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Author: Takaoka, Sadao

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Regional Variations in Vegetation Patterns on Landslides in the Snowy Mountains of Central Japan

Sadao Takaoka

takaoka@isc.senshu-u.ac.jp

Department of Geography, Senshu University, Kawasaki-Shi, Kanagawa 214-8580, Japan

Landslides have emerged as one of the most important disturbance agents in mountainous ecosystems. In mountainous regions in Japan, the locations of old landslides often have heterogeneous vegetation that is peculiar to landslide areas. However, little is known about how and why vegetation patterns differ among landslide sites within a region. In this study, I describe the variations in vegetation at different landslide sites within a region and examine the possible causes of the regional diversity of vegetation at these sites. I classified the vegetation on 1703 landslides by interpreting aerial photos of the 1421 km^2 study region. Nine types of vegetation were classified. The results show that the heterogeneity of the vegetation increased with the maximum snow depth, and the number of vegetation types on landslide bodies increased with latitude and altitude. Among the 1703 landslides studied herein, 62 included mires (wetlands). Sites with mires were concentrated in areas with heavy snowfall and certain lithologies, such as ultramafic rocks and nonalkaline mafic volcanic rocks. My analysis using Random Forest, a machine-learning algorithm, indicates that maximum snow depth and summer temperatures had the greatest impact on the number of vegetation types and mires on the landslide bodies. The results of this study suggest that snowy conditions have long-term effects on vegetation structure and diversity on old landslide sites.

Keywords: Landslide ecosystem; vegetation diversity; mountain wetland; snowy conditions; lithology; Japan.

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Introduction

In recent years, landslides have emerged as one of the most important disturbance agents in mountainous ecosystems, especially in humid tropical regions (Restrepo et al 2009; Walker and Shiels 2013). A landslide results in heterogeneous vegetation (Parker and Bendix 1996). One of the causes of this heterogeneity is the different stages of plant succession that follow disturbances by landslides. Spatial variations in plant succession have been found both within landslide sites (Myster and Fernández 1995; Walker et al 1996; Velázquez and Gómez-Sal 2008) and among landslide sites in a region (Miles and Swanson 1986; Myster et al 1997; Shiels et al 2008; Elias and Dias 2009). Most previous studies have focused on the initial stages of plant succession over a few years or decades after a landslide had occurred. Such heterogeneity within landslides can change or disappear gradually over the course of long-term ecological succession.

However, a variety of vegetation types can be observed on landslide scars, even if the landslide occurred several hundred or thousands of years ago (Takahashi 1990; Kariya et al 2013). This implies that the heterogeneity of the vegetation was not exclusively due to differences between successional stages, but also to spatial variations in environmental conditions within the landslide site. Large-scale landslides create heterogeneous environments related to micro-landforms within the landslide scar, such as

unstable steep scarps, mesic depressions, dry hills, and well-drained boulder fields (Hamasaki and Miyagi 2018). Past studies have reported that these micro-environments affect vegetation patterns within the sites of old landslides (Mishima et al 2009; Kariya et al 2013; Sasaki and Sugai 2015).

It is essential to consider landslides when trying to understand the patterns and processes of vegetation dynamics in Japanese mountains, where heavy rains and earthquakes cause frequent landslides (Yoshimatsu and Abe 2006). Previous studies conducted in mountainous regions of Japan have clarified the relationships between vegetation patterns and conditions at the sites of both old (Koizumi 1999; Mishima et al 2009) and recent landslides (Nakashizuka et al 1993). However, little is known about how and why vegetation patterns vary between landslide sites in a region. Heterogeneous vegetation on old landslide scars, as exemplified in the landslide site shown in Figure 1, does not occur on all sites; some old landslide sites are covered in homogeneous forest vegetation (Takaoka 2013). It seems that some landslides have long-term effects on vegetation, and others do not. This implies that regional environmental conditions, such as climate and geology, affect the development of vegetation after landslides.

The objectives of this study were to describe the variations in vegetation among different landslide locations within a region, and to examine possible causes of the regional diversity of vegetation on landslides. No previous

