Chapter 7

Relation between Infiltration Rate, Cover Materials and Hydraulic Conductivity of Forest Soils in Japanese Cedar and Hiba Arborvitae Plantation Forests under Artificial Rainfall in Ishikawa Prefecture, Japan

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Additional information is available at the end of the chapter

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Abstract

To ascertain the relation between the infiltration rate, cover material and hydraulic conductivity of forest soils in Japanese cedar (*Cryptomeria japonica*) and Hiba arborvitae (*Thujopsis dolabrata*) plantations, we conducted artificial rainfall experiments using an oscillating nozzle rainfall simulator. The maximum infiltration rate (*FIRmax*) was higher than that found in previous studies of cypress plantations. Especially in the conditions where surface cover materials are less than 1000 g/m^2, *FIRmax* tends to become higher than the value of the cypress forest by several magnitudes. *FIRmax* was over 100 mm/h, irrespective of the amount of surface cover materials. The result confirmed little or no correlation between *FIRmax* and surface cover materials in either of the studied tree species. *FIRmax* were lower than hydraulic conductivity. *FIRmax* showed no correlation with hydraulic conductivity and fine fraction content. Therefore, the differences of *FIRmax* between cedar and Hiba plantation were not explainable by surface cover materials, hydraulic conductivity or the fine soil fraction content, which contrasts with results of previous studies of cypress plantations.

Keywords: Japanese cedar, Hiba arborvitae, infiltration rate, cover materials, hydraulic conductivity

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.

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This overland flow might occur when the infiltration rate decreases with increasing uncovered forest floor [1–3]. Moreover, the heavy rain events have an effect on increasing the risk of floods [4]. Infiltration has been traditionally studied using a flood-type or mist-type rainfall simulator [5, 6]. 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. [7] 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. [8] was used for the experiments. The experiments showed a positive correlation between surface cover materials and infiltration rate [8–10]. A similar experiment was carried out in the semi-arid region, and obtained results indicated a noticeable positive correlation between these two variables [11, 12]. 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 [9, 13–16]. 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 [17]. 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 [18]. 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. [19] argue that the effect 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 [3, 20, 21]. A correlation was observed between the hydraulic conductivity and infiltration rate [5, 22], 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 [3]. 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. A portable oscillating nozzle rainfall simulator has been introduced by Refs. [8, 9] as a new method mainly in *C. obtusa* forests. 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 through Ishikawa Forest Environmental Tax project [10].

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2. Background of Ishikawa Forest Environmental Tax project

2.1. Sediment and flood damage in Japan

Japan is a country with many flood disasters. Muroto Typhoon in 1934, Makurazaki Typhoon in 1945 and Isewan Typhoon in 1959 were the three major typhoons in the Showa era, which caused massive damage. In the Makurazaki Typhoon, sediment-related disasters occurred frequently in the logged mountains area that was weakened by heavy rains, taking a heavy toll of life.

Forestry Agency [23] showed that Japanese government had been promoting the creation of artificial forest for Japanese cypress, Japanese cedar and more species to be restored in the site, which was located in the logged forest after World War II and during the high economic growth period. Changing forest economic conditions in Japan since World War II have caused many plantation forests to be poorly managed. Since the 1980s, wood prices in Japan have been on a declining trend, but the profitability of forestry management has deteriorated drastically since the management costs of employment cost and materials had increased. For this reason, forest owners' willingness to management had declined, and forestry production activities have stagnated. Moreover, mountainous areas where many forestry workers and forest owners live have problems of depopulation and the rapidly aging society.

In 1998, severe natural disasters occurred due to 24-h rainfall of an unprecedented 900 mm in Kochi Prefecture, Japan [24]. The area seemed to have many artificial forests of Japanese cypress and landslides 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 forests in the reservoir area. Sediment disasters have been caused by typhoons in recent years, and the importance of countermeasures at basin scale including forest management has been reported.

Further, reports on previous flood disasters are available at the homepage of the Ministry of Land, Infrastructure, Transport and Tourism [25] and Japan Society of Civil Engineers [26].

