Effects of Surface Cover and Slope Gradient on Overland Flow Generation from Bare and Forested Hillslopes

March 2018

Yoshitaka KOMATSU

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A Dissertation Submitted to

Graduate School of Life and Environmental Sciences,

the University of Tsukuba

in Partial Fulfillment of the Requirements

for the Degree of Doctor of Philosophy in Science

(Doctoral Program in Integrative Environmental Sciences)

Yoshitaka KOMATSU

Contents

Abstract

In order to clarify the fundamental mechanisms of the rainfall-runoff processes, many field observations and experiments have been conducted so far, and the development of a rainfall runoff model (hereinafter called a model) has been advanced. Influences of soil physical properties such as permeability and topographic characteristics such as slope gradient are considered in theoretical formula or governing equation as an important parameter in determination of runoff generation along hillslope. Previous studies have shown that surface runoff decreases (infiltration rate increases) with increasing surface cover ratio and amount of surface cover materials. On the other hand, it was shown that surface runoff increases as the slope gradient increases. Fundamental relationships observed by those previous studies can be found in numerous classical/present researches published in academia. However, recent research suggested that the effect of surface cover materials and slope gradient on rainfall runoff processes depend on the soil type and experimental/observational conditions in each study. From these reasons, this study investigated effects of surface cover and slope gradient on rainfall runoff processes for three different soil types: namely, Japanese forest soil under temperate climate, sandy loam and loess by East Asian monsoon area, and purple soil in semi-arid area.

In chapter 2, the relation among infiltration rate, surface cover material, and physical parameters of surface soil such as hydraulic conductivity and texture was investigated in Japanese cedar and Hiba arborvitae plantations in Ishikawa prefecture. The measured maximum infiltration rates (hereinafter called a FIR_{max}) under simulated rainfall condition for the Japanese cedar and Hiba arborvitae stands were in ranges of 141.9 to 562.3 mm/h and 93.3 to 641.0 mm/h, respectively. Different from the results of previous studies, there was no significant relationship observed between the infiltration rate and the surface cover condition. Furthermore, hydraulic conductivity of surface soil showed markedly higher value than maximum infiltration rate. These results suggested that either surface cover or soil physical properties such as hydraulic conductivity and fine fraction content were of minor importance on the measured infiltration rate in the studied forest sites. Filed observation of soil condition after the rainfall simulation indicated that non-uniform rainwater infiltration such as preferential flow through macropores or highly permeable parts occurred during the experiment. These results suggested that infiltration rate in Japanese cedar and Hiba arborvitae where was covered by thick litter layers could not be explained by neither surface cover condition nor soil physical properties.

In chapter 3,.

In chapter 4,

Keywords: Surface cover effect, Slope effect, Rainfall simulator, Natural rainfall, Runoff, Infiltration, Runoff plot

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Chapter 1. General Introduction

1.1 Previous studies on the relationship among rainfall, runoff and infiltration

The infiltration excess overland flow is formed, when the rainfall intensity exceeds the soil infiltration capacity in target area. Infiltration capacity was first defined by Horton (1933) as the maximum rate at which rain can be absorbed by a given soil when in a given condition (Horton, 1940). The infiltration capacity falls below the rainfall intensity, overland flow begins all over the hillslope. Overland flow is the movement of water over the land, downslope toward a surface water body. Oka (2001) summarized the research for infiltration concept by Horton (1933; 1937; 1940) and the infiltration equation proposed by Richards (1931). Further, as far as Japan is concerned, the unsaturated zone moisture research has been advanced in the field of soil physics related to agriculture, and there are research results through observation and experiments (Oka, 2001). Horton (1933) assumes that infiltration capacity of the soil divides rainfall into two components: "one which infiltrates into the soil and partly recharges groundwater and is partly returned to the atmosphere via evapotranspiration and the other, which flows overland and directly contributes to stormflow in streams". The proportion of this latter component, which has become known as Hortonian overland flow (HOF) (Figure 1.1), can be determined at any time during a storm by measuring the dynamic surface infiltration capacity and comparing this with rainfall intensity.

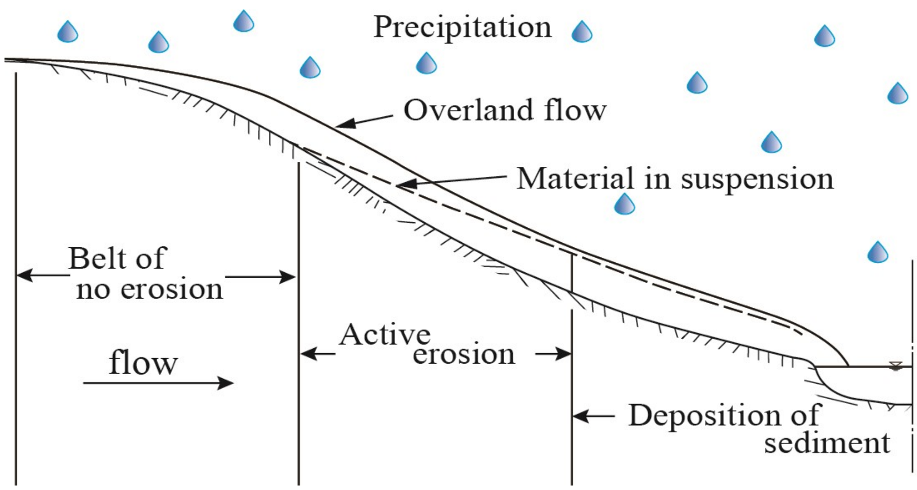

Figure 1.1 Conceptual diagram relationship between rainfall, HOF and infiltrate (Modified from Horton, 1945)

Hirata (1956) installed a infiltrometer in the mountains and measured the infiltration capacity of the forest soil. As a result, the infiltration/retention capacity of forest area showed a higher value than the rainfall intensity, and it is pointed out that there will be little runoff due to rain of any rainfall intensity. However, Hirata (1956) reviewed previous hydrologic data, and flood damage occurred even under some degree of rainfall intensity. It was pointed out that the relationship between soil and surface cover materials is important such as increasing the infiltration capacity of the topsoil layer. Yamada et al. (1982) clearly indicated that to elucidate the runoff route by conducting under laboratory experiment with rainfall simulator and *in-situ* experiment with rainfall simulator on a slope with multilayered soil. The rainfall-runoff route was started from the vertical infiltration of rainwater in the soil layer. The natural vegetation cover plays a remarkable role in intercepting splash erosion and reducing crust formation (e.g., El-Hassanin et al., 1993; Onda and Yukawa, 1995).

1.2 Why do we measure the infiltration and runoff rate?

The answer to "Why do we measure the infiltration and runoff rate?" is very simple. Where the rainfall strikes ground as raindrop, it does not infiltrate the ground surface immediately, leading to whether or not runoff will occur. There are important elements such as precipitation, canopy interception, stem flow, throughfall, evapotranspiration, infiltration, runoff, etc. Especially the investigation of the quantitative, qualitative and temporal relationships of precipitation and runoff is the most important theme for hydrology. Takasao (1963) indicated "I myself deeply sensed below. Despite numerous studies published, it is still not clearly grasping the rainfall-runoff phenomenon, which is one of the most important processes of hydrological cycle, and more fundamentally the methodology of phenomena." More than half a century passed since then, how much progress has been made in terms of grasping the phenomenon? Of course, it is a fact that many things have been elucidated by the development of computers and the development of measurement technology. However, it is also a fact that there are still many unclear points. This is the best part of research on hydrology that contains a lot of spatially distributed parameters. The infiltration phenomenon examined in this study is used for the movement of water in the porous medium of the rainwater. Here it can be limited to rainwater infiltration. The infiltration capacity is used as an infiltration index for the ground surface, and as a field of penetration, it is targeted to an unsaturated zone of about several cm from the ground surface. During the often spectacular rainstorms, rainfall intensity exceeds infiltration capacity and surface runoff is seen to occur everywhere (van de Giesen et al., 2000).

Takahashi (2008) indicate that the catchment scale was based on river engineering, the flow in the river channel collects from the total drainage area, thus faithfully reflecting the various natural and social conditions of the catchment. Therefore, it is pointed out that the water resources management and planning way of existence of land are diverse, depending on the country and region, the size of basin, natural conditions, social environment, socio-economic impact added to the basin. Moreover, natural conditions such as topography, geology, forestry and precipitation of the basin, artificial conditions such as land use planning, water use management, development, conservation, management, etc., have significant effects for runoff, river channel formation, flood characteristics, etc. The natural phenomenon of precipitation, which is the most important factor that dominates the runoff of a river, is dominated by artificial factors such as land use and water use, in the process of flowing out into the river channel after it has fallen into the basin as runoff. Therefore, rainfall runoff processes dominated by natural and anthropogenic factors. It seems that there is a different view depending on the research field, which role the forest plays in the flow of the river. For example, in the field of engineering, it is judged that the forest is a pervious area, and "runoff coefficient" is calculated using an empirical value when performing rainfall runoff analysis. On the other hand, in the field of forest hydrology, these researchers focus only on the runoff in the forest area. This difference is probably due to the fact that the field of engineering does not focus for calculation only on forests, considering the runoff from the forest to the inflow for the river. The forest plantation has potential for high infiltration capacity, and in the degraded land as early as the surface flow it leads to the ground-water artery as the subsurface flow and enriches the low water discharge. In addition, the rainfall infiltration phenomenon of forest soil is greatly affected by geology and leads to have a great influence on river drought and low runoff, due to the difference in the process of converting precipitation into overland flow, subsurface flow and groundwater runoff. Here, I (author) focus on the overland flow and infiltration phenomenon on the forest, bare land and surface covered area. Since plot size is small and just plot-scale and for a short duration time, evapotranspiration was ignored.

Looking at China, and which is the focus of the present research, there is the unpredictable situation on whether it can maintain food self-sufficiency in regard to changes in land-use pattern and decreasing of cultivated land (Smil, 1993; Shi et al., 2007). Soil erosion has been considered to be one of the biggest factors of decreasing cultivated area in China (Smil, 1993; Liu and Diamond, 2005). Therefore, in order to avoid a potential food crisis in the future, it would be critical to reduce soil erosion of the cultivated area and to revert of barren to arable land. The current research looks into the major factor of soil erosion, that is rainfall and infiltration capacity, which will play an important role in understanding soil erosion and efforts to stop cultivable land becoming less productive. In China, accelerated soil erosion and surface runoff have been caused by farmland development in parallel with the rapid population growth after the 1950s. A massive flood occurred in the Yangtze River basin and Songhua River basin in 1998, causing serious damage, devastation and soil erosion by rainfall on a large scale (Nakagawa et al., 1999; Matsunaga, 2013). The cause of flooding was also attributed to a combination of diverse factors, such as cultivation of the slopes on the hills and mountains, destruction of forests, and all of which resulted in large amounts of water and soil flowing into the river following heavy rains. Moreover, investigations revealed that a sufficient discharge capacity was not provided in this region (Matsunaga, 2013). The central government, which believed that the cause of the great flood was due to the deforestation associated with arable land expansion, initiated the program Convert Cropland to Forest Policy in 1999 (Chen, 2005; Sato et al., 2012; Matsunaga, 2013). Primarily, in the case of steep arable land with a slope of 25 degrees or more, the "water and soil loss" is a serious issue, but other problems associated with high salinity and desertification and food production are also important to consider (Chen, 2005; Sato et al., 2012; Matsunaga, 2013). This was only possible due to the planting of vegetation on reclaimed slopes, resulting in reduction of soil erosion and restoration of the infiltration rate. Moreover, the vegetation cover and forest ratio has improved and environmental reform projects like water cultivation were successfully achieved (e.g., Zhou et al., 2009; Zhang, 2010; Yang, 2015).