FIGURE 1 Vegetation mosaics at the site of an old landslide on Mount Happo, central Japan. A view of landslide bodies from the upper edge of a main scarp. Bf, broadleaved forest; Cf, coniferous forest; Pn, pond; Md, meadow; Mr, mire; Rf, rubble field; Sg, *Sasa* grassland; Sh, shrub. (Photo by Sadao Takaoka)
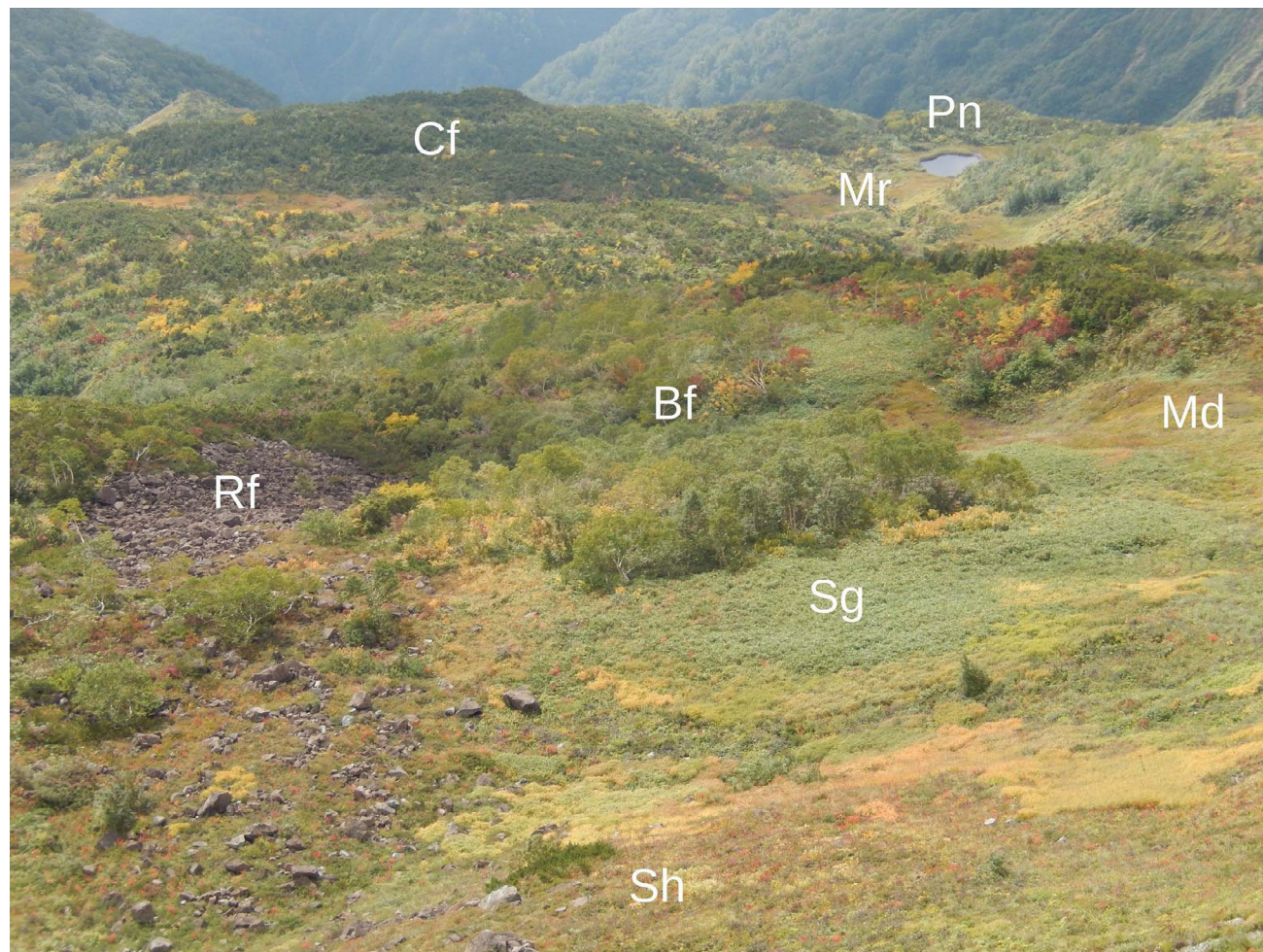
studies have been conducted over an area large enough to determine fully the effects of regional climatic conditions on variations in vegetation patterns at the sites of landslides. Thus, I set the study area such that regional differences in air temperature and snowfall could be taken into consideration. Such understanding of regional variations is useful as basic knowledge for conservation and sustainable management of landslide-prone ecosystems.

Study area

This study was conducted in a 1421 km^2 region of Hida Mountain Range, central Japan. The region encompasses a wide variety of climatic conditions, geological formations, and vegetation types. Most parts of the study region are bounded by a 1000 m contour line, although the south and south-western parts are bounded by rivers, as shown in Figure 2A.

According to the Mesh Climate Data 2010 (Japan Meteorological Agency 2012), average summer temperatures (July to September) range from 9.7°C (2603 masl) to 20.4°C (1094 masl). The maximum annual average snow depth is over 200 cm in the snowiest area of the study region; snowfall decreases toward the south (Figure 2B).