2.2. What is forest environmental tax?

Recently, 'forest environmental tax' as individualistic tax was considered and introduced in each prefecture of Japan. In the background of the introduction of 'forest environment tax', there is a move towards centralization of national economy that the decentralization law was enacted in April 2000. As a result, the Local Tax Act was revised in an effort to expand local taxation autonomy, and conventional local discretionary taxes were changed from approval system by government to prior consultation system. In addition, the establishment of special taxes for specific purposes by the prior consultation system was also conducted, possibly to implement the political management taking advantage of the characteristics of the region [27].

Yamaguchi Prefecture started to collect taxes for the purpose of forest protection called 'Yamaguchi Forest Management Prefectural Residence Tax', from April 2005 [28]. A detailed report on the introduction and introduction effect of forest environmental tax has been reported [29, 30].

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 prices of timber and depopulation of mountain area. As a result of this, 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, we attended/conducted a water soil conservation function survey in the same way as the verification of Yamaguchi Forest Management Prefectural Residence Tax [28]. 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.

3. Infiltration capacity in Japanese cedar and Hiba arborvitae plantation forests

3.1. 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% of the total forests in this Prefecture. In terms of species composition of the plantations, cedar forests tops with 71% followed by Hiba arborvitae with 12% and pine trees with 9%. 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 [31]. We 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 1**). The study sites are dominated by brown forest soils, and have a slope of 40°. Forest leaf litter accumulates at all the sites with dense and sparse understories. According to AMeDAS data [32], annual rainfall averages nearly 2302 mm (1976–2012) with an average temperature of 13°C (55°F) in Ishikawa Prefecture.

3.2. Definition of infiltration rate

Horton equation is based on the observation that infiltration capacity is gradually exponentially reduced with time when, although ground surface is always thin, fresh state is sufficiently supplied. Horton [33] proposed excess rainfall/infiltration processes and introduced that while the equation may not actually represent the law governing the physical processes

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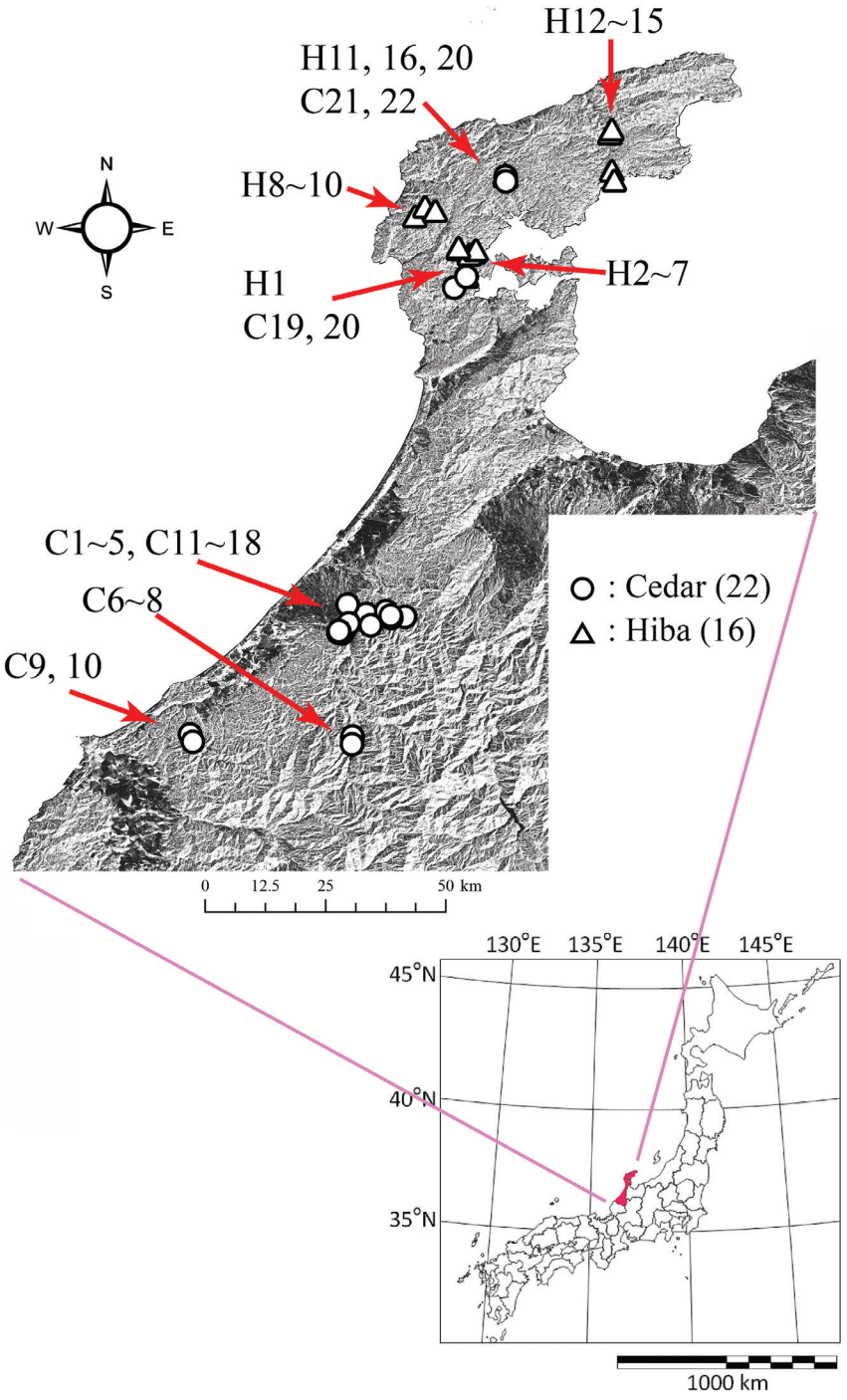


