Geomorphology 276 (2017) 1–7

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Effect of forest clear-cutting on landslide occurrences: Analysis of rainfall thresholds at Mt. Ichifusa, Japan

Hitoshi Saito [a,b,*], Wataru Murakami [c], Hiromu Daimaru [c], Takashi Oguchi [b]

[a] College of Economics, Kanto Gakuin University, Yokohama, 236-8501 Kanagawa, Japan
[b] Center for Spatial Information Science, The University of Tokyo, Kashiwa, 277-8568 Chiba, Japan
[c] Forestry and Forest Product Research Institute, Tsukuba, 305-8687 Ibaraki, Japan

ARTICLE INFO

Article history:
Received 25 April 2016
Received in revised form 9 September 2016
Accepted 10 September 2016
Available online 24 September 2016

Keywords:
Landslide
Forest clear-cutting
Rainfall intensity–duration thresholds
Return period
Forest management

ABSTRACT

Vegetation cover is an important factor for rainfall-induced landslides. We analyzed the effect of forest clear-cutting on the initiation of landslides using empirical rainfall intensity–duration (*I*–*D*) thresholds at Mt. Ichifusa, Japan, which is characterized by granitic rocks. Extensive clear-cutting was conducted for the forest industry during the late 1960s in the northern part of Mt. Ichifusa. This single episode of clear-cutting caused frequent shallow landslides triggered by rainfall. We interpreted orthorectified aerial photographs from 1969, 1976, 1980, 1985, 1990, 1995, 1999, and 2005 using GIS and mapped landslides based on these photographs. We then analyzed all rainfall events of the warm seasons (Apr.–Oct.) of 1952–2011 (60 years) based on hourly rain gauge data. We used basic rainfall parameters such as mean rainfall intensity (*I*, mm/h) and duration (*D*, h) and estimated the return periods of these rainfall conditions. We investigated rainfall *I*–*D* thresholds for landslide occurrences in each period represented by the aerial photographs and assessed the relationships between landslide occurrences and topographic characteristics from 10-m DEMs. The results show that several landslides occurred after clear-cutting before 1976 but that they have occurred most frequently during the periods 1976–1980, 1980–1985, and 1990–1995. Numerous landslides occurred in these years at steeper and gentler slopes in the clear-cut area, but few landslides occurred in the non-clear-cut area. Rainfall analysis demonstrates that rainfall *I*–*D* thresholds after clear-cutting declined to half of those of the non-clear-cut area. The return periods of these rainfall *I*–*D* thresholds also declined to ~1 year for short durations of <12 h and to <3 years for 72 h in the clear-cut area. Our findings underscore the substantial hysteresis effects between clear-cutting and landslide occurrences at Mt. Ichifusa.

1. Introduction

Vegetation cover is an important factor for rainfall-induced landslides and debris flows. Various studies have revealed that forest clear-cutting (forest harvesting) has effects on hydrogeomorphological processes in forest terrain, including changes in hillslope hydrology (Dhakal and Sidle, 2004; Imaizumi and Sidle, 2012) and increases in the frequency of landslides and debris flows (Sidle et al., 1985; Montgomery et al., 2000; Glade, 2003; Jakob et al., 2005; Imaizumi et al., 2008). Landslides supply large volumes of sediment to streams and threaten human habitation in mountainous and downstream areas (e.g., Imaizumi et al., 2008). Quantifying the relationship between clear-cutting and landslide occurrences is therefore important for assessing landslide hazards and the environmental impacts of forest management (i.e., clear-cutting and subsequent replanting of artificial forests).

Vegetation resists shallow landslides because tree roots increase shearing resistance and thereby prevent slope failure. Statistical and physical modeling studies of the impact of clear-cutting on landslide occurrence have been conducted, especially in the Pacific Northwest of North America (e.g., Swanson and Dyrness, 1975; Montgomery et al., 2000), New Zealand (e.g., Reid and Page, 2003; Glade, 2003), and Japan (e.g., Imaizumi et al., 2008; Imaizumi and Sidle, 2012). For these studies, researchers examined the frequencies and volumes of landslides and investigated slope hydrology. Although the results of these studies showed that clear-cutting accelerates landslide occurrences in steep mountainous terrain, the impacts of clear-cutting differ among regions in response to environmental conditions such as climate, topography, geology, soils, and vegetation types. Consequently, the impacts of clear-cutting must be assessed in terms of site-specific environmental characteristics.