Some mountains in the study region are Middle Pleistocene to Holocene volcanoes; others were formed by uplifts during the Quaternary and consist of Paleozoic to Mesozoic sedimentary rocks, Cretaceous granitic rocks, and Paleozoic to Mesozoic metamorphic rocks (Geological Survey of Japan 2009).

The mountain slopes are mainly covered with forests. The subalpine zone (~1600–2500 m) is dominated by *Abies mariesii*, *Abies veitchii*, *Tsuga diversifolia*, and *Betula ermanii*, while the montane zone (~700–1600 m) is covered by broadleaved forests that are dominated by *Fagus crenata*, *Tilia japonica*, and *Abies homolepis*. *B. ermanii* forests form in the topmost parts of the subalpine zone in some areas (Okitsu 1991). Alpine vegetation, mainly composed of *Pinus pumila* shrub and alpine meadows, occurs in the area above the forest limit. The forest limit occurs at around 2500 m, although prolonged snow cover causes the descent of this limit by 800 to 1000 m in the northern area of the study region (Gansert 2004).

A geographical information system (GIS)-based landslide map has been published by the National Research Institute for Earth Science and Disaster Prevention (NIED) (http://www.j-shis.bosai.go.jp/map/). This map shows the distribution of large landslides (ie with widths of at least 150 m). The study region contained 1703 landslide polygons in total, representing landslide bodies referred to as "moved or moving masses" by NIED (Figure 2C). The combined area of the landslide bodies represented 13.9% of the study region.

FIGURE 2 Study area. (A) Shaded relief map based on a 10 m digital elevation model provided by the Geospatial Information Authority of Japan. (B) Thirty year average values (1981–2010) of maximum snow depths obtained from the Mesh Climate Data 2010 dataset (Japan Meteorological Agency 2012). (C) Landslide bodies based on the landslide map published by the National Research Institute for Earth Science and Disaster Prevention (2013). (Maps by Sadao Takaoka)
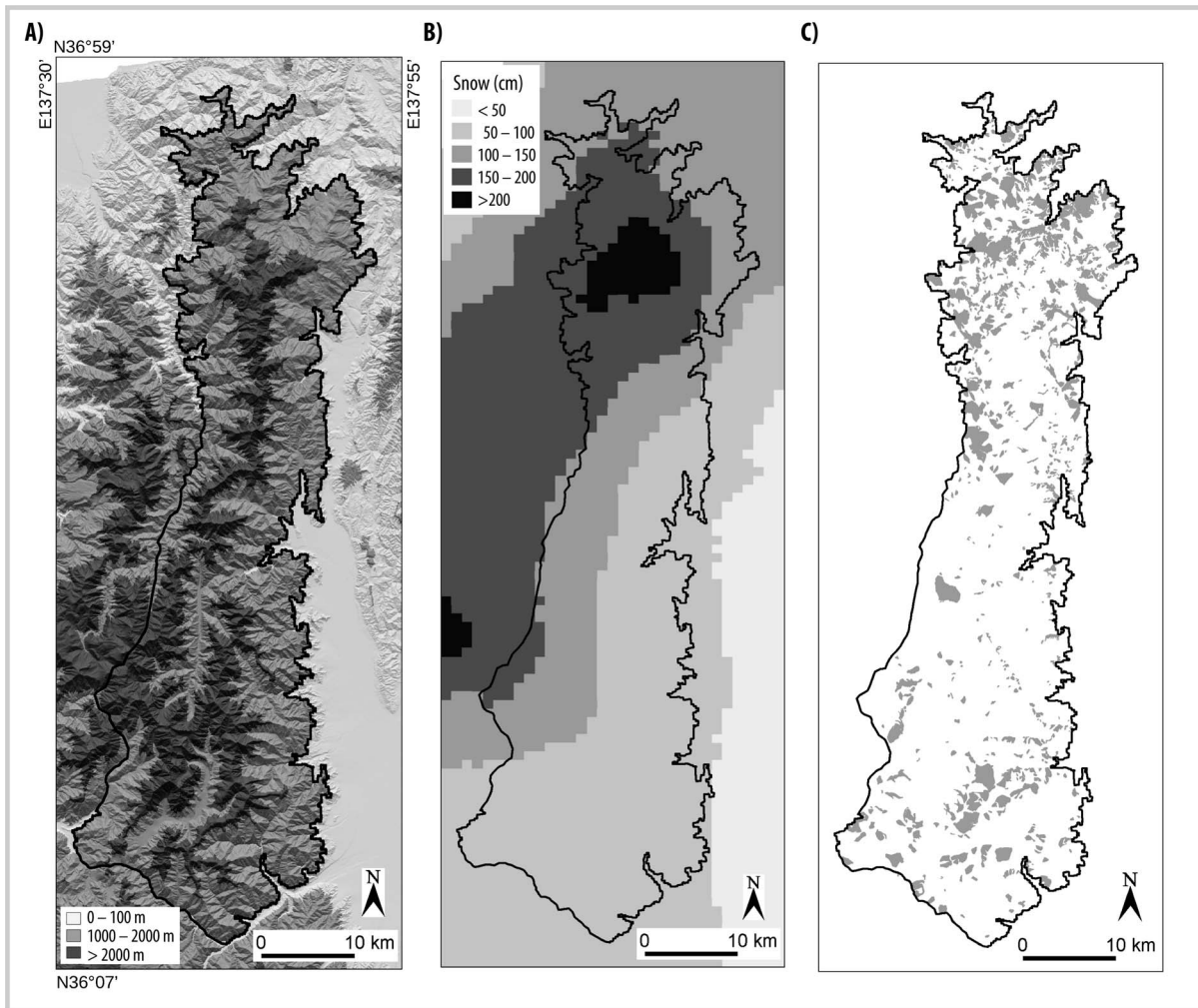
None of the landslides studied was newly created; no major changes in landforms or vegetation were observed when comparing the most recent aerial photographs to those taken in 1976–1977, except for landslide sites where afforestation or deforestation had taken place. Minor changes that may be due to reactivation or erosion were observed within some of the landslide bodies. Most seemed dormant and very old, although their numerical age is not known. Based on the geomorphological features, most landslides belonged to the relative age class (McCalpin 1984) of inactive young (100–5000 years) or inactive mature (5000–10,000 years). Radiocarbon ages obtained from landslide sites in and around the study area range from 1383 to 8916 years (Kariya et al 2013).

