed statistical analysis using Student’s t-test with a 95% confidence interval to obtain the differences between landslide characteristics occurring on FA and LA. All GIS analysis was performed in ArcGIS 10.3 (Esri, Redlands, CA, USA).

4. RESULTS

A total of 1440 landslide scars were identified with a mean overall density of 48 landslides/km$^2$ and a maximum density for an individual sub-catchment of 218 landslides/km$^2$ (standard deviation [SD]: 50.6 landslides/km$^2$). Of these, 92% had an area $< 3 \times 10^3$ m$^2$, while the area of the largest landslide was $18 \times 10^3$ m$^2$; the median of landslides area was 1377 m$^2$. The landslide area per unit area (landslide area ratios) was 0.14 km$^2$/km$^2$. There were 1243 FA landslides (86.3%) with a density of 76 landslides/km$^2$ and 197 LA landslides (13.7%) with a density of 79 landslides/km$^2$. The mean and median FA landslide areas were 1764 m$^2$ and 1306 m$^2$, and the mean and median LA landslide areas were 2375 m$^2$ and 1998 m$^2$, respectively. The landslide area ratios of FA and LA were 0.15 km$^2$/km$^2$ and 0.18 km$^2$/km$^2$, respectively.
All landslides occurred within an elevation range of 40-340 m, with a high percentage of landslides occurring between 120 and 200 m (Fig. 5a). The elevation range for FA landslides was higher (40-340 m) than the LA range (60-240 m). Both FA and LA landslides were concentrated on slopes with gradients ranging from 25 to 40° (45%) (Fig. 5b).

For the 25 landslides in the field investigation (Fig. 6), the mean values of the landslide length and width were 80 m (SD : 43 m) and 35 m (SD : 19 m), respectively. The mean landslide area (2898 m²) was similar to the mean value estimated in the GIS analysis (2626 m²). The mean landslide width did not differ significantly between FA and LA, although the landslide length was significantly longer in LA (mean : 108 m) than in FA (mean : 63 m) (p-value < 0.05).

The mean depth of landslide scars was 1.5 m (SD : 0.3 m) in FA and 1.4 m (SD : 0.5 m) in LA. The landslide slips surfaces in FA and LA occurred at the interface with the Ta-d soil layer or within the Ta-d with mean depth of 1 m. The root depth differed significantly between FA (mean : 0.9 m ; SD : 0.5 m) and LA (mean : 0.4 m ; SD : 0.5 m) (p-value < 0.05). The overall mean volume was 4709 m³, with an FA mean of 3610 m³ and an LA mean of 6359 m³.

The runout distances of 342 landslides in FA and 35 landslides in LA were identified. The mean runout distance was 154 m, ranging from 14 to 960 m. The mean runout distance in FA was 146 m (SD : 140 m), while that in LA was 231 m (SD : 168 m). In FA, 87% of runout distances fell in the range of 20-250 m. By contrast, 86% of the runout distances in LA landslides were between 100 and 500 m (Fig. 5c).

5. DISCUSSION

5.1 Characteristics of landslides
The landslide density observed in our study area, 48 landslides/km², was higher than that reported in previous studies. For example, Koyanagi et al. [2020] showed that the landslide density in the 6.9 km² Tokosegawa watershed in Kumamoto was 12.4 landslides/km². The maximum landslide density in a single sub-catchment in our study was 218 landslides/km², whereas other studies have reported 1.36 landslides/km² for the 2008 Mw 7.9 Wenchuan earthquake, China [Dai et al., 2011] and 30 landslides/km² for the 2004 Mw 6.6 Niigata Chuetsu Earthquake, Japan [Kieffer et al., 2006]. The high density of landslides in our study area is possibly related to the poorly consolidated volcanic soil deposits and liquefaction by shaking on hillslopes, particularly at slope gradients of 30-40° [Koyanagi et al., 2020; Ling and Chigira, 2020].