Figure 1. Location of the study site in Ishikawa Prefecture, Japan.

involved, his equation is rationally formed, 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.

Recent studies, however, have shown that infiltration rates can increase with increasing rainfall intensity until it reaches a constant value [5, 34]. 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 [34], so f_s can be given by:

$$f_s = f_{max}\left(1 - exp\left(-i/f_{max}\right)\right) \tag{1}$$

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. [35] and Stone et al. [36] applied the exponential model to their rainfall-runoff data, which yielded much better results than the application of a model with a constant K_e. Langhans et al. [37] adapted his results, so fitting Eq. (1) 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 [38] suggested the following hyperbolic function, which gives the relation between rainfall intensity and final infiltration rate:

$$f(i) = FIR_{max} \cdot tanh\left(i/FIR_{max}\right) \tag{2}$$

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

3.3. On-site infiltration test using rainfall simulator

Sprinkling experiments corresponding to a certain degree of rainfall intensity were conducted in small size of plots established in each experimental site. We 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. We established a plot 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 that will contain only the materials above the interface. An oscillating nozzle rainfall simulator was used for sprinkling water. The simulator was set, according to Hiraoka et al. [9] who used this device, with flow rate 12.5 L/min and nozzle height 2 m from the centre of sprinkled plot (**Figure 2**). The angle of nozzle was adjusted to obtain the targeted value for rainfall intensity (180 mm/h). To measure actual

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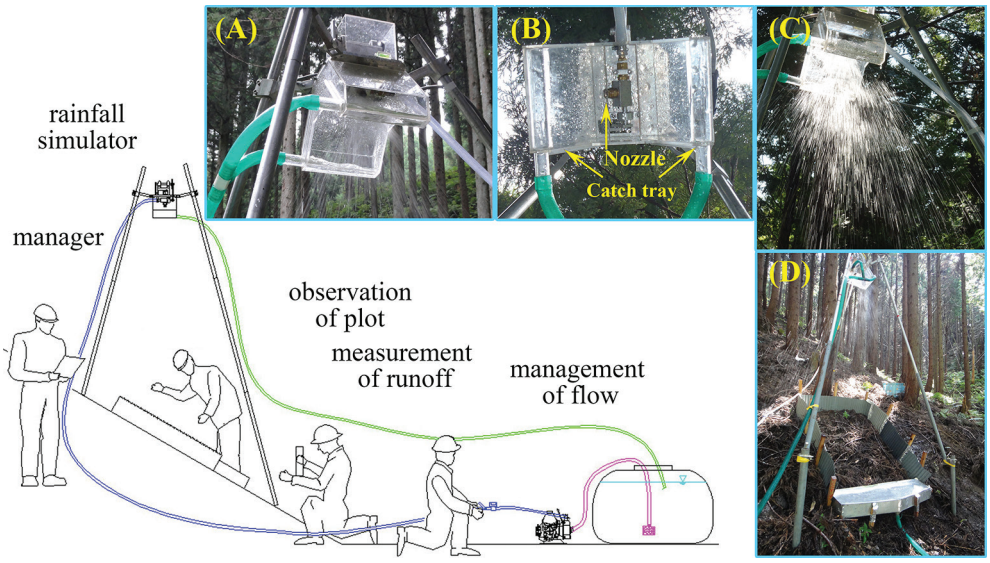