Methods

Vegetation classification

The target landforms for vegetation analyses were landslide bodies, which are landforms made of materials displaced by landslides. I extracted all the polygons of landslide bodies from the landslide map published by NIED and classified the vegetation in the landslide polygons by interpreting aerial photos taken by the Geospatial Information Authority of Japan during the period 2000–2006.

I classified nine types of vegetation in areas covered by more than 100 m^2 of vegetation. The vegetation classification was carried out by stereoscopic air-photo interpretation, based on color and texture of the image, relative vegetation height, and tree canopy size. The types included broadleaved forest, coniferous forest, shrub, *Sasa* grassland, meadow, mire (bog and fen), pond, rubble field, and artificial vegetation. *Sasa* grasslands are dominated by *Sasa* species, including *Sasa pygmaea*, *Sasa senanensis*, and *Sasa kurilensis*. It is essential to consider ponds when analyzing biodiversity in mountainous areas (Takaoka 2015); therefore even ponds with areas smaller than 100 m^2 were recorded.

The nine types are representative of the vegetation in the region. I considered the number of vegetation types in each landslide polygon as an indicator of vegetation heterogeneity.

Spatial analysis

I employed the Random Forest algorithm for spatial analysis. Random Forest is a nonparametric machine-learning technique developed by Breiman (2001) to predict and assess

TABLE 1 Datasets used for the Random Forest analysis.

Dataset[a]	Class	Number of landslide polygons
Dataset 1	Forest	950
	Shrub	482
	Sasa grassland	50
	Meadow	43
Dataset 2	Without mires	1465
	With mires	62

[a] Dataset 1 was used for the Random Forest analysis of vegetation diversity, and dataset 2 was used for mire occurrence.

the relationships between a predictor and a response variable. I carried out a Random Forest analysis to identify predictors of vegetation diversity on landslide bodies and ranked these by importance. Predictors included terrain variables (slope and aspect), climate variables (temperature, rainfall, and snowfall), and the lithology of bedrocks.

I used a 10 m digital elevation model provided by the Geospatial Information Authority of Japan to produce maps of slopes and aspects using GIS (TNTmips, MicroImages, Inc). The aspect was translated into a continuous north–south gradient (northness) using the following equation: northness = cosine (aspect). The terrain variables were calculated as the means of each of the 10×10 m cells making up each landslide polygon.

The 30 year average values (1981–2010) of the climate variables were obtained from the Mesh Climate Data 2010 dataset. The average summer temperature (July to September), total summer rainfall (July to September), and maximum snow depth were used as climate variables for each polygon.

The lithology of each polygon was defined as the most dominant lithology in that polygon, according to a geological map at a scale of 1:200,000 (Geological Survey of Japan 2009). The lithology was transformed into a dummy variable (numeric variable).

