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The Effect of Raindrop Impact and Initial Soil Conditions on Surface Crust Formation

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Abstract

This study focused on the effect of raindrop impact on the crust formation processes using two clay loam soils, Hokudai and Biei from Hokkaido, Japan. Four different treatments AD (air dried), PS (large aggregate), BD (bulk density) and WET (wet) have been prepared from disturbed samples in a laboratory. A miniature type rainfall simulator with rainfall intensity of 63 mm/hr was used for duration of one hour from a height of 170 cm to measure the impact of raindrop on bare soils. The final infiltration rates were PS＞AD＞WET＞BD by raindrop impact. Therefore, the impact of raindrop in impeding infiltration was high in smaller aggregates of AD and WET treatments compared with PS. Furthermore, the impact was higher for Biei soil than for Hokudai soil. The hydraulic conductivity of the crust layer for Hokudai and Biei had different trends. The order of reduction for Hokudai soil was WET＞PS＞AD＞BD. The reason for this trend could be the aggregate stability or resistance to breakage. While the magnitude of reduction in Biei was AD＞PS＞WET＞BD. The initial moisture content appears to be more important factor for Biei soil.

Key words : soil crust, raindrop impact, initial soil conditions, hydraulic conductivity, rainfall simulator

1. Introduction

Crust formation is an important phenomenon occurring on bare soils that affect the behavior of soil physical and hydrological properties like infiltration, erosion, runoff and seedling emergence. According to Valentine and Bresson (1997), the term soil crusting refers to the formation processes and the consequence of a thin layer at the soil surface with reduced porosity and high penetration resistance.

The formation of surface crusting is affected by the initial soil surface conditions, rainfall characteristics and composition of the infiltrating solution (Hillel, 1998). The initial soil surface conditions prior to raindrop impact such as initial moisture content, aggregate size, bulk density, slope of the soil, and texture are believed to have an enormous impact on the process of surface crust formation and as a result on the hydrological properties of the soil surface. The drier the initial moisture content is the higher the probability of crust development. This phenomenon is related with slaking and dispersion of the surface soil (Norton, 1987 ; Le Bissonnais, 1990) and other soil characteristics that cause swelling and microcracking. Initially large aggregates have lower final infiltration rate than small aggregates (Moldenhauer and Kemper, 1969) whilst Farres (1978) obtained the opposite result. Surface crust also reduces the hydraulic conductivity of the soil (Hillel and Gardner, 1970 ; Ahuja, 1973). Oster and Singer (1984) studied how the crusting affected water infiltration in Californian soils and showed that over one million ha of land was affected by slower infiltration problems due to surface crust. The formation processes in arid and semi-arid regions under sodic conditions have been studied well (Sumner and Stewart, 1992). However, sodic conditions are absent in high rainfall regions as the amount of rainfall exceeds the amount of evapotranspiration. Mechanical energy created by raindrops at the soil surface disrupts the aggregates and restructuring of soil aggregates which forms the surface crust. The restructuring of the aggregates differs depending on the initial soil conditions. The use of different tillage instruments in the area and difference in climate also create different initial soil conditions during the cultivation period.

In Biei-Furano area of central Hokkaido, the land is covered with pyroclastic flow sediments and is very susceptible to soil erosion (Kashiwagi and Sakuma, 1995). Soil crusting is thought to be a major cause for surface runoff and as a result soil erosion occurs. By studying the effects of change of the initial soil conditions on crust formation in the crust affected area of Biei by comparing with the Hokudai alluvial soil can clarify the crust formation process. Moreover, the problem of soil crusting in central Hokkaido is not addressed yet and as it is a high rainfall region (1,000 mm per year), a study on soil crusting with emphasis on the mechanisms and nature of disruption of aggregates is vital.

Some of the studies on crust still have different thoughts on the process of formation ; such as,

1. Crusts are mainly formed through the impact of raindrops on bare soil, an aggregate induced by entrapped air compression (Boiffin, 1986) or micro-cracking from shrink-swell phenomena (Valentine, 1991),
2. The process and formation of surface crusting is the effect of structural disturbances (Duley, 1939),
3. The formation of crust is affected by the wash-in effect of the smaller soil particles into the relatively large pores which results in the decrease of infiltration rate (McIntyre, 1958 ; Nishimura *et al.,* 1993),
4. The formation of crust is due to particle deposition and compaction (Lemos and Lutz, 1957),
5. Crust formation is the effect of suction force (Morin *et al.,* 1981) which is developed at the crust-soil interference and causes crust densification and stabilization,
6. Crust is formed due to ponding, suspension and settlement of soil particles during rainfall (Chen *et al.,* 1980) and
7. Crust is formed due to a hard setting of soil by structural breakdown of weakened soil aggregates during wetting (Mullins and Lei, 1995).