The Japanese archipelago is characterized by its high-relief topography and complex geological conditions. Almost all mountains in Japan are covered by forest. Many residents have lived in mountainous areas and have repeatedly harvested the forests (e.g., Imaizumi and Sidle, 2012). Japan lies within the East Asian monsoon region. Especially

* Corresponding author at: College of Economics, Kanto Gakuin University, 1-50-1, Mutsuura-higashi, Yokohama, 236-8501 Kanagawa, Japan.
E-mail address: hsaito@kanto-gakuin.ac.jp (H. Saito).

http://dx.doi.org/10.1016/j.geomorph.2016.09.024
0169-555X/

during the summer monsoon, heavy rainfall occurs frequently (Matsumoto, 1989; Saito and Matsuyama, 2015), which can cause landslide-related disasters (Saito et al., 2014). Consequently, landslides are the most important hazard for forest management and for residents in these mountainous areas. Previous studies have analyzed the impacts of clear-cutting on landslide occurrences in Japanese mountains (Tsukamoto, 1987; Marutani et al., 2000; Abe et al., 2004; Imaizumi et al., 2008; Imaizumi and Sidle, 2012); for example, Imaizumi et al. (2008) examined the relationship between clear-cutting and landslide occurrences in the Kii Mountains of central Japan using aerial photographs for the period of 1964–2003. They demonstrated that time-series changes in landslide occurrences were explained by root strength decay and recovery. The direct impact of clear-cutting was greatest within 1–10 years, with the effects progressively weakening up to 25 years after clear-cutting (Imaizumi et al., 2008). However, the effects of clear-cutting on hydrogeomorphological processes cannot be estimated based simply on the time elapsed after clear-cutting; rainfall magnitude and the history of landslides must also be considered (Imaizumi and Sidle, 2012).

Numerous studies have focused on meteorological characteristics such as the minimum rainfall intensity (I, mm/h) and duration (D, h) associated with reported occurrences of landslides to derive empirical critical thresholds (Caine, 1980; Guzzetti et al., 2008, offer a detailed review). The simplicity of this approach neglects important hydrological controls such as antecedent soil water (Crozier, 1999; Shuin et al., 2012), but it offers a straightforward and practical means to issue regional-scale landslide warnings. Many rainfall parameters, such as rainfall intensity, duration, cumulative event rainfall, and antecedent rainfall, have been proposed to assess landslide hazards. Landslide initiation caused by heavy rainfall has been associated with rainfall intensity and duration (I–D). The I–D thresholds are often used to predict landslides so that the appropriate authorities can be warned of potential landslide hazards (Caine, 1980; Keefer and Larsen, 2007; Cannon et al., 2008; Guzzetti et al., 2008; Saito et al., 2010; Chen et al., 2015). Although numerous studies have addressed the impact of clear-cutting on landslide occurrences, few have explored systematic links between landslide initiation after clear-cutting and changes in rainfall thresholds, particularly based on rainfall I–D (e.g., Montgomery et al., 2000).

We have addressed these problems in our study of Mt. Ichifusa on Kyushu, Japan (Fig. 1), where clear-cutting in the late 1960s increased the rate of shallow landslide occurrence (Ebisu et al., 2000; Marutani et al., 2000), using time series of aerial photographs and hourly rainfall data from 1952 to 2011 (60 years). Mt. Ichifusa is characterized by weathered granites, steep slopes of >30°, and a mean annual precipitation of >3400 mm. Our objective is to elucidate the effects of clear-cutting on shallow landslides in terms of rainfall I–D thresholds. Specifically, we have examined the decrease in rainfall I–D thresholds after clear-cutting relative to those in a non-clear-cut area.