Figure 2. Rainfall simulator and experimental guideline. (A) is machine body (B) is nozzle by under view, (C) is sprinkling condition and (D) is experiment condition.

rainfall intensity, we collected total sprinkled water 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 [39]. Please also see the work by Kato et al. [8, 12]. The influence of moisture content cannot be ignored, but we sprinkled water with an intensity of 180 mm/h for 2 h 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 min, and the final infiltration rate was defined as the average value of the results taken over the last 5 min. 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 min before and after the infiltration intensity reaches minimum values.

3.4. Measurement of surface cover materials

Surface cover materials are composed of understories and leaf litter. In response to the research by Miura [15], small fractions (<2 mm) were excluded from the litter category because protection of the soil surface cannot be achieved. We collected understories (ground layer) and leaf litter after the experiment. These surface cover materials were air-dried for a week, then

re-dried in an oven at 70°C for 48 h 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.

3.5. 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. pF test, permeability test) using a small sample of soil *in situ* to obtain the characteristic value.

We collected soil samples after the 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 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 h. Determination of permeability was carried out using a constant head permeability test, but a falling head permeability test was used for the lower permeability materials. Then, to find the dry bulk density, the soil was oven dried at 105°C for 24 h and the weight of oven-dried soil was measured.

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. We observed the content of particles finer than 0.063 mm, especially clay and silt fractions, in this experiment.

4. Functional assessment of some ground surface parameters

4.1. *FIRmax* in Japanese cedar and Hiba arborvitae plantation forests

Table 1 shows the measurement results of surface cover materials, hydraulic conductivity, dry bulk density and *FIRmax*. In all the cases during the experiment, rainfall intensity is in excess of final infiltration rate ('Rainfall intensity' and '*FIR*' in **Table 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.

FIRmax ('*FIRmax*' in **Table 1**) was obtained by applying the Eq. (2) to the rainfall intensity and final infiltration rate obtained in this experiment. *FIRmax*, as shown in **Table 1**, distributes in

			Cover				Soil					Experiment		
Type	Plot ID	Elapsed time after thinning (year)	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})	*FIRmax* (mm h^{-1})
								0–5 cm	5–10 cm	0–5 cm	5–10 cm			
Cedar	C1	1	100	70	220	290	18	0.51	0.69	1420	559	171	147	241
	C2	Un-thinned	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	Un-thinned	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	Un-thinned	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	Un-thinned	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	Un-thinned	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	Un-thinned	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	Un-thinned	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

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			Cover				Soil					Experiment		
Type	Plot ID	Elapsed time after thinning (year)	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})	*FIRmax* (mm h^{-1})
								0–5 cm	5–10 cm	0–5 cm	5–10 cm			
Hiba	H1	3	100	60	580	640	18	0.54	0.71	1340	581	230	164	204
	H2	Un-thinned	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	Un-thinned	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	Un-thinned	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	Un-thinned	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	Un-thinned	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

Table 1. Result of ***in situ*** artificial rainfall experiments using an oscillating nozzle rainfall simulator.

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 3** shows frequency distribution of *FIRmax* for every 100 mm. A peak is observed in the *FIRmax* distribution in Hiba arborvitae forests around 200–300 mm/h, but tends to distribute equally in the range of 100–700 mm/h in both forests. Low *FIRmax* (<100 mm/h) was observed at only one site in Hiba arborvitae forests.