The objective of the present study was to examine the effect of raindrop impact on crust formation processes using two different soils and to verify how soil physical properties like initial moisture content, aggregate size and bulk density affect crust formation, infiltration and hydraulic conductivity values using a rainfall simulator in a laboratory.

2. Materials and Methodology

2.1 Soil and soil column

Two types of soils from Hokkaido prefecture, Japan were used. Disturbed samples of an alluvial soil (Udifluvent) from Hokkaido University Farm in Sapporo (Hokudai soil) and a brown forest soil (Typic Dystrochrepts) in a private farm from Kamikawa district, Biei town (Biei soil) were sampled from an Ap 1 horizon (0–16 cm). The field physical properties of the two soils are shown in Table 1. After sieving to the appropriate size depending on the experiment to be executed, the samples were packed into a column with diameter of 6 cm and height of 13 cm to a length of 10 cm. Four combinations of treatments named as AD (air-dried), PS (large aggregate), BD (bulk density) and WET (wet) were used as shown in Table 2. The Bulk densities at field conditions were 0.99 and 1.19 Mg/m^3 for Hokudai and Biei soils, respectively. AD sample, which was taken as the control sample, was made to resemble the field conditions when dry. The

Table 1 Physical properties of the soils

Type of soil	ρ_d (Mg/m^3)	f (m^3/m^3)	OMC (%)	Particle size distribution (%)			Texture
				Sand	Silt	Clay	
Hokudai	0.99	0.66	13	48	23	29	Clay loam
Biei	1.19	0.42	5	47	32	21	Clay loam

ρ_d = dry bulk density, f = porosity, OMC = organic matter content.

Table 2 Physical properties of the samples

Type of soil	Group	ρ_d (Mg/m^3)	ϕ (mm)	ω (kg/kg)
Hokudai	PS	1.00	5	0.20
	AD	1.00	2	0.20
	BD	1.20	2	0.20
	WET	1.00	2	0.42
Biei	PS	1.20	5	0.03
	AD	1.20	2	0.03
	BD	1.50	2	0.03
	WET	1.20	2	0.23

ρ_d = dry bulk density ϕ = aggregate size, ω = initial moisture content
AD : air dried soil, PS : large aggregate size soil, BD : high bulk density soil and WET : wet soil

moisture contents of the samples were adjusted to 0.20 and 0.03 kg/ kg for Hokudai and Biei soils, respectively. PS sample had a larger aggregate size than the control size. BD sample had higher bulk density than the control sample which corresponded to the compacted state under field conditions. WET sample was made to be high in moisture content to resemble the wet field conditions of around −6 to −10 kPa. The soil column had a runoff outlet just on the surface of the soil with a collector connected to it. At the bottom of the soil column another collecting apparatus was used to collect the drained water. The soil column had lateral holes at depths of 1.5, 5 and 10 cm from the soil surface to insert the tensiometers into the soil.

2.2 Rainfall Simulator

A miniature rainfall simulator of a drop forming type was used in the laboratory. The rainfall simulator consists of an airtight reservoir with a number of capillary tubes (25 nozzles) pierced to the bottom. A Mariotte type bubbling tube for keeping the pressure head constant was placed as used by Ogden *et al.* (1997). The intensity of the rainfall was adjusted to a range of 60–63 mm/hr with an average raindrop size of 2 mm. The rainfall simulator had a fall height of 170 and 18 cm from the soil sample. The 170 cm height (called as raindrop impact hereafter) was chosen to evaluate the effect of raindrop impact from a height with energy to create free fall raindrops with terminal velocity of 5.8 m s^{-1} as calculated from the energy conservation principle. The 18 cm height (called as no-raindrop impact hereafter) was used as no or minimum impact on the soil surface.

2.3 Experimental setup

Fig. 1 illustrates the experimental setup. Measurements of matric potential were taken using three tensiometers, each equipped with pressure transducers (Copal PA500–102), which was connected to a data logger (M.S.C. free slot 68 KD/H) and a computer, inserted at depths of 1.5, 5, and 10 cm from the top of the soil surface.