The response variables were coded as the four classes of vegetation occupying the largest area in each landslide polygon. These classes were forest, shrub, *Sasa* grassland, and meadow (Table 1, dataset 1). Mire, pond, and rubble fields were not included because they did not occupy the largest area of any polygon. I combined coniferous and broadleaved forests into one class, denoted forest. Polygons that had been artificially vegetated were excluded from the analysis.

A Random Forest analysis was also conducted to identify predictors of mires on landslide bodies (Table 1, dataset 2). A mountain mire, which is occasionally observed in landslide landforms, is an important element in mountain landscapes because it often provides regional refugia for rare species (Chimner et al 2010). The predictors were the same as those used in the analysis of dataset 1.

The datasets were not balanced for the different response classes (Table 1). I addressed the issue of unbalanced data by applying the synthetic minority oversampling technique (SMOTE; Chawla et al 2002) to generate synthetic calibration samples for the minority classes.

I simulated the Random Forest models using the randomForest package (Liaw and Wiener 2002) in R (ver. 3.3.2; R Core Team 2016). The datasets were balanced using the SMOTE algorithm from the DMwR package in R (Torgo 2010). As part of the Random Forest procedure, 500 classification trees were built for each dataset.

Results

Vegetation on landslide bodies

The distributions of the most dominant vegetation types in each landslide-body polygon are shown in Figure 3A. In 176 of the 1703 polygons in the study region, the natural vegetation had been replaced by artificial forests and artificial meadows. The other polygons were covered with natural vegetation, although some of them seem to have been affected by past human influence. Deciduous broadleaved forests were dominant at elevations below ~1700 m. Coniferous forests occupied most of the area above ~1500 m in the southern part of the study area, while shrubs, *Sasa* grasslands, and meadows were dominant at the same elevations in the northern part of the region. Deciduous broadleaved forests occurred at elevations above 2000 m. These were dominated by *B. ermanii*, which was often mixed with coniferous trees in subalpine forests.

The heterogeneity of the vegetation increased with the maximum snow depth. Landslide polygons with more types of vegetation were dominant in areas with greater maximum snow depths. Specifically, the number of vegetation types within polygons increased with the latitude and elevation (Figure 3B), as did maximum snow depth (Figure 3C). In areas with maximum snow depths of 50–100 cm, 59.8% of polygons were occupied by one type of vegetation (Figure 4). This percentage decreased as the maximum snow depth increased; only 13.8% of polygons were covered by one type of vegetation in areas where the snow depth was 200 cm or more.

In total, 546 (35.8%) of the landslide polygons were occupied by one type of vegetation. These polygons included 385 broadleaved forests (70.5%), 85 coniferous forests (15.6%), and 73 shrublands (13.4%) (Table 2). The occurrence of shrubs, *Sasa* grasslands, and meadows contributed to the increase in the number of vegetation types within polygons, and the occurrence of mires, ponds, and rubble fields increased this number further.

Distribution of mountain mires

Of the 1703 landslide polygons studied, 62 included mires, as shown in Figure 5. These polygons contained 285 mires (Table 3). The areas of the mires were between 101.2 and 20,982.3 m^2; 80.7% of them were smaller than 2000 m^2.

The landslide polygons that contained mires occurred at elevations greater than 1455 m and at latitudes north of 36.6°N (Figure 5). This area overlapped with the region of heavy snowfall, as shown in Figure 3C. The polygons that contained mires also seemed to be concentrated in areas of certain lithologies, such as ultramafic rocks and nonalkaline mafic volcanic rocks (Table 4). Mires occurred twice as often as expected in ultramafic rocks and nonalkaline mafic volcanic rocks, while there were no mires in areas with sandstone and granite rocks.