With regards to the relationship between rainfall and discharge for river, Horton (1933, 1939) advocated on the infiltration theory trying to deal with the relationship between rainfall and river channel, taking into account the route to rainfall. The surface ground has an infiltration potential, such as the maximum infiltration rate according to the soil physics parameter and ground condition, and rainwater reaching the ground can be divided into surface runoff and infiltration. The rainfall intensity exceeds the permeability will be occurred a surface runoff, which is called Hortonian overland flow (HOF). On the contrary, Tsukamoto (1961) conducted *in-situ* experiments on the sloping mountain site, which suggested subsurface flow is superior than surface runoff during short-term runoff at the slope and the occurrence of surface runoff was rare. Incidentally, impermeable layer or aquiclude with very low hydraulic conductivity located under the ground surface, rain water arriving at the ground surface infiltrates vertically and flows for downward direction which reaches saturation on the upper surface of the impermeable layer, such as throughflow. It flowed out in the direction of flowing downward and was generated after a water depth of flow exceeded the surface soil layer thickness in the vicinity of the end of the slope, called the Takasao-typed surface flow (Takasao, 1963). If infiltration capacity was not understood in terms of the ground surface, a major disaster will occur at the time of flooding. For example, in 1998, severe natural disasters occurred due to 24-hour rainfall around of the unprecedented 900 mm rainfall in Kochi prefecture, Japan (Hiramatsu et al., 1999). The area seemed to have many artificial forests of Japanese cypress and landslide occurred under the heavy rain. With such a background, in 2003, Kochi Prefecture became the first local government to introduce forest environment tax before the whole country in order to improve the forest in reservoir area. For comparison, forest environment tax will be explained in detail in section 1.5.

1.3 Key factors for rainfall-runoff/erosion phenomenon

Previous researchers suggested parameter of rainfall factor, slope, slope length, vegetation ratio or materials, surface condition, soil properties, antecedent soil moisture are key factors for runoff/erosion/infiltration.

1.4 How to measure/calculate the rainfall-runoff/infiltration process

The monitoring data required and hence the method by which they are obtained depends on the spatial and temporal scales of the problem being investigated. Spatial discontinuities might result from the effect of regolith or surface properties on redistributing rainfall and concentrating infiltration. Evans (1980) suggested parameter of rainfall factor, slope, vegetation, surface condition, soil properties, antecedent soil moisture are key factors for runoff/erosion/infiltration.

Rainfall can be measured by installing a rain gauge. However, it is self-evident that how rain falls is affected by the wind, so it will not become uniform, and no matter how accurately it is measured including some errors (Ota and Shinohara, 1963).

The occurrence of overland flow can be measured by installing a water level sensor in a weir or storage tank. By preparing the discharge rating curve in advance, it is possible to easily calculate the discharge by measuring the water level. Here, following a previous study on the runoff from plot, this study was followed a similar method based on previous studies (e.g., Kinosita and Nakane, 1977; Sidle et al., 2007; Gomi et al., 2008; Miyata et al., 2009).

Local moist environments created in this way are exploited by plants and animals; further, there are complex interactions between ecological and hydrological processes that lead to the divergence of separate ecological subsystems (Imeson et al., 1992). It has been found from numerous studies that the parameters related to water transfer in soil measured from small samples taken at the same soil site are greatly changed due to the heterogeneity of the pore distribution (Nakaegawa et al., 2000).

1.5 Objectives of this study

In this thesis, the effect of surface cover material, cover ratio and slope on the runoff/infiltration was examined under simulated and natural rainfall conditions using experimental plots of different cover material/condition.

In chapter 2, in order to investigate the infiltration rate in the Japanese cedar and Hiba arborvitae forest, an experiment using an oscillating nozzle artificial rainfall simulator was conducted. Next, the surface cover materials were collected and classified as understory, litter and root. Finally, the soil sample was taken and subjected to permeability test, pF test and particle size analysis. Based on these data, I (author) examined what kind of variables contributed to infiltrability. The reason for selecting the study site in Ishikawa prefecture, the decline in infiltration capacity due to the wash out of litter in a Japanese cypress forest is a problem, and although there are many observations targeting cypress plantation forests, observation cases in other tree species are few in Japan. Japan was that 'forest environmental tax' as individualistic tax were considered and introduced in each prefecture of Japan, recently. In the background of the introduction of "forest environment tax", there is a move toward centralization of national economy that the decentralization law was enacted in April 2000 (Tachibana, 2005). Ishikawa Prefecture introduced "Ishikawa Forest Environmental Tax" in fiscal 2007, intensive thinning of degraded plantations mainly in the water source area, and an attempt to save public function of forests. Therefore, since it is necessary to verify the effect of introducing the Ishikawa Forest Environmental Tax (Ishikawa forest environmental tax, 2007; Institute for Environmental Monitoring, 2010; Ogura et al., 2012)

Chapter 3 is based on

Chapter 4 is based on

In chapter 5, the summary, final conclusions, prospective and limitation of the main findings from each chapter are described.

Reference

Chapter 2. Effects of surface cover and soil properties on infiltration rate in Japanese cedar and Hiba arborvitae plantations

2.1 Introduction

Previous studies have reported that the Hortonian overland flow (HOF) generation seldom occurs in forest soils that are generally rich in macropore-containing organic matter, but in recent years HOF generation has been observed in part of the unmanaged forests. This overland flow might occur when the infiltration rate decreases with increasing uncovered forest floor (e.g., Tsujimura et al., 2006; Gomi et al., 2008; Miyata et al., 2009). Moreover, the heavy rain events have an effect on increasing the risk of floods (Onda, 2008).

Infiltration has been traditionally studied using a flood-type or mist-type rainfall simulator (e.g., Murai and Iwasaki, 1975; Takeuchi, 1976). Because a flood-type rainfall simulator supplies an excessive amount of water and as the mist-type simulator cannot reproduce raindrop impacts, the conventional method using these simulators does not accurately reproduce natural rainfall. For accurate reproduction of rainfall, Onda et al. (2005) presented a series of large-scale sprinkling experiments in which water was sprinkled from the upper canopy. It is presumed in this investigation that infiltration rate observed in previous experiments should be about one order of magnitude more than the actual value. A large-capacity tank truck was installed in this investigation, but a small portable oscillating nozzle rainfall simulator recently developed by Kato et al. (2008) was used for the experiments. The experiments showed a positive correlation between surface cover materials and infiltration rate (e.g., Kato et al., 2008; Hiraoka et el., 2010; Ogura et el., 2012). A similar experiment was carried out in the semi-arid region, and obtained results indicated a noticeable positive correlation between these two variables (e.g., Loch, 2000a; Kato et al., 2009).

Previous studies showed that the effect of understories and leaf litters on infiltration rate is significant, which suggests that the surface cover materials reduce raindrop impact on the soil surface, and therefore the formation of surface crusts and HOF are restricted (e.g., Onda and Yukawa, 1995; Miura, 2000; Tsukamoto et al., 1998; Abe and Sato, 2008; Hiraoka et al., 2010). A related finding of these studies is that fragmentation process of *Chamaecyparis obtusa* leaf litter progresses rapidly, and thus the *C. obtusa* forests are likely to become uncovered due to soil loss from steep slopes (Kiyono, 1988). Fragmentation of Hiba arborvitae leaves is less likely to occur than those of *C. obtusa*, and the fragmentation of cedar leaves is mostly unlikely to occur. Therefore, the Japanese cedar and Hiba arborvitae forests have larger effects on soil conservation than *C. obtusa* forests (Ogura and Kodani, 2008). The case studies using the recently developed method does not, however, allow for the sufficient examination of infiltration rate in Japanese cedar and Hiba arborvitae forests. Thus, an additional investigation should be carried out in these forests using a new method. Furthermore, Miyazaki et al. (1998) argues that the effects of leaf shape on soil conservation is not clear. Further consideration will be needed on this viewpoint.

The results from previously published studies have revealed that the hydraulic conductivity of forest floor and soil surface was greater than several hundred mm/h (e.g., Tsukamoto, 1992; Kosugi, 1999; Miyata et al., 2009). A correlation was observed between the hydraulic conductivity and infiltration rate (e.g., Murai and Iwasaki, 1975; Dunne et al., 1991), as well as surface cover materials and infiltration rate. However, according to the observation results of plot runoff due to rainfall, there was no obvious correlation between infiltration rate and hydraulic conductivity in *C. obtusa* forests, suggesting that soil detachment by raindrops has a potentially significant impact on the infiltration rate (Miyata et al., 2009). It is usually assumed that the hydraulic conductivities of surface cover materials and surface soil are the significant factors impacting infiltration rate in forests, but more detailed consideration needs to be given to explain this assumption.

In Ishikawa Prefecture, Japan, there are forests accounting for about 70% of the prefecture land, due to the restoration of the devastated forest land after the World War II, afforestation has been rapidly carried out on about 990 km^2 of plantation. The maintenance area of 290 km^2 of the forest degradation without thinning was concerned an urgent task in 2005. Ishikawa prefectural government stressed that it is necessary to focus on maintenance of degraded forests. The maintenance cannot be performed only by the people involved in forestry or forestry-related works as a living but have to involve professionals. The functions of forests have been maintained through forest management. However, forestry business has been concerned with declining public benefit with degradation, water recharge and conservation of mountain area has grown unprofitable due to the soaring the prices of timber and depopulation of mountain area. As a result of this, Ishikawa Prefecture introduced "Ishikawa Forest Environmental Tax" in fiscal 2007 (Ishikawa forest environmental tax, 2007; Institute for Environmental Monitoring, 2010; Ogura et al., 2012), intensive thinning of degraded plantations mainly in the water source area, and an attempt to save public function of forests. Therefore, since it is necessary to verify the effect of introducing the Ishikawa Forest Environmental Tax, we attended/conducted a water soil conservation function survey in the same way as the verification of Yamaguchi Forest Management Prefectural Residence Tax (Yamaguchi Prefecture, 2007, 2008, 2009). The verification method is *in-situ* permeability test using an artificial rainfall apparatus. As for the effect of introducing the Ishikawa Forest Environmental Tax was conducted along with the soil conservation function survey and function of biodiversity conservation.

Therefore, field measurement of infiltration rate using the new method was conducted in Japanese cedar and Hiba arborvitae forests to examine the relation between infiltration rate, surface cover materials, and hydraulic conductivity of forest soil.

2.2 Methods

2.2.1 Site description and test plot design

All sites were located in the environmental community forests developed through a conservation project in Ishikawa Prefecture, Japan. Plantations cover about 40 percent of the total forests in this Prefecture. In terms of species composition of the plantations, Japanese cedar forests tops with 71 percent followed by Hiba arborvitae with 12 percent and pine trees with 9 percent. Cedar forests are distributed equally throughout the entire areas in Ishikawa Prefecture, while Hiba arborvitae forests show unequal distribution with a large part of the forests located in the Noto Peninsula (Ishikawa Prefecture Department of Agriculture, Forestry and Fisheries, 1997). This study selected 22 Japanese cedar and 16 Hiba Arborvitae sites in all available forests before thinning or the forests with different years elapsed after thinning (Figure 2.1). The study sites are dominated by brown forest soils, and have a slope of 40 degrees. Forest leaf litter accumulates at all the sites with dense and sparse understories. According to AMeDAS data (http://www.data.jma.go.jp/obd/stats/etrn/select/prefecture.php?prec_no=56&block_no=&year=&month=&day=&view=), annual rainfall averages nearly 2302 mm (1976−2012) with an average temperature of 13° C (55°F) in Ishikawa Prefecture.