Despite the high density, the areas of our individual landslides (mean : 1835 m²) tended to be small compared to values reported in previous studies. For example, among 22,528 identified landslides in the 2013 Mw 6.6 Lushan earthquake, China, 49% of landslide areas fell in the range of 10²-10³ m² [Xu et al., 2015]. Tsou et al. [2018] showed that more than 50% of 13,097 landslides in the 2015 Mw 7.8 Gorkha
earthquake in Nepal had areas ranging from $10^3$ to $10^6$ m$^2$. These landslides occurred in areas of high relief, but the sizes of the landslides of our study were similar to the landslides reported by Koyanagi et al. [2020] in the 2016 M$_{w}$ 7.0 Kumamoto earthquake, Japan (range: 34-8835 m$^2$; mean: 1511 m$^2$), possibly because of similar local relief.

The proportion of small landslides ($< 500$ m$^2$) identified on the LiDAR image was 15%. The smallest landslides in FA and LA were 17 and 25 m$^2$, respectively. Brardinoni et al. [2003] found that landslides with areas $< 650$ m$^2$ in a 50-year-old forest and those with areas $< 150$ m$^2$ in a clear-cut region were not detectable, and could bias monitoring based on aerial imagery investigations. Therefore, although we successfully examined the detectability of small landslides, a full investigation of landslide patterns should still use a range of methods to improve the detectability across a range of different land cover types [Guzzetti et al., 2012].

5.2 Land cover and landslides

The difference in landslide area between FA and LA is possibly associated with differences in the availability of root networks. Landslide scars in our study sites were associated with tephra layer, which was agreed to findings by Yamagishi and Yamazaki [2018] and Osanaï et al. [2019]. Importance of sequences of soil layers (e.g., tephra and andisol) for landslide scars were also reported by Arata et al. [2020] in Kumamoto earthquake. Because the landslide scars were deeper than root depths (Fig. 7b), the hillslope stability was not affected by the vertical root network. Hence, the availability of the horizontal root system likely affected the width and length of the landslide scars. LA landslides mostly occurred in areas with Sasa kurilensis ground cover, which has a fine and shallow root system (Fig. 8b) [Fukuzawa et al., 2007] compared to tree roots (Fig. 8a). By contrast, the extended horizontal tree root networks in FA provide more cohesive and lateral hillslope reinforcement [e.g., Armone et al., 2016]. Koyanagi et al. (2020) also found that landslide in forested area tended to be small compared to grass lands in 2016 Kumamoto Earthquake. Schmidt et al. [2014] found that tree density and the related lateral root network is important for hillslope stability. By numerical models, availability of lateral roots reduced the probability of large landslides [Sakals and Sidle, 2004; Schwarz et al., 2010; Schwarz et al., 2016]. The volume of sediment produced by landslides in LA was greater than in FA because of the difference in landslide area (Fig. 7a).

By contrast with landslide area and volume, we were not able to find any effect from land cover on the occurrence of landslides at different slope gradients. Koyanagi et al. [2020] observed a high landslide density on steep slopes (> 40°) in the 2016 M$_{w}$ 7.0 Kumamoto earthquake. The differences between our study and the findings of Koyanagi et al. [2020] may be associated with differences between the landscapes, as the Iburi area has far fewer steep hillslopes than the Kumamoto area.

The mobility of landslides also differed between FA and LA. The mixture of trees and sediment within the landslide materials in FA results in lower mobility [Booth et al., 2020]. A logjam formation provides more opportunities for sediment storage in channels in FA [Sidle et al., 2018; Koyanagi et al., 2020], and the momentum of landslide materials may also be reduced by riparian stands along channels [Guthrie et al., 2010]. Furthermore, the presence of trees on a
hillslope may reduce the availability of soil water by interception loss and transpiration. In general, interception loss and transpiration are higher in FA than in LA [Goeking et al., 2020]. The lower interception loss and transpiration in LA likely elevates initial soil moisture conditions [i.e., Rodriguez-Iturbe, 2000] and promotes liquefaction for soil mobility. Therefore, vegetation plays an important role in altering the size and mobility of landslides by changing the hydrogeomorphic properties of the soil in hillslopes and the mobilized sediment in runout processes.

6. CONCLUSION

A detailed investigation based on GIS analysis and field investigation revealed that a high density of landslides produced a large amount of sediment in channels. Although a similar landslide depth was observed in both FA and LA, a difference was observed in the sizes of landslides in different land cover types, possibly due to reinforcement by the lateral root network. The runout distance of landslides was also affected by the availability of trees on the hillslope. The findings of our study will help in evaluating sediment budgets and subsequent sediment movement after earthquakes in catchments with different vegetation cover [Sidle et al., 2018].

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