It is well-known that infiltration rate is affected by the amount of surface cover materials [1, 4, 17]. Also reported is an increasing trend of surface cover materials and understories with increasing time elapsed after thinning [40]. 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, we could not clarify the correlation, because of only a few numbers of data for surface cover materials corresponding to elapsed year after thinning. We 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. We compared the effects on volume of surface cover materials 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 4** shows the box-and-whisker plots of *FIRmax* in un-thinned and post-thinned sites. Despite a decrease in surface cover materials due to thinning, *FIRmax* increases in both types of forest. This result challenges the widely accepted notion that there is correlation between surface cover materials and *FIRmax* in Japanese cedar and Hiba arborvitae forests, and no correlation was observed especially in Hiba arborvitae forests.

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 HOF is restricted (e.g. [9, 12, 15]).

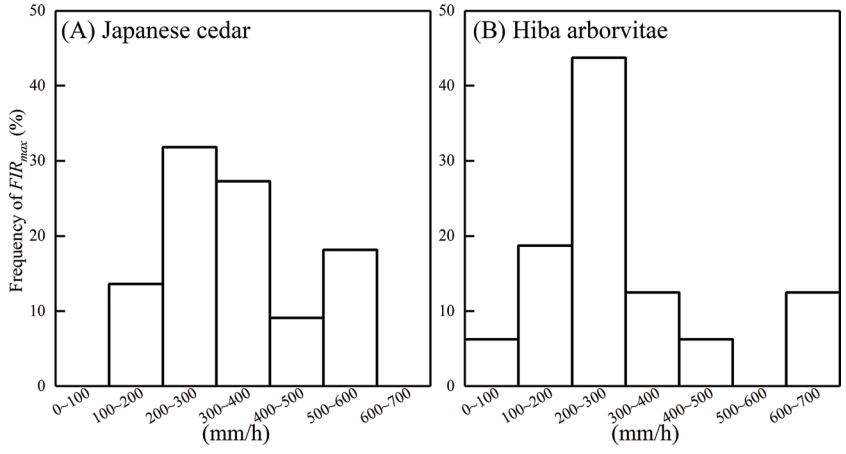


Figure 3. Frequency distribution of FIR_{max}. (A) Japanese cedar and (B) Hiba arborvitae.

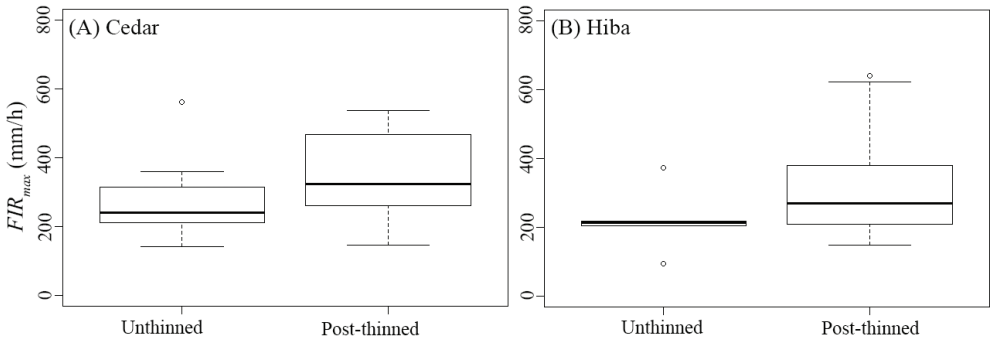


Figure 4. Box-and-whisker plots of *FIRmax* in un-thinned and post-thinned sites. (A) is Japanese cedar and (B) is Hiba arborvitae. The box represents 50% of the data between the 25th and the 75th percentile, the line represents the median and whiskers the minimum and maximum.

Previous study pointed out that relationship surface cover ratio and final infiltration have a positive correlation. **Figure 5** shows the relationship surface cover ratio and final infiltration, but in my case, there is no 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 do not think about denying statistical analysis, but it is unknown whether it is easy to reach such consideration easily.