FIGURE 3 (A) Distribution of the most dominant vegetation. (B) Number of vegetation types. (C) Maximum snow depth. The centroids of the polygons are plotted.
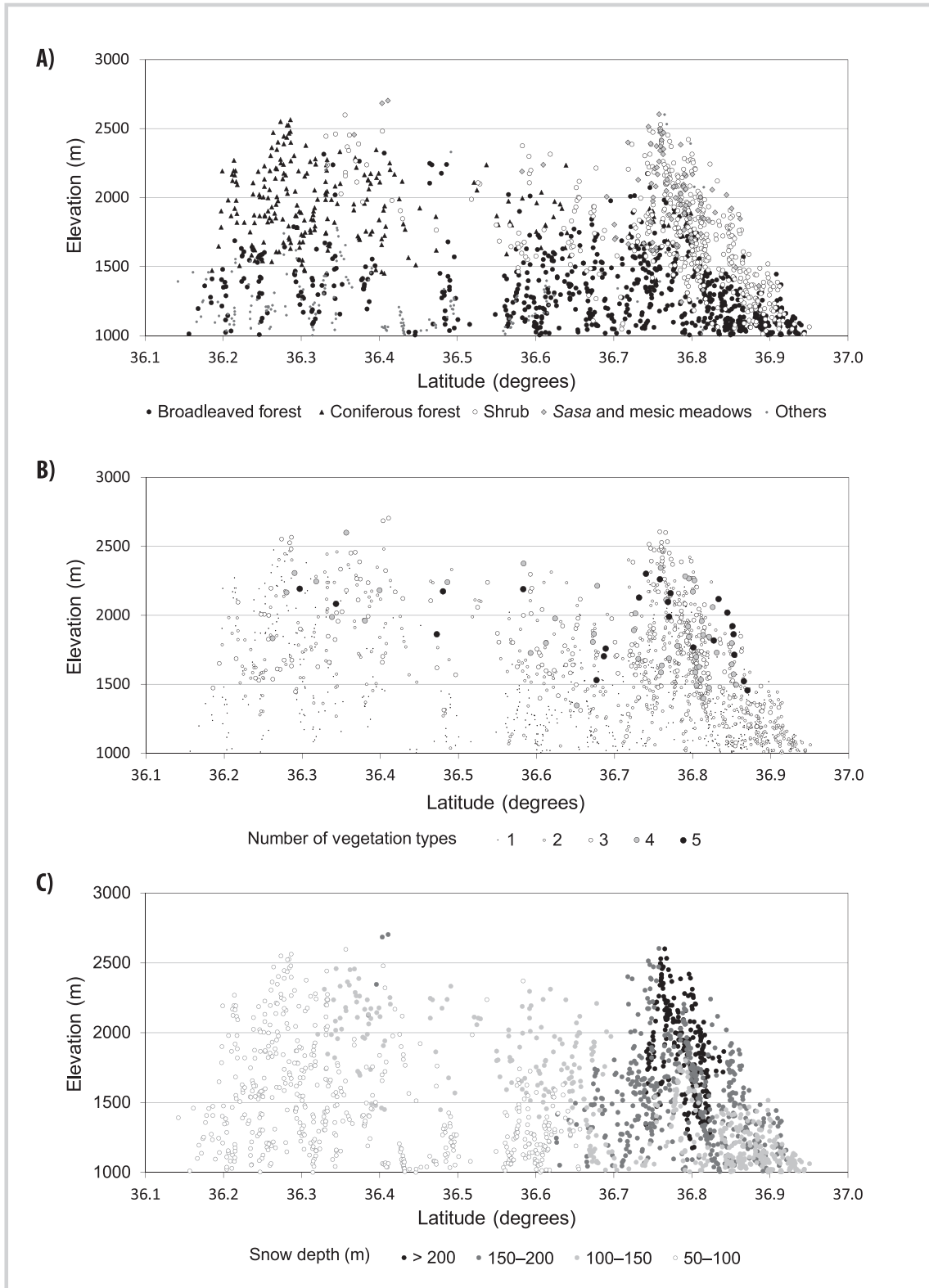
Importance of variables

The mean decrease in the Gini coefficient, which was calculated using Random Forest analysis, provided an estimate of the degree to which a variable reduced the variability between landslide polygons. Higher values of the mean decrease in the Gini coefficient indicate a more

important variable. The results indicate that both the diversity of vegetation and occurrence of mires were mainly predicted by three common variables: summer temperatures, maximum snow depth, and lithology. Based on the mean decrease in the Gini coefficient (Table 5), summer temperatures were the most important variable

TABLE 2 Distribution of vegetation types within landslide polygons.

Number of vegetation types in a landslide polygon	Total number of polygons	Number of polygons with each vegetation type							
		Broadleaved forest	Coniferous forest	Shrub	*Sasa* grassland	Meadow	Mire	Pond	Rubble field
1	546	385	85	73	2	1	0	0	0
2	569	419	140	445	43	83	2	3	3
3	267	172	99	250	111	106	13	13	37
4	101	77	48	99	72	59	21	16	12
>4	44	29	18	44	32	39	26	32	17

determining vegetation diversity, and maximum snow depth was the second most important variable. On the other hand, maximum snow depth was almost as important as summer temperatures with respect to the occurrence of mires.

Discussion

The dominant vegetation in landslide-body polygons varied with elevation; broadleaved forests dominated at elevations below 1700 m, while coniferous forests occupied areas above 1500 m (although shrubs, *Sasa* grasslands, and meadows were dominant, rather than coniferous forests, in the northern part of the region; Figure 3A). On the whole, this distribution pattern resembled that of the mature vegetation in the region (Ozeki 2001; Gansert 2004). I considered the locations of large-scale landslides characterized in this study to be old enough to contain mature vegetation. However, the vegetation at landslide sites was not exactly the same as undisturbed mature vegetation, as described below.