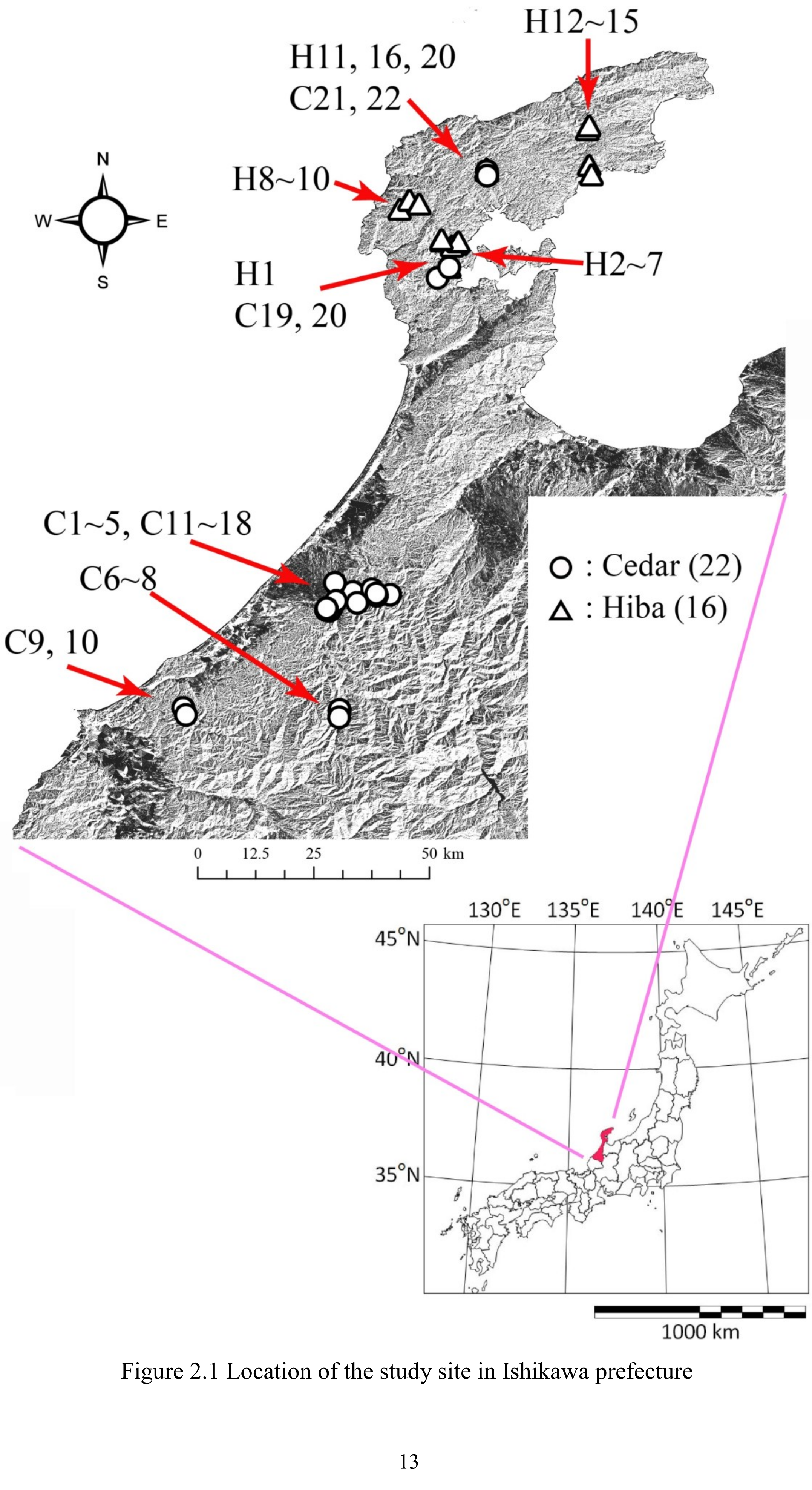

Figure 2.1 Location of the study site in Ishikawa prefecture

2.2.2 Definition of infiltration rate

Horton equation is based on the observation that infiltration capacity is gradually exponentially reduced with time when although thin ground surface is always thin fresh state is sufficiently supplied. Horton (1939) proposed following equation excess rainfall/infiltration processes.

$$f(t) = f_c + (f_0 - f_c) \cdot e^{-kt} \qquad \ldots(2.1)$$

where $f(t)$ is infiltration rate at the time from infiltration start to elapsed time (mm/h), f_0 is initial infiltration rate (mm/h), k is reduction coefficient and t is time. Horton (1939) introduced that while equation (2.1) may not actually represent the law governing the physical processes involved, this equation is rational inform, since it not only represents the observed data within the range of observation but also gives results in agreement with known facts for the limiting or boundary conditions. While this equation is very useful, but many researchers pointed out that could not be acceptable error from the theoretical analysis resulted by Richard-equation (Oka, 2001; Brutsaert, 2005) Conversely, the many researchers adapted themselves data and modified equations.

The basic assumption is that the process of runoff generation occurs when the rainfall intensity exceeds the actual infiltration rate of the soil. The soil layer was expected to absorb and hold rainfall when the rainfall intensity drops below the actual infiltration rate. Recent studies, however, have shown that infiltration rates can increase with increasing rainfall intensity until it reaches a constant value (Murai and Miyazaki, 1975; Hawkins and Cundy, 1987). Their 'apparent' infiltration rate at steady state (f_s) is defined as area-averaged infiltration rate of which a certain fraction contributes to rainfall excess production. Infiltration capacities can be assumed to have an exponential distribution (Hawkins and

Cundy, 1987), so f_s can be given by:

$$f_s = f_{\max}\left(1 - \exp\left(-i/f_{\max}\right)\right) \quad \text{...(2.2)}$$

where i is rainfall intensity (mm/h), f_{max} is average infiltration rate(mm/h), when the whole plot is contributing to rainfall excess production.

With given f and i, the model has only one empirical parameter, f_{max}, which makes it attractive for practical use. Yu et al. (1997) and Stone et al. (2008) applied the exponential model (using equation 2.2) to their rainfall–runoff data, which yielded much better results than the application of a model with a constant K_e. Langhans et al. (2011) adapted his results, so fitting equation (2.2) to the logarithmic data gives a suitable description of the data in terms of fit, without allowing for any physical interpretation.

Also, based on experiments in plots with different land-use patterns such as parks and pastures under artificial precipitation system, Tanaka and Tokioka (2007) suggested the following hyperbolic function, which gives the relation between rainfall intensity and final infiltration rate;

$$f(i) = FIR_{\max} \cdot \tanh\left(i/FIR_{\max}\right) \quad \text{...(2.3)}$$

where i is rainfall intensity (mm/h), f is final infiltration rate, and FIR_{max} is the maximum infiltration rate.

For hyperbolic function equation, Boughton (1966) already introduced / modified the daily rainfall and runoff equation for predictions of daily runoff from daily rainfall.

$$Q = R - F_r \cdot \tanh\left(R/F_r\right) \quad \text{...(2.4)}$$

where R and Q are the amounts of daily rainfall and runoff respectively, F_r is a parameter termed the daily infiltration potential at the beginning of runoff.

Recently, Langhans et al. (2014) modified a Hawkins and Cundy equation (equation 2.2) on rainfall intensity and final infiltration rate. The equation is developing that some researchers found a limitation and improve by mathematics thinking, it will be cleared that things suitable for calculating infiltration rate.

Hiraoka et al. (2010) introduced Tanaka's personal letter that Equation (2.3) is thought to be best equation and Murai and Miyazaki (1975) and Hawkins and Cundy (1987) has applicability has been confirmed for the data of Hawkins and Cundy (1987), supporting the private correspondence of Equation (2.3) that can be accurately applied than Equation (2.2). However, this evidence has not been shown yet nowhere, Hiraoka et al. (2010) also did not mention. Figure 2.2 shows relationship Rainfall intensity between Infiltration rate using equation (2.2) and (2.3) under FIR_{max} is 100 (mm/h).

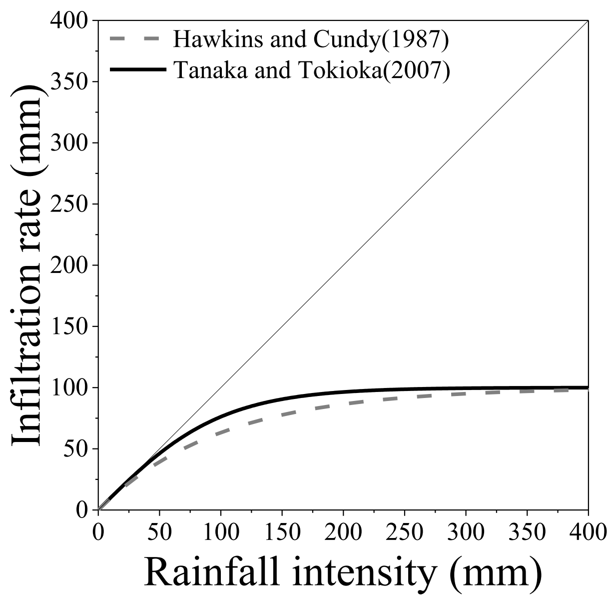

Figure 2.2 Relationship rainfall intensity between infiltration rate using equation (2.2) and (2.3). Equation (2.2) based on Hawkins and Cundy (1987) and Equation (2.3) based on Tanaka and Tokioka (2007) under FIR_{max} parameter is "100" (mm/h).

Figure 2.3 shows Tanaka and Tokioka (2007) equation divided by Hawkins and Cundy (1987) equation is following relation. There is a big difference until less than 600 mm/h of rainfall intensity, especially over about 20 % with around at 100 mm/h. The definition of f_s in Equation (2.2) implies that at any rainfall intensity there are patches that contribute to runoff and that the soil is at least partly saturated. On the other hand, Equation (2.3) was obtained based on the *in-situ* permeability test using an artificial rainfall simulator (Kyowa Environmental Monitoring Research Co, Ltd., 2007; Tanaka and Tokioka, 2007). This formula was obtained by the same method as this study method. So, Equation (2.3) was used following this study for simplified to calculate FIR_{max} and compare to previous studies.

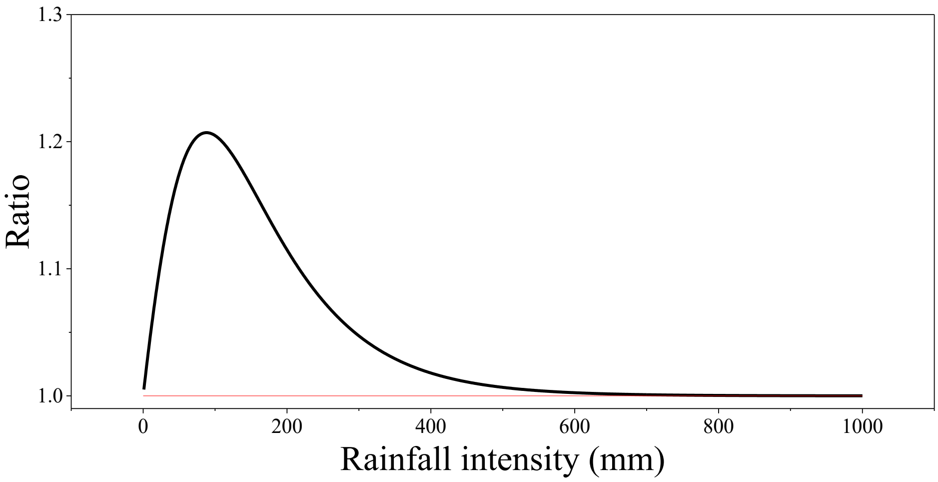

Figure 2.3 Relationship Rainfall intensity between Equation (2.3) divided by Equation (2.2). Red line shows one-on-one.

Infiltration rate varies depending on rainfall intensities in field experiments, but FIR_{max} is suggested as a reasonable first approximation. Using these equations, the final infiltration rate at a given rainfall intensity can be determined if FIR_{max} is defined. Overland flow may be generated when rainfall intensity exceeds final infiltration rate, but that might not occur until rainfall intensity reaches a certain level. This model does not take into account the minimum rainfall intensities that induce the overland flow. In this paper, however, we focus only on the maximum infiltration rate and make a comparison of the results.

2.2.3 *In-situ* permeability tests

Sprinkling experiments corresponding to a certain degree of rainfall intensity were conducted in small size of plots established in each experimental site. I (author) measured the amount of water applied to sprinkling and overland runoff from each plot on a regular basis. The difference between these two amounts means infiltration volume, and the final infiltration rate can be estimated using this infiltration volume.

The plot was established in each study site with horizontal projected area of 1 m^2 (1 m × 1 m). Wave-board panels (about 25 cm height) were placed at the upper end and both sides of the plots. The panels were inserted vertically at a depth of 5 cm under soil surface to prevent the inflow from outside the plot and runoff from the plot. Trays are placed at the cover material-soil interface at the lower end of the plot. This system was adopted to catch and collect overland flow. An oscillating nozzle rainfall simulator was used for sprinkling water. The simulator was set, according to Hiraoka et al. (2010) who used this device, with flow rate 12.5 L/min and nozzle height 2 m from the center of sprinkled plot (Figure 2.4). The angle of nozzle was adjusted to obtain the targeted value for rainfall intensity (180 mm/h). To measure actual rainfall intensity, total sprinkled water was collected using plastic sheet. Impact energy of raindrop produced in this experiment was about 16.8 J/m^2/mm, which was similar to the average energy obtained in the experiment in the *C. obtusa* forests (Nanko et al., 2004). The influence of moisture content cannot be ignored, but we sprinkled water with an intensity of 180 mm/h for 2 hours to obtain an accurate final infiltration rate. The rainfall intensity of 180 mm/h is approximately equal to the maximum rainfall intensity that has ever been observed in Japan (187 mm/h: observed at Nagayo-cho municipal office during the 1982 flood disaster in Nagasaki Prefecture). The amount of water stored in a tray at the lower end of the plot was measured every hour to determine the discharge of overland flow.

Rainfall was artificially produced until the discharge returned to original steady-state. The experiment could be usually completed within approximately 20–30 minutes, and the final infiltration rate was defined as the average value of the results taken over the last five minutes. Infiltration intensity may, in some cases, begin to slightly increase after the initial decreasing trend, followed by leveling off to the decreased values. If this is the case, the final infiltration rate was defined as the average value obtained from the values over 3 minutes before and after the infiltration intensity reaches minimum values.