Surface cover materials were measured using image analysis. A high concentration (>60%) of cover materials was seen both in Japanese cedar and in Hiba arborvitae forests, but no correlation was observed between *FIRmax* and surface cover materials. **Figure 6** shows relation between surface cover materials and *FIRmax* in Japanese cedar and Hiba arborvitae forests. For comparison purposes, also included in the figure are the data of *C. obtusa* plantations [9]. **Figure 6** clearly shows that *FIRmax* 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 *FIRmax* 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 [46] and Ogura and Kodani [18]. The regression line in **Figure 8** might show a positive correlation between the amount of surface cover materials and *FIRmax*. A similar finding was also reported by Kato et al. [8]. As shown in **Figure 6** (Japanese cedar: $r = 0.173$, $p = 0.443$; Hiba arborvitae: $r = 0.024$, $p = 0.929$), however, no such correlation was recognized between the amount of surface cover materials and *FIRmax*. Both Japanese cedar and Hiba arborvitae forests gave a relatively high *FIRmax* values (>100 mm/h) for any amount of surface cover materials. We also took the separate correlation of understories and litter materials with *FIRmax*, but no correlation was found among these three groups.

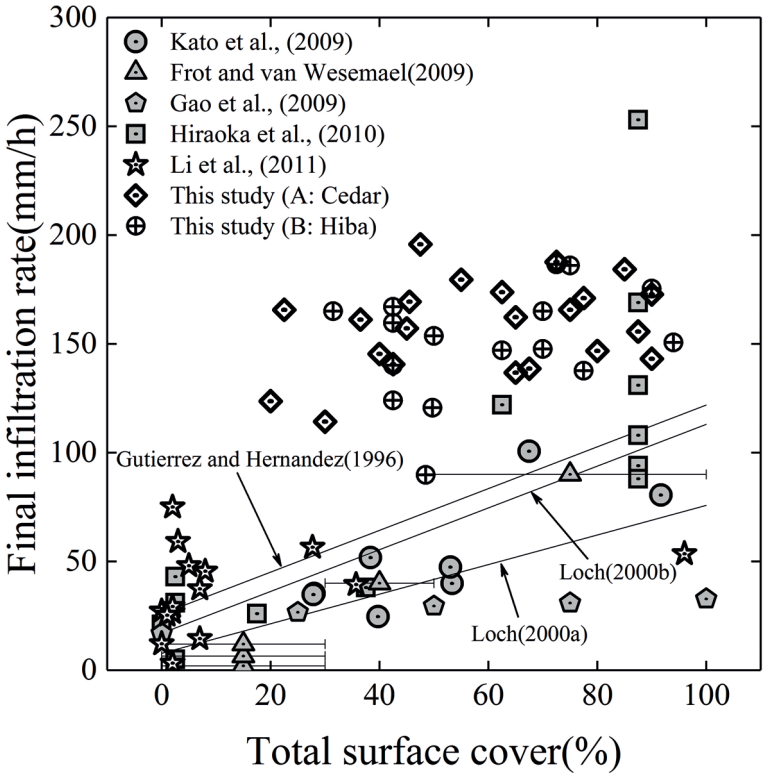


Figure 5. Relationships between the total surface cover and the infiltration rate at the (A) Japanese cedar and the (B) Hiba arborvitae sites (the solid square and open triangle indicate the desert grassland site and shrubland site, respectively. Steppe grassland ($y = 0.92x + 5.74$, $r^2 = 0.59$, $p = 0.029$) and desert grassland ($y = -7.67x + 220.4$, $r^2 = 0.98$, $p = 0.042$) In Mongolia, results by Gutierrez and Hernandez [41] ($y = 0.96x + 25.9$), Loch [11] ($y = 0.96x + 17.0$), Loch [42] ($y = 0.68x + 7.74$), Kato et al. [12], Frot and van Wesemael [43], Gao et al. [44], Hiraoka et al. [15] and Li et al. [45]. Modified from Kato et al. [12]).

4.2. Surface cover materials in Japanese cedar and Hiba arborvitae plantation forests

Measurement of surface cover materials ('Understory vegetation' and 'Litter materials' in **Table 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 500–1000 g/m^2 in both types of forest, and an increase in weight (1000–1500 g/m^2, 1500–2000 g/m^2) induced the lowering of the frequency.