The number of vegetation types in landslide polygons varied among study areas (Figure 3B). The results of my Random Forest analysis suggest that summer temperatures and maximum snow depth are the most important variables determining the diversity of vegetation (Table 5). The occurrence of nonforest vegetation, including shrubs, *Sasa* grasslands, and meadows, contributed to an increased number of vegetation types within the landslide polygons

(Table 2). This implies that the increase in the number of vegetation types was partly due to the landslide polygons overlapping the alpine zone, where nonforest vegetation was dominant. However, nonforest vegetation frequently occurred in polygons in subalpine zones in the snowy part of the study region (Figure 3A). The growth and establishment of subalpine coniferous trees are reported to be affected by heavy snow accumulation (Takaoka 1999; Kajimoto et al 2002). Within the landslide bodies studied, nonforest vegetation was observed both in depressions, where snow patches develop and reduce the length of the growing season, and on steep slopes, where the snow creep caused by snow patches causes mechanical damage to trees. These observations suggest that snowy conditions hindered ecological succession and maintained the effects of past landslides on vegetation, even when the landslides occurred a long time ago.

Rubble fields also contributed to the richness of vegetation types (Table 2) and were often observed on slopes around long-lived and perennial snow patches that shortened the length of the growing season (Iwata 1983). This indicates that snowy conditions contributed to the

FIGURE 4 Diversity of vegetation with respect to snow-depth class.
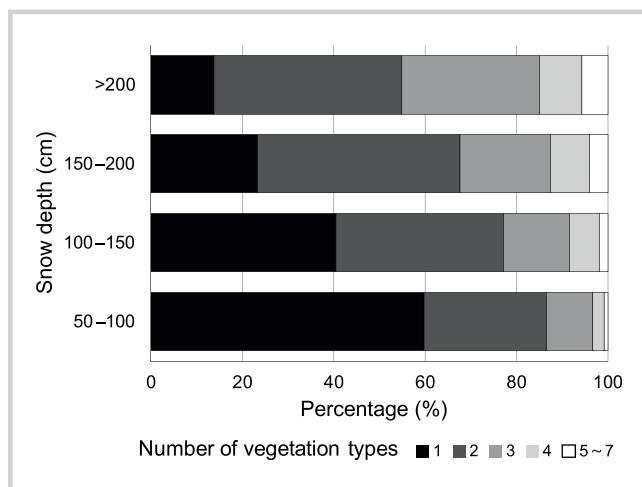
TABLE 3 Size distribution of mires.

Area (m^2)	Number of mires
0–1000	170
1000–2000	60
2000–3000	15
3000–4000	10
4000–5000	6
5000–6000	7
6000–7000	8
7000–8000	3
8000–9000	2
9000–10,000	0
>10,000	4
Total	285

FIGURE 5 Distribution of landslide bodies with mires. The centroids of the polygons are plotted.
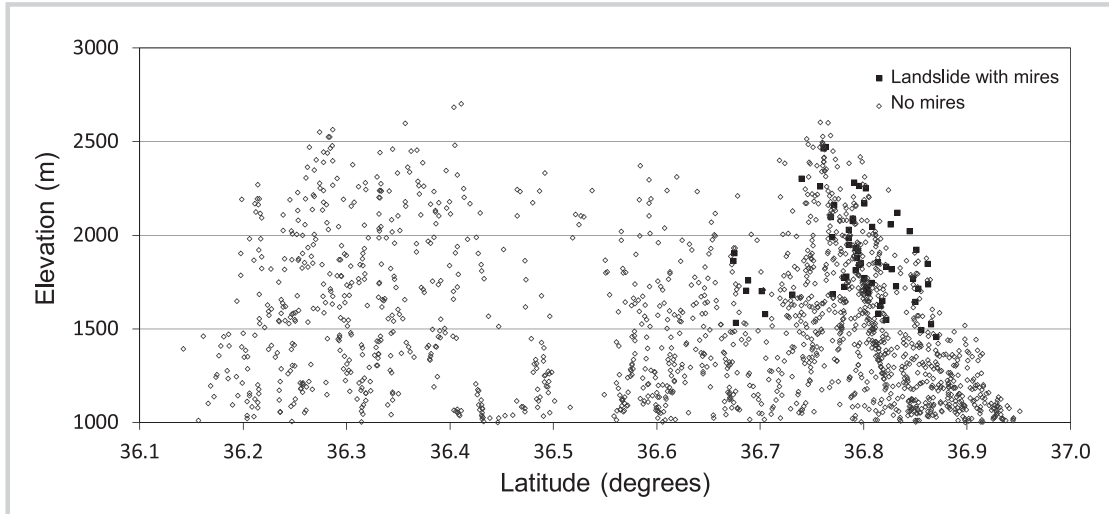
development of rubble fields on landslide bodies, increasing the diversity of vegetation types.