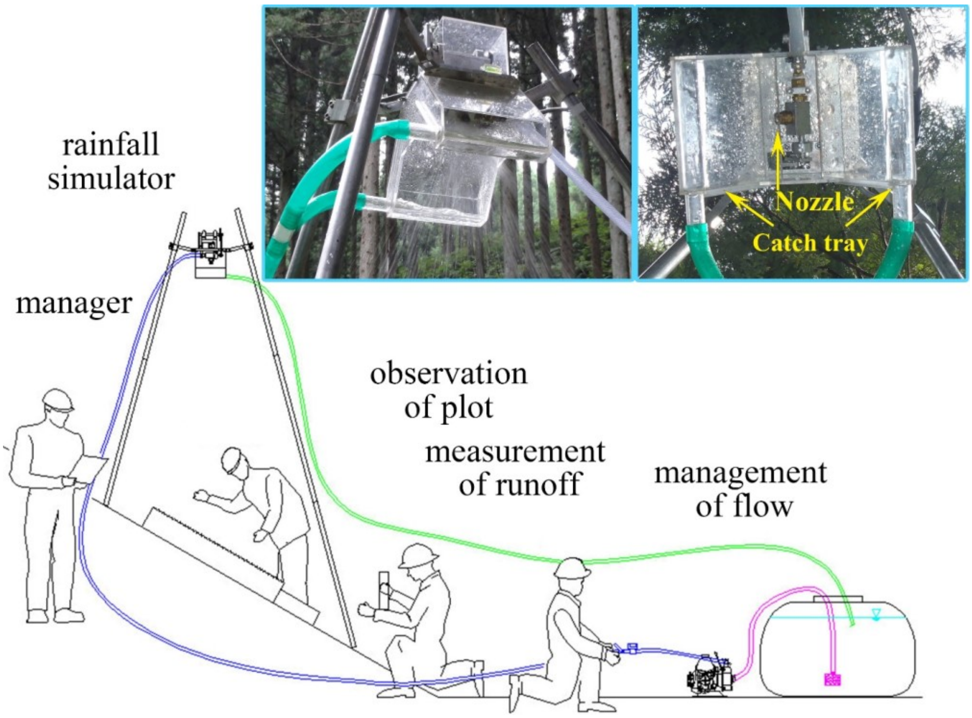

Figure 2.4 Rainfall simulator and experimental guideline.

2.2.4 Measurement of surface cover materials

Surface cover materials are composed of understories and leaf litter. In response to the research by Miura (2000), small fractions (< 2 mm) were excluded from the litter category because protection of the soil surface cannot be achieved. The understories (ground layer) and leaf litter were collected after the experiment. These surface cover materials were air-dried for a week, then re-dried in an oven at 70°C for 48 hours to determine the dry weight. Photos were taken directly above the plot, and the floor cover percentage was estimated by calculating the percentage of forest floor that is covered with either litter or understories based on image analysis.

2.2.5 Measurement of soil properties

Generally, soil properties not only change for each type of soil, vary depending on the location in the same type of soil. It is desirable to make laboratory test (e.g., permeability test, pF test, grain size analysis) using a small sample of soil *in-situ* to obtain the characteristic value.

The soil samples were collected after the rainfall simulation experiments to estimate soil properties. To investigate soil properties affecting final infiltration rate, particle size, hydraulic conductivity, and bulk density were estimated. Sampling and test were conducted by the following methods. After collecting surface cover materials, collection of undistributed sample soils was made using 400 cc core sampler (cross section area of 100 cm^2 and 4 cm in height) to measure particle size. The reason for examining the physical properties of the surface layer (up to 10 cm from the surface) was because the surface layer was found to be a major influencing factor on infiltration rate. Undistributed soil samples were taken to a depth of 0−5 cm and 5−10 cm using 100 cc core sampler (cross section area of 19.6 cm^2 and 5.1 cm in height). Three samples were collected at each layer to overcome the difficulties caused by inhomogeneity of soil properties. The average size of these three samples was taken to be the representative value.

Saturated hydraulic conductivity was measured by a permeability test after capillary rise for over 48 hours. Determination of permeability was carried out using a constant head permeability test (Equation 2.5), but a falling head permeability test (Equation 2.6) was used for the lower permeability samples. Then, to find the dry bulk density, the soil was oven dried at 105°C for 24 hours and the weight of oven-dried soil was measured.

$$k_0 = \frac{Q}{At} \cdot \frac{l}{h} \qquad \text{…(2.5)}$$

$$k_0 = \frac{2.3al}{At} \cdot \log_{10}\left(\frac{h_1}{h_2}\right) \qquad \text{…(2.6)}$$

where *ko* is saturated hydraulic conductivity (m/s), Q is unit area drainage discharge (cm^3), A is cross sectional area for sampler (cm^2), a is cross sectional area for pipe (cm^2), l is length (cm), t is time (s), h is water head (cm).

The pF value and bulk density were measured after finishing the permeability test. As a test method are following on our case, centrifuging-method, soil column method, and suction method. Here with soil column method and the suction method, it was decided to obtain a value of around pF2. Further, by applying the conventional proposals type volumetric moisture content curve obtained, to determine the soil parameters. Numerous empirical formula or the like have conventionally been proposed as this expression technique, wherein employing the van Genuchten (1980) equation is being used relatively often in recent studies.

$$Se = \left(\frac{1}{1+|\alpha \psi|^n}\right)^{1-\frac{1}{n}} \qquad \text{…(2.7)}$$

where α and n are soil characteristics parameter.

And, effective saturation is defined following equation.

$$Se = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad \text{…(2.8)}$$

where θ_s is saturated water content, θ_r is residual moisture content.

θ_r and θ_s were used as a value that can be read from the graph. As for the other parameters, compatibility with the experimental values using the method of least squares was determined by fitting the best curve. Komatsu (2006) reported more details and here I (author) measured water absorption process that ignored the hysteresis effect.

Particle size distribution was determined by means of the sieving method and by using a particle size analyzer (SALD-3100; Shimadzu Corp., Kyoto, Japan) for fine fractions. Content of particles finer than 0.063 mm was observed, especially clay and silt fractions, in this experiment.

2.2.6 Relation between FIR_{max} and hydraulic conductivity

To explore the relation of surface cover materials and hydraulic conductivity with FIR_{max}, correlation coefficients (r) and (p) were calculated using PASW statistic 18 (SPSS Japan Inc.) and R version 2.13.2 (The R Foundation, 2011).

2.3 Results

2.3.1 FIR_{max} in Japanese cedar and Hiba arborvitae plantation forests

Table 2.1 shows the measurement results of surface cover materials, hydraulic conductivity, dry bulk density, and FIR_{max}. In all the cases during the experiment, rainfall intensity is in excess of final infiltration rate ("Rainfall intensity" and "*FIR*" in Table 2.1), which suggests that overland flow may occur in Japanese cedar and Hiba arborvitae forests during the intense rainfall events with around 180 mm/h.

FIR_{max} ("FIR_{max}" in Table 2.1) was obtained by applying the equation (2.3) to the rainfall intensity and final infiltration rate obtained in this experiment. FIR_{max}, as shown in Figure 2.5, distributes in a range from 141.9 to 562.3 mm/h in the Japanese cedar forest and from 93.3 to 641.0 mm/h in the Hiba arborvitae forests. Figure 2.5 shows frequency distribution of FIR_{max} for every 100 mm. A peak is observed in the FIR_{max} distribution in Hiba arborvitae forests around 200 to 300 mm/h, but tends to distribute equally in the range of 100 to 700 mm/h in both forests. Low FIR_{max} (less than 100 mm/h) was observed at only one site in Hiba arborvitae forests.

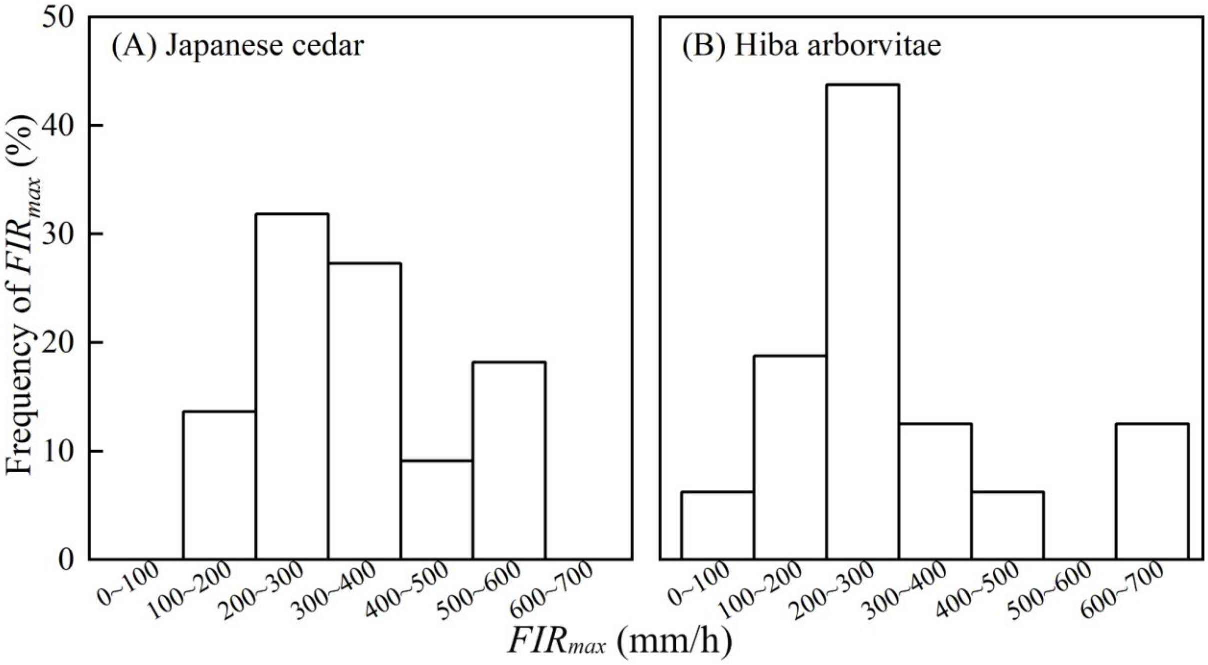

Figure 2.5 Frequency distribution of FIR_{max}. (A) Japanese cedar and (B) Hiba arborvitae.

2.3.2 Surface cover materials in Japanese cedar and Hiba arborvitae plantation forests

Measurement of surface cover materials ("Understory vegetation" and "Litter materials" in Table 2.1) shows that understories comprised approximately 10% of surface cover materials and the remaining 90% of litter materials, which signifies that litter materials are a major component in Japanese cedar and Hiba arborvitae forests. The frequency distribution of surface cover materials per area of 500 m^2 (no figure is presented) shows that the highest peak is at the frequency of 500 to 1000 g/m^2 in both types of forest, and an increase in weight (1000 to 1500 g/m^2, 1500 to 2000 g/m^2) induced the lowering of the frequency.

2.3.3 Soil properties in Japanese cedar and Hiba arborvitae plantation forests

A high degree of variability in hydraulic conductivity was found, but high values

(100 to 2000 mm/h) were obtained in the 0 to 5 cm and 5 to 10 cm layers in both types of forest (except for C19). The same trend was commonly seen in other forests as reported in previous studies (Kosugi, 1999; Miyata et al., 2009). Hiba arborvitae forests had relatively higher hydraulic conductivity than Japanese cedar forests. It was also found that hydraulic conductivity measured at depth of 5 to 10 cm was comparatively lower than those at depth of 0 to 5 cm depth. Dry bulk density ("Bulk density" in Table 2.1) was as follows: 0.38 to 0.86 g/cm^3 in Japanese cedar forests and 0.37 to 0.72 g/cm^3 in Hiba arborvitae forests at depth of 0 to 5 cm; 0.49 to 0.995 g/cm^3 in Japanese cedar forests and 0.49 to 0.91 g/cm^3 in Hiba arborvitae forests at depth of 5 to 10 cm. Although there was considerable variability, it was found that the bulk density increased with depth and was higher in Hiba arborvitae forests compared to Japanese cedar forests. According to Miyata et al. (2009), the average bulk density was 0.75 g/cm^3 in Hiba arborvitae forests, which was slightly lower than those obtained in our experiment (Japanese cedar forests: 0.67 g/cm^3; Hiba arborvitae forests: 0.51 g/cm^3). It was presumed that a decrease of porosity induced by an increasing bulk density results in a decrease of hydraulic conductivity with increasing depth. However, we could not find significant correlation between hydraulic conductivity and bulk density. Therefore, there is another unknown factor for the decrease of hydraulic conductivity.