4.3. Soil properties in Japanese cedar and Hiba arborvitae plantation forests

A high degree of variability in hydraulic conductivity was found, but high values (100–2000 mm/h) were obtained in the 0–5 cm and 5–10 cm layers in both types of forest (except for

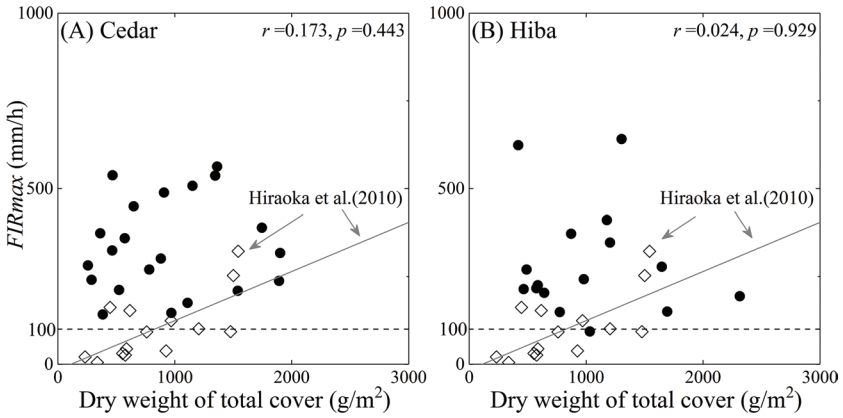


Figure 6. Relation between ground cover materials and *FIRmax*. (A) is Japanese cedar and (B) is Hiba arborvitae and results by Hiraoka et al. [9] (*FIRmax* = 0.14 × (dry weight of total cover) − 15.65).

C19). The same trend was commonly seen in other forests as reported in previous studies [3, 21]. Hiba arborvitae forests had relatively higher hydraulic conductivity than Japanese cedar forests. It was also found that hydraulic conductivity measured at depth of 5–10 cm was comparatively lower than those at depth of 0–5 cm depth.

Dry bulk density ('bulk density' in **Table 1**) was as follows: 0.38–0.86 g/cm^3 in Japanese cedar forests and 0.37–0.72 g/cm^3 in Hiba arborvitae forests at depth of 0–5 cm; 0.49–0.995 g/cm^3 in Japanese cedar forests and 0.49–0.91 g/cm^3 in Hiba arborvitae forests at depth of 5–10 cm. Although there was considerable variability, we found that bulk density increased with depth and was higher in Hiba arborvitae forests compared to Japanese cedar forests. According to Miyata et al. [3], the average bulk density was 0.75 g/cm3 in Hiba arborvitae forests, which was slightly lower than those obtained in our experiment (Japanese cedar forests: 0.67 g/cm3; Hiba arborvitae forests: 0.51 g/cm3). It was presumed that a decrease of porosity induced by an increasing bulk density results in a decrease of hydraulic conductivity with increasing depth. We, however, 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 1**) was 4–38% (average 22%) in Japanese cedar forests and 17–36% (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.

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 [3]. Yokoi et al.

[47] 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. [47] 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 7** is the relation between fine fraction content and *FIRmax*, but we could not find significant correlation (Japanese cedar: $r = 0.033$, $p = 0.883$; Hiba arborvitae: $r = 0.013$, $p = 0.154$). **Figure 8** shows the relation between fine fraction content and hydraulic conductivity, in which no correlation could be established.

Figure 9 shows relation between hydraulic conductivity and *FIRmax* 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 *FIRmax* for soil at 5–10 cm depth. It also became clear that *FIRmax* 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 one and that *FIRmax* had the similar value to hydraulic conductivity, which needs careful consideration. The 2–3 cm layer within 1 h 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. 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 *FIRmax* compared to the permeability test for fully saturated soil.

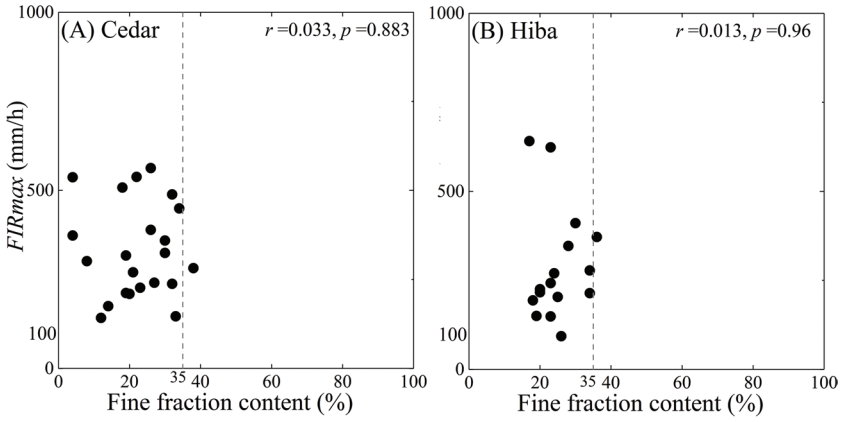


Figure 7. Relation between fine fraction content and *FIRmax*. (A) is Japanese cedar and (B) is Hiba arborvitae.