Rainfall was applied for duration of one hour for all experiments. Total amount of rainfall was 63 mm or equivalent to 178 cm^3 per soil column. Each treatment had at least two replications. The rainfall simulator had been vibrated manually throughout the experiment to form uniform distribution of the rainfall on the soil surface. Amounts of runoff and drainage were collected at 15 min interval. Saturat-

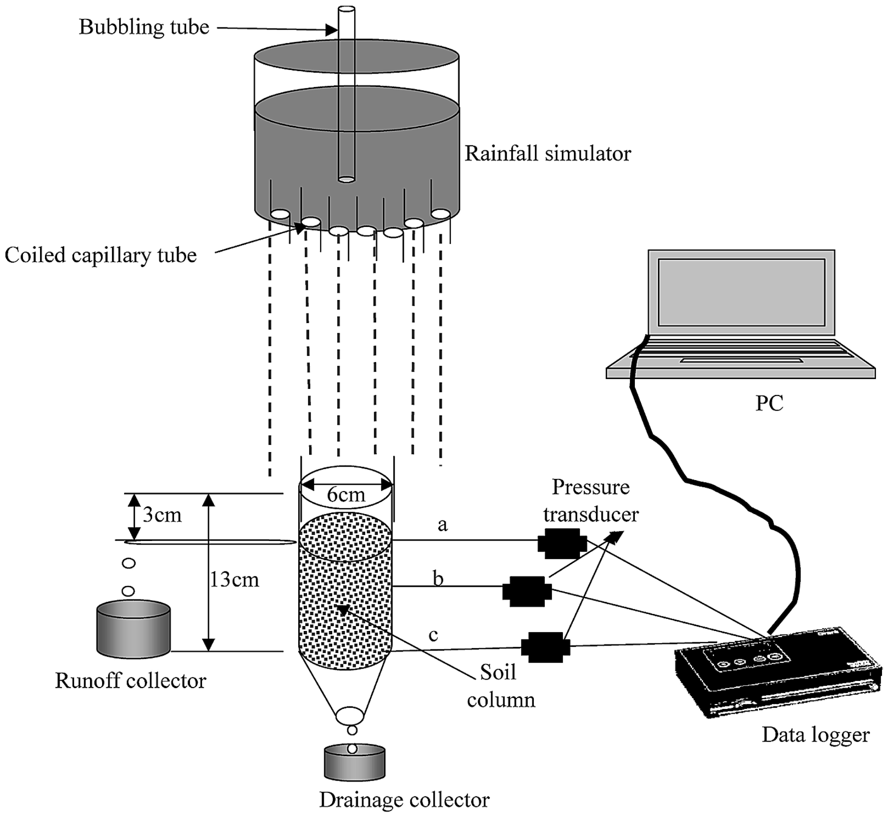

Fig. 1 Experimental setup, a, b and c are depths of tensiometer at 1.5, 5 and 10 cm, respectively.

ed hydraulic conductivity was measured using a constant head method immediately after the rainfall.

3. Results and discussion

3.1 Effect of raindrop impact

3.1.1 Hokudai soil

All the rainfall infiltrated into the soil in the AD, PS and WET samples under no raindrop impact. However, runoff was observed in BD sample. The samples which all amount of rainfall infiltrated into the soil indicate that the main factor for infiltration was the rainfall intensity not the soil surface conditions. In other words, the rainfall intensity was less than the soil infiltration capacity except in BD. Runoff started in BD soil at 11, 15 and 25 min after rainfall for the three replicates. The corresponding amounts of runoff ranged from 96–161 cm^3/hr or corresponded to 54–90% of the amount of the rainfall. We believed that the big gap seen between the results happened as results of sample preparation.

For the raindrop impact, runoff was observed in all samples as shown in Table 3. Fig. 2 (a) shows cumulative infiltration versus time for Hokudai under raindrop impact. Fig. 2 (a) as well as Table 3 indicates that the amounts of runoff for the two replicates of PS were nearly nil and 11% of the total rainfall which were the least amount of runoff. Lines shown in Figures 2, 3, and 4 are average values and the ranges of the measured values are shown in Fig. 2 by bars. In AD and WET, the amounts of runoff were 19 & 26% and 17 & 30% of the total rainfall for the replicates and the difference between AD and WET was minimal. BD had the highest runoff observed, i.e, 63 & 71% of the

Table 3 Hydrological conditions during rainfall of Hokudai soil

Type of soil		Runoff (cm^3) (%)	Stored (cm^3)	Infiltrated (cm^3)	Time to runoff (min)
AD	Impacted	33 (19)	145	145	11
		47 (26)	131	131	11
	No impact	0	129	178	—
		0	101	178	—
PS	Impacted	1 (1)	177	177	50
		20 (11)	158	158	50
	No impact	0	73	178	—
		0	69	178	—
WET	Impacted	53 