Fine fraction content ("Fine fraction content" in Table 2.1) was 4 to 38% (average 22%) in Japanese cedar forests and 17 to 36% (average 25%) in Hiba arborvitae forests, but most of the data for both types of forest were below 35% except maximum values. The maximum values for these forests do not vary significantly as much as the minimum values. The minimum value was 4% for Japanese cedar forests and 17% for Hiba arborvitae forests, respectively. The result obtained in Japanese cedar forests exhibits a larger variability compared to Hiba arborvitae forests.

Table 2.1 Result of *in-situ* artificial rainfall experiments using an oscillating nozzle rainfall simulator

			Cover				Soil					Experiment		
Type	Plot ID	Elapsed time after thinning (yesr)	Ground cover ratio(%)	Dry weight of understory vegetation (g m^{-2})	Dry weight of litter materials (g m^{-2})	Dry weight of total cover (g m^{-2})	Fine fraction content (%)	Bulk density (g cm^{-3})		Hydraulic conductivity (mm h^{-1})		Rainfall intensity (mm h^{-1})	*FIR* (mm h^{-1})	FIR_{max} (mm h^{-1})
								0-5cm	5-10cm	0-5cm	5-10cm			
Cedar	C1	1	100	70	220	290	18	0.51	0.69	1420	559	171	147	241
	C2	unthinned	80	30	490	520	8	0.72	0.78	1060	429	170	141	212
	C3	over 5	70	70	500	570	26	0.47	0.58	1120	620	186	171	359
	C4	2	90	190	1170	1360	19	0.60	0.75	1650	593	186	180	562
	C5	3	70	270	1270	1540	30	0.66	0.95	430	202	179	152	209
	C6	1	70	200	580	780	19	0.77	0.89	710	584	178	158	270
	C7	unthinned	80	70	320	390	33	0.80	0.79	810	565	190	128	142
	C8	over 5	90	290	1200	1490	12	0.86	0.81	1170	1239	169	146	227
	C9	unthinned	100	190	1710	1900	22	0.80	0.83	700	697	178	171	317
	C10	1	80	20	630	650	38	0.56	0.64	1020	1195	170	162	449
	C11	1	70	370	540	910	34	0.81	0.79	840	1218	194	183	488
	C12	unthinned	30	10	460	470	4	0.85	0.95	1300	1799	183	173	324
	C13	over 5	40	180	1160	1340	27	0.55	0.57	1110	1651	180	174	537
	C14	1	100	0	250	250	14	0.44	0.58	1120	169	149	137	282
	C15	unthinned	60	290	680	970	21	0.83	0.90	340	330	153	114	146
	C16	3	80	110	1780	1890	32	0.49	0.73	740	673	189	156	238
	C17	2	90	80	1670	1750	26	0.85	0.995	100	155	177	166	389
	C18	1	90	0	360	360	20	0.59	0.69	560	717	206	187	373
	C19	unthinned	90	0	880	880	32	0.77	0.81	1	2	192	169	301
	C20	1	80	50	420	470	4	0.60	0.78	1370	330	179	173	538
	C21	unthinned	100	0	1150	1150	30	0.74	0.84	210	296	206	196	508
	C22	1	100	160	950	1110	23	0.38	0.49	680	505	188	142	175
Hiba	H1	3	100	60	580	640	18	0.54	0.71	1340	581	230	164	204
	H2	unthinned	60	10	1020	1030	34	0.42	0.61	1360	858	185	90	93
	H3	2	60	0	470	470	19	0.51	0.69	1140	674	193	153	214
	H4	1	80	10	860	870	26	0.50	0.59	1630	782	177	165	372
	H5	1	90	0	570	570	23	0.56	0.90	460	489	179	146	217
	H6	over 5	90	50	930	980	23	0.53	0.81	610	192	176	151	242
	H7	unthinned	100	900	800	1700	30	0.44	0.67	530	310	166	128	150
	H8	1	100	0	420	420	36	0.50	0.73	1290	403	192	187	623
	H9	unthinned	80	70	1570	1640	20	0.40	0.45	950	944	193	171	278
	H10	over 5	100	70	1240	1310	28	0.54	0.85	770	533	192	188	641
	H11	3	80	40	450	490	34	0.51	0.58	1050	684	183	163	270
	H12	unthinned	70	400	1910	2310	20	0.67	0.84	1840	284	177	156	194
	H13	1	70	0	1200	1200	24	0.37	0.45	2170	625	146	138	347
	H14	unthinned	60	310	470	780	25	0.72	0.91	1030	312	178	135	149
	H15	1	100	0	1180	1180	17	0.55	0.74	1290	485	187	178	411
	H16	2	90	10	580	590	23	0.42	0.53	740	818	177	151	225

2.4 Discussion

2.4.1 Correlation between FIR_{max} and surface cover material properties

It is well-known that infiltration rate is affected by the amount of surface cover materials (e.g., Kiyono, 1988; Tsujimura et al., 2006; Onda, 2008). Also reported is an increasing trend of surface cover materials and understories with increasing time elapsed after thinning (Muramoto et al., 2005). However, there was apparent variability among data, and no correlation was found between the elapsed year after thinning and the amount of surface cover materials for both types of forest. In fact, the correlation could not be clarified, because of only a few numbers of data for surface cover materials corresponding to elapsed year after thinning. The research also looked at the separate correlation of understories and litter materials with elapsed year, but no correlation was found among these three groups. The effect of thinning on surface cover materials was also examined in both types of forest. Effects on volume of surface cover materials was compared between un-thinned plots and post-thinned sites with a variety of elapsed years. As a result, there was no noticeable difference in volume of surface cover materials between un-thinned and post-thinned sites in Japanese cedar forests, while a marked decrease in cover materials was observed in post-thinned plots in Hiba arborvitae forests. Figure 2.6 shows the box-and-whisker plots of FIR_{max} in un-thinned and post-thinned sites. Despite a decrease in surface cover materials due to thinning, FIR_{max} increases in both types of forest. This result challenges the widely accepted notion that there is correlation between surface cover materials and FIR_{max} in Japanese cedar and Hiba arborvitae forests, and no correlation was observed especially in Hiba arborvitae forests.

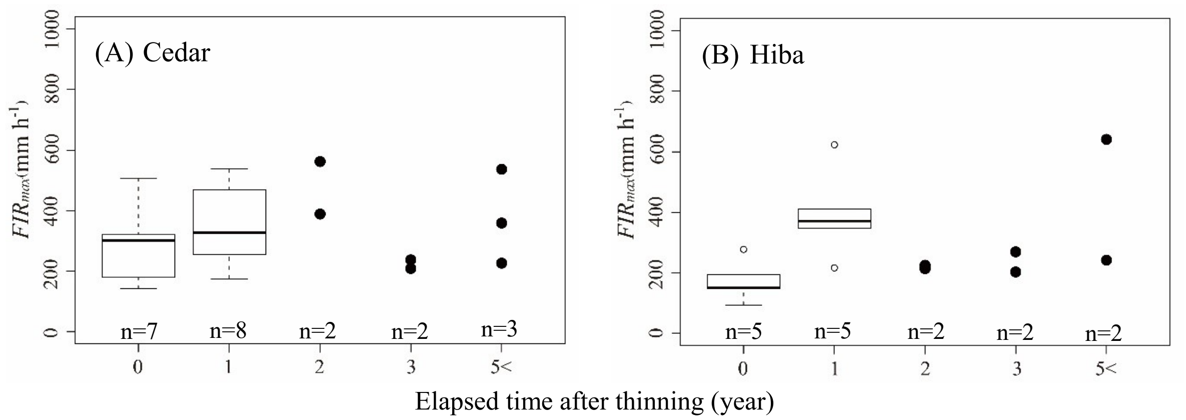

Figure 2.6 Box-and-whisker plots of FIR_{max} in unthinned and post-thinned sites. (A) is Japanese cedar and (B) is Hiba arborvitae. The box represents 50% of the data between the 25th and the 75th percentile, the line represents the median and whiskers the minimum and maximum.

Previous studies have shown that the effect of understories and leaf litters on infiltration rate is significant, which suggests that surface cover materials reduce raindrop impact on surface soil, and therefore the formation of surface crusts and high infiltration rate was kept (e.g., Miura, 2000; Kato et al., 2009; Hiraoka et al., 2010). Previous study pointed out that relationship surface cover ratio and final infiltration have a positive correlation. Figure 2.7 shows the relationship surface cover ratio and final infiltration but in this case, there is no significant correlation. Some researchers adapt a linear approximation to the relationship between the two sides. Although statistical analysis was carried out and significance was observed, despite the low correlation coefficient, there was a close relationship between the two, and by using this relationship. It is expected that it will lead to appropriate management guidelines considering maintenance functions. I (author) do not think about denying statistical analysis, but it is unknown whether it is easy to reach such consideration easily. On the other hand, the water storage capacity of litter layers increased linearly to litter mass on Japanese cedar and Japanese false oak site (Sato et al., 2004). The relationship between litter layer thickness and runoff has a negative correlation with less than

10 % variability (Vega et al., 2005). And, the relationship between litter layer thickness and hydraulic conductivity has a positive linear correlation with large variability (Marín-Castro et al., 2017). From these results, the influence of the vegetation cover on the runoff could be effective even if it does not appear in the statistic results.

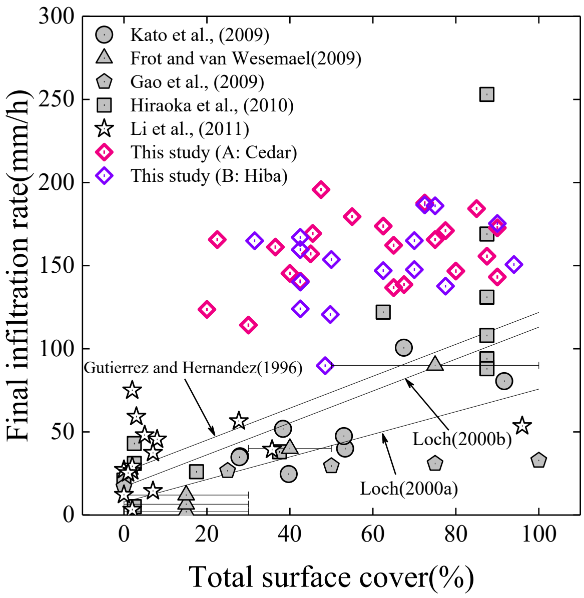

Figure 2.7 Relationships between the total surface cover and the infiltration rate at the (A) Japanese cedar and the (B) Hiba Arborvitae sites. (The solid square and open triangle indicate the desert grassland site and shrubland site, respectively. Steppe grassland (y=0.92x+5.74, r^2=0.59, p=0.029) and desert grassland (y=−7.67x+220.4, r^2=0.98, p=0.042) in Mongolia, results by Gutierrez and Hernandez (1996) (y=0.96x+25.9), Loch (2000a) (y=0.96x+17.0), Loch (2000b) (y=0.68x+7.74), Kato et al., (2009), Frot and van Wesemael (2009), Gao et al., (2009), Hiraoka et al., (2010) and Li et al., (2011). Modified from Kato et al., (2009))

Surface cover materials were measured using image analysis. A high concentration (> 60%) of cover materials was seen both in Japanese cedar and Hiba arborvitae forests, but no correlation was observed between FIR_{max} and surface cover materials. Figure 2.8 shows relation between surface cover materials and FIR_{max} in Japanese cedar and Hiba arborvitae forests. For comparison purposes, also included in the figure is the data of *C. obtusa* plantations (Hiraoka et al., 2010). Figure 2.8 clearly shows that FIR_{max} in Japanese cedar and Hiba arborvitae forests is generally higher than that in *C. obtusa* plantations. Japanese cedar and Hiba arborvitae forests, especially at sites with a low concentration of surface cover materials (< 1000 g/m^2), had a twofold to threefold greater FIR_{max} than that in *C. obtusa* plantations. This means that Japanese cedar and Hiba arborvitae forests may limit the occurrence of overland flow and soil erosion compared to *C. obtusa* plantations. Thus, Japanese cedar and Hiba arborvitae forests may provide a more effective protection of soil surface. The results of our experiment support previous studies and conclusions presented by Ogura and Takahashi (2006) and Ogura and Kodani (2008). The regression line in Figure 2.8 might show a positive correlation between the amount of surface cover materials and FIR_{max}. A similar finding was also reported by Kato et al. (2008). As shown in Figure 2.8 (Japanese cedar: r^2=0.173, p=0.443; Hiba arborvitae: r^2=0.024, p=0.929), however, no such correlation was recognized between the amount of surface cover materials and FIR_{max}. Both Japanese cedar and Hiba arborvitae forests gave a relatively high FIR_{max} values (> 100 mm/h) for any amount of surface cover materials. The research also took the separate correlation of understories and litter materials with FIR_{max}, but no correlation was found among these three groups.