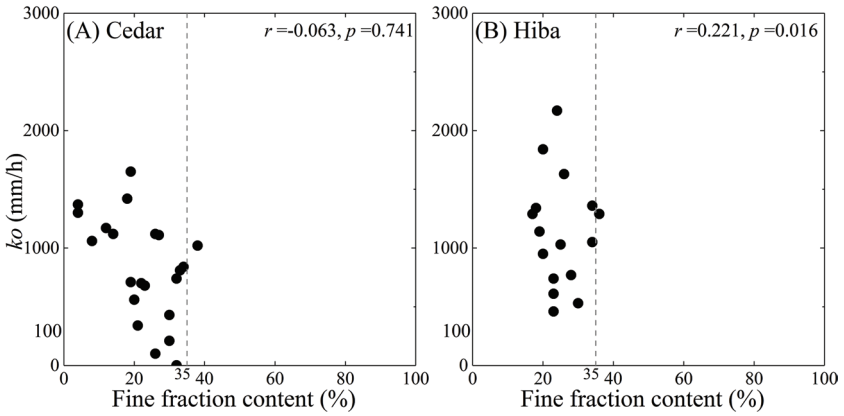


Figure 8. Relation between fine fraction content and hydraulic conductivity (*ko*). (A) is Japanese cedar and (B) is Hiba arborvitae.

In summary, surface cover materials, fine fraction content, and hydraulic conductivity had no correlation with *FIRmax* in either type of the forests examined in this study. Both Japanese cedar and Hiba arborvitae forests gave relatively high *FIRmax* 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 *FIRmax* than that in C. obtusa plantations. Thus, Japanese cedar and Hiba arborvitae forests may provide a more effective protection of the soil surface. 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. In both types of forest, *FIRmax* is exceptionally lower than hydraulic conductivity at the soil surface. Fingering might occur during infiltration due to entrapped air and hyphae respiration.

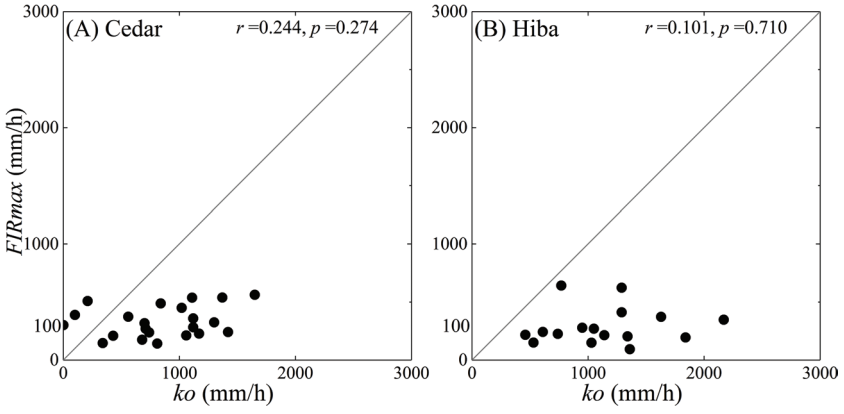


Figure 9. Relation between hydraulic conductivity (*ko*) and *FIRmax*. (A) is Japanese cedar and (B) is Hiba arborvitae.

The above results prove that the change in *FIRmax* in either type of forest cannot be explained by surface cover materials, hydraulic conductivity or fine fraction content. In the present research, we could not clarify the influencing factors to *FIRmax* in Japanese cedar and Hiba arborvitae forests. However, we found that *FIRmax* increased after thinning, and this might be attributed to Ishikawa Forest Environmental Tax effect.

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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