Mires and ponds, which were also associated with an increase in the number of vegetation types in landslide-body polygons, also appeared to be influenced by snowy conditions and micro-landforms within landslide bodies. These wetlands occur in depressions in landslide bodies (Kariya et al 2013; Takaoka 2015) where the depressions collect rainwater and snowmelt. The results of my Random Forest analysis suggest that maximum snow depth and summer temperature are important variables with respect to the development of mires (Table 5). This implies that a supply of snowmelt water and suppression of evapotranspiration by lower than usual summer temperatures help to maintain mires. Most of the mires in the landslide bodies were small, but there were many of them (Table 3). This population of small-scale mires may play an important role in maintaining the biodiversity of mountainous regions, as it does in lowland regions (Blackwell and Pilgrim 2011).

According to the Random Forest analysis, the lithology was the third most important variable determining mire occurrence (Table 5). In general, differences in lithology lead to regional differences in weathering and geomorphic processes, causing regional differences in the frequency of wetland occurrence. A certain kind of wetland commonly forms in ultramafic outcrops (Kruckeberg 2004: 220–221). In the present study region, landslide bodies containing mires were frequently formed in areas of ultramafic rock. Further research is necessary to elucidate the relationship between lithology and mire development on landslide bodies in detail.

Vegetation succession in a landslide site is hierarchically influenced by regional, local, and microsite conditions (Walker and Shiels 2013). The findings of the present study clarified the effects of regional conditions, about which little has been known. The findings suggest that the regional conditions direct the function of local conditions (ie landform effects inside a landslide site), although additional studies are needed to quantify the linkage.

TABLE 4 Number of observed and expected mires in areas with different types of bedrock. Only rocks that occurred in 100 or more landslide-body polygons are shown.

Dominant rock	Number of landslide-body polygons	Observed number of polygons with mires (a)	Expected number[a] of polygons with mires (b)	a/b
Marine and nonmarine sedimentary rocks	170	4	6.2	0.6
Mélange matrix of accretionary complex	280	19	10.2	1.9*
Sandstone of J2-3 accretionary complex	189	0	6.9	0.0*
Ultramafic rocks	146	15	5.3	2.8*
Nonalkaline mafic volcanic rocks	102	15	3.7	4.0*
Felsic plutonic rocks	147	3	5.4	0.6
Granite (Younger Ryoke Granite)	210	0	7.6	0.0*

[a] The expected value was calculated as (number of landslides in each geological unit/total number of landslides) × total number of observed landslides with mires.
* $P < 0.01$ based on the binomial test.

TABLE 5 Importance of variables according to the mean decrease in the Gini coefficient for each variable.

Variable	Mean decrease in Gini coefficient
Dataset 1	
Summer temperature	368.1
Maximum snow depth	338.6
Lithology	307.4
Summer rainfall	287.1
Slope	198.6
Northness	186.3
Dataset 2	
Maximum snow depth	395.1
Summer temperature	380.8
Lithology	229.8
Northness	157.8
Summer rainfall	154.5
Slope	134.8

Conclusions

This study demonstrates that variations in vegetation among the sites of landslides in the region studied were caused by maximum snow depth, summer temperatures, and lithological conditions. In the snowier parts of the region, snow had a greater effect on the development of vegetation at the sites of landslides. This was probably because the presence of snow reduces the growing season, and snow creep causes pressure on specific micro-landforms within landslide bodies. I also showed that snowy conditions maintained the effects of landslides, even when the landslides occurred a long time ago. These observations suggest that snowy conditions have long-term effects on vegetation structure and diversity at landslide sites. Differences in lithology contributed to regional differences in hydrological conditions, which are determined by the micro-landforms and weathered materials that are present in landslide bodies. Thus, these differences were associated with larger varieties of vegetation types.

Previous studies have failed to detect the effects of snow on landslide ecosystems from a broad-scale perspective because most were carried out in humid subtropical and tropical regions. Hu et al (2018) studied plant recolonization after landslides in a semiarid climate and reported different aspects of the effects of landslides on the development of soil and vegetation. Further studies on a broad range of variables at landslide sites under different climatic regimes should be carried out to improve our understanding of landslide ecosystems. This could help ecosystem management in landslide-prone regions.

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