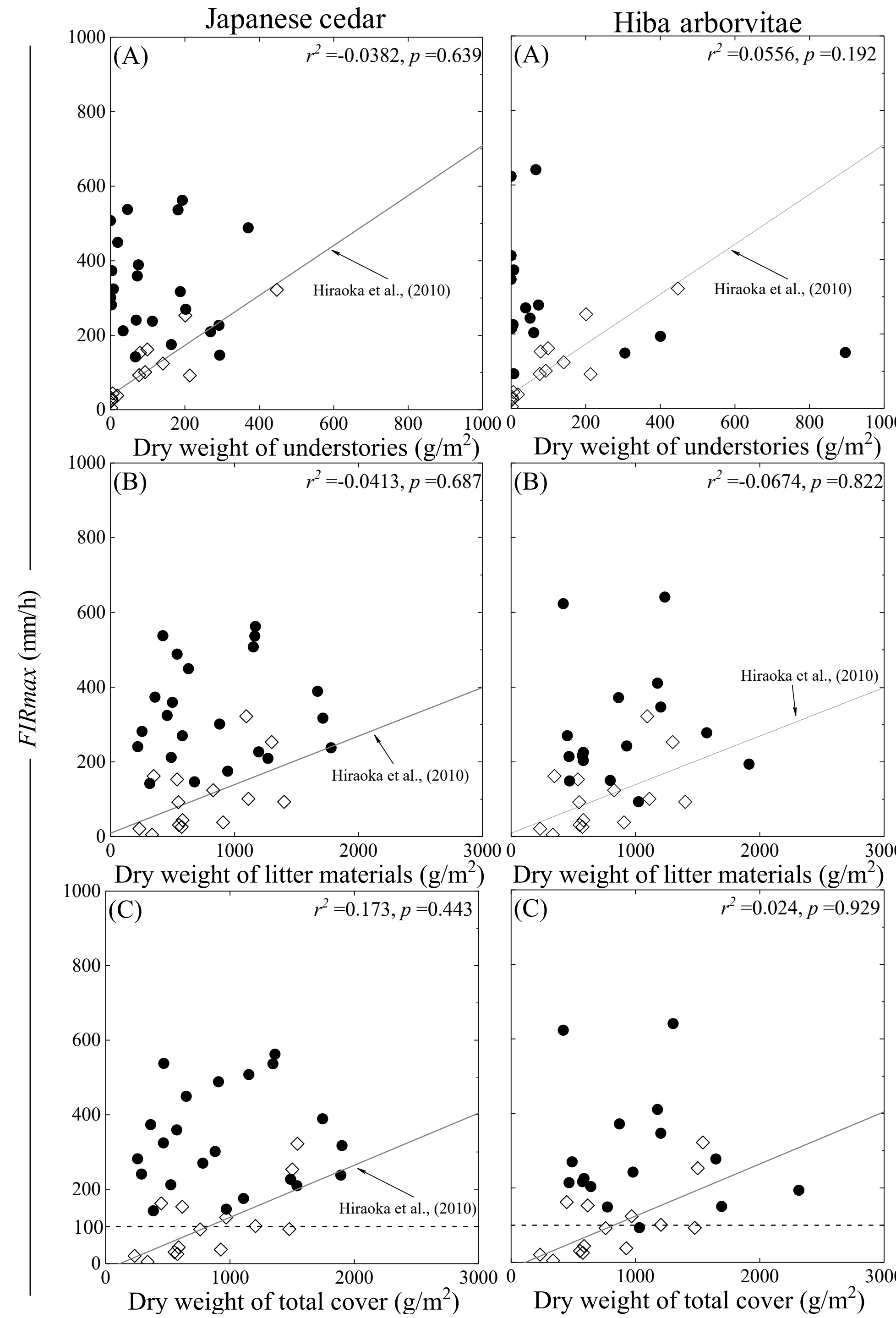

Figure 2.8 Relation between ground cover materials and FIR_{max} (A) is Dry weight of understories, (B) is Dry weight of litter materials and (C) is Dry weight of total cover. (The solid line and open triangle indicate the Japanese cypress site (A): FIR_{max}=0.67*(Dry weight of understories)+38.89, r^2=0.79**. (B): FIR_{max}=0.13*(Dry weight of litter materials)+9.14, r^2=0.27. (C): FIR_{max}=0.14*(Dry weight of total cover)-15.65, r^2=0.46**. Results by Hiraoka et al., (2010). ** is 1 % significant level)

2.4.2 Correlation between FIR_{max} and soil properties

The high fine fraction (clay + silt) content may increase the effect of clogging under the impacts of raindrops, which can reduce the infiltration rate and hydraulic conductivity (Miyata et al., 2009). Yokoi et al. (1998) reported that crust was formed when the fine fraction content in the sand pyroclastic flow deposits exceeded 35%. A soil profile at our experimental sites appears to be a brown forest soil. Therefore, the use of a theory developed by Yokoi et al. (1998) will be constrained. If the theory is to be applicable, it seems difficult to form crust in Japanese cedar and Hiba arborvitae forests as a whole because the fine fraction content does not generally exceed 35% in these types of forest. In fact, no crust could be visually observed after the experiment, and from the final infiltration rate obtained from the experiment, it also seemed unlikely that the formation of crust occurred. Figure 2.9 is the relation between fine fraction content and FIR_{max}, but this study could not find significant correlation (Japanese cedar: r=0.033, p=0.883; Hiba arborvitae: r=0.013, p=0.154). Figure 2.10 shows the relation between fine fraction content and hydraulic conductivity, in which no correlation could be established.

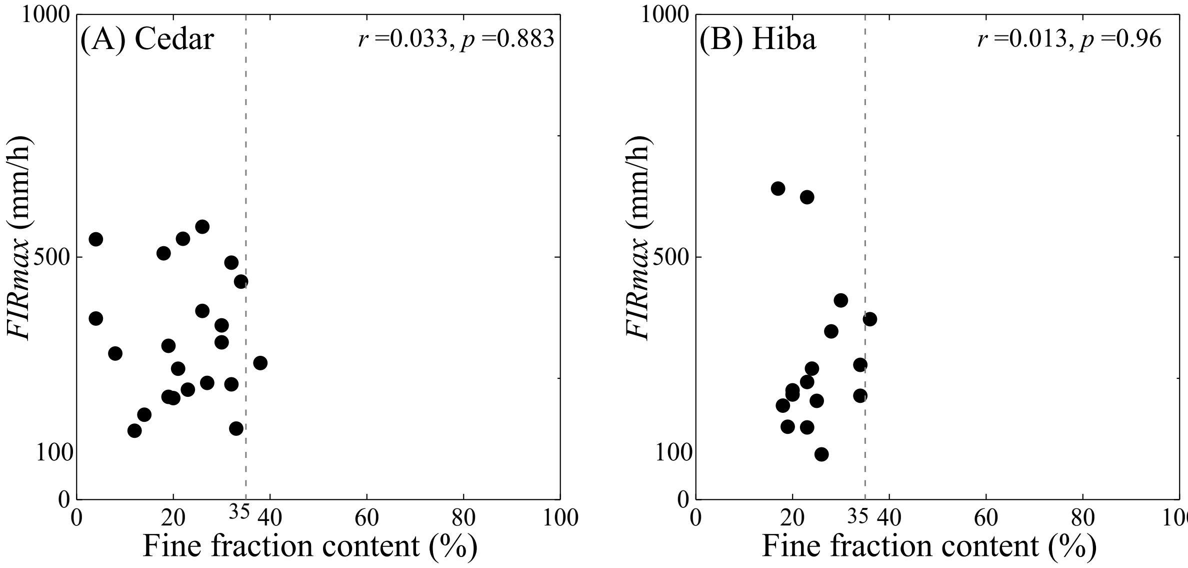

Figure 2.9 Relation between fine fraction content and FIR_{max}. (A) is Japanese cedar and (b) is Hiba arborvitae.

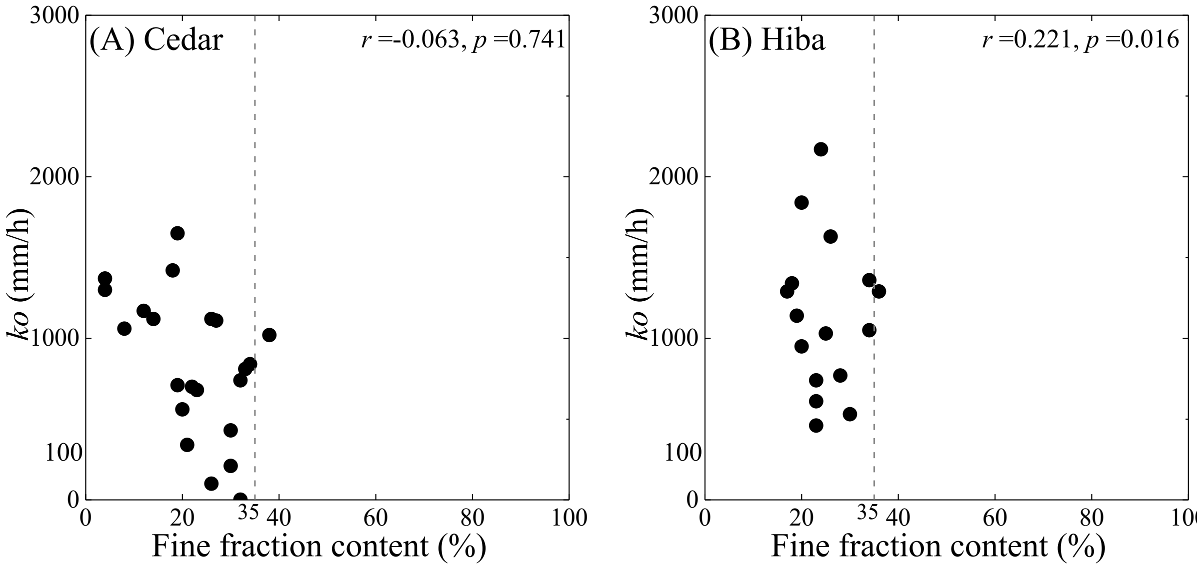

Figure 2.10 Relation between fine fraction content and hydraulic conductivity (*ko*). (A) is Japanese cedar and (B) is Hiba arborvitae.

Figure 2.11 shows relation between hydraulic conductivity and FIR_{max} in the 0-5 cm surface layer, which revealed no correlation in either type of forests (Japanese cedar: r=0.244, p=0.274; Hiba arborvitae: r=0.101, p=0.710). Similarly, no correlation was detected between hydraulic conductivity and FIR_{max} for soil at 5-10 cm depth. It also became clear that FIR_{max} is definitely lower than hydraulic conductivity at most sites in Japanese cedar forest (19 out of 22 sites) and all sites in Hiba arborvitae forest (16 sites). It is postulated that the hydraulic gradient in the surface soil layer was estimated to be about 1 and that FIR_{max} had the similar value to hydraulic conductivity, which needs careful consideration. The 2 to 3 cm layer within 1 hour after the sprinkling experiment was moistened, but the dry soil underlay in the deeper soil layers. The presence of macropores in soils might lead to the preferentially infiltration of sprinkled water. With fingering infiltration (unstable infiltration), the preferential water was infiltrated into the soils that are exceptionally conductive. Kobayashi and Shimizu (2007) pointed out that the discontinuous flow paths stained by the dye indicated preferential water movement in Japanese cypress with macropores and living roots. The effect of entrapped air, hyphae respiration, and bacteria in unsaturated soil also needs to be examined in future studies. There may be an underlying mechanism to limit infiltration of water into soil profile, which caused lower FIR_{max} compared to the permeability test for fully saturated soil.