2. Study area and methods

2.1. Mt. Ichifusa

Mt. Ichifusa (1720 m) is located in the central part of Kyushu, Japan (Fig. 1). This mountain consists of weathered middle to late Miocene granitic rocks. The hillslopes are ~30–35°, whereas the channel slope is 10–24° (Marutani et al., 2000). The northern part of the mountain was covered by natural broadleaf forest until the late 1960s, when extensive clear-cutting was conducted for the forest industry. Shallow landslides have occurred frequently after this single episode of clear-cutting (Takahashi and Taniguchi, 1987; Ebisu et al., 2000; Marutani et al., 2000).

The mean annual precipitation and cumulative warm season (April–October) precipitation respectively exceed 3400 and 2400 mm in this region, as recorded by the Japan Meteorological Agency (JMA). During the warm season, heavy rainfall caused by frontal storms and typhoons occurs frequently. For example, heavy rainfall from two typhoons in August 1971 caused landslide disasters in and around this area (Sue et al., 1973). Frontal storms and typhoon events in July and August 1982 caused shallow landslides across large areas of the northern part of the mountain (Marutani et al., 2000).

2.2. Mapping of clear-cut areas and landslides

To detect landslide locations, using ArcGIS, we interpreted orthorectified aerial photographs from 1969, 1976, 1980, 1985, 1990, 1999, and 2005 that were captured by the Forest Agency of Japan and the Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT; Murakami and Daimaru, 2013; Table 1). The intervals between photographs were ca. 5 years.

We analyzed 9.8 km^2 of the northwestern part of Mt. Ichifusa (Fig. 1). This area was covered by all of the sequential aerial photographs, including the clear-cut and non-clear-cut areas (Fig. 2). The clear-cut and non-clear-cut areas are characterized by steep hillslopes (Fig. 1) and deeply weathered granitic rocks around ridgelines (Takahashi and Taniguchi, 1987; Marutani et al., 2000). The non-clear-cut area was regarded as the control site, which showed natural conditions for landslide occurrence.

We mapped the clear-cut area and the locations of landslides that occurred during each period between the aerial photographs. For this

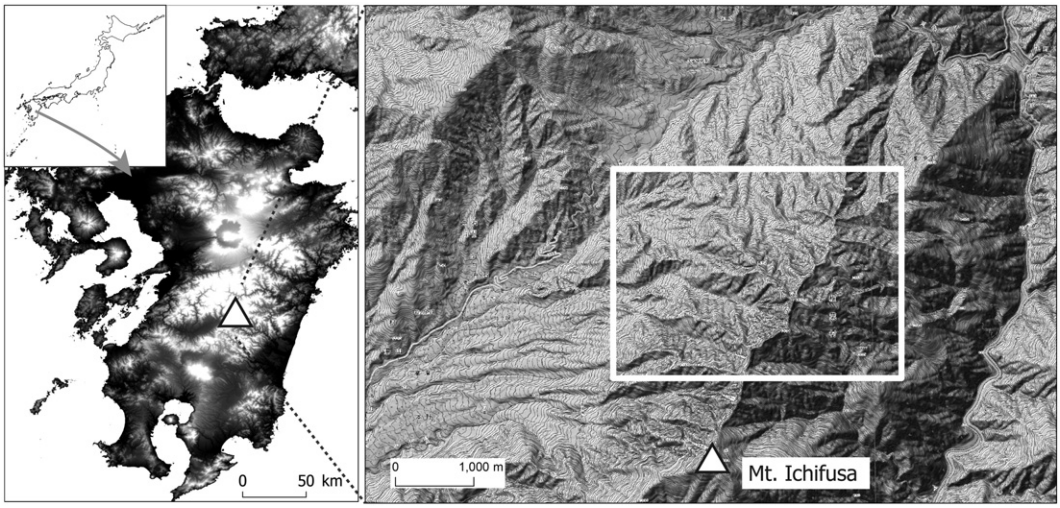

Fig. 1. Location and relief map of Mt. Ichifusa (1720 m, white triangle). The northern part of the mountain (9.8 km^2, white rectangle, Fig. 2) was analyzed.