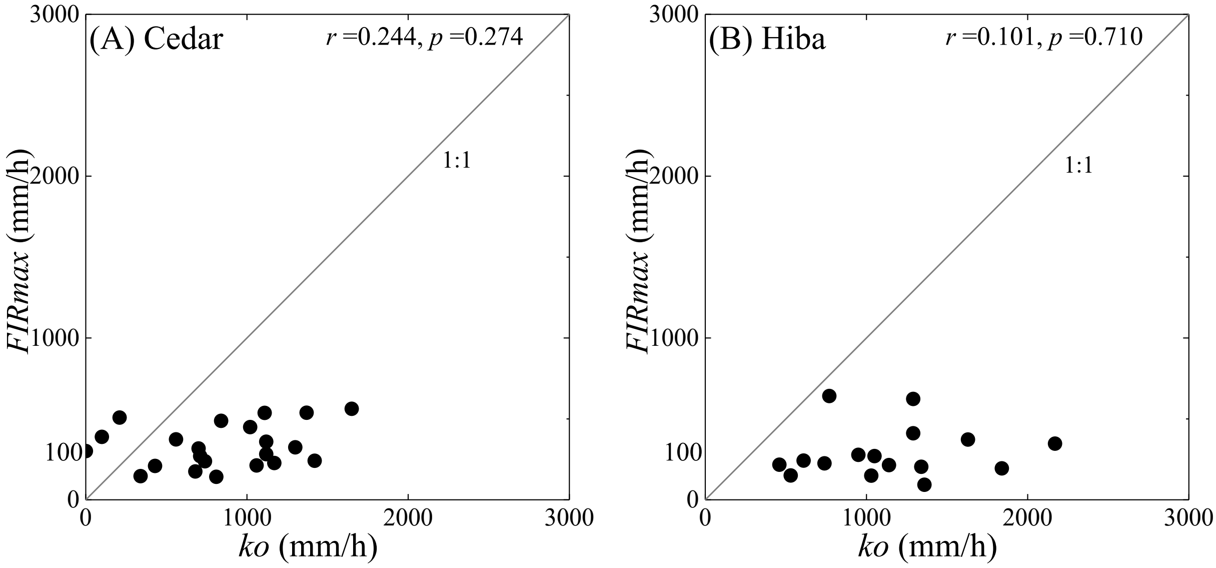

Figure 2.11 Relation between hydraulic conductivity (*ko*) and FIR_{max}. (A) is Japanese cedar and (B) is Hiba arborvitae.

2.4.3 Correlation between pF test and Soil physics parameter

2.4.4 Evaluation of FIR_{max} based on observation conditions of near the ground surface

Previously, here reported that there is no correlation between infiltration rate, surface cover materials and soil physics parameters. Therefore, I (author) present the view based on surface cover condition. In the case of a Japanese cypress plantation, litter tends to be lost and the effect of ground surface protection was small. In other words, the understory is important effect for surface protect (Hiraoka et al., 2010). Therefore, here focus on litter deposition condition on Japanese cedar and Hiba arborvitae. As a result, both litter was widely spread on ground surface and intertwined (Figure 2.12). This is very different from the condition in the

Japanese cypress plantation. In other words, if there are many surface cover materials (especially litter) like Japanese cedar and Hiba arborvitae forests, the surface cover effect might not be clear. Some researchers pointed out that litter thickness was also a very important variable influencing on erosion and runoff. The water storage capacity of litter layers increased linearly to litter mass on Japanese cedar and Japanese false oak site (Sato et al., 2004). The relationship between litter layer thickness and runoff has a negative correlation with less than 10 % variability (Vega et al., 2005). And, the relationship between litter layer thickness and hydraulic conductivity has a positive linear correlation with large variability (Marín-Castro et al., 2017).

Figure 2.12 Surface cover condition by litter (A) Japanese cedar, (B) Hiba arborvitae

Further, the cross section of both soils, the rainwater had a nonuniform wetting front that is fingering phenomenon by the roots, macropore and spatial distribution of soil physical characteristics. It is impossible to compare because of the lack of photograph in the Japanese cypress plantation, the infiltration rate and hydraulic conductivity were high and could not explained by the surface cover materials and soil physics parameter by fingering phenomenon. Fingering phenomenon was affected by dry density and soil moisture content (Ritsema and Dekker, 1994). Here showed relationship between bulk density, FIR_{max} and hydraulic conductivity (*ko*) (Figure 2.13). As a result, neither FIR_{max} nor hydraulic conductivity had a significant difference with dry density. Although it will be possible to reproduce the infiltration phenomenon with fingering on the numerical simulation by taking detailed data, it is questionable whether evaluation is possible or not by applying it to the field soil. Forest soil has a spatial distribution, so I (author) have to decide/judge it is difficult to easily show it with some parameters. As described above, in forest soil where there are many surface cover materials and macropore developed, in evaluating the preferential flow mechanism, for example, the *in-situ* permeability test using borehole by Association for Rainwater Storage and Infiltration Technology (2006) will be considered to be necessary.

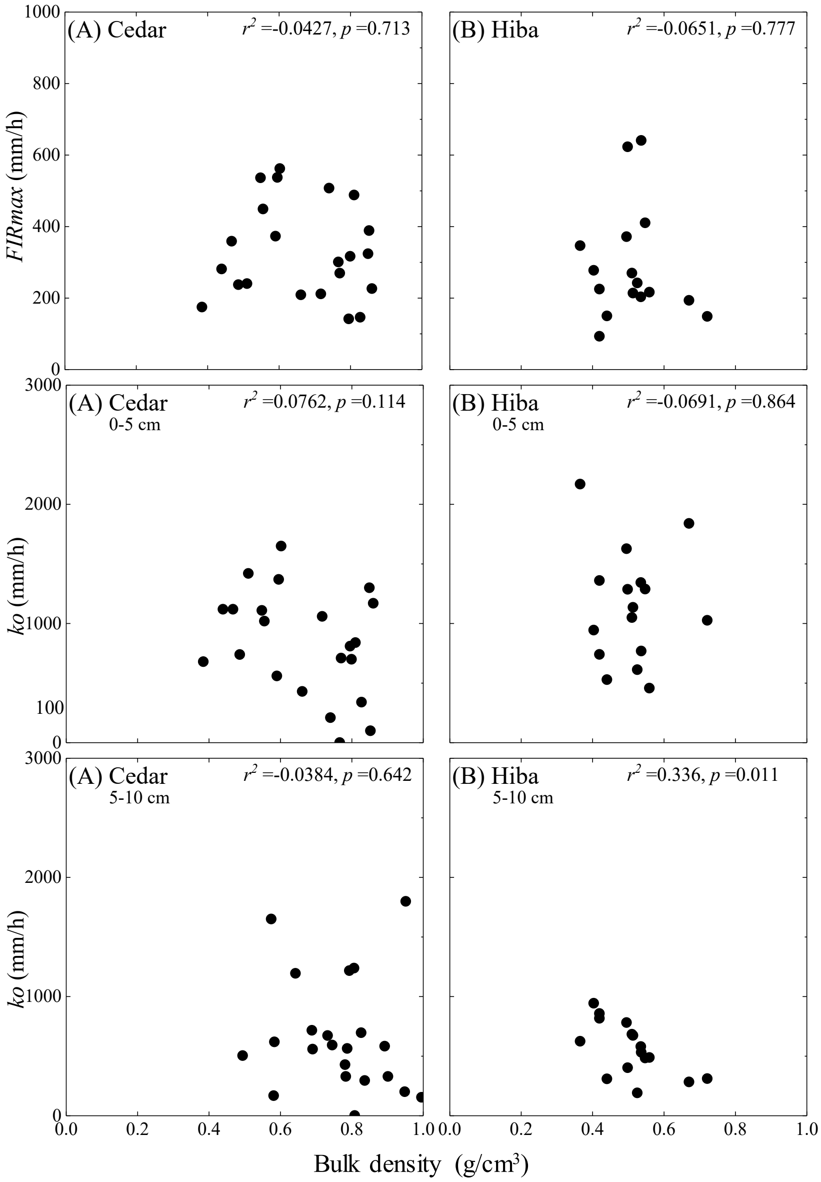

Figure 2.13 Relationship between bulk density, FIR_{max} and ko of each depth

2.5 Conclusions

Based on the measurement of infiltration rate and soil properties using an oscillating nozzle rainfall simulator, the relation between infiltration rate was investigated, soil properties and vegetated effect in Japanese cedar and Hiba arborvitae forests. The following results were obtained with our analysis, and are summarized below.

1) Surface cover materials, fine fraction content, and hydraulic conductivity had no correlation with FIR_{max} in either type of the forests examined in this study.
2) Both Japanese cedar and Hiba arborvitae forests gave relatively high FIR_{max} values (> 100 mm/h), which is higher than that of the entire *C. obtusa* plantations. These forests, especially at sites with a low concentration of surface cover materials (< 1000 g/m^2), had a twofold to threefold greater FIR_{max} than that in *C. obtusa* plantations. Thus, Japanese cedar and Hiba arborvitae forests may provide a more effective protection of the soil surface.
3) Based on fine fraction content, visual observation, and final infiltration rate, it seemed unlikely that the formation of crust occurs in both types of forest.
4) In both types of forest, FIR_{max} is exceptionally lower than hydraulic conductivity at the soil surface. Fingering might occur during infiltration due to entrapped air and hyphae respiration.
5) Both Japanese cedar and Hiba arborvitae forests
6) The high infiltrability of much litter-covered

The above results prove that the change in FIR_{max} in either type of forest cannot be explained by surface cover materials, hydraulic conductivity, or fine fraction content. However, we found that FIR_{max} increased after thinning, which suggests that the change in soil physical properties other than surface cover materials may be a possible factor. Further investigation and discussion is necessary on factors influencing FIR_{max} change.

Ishikawa Prefecture is currently collecting “Ishikawa Forest Environmental Tax”, and implementing intensive thinning in forest degradation area throughout the prefecture to improve the public function of forests, such as watershed conservation and preventing landslide disaster. Since fiscal 2017, Ishikawa Prefecture has implemented additional efforts to promote the use of timber.

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Chapter 3. Effect of vegetation cover for

Chapter 4. Effects of slope gradient on

Chapter 5. General discussion and conclusions

Generally, the surface cover materials that may occur due to vegetation help prevent clogging of soil pore by aggregate destruction, protect from raindrops impact on the ground surface help to generate over land flow by increasing the ground surface roughness, and are shown to have the effect of reducing the runoff (e.g., Dunne et al., 1991). Almost all previous researches showed that relationship between surface cover ratio and infiltration rate had positive linear correlation (e.g., Loch, 2000; Zimmermann et al., 2006; Chen et al., 2007; Kato et al., 2009; Hiraoka et al., 2010; Liu et al., 2016). In the theoretical equation concerning the rainfall runoff and the governing equation of the rainfall runoff model and the soil erosion model, the parameter of slope gradient has a positive linear relation (e.g., EUROSEM, Kinematic Wave model, USLE, and WEPP). Parsons et al. (2004) proposed soil erosion model that assumes spatially uniform infiltration and a steady rainfall rate. Neither assumption might be met in the field experiment. In estimating runoff and soil erosion by numerical model, what will be the proper parameters? Whether it is better to use values that are considered empirical parameter, obtained from experiments parameter or sensitivity analysis parameter. It is almost impossible to conduct experiments and observations for everything, so it fully understands that numerical simulation is a very useful tool.

Recently, negligible effects of surface cover on increasing rainwater infiltration into soil was reported for desert grassland with sparse vegetation cover in the semi-arid ration, Japanese forest soil covered by thick litter layer in the climate of Japan Sea area, and the sandy soils in the semi-arid region (e.g., Kato et al., 2009; Komatsu et al., 2014; Rodrigo Comino et al., 2016). Furthermore, the slope effect on soil erosion and the amount of surface runoff generation were investigated by Ribolzi et al. (2011), where, a positive, negative, and no correlation were found between the various previous research.

Many experiments and observation results are shown. The case study showed/concluded that the surface cover and slope affected and numerical simulation using appropriate parameters was developed for rainfall runoff processes. Some researchers explained that the surface cover and slope effect for runoff/infiltration has not been clarified, this was an important guideline to proceed.

The major goal of this research was to investigate how the surface cover material/ratio and slope affect the runoff through experiments and observations under artificial rainfall and natural rainfall.

5.1 The surface cover material/ratio effect in forest soil and sandy loam

Saturation-excess overland flow is one form of transfer directly through the forest floor to the downstream. The forest cover changes not only alter the annual mean flow substantially, but also change the peak flow. However, rarely studies have been conducted on assessing forest cover changes and peak flows in large watersheds. In addition, the results on peak flow response to forest cover changes are inconsistent with large variations.

The results from previous studies have revealed that water retentivity of forest soil has high value and the hydraulic conductivity of forest soil was greater than several hundred mm/h (e.g., Tsukamoto, 1992; Kosugi, 1999; Miyata et al., 2009). Because forest soil has a spatial distribution of porosity. On the other hand, generally, sandy soil has high permeability but low water retentivity, and the clay soil has high water retention but low water permeability was shown from the moisture characteristic curve and previous study (e.g., Mualem, 1976; Bouwer, 1978; Arora et al., 1991). The surface cover effect is still unclear for rainfall runoff phenomenon because some researchers showed not only positive correlation but also negative or unclear correlation relationship between surface cover ratio and runoff (Chapter 2 and Chapter 3). The reason could be not only the physicochemical characteristics of the soil but also different climatic conditions and growth of different vegetation.

In calculating FIR_{max} in forest soil area from rainfall intensity and final infiltration rate of the target area through experiments using an oscillating rainfall simulator (e.g., Kato et al., 2008, 2009; Hiraoka et al., 2010). The relationship between surface cover materials and infiltration rate have a positive correlation in the semi-arid region with sandy soil (Loch, 2000; Kato et al., 2009) and Japanese cypress area with much understory vegetation (Hiraoka et al., 2010). However, what kind of results would be obtained by carrying out the experiment by changing the rainfall intensity at the same point as Murai and Iwasaki (1975) and Tanaka and Tokioka (2007). As shown in Figure 2.2 and Figure 2.3, there is a difference between equation (2.2) and equation (2.3) where the rainfall intensity is low. Tanaka and Tokioka (2007) adapted the obtained equation to them and previous result in Japan. They described that "This fitting equation is approximately good except for highly dispersed bare ground". Equation (2.3) can relatively represent the change in the stable infiltration rate when the rainfall intensity changes.

In chapter 2, both Japanese cedar and Hiba arborvitae forests gave relatively high FIR_{max} values (> 100 mm/h) without thinning/management. The results showed the influence of thinning, management seems to be small (Figure 2.6 and Table 2.1). Even at unthinned points, the FIR showed a value of 100 mm/h or more, showing high FIR_{max} regardless of the value of dry weight of litter materials and total cover by statistical analysis. From this result, it is suggested that the surface cover effect was large in this study site where maintenance such as thinning management, and it is suggested that the influence by tree species or amount of litter material are significant in infiltration capacity. The relationship between surface cover ratio and FIR_{max} was found to have no significant correlation in Japanese cedar and Hiba arborvitae sites. Previous studies showed that infiltration capacity was denoted by some soil physics parameter, but this was not clear in this study. The above results prove that the change in FIR_{max} in either type of forest cannot be explained by surface cover materials, hydraulic conductivity, or fine fraction content. In the present experiment could not clarify the influencing factors to FIR_{max} in Japanese cedar and Hiba arborvitae forests with much litter layer.

From this result, it was found that the high infiltrability of much litter-covered forests could not be explained by ground surface cover materials and soil physical properties with fingering phenomenon (and Figure 5.1). But, it is the measurement result by plot scale, and it cannot be easily expanded and applied to the catchment scale, but this study area has sufficient infiltration rate/capacity.

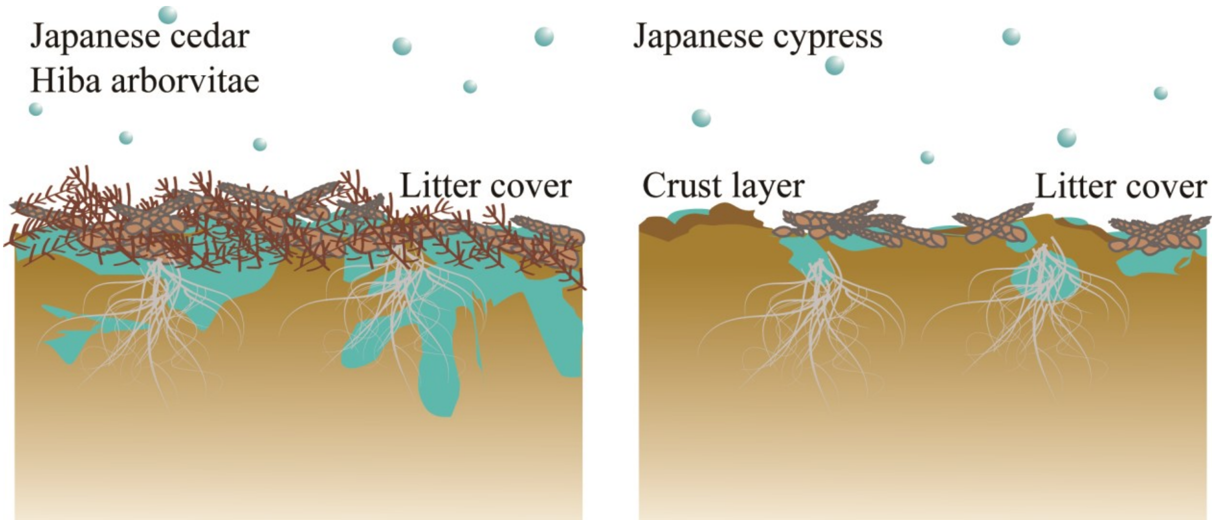

Figure 5.1 Sketch of infiltration in Japanese cedar, Hiba arborvitae and Japanese cypress

In chapter 3,

5.2 The

5.3 Conclusions

Despite the fact that many phenomenon/effects are unclear for rainfall runoff process, many researchers explained the specious aspect. This study could not show the precise effect of surface cover material, surface cover ratio, slope gradient and soil physics properties on the relationship between rainfall, runoff and infiltration under simulated and natural rainfall conditions.

References

Chapter 6. Limitation and future study

6.1 Ishikawa site

Here show took after the three samples of two depths in target plot with 1 m^2, but it was considerably disturbed outside the insertion section (Figure 6.1). It was difficult to find the optimum place for collecting because the target is below the ground surface. Although the weight at the time of collect is also important, but these soil sample was saturated by capillary rise after back to laboratory. This might be acceptable for collect from outside the plot. The water droplets rolled on the litter or the ground surface like a ball at some site. This is attributed to occur water repellency phenomenon, adding a water repellency test will confirm the contribution to infiltration at those points.

Figure 6.1 Surface condition during take some samples

6.2

6.3

Acknowledgments

During doctoral program the author has learned abundantly, was given numerous opportunities and received great help from many of my professors and mentors, laboratory members and many community members from Tsukuba, Beijing and Chengdu. The hospitality the author received from everyone in each of the places traveled was tremendous. The author would like to take this opportunity to acknowledge and thank all the people from whom he received kind support.

First, the author would like to express appreciation to his supervisor, Associate Professor KATO Hiroaki, for their initial direction and support in the course of this study.

The author expresses his utmost gratitude and appreciation to Professor RAKWAL Randeep who guided me fiercely and provided intensive instruction and resources as well as support that motivated the author to continue with his research and achieve progress. The author can never thank him enough. Words cannot express how much the author appreciate his kindness.

The author is also very grateful to Emeritus Professor FUKUSHIMA Takehiko from University of Tsukuba, Ibaraki Kasumigaura Environmental Science Center, Professor ONDA Yuichi from University of Tsukuba, Associate Professor MARUOKA Teruyuki from University of Tsukuba, Lecturer ANMA Ryo from University of Tsukuba, Associate Professor MATSUSHITA Bunkei from University of Tsukuba, Professor TSUJIMURA Maki from University of Tsukuba, Professor SONG Xianfang from the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Professor ASANUMA Jun from University of Tsukuba, Assistant Professor TAKAHASHI Junko from University of Tsukuba, Assistant Professor PARKNER Thomas, and staff members from the Geomorphology Laboratory at University of Tsukuba for all their constructive comments which helped the author immensely in the process of shaping the structure of this research.

Author greatly appreciates Prof. SONG Xianfang, Prof. TSUJIMURA Maki, and

Prof. WANG Shiqin from the Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Dr. YANG Lihu from the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Professor ZHU Bo and Associate Professor WANG Tao from the Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Mr. ZHANG Guangying and Mr. WANG Shengbao from the Laboratory of Soil and Water Conservation in Baoding City, many field workers and members of Yanting Agro-ecological Experimental Station of Purple Soil, Chinese Academy of Sciences. Thank you all. The author is extremely grateful for all your support.

Author is grateful to the Staffs of Ishikawa - Ken Forest Experiment Station, Ishikawa Prefecture (Mr. OGURA Akira and all Ishikawa prefecture staffs jointed this project) and Kyowa Environmental Monitoring Research Co., Ltd. (Mr. KANNO Shuhei and Mr. HIROOKA Atsushi) for their support during the experiments. The two men are the author’s seniors of his company employment era, and together were able to proceed with the investigation smoothly. For this reason, the author could get over the tough investigation of despite the tight schedule.

Author is pleased to express his gratitude for Emeritus Professor PARSONS A.J. from University of Sheffield for his encouragement and valuable advice along the course of this study.

Author also wants to thank Dr. LIU Fei from Hebei University of Engineering, Dr. MIN Leilei and Dr. WEI Shoucai from the Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Dr. YU Yilei from the Chinese Academy of Forestry, Dr. ZHANG Bing from Tianjin Normal University, Dr. ZHANG Jie from Nippon Koei Co., Ltd., Mr. SAKAKIBARA Koichi from University of Tsukuba, Dr. LUO Yong from Chengdu university of technology for their considerable efforts in the field work of this thesis.

Authors gratitude also goes to Professor SUZUKI Iwane, Professor ZHANG Zhen Ya and Mr. AKIYAMA Kazuhiro from University of Tsukuba. Thank you for all your support.

Authors special thanks extend to Assistant Professor YAMADA Eiko, Ms. HATORI Keiko and Ms. OKINAGA Yukie from University of Tsukuba who helped the author during the hardest moments of his thesis process.

Author is immensely pleased for warm cooperation and support on his study and laboratory life from Associate Professor SAKAGUCHI Aya, Assistant Professor HIRAOKA Marino (University of Tsukuba), Assistant Professor KIM JinKwan (Chonnam National University), Lecturer WAKIYAMA Yoshifumi (Fukushima University), Dr. ABE Yutaka (Suntory Holdings Limited.), Dr. HIRATA Akiko, Dr. IIDA Tomoyuki (National Research Institute for Earth Science and Disaster Resilience), Dr. IWAGAMI Sho, Dr. KIM MinSeok (Korea Institute of Geoscience and Mineral Resources), Dr. MANUEL López-Vicente (Spanish National Research Council), Dr. Mengistu T. Teramage (Institut de Radioprotection et de Sûreté Nucléaire), Dr. NANKO Kazuki (Forestry and Forest Products Research Institute), Dr. PATIN Jeremy, Dr. TANIGUCHI Keisuke (Fukushima Prefecture), Dr. YANG Fang (TECNOS Data Science Engineering Inc.), Dr. YOSHIMURA Kazuya (Japan Atomic Energy Agency), Dr. WAKAHARA Taeko (Tokyo University of Technology and Agriculture), Mr. HISADOME Keigo, Mr. TAKEUCHI Yukio, Mr. GAO Xiang, Ms. FUJII Kazumi, Ms. KOIWA Fumiko, Ms. OKAZAKI Asami, Ms. SUMIYA Keiko, Ms. TAKENAKA Emi, and Ms. YOSHIMURA Fumiko.

Author also wishes to thank Lecturer ANMA Ryo, Professor TSUNEKI Akira, Associate Professor SHIBATA Daisuke, Ms AWANO Naoko, Ms. FUKUZOE Masako, Ms. HIRONAGA Naoko, and Research Center for West Asian Civilization office, staff and student members from University of Tsukuba.

Author expresses thanks to deceased (June 17th. 2012) Professor OKA Yasumiti from HOSEI University who was his supervisor and mentor during the bachelor’s and master’s degree.

Author is pleased to express his gratitude to Mr. ISHIKAWA Nobuaki, for his encouragement and valuable help for data reduction and more.

Author would also like to thank his friend, Ms. YANAGISAWA Yoshie, who always encouraged him not to give up.

Finally, above all, author deeply thanks his family, Mr. Masanori, Ms. Yoko, Ms. Yasuko, Ms. Toshi, Mr. Mitsuo, Shima-san and Tetsu, for their priceless support. It has been a long journey, but everybody encouraged author to seize the opportunity and succeed. Author was able to complete his doctorate and graduate from this program because of you. Author can never thank you enough. Thank you, thank you all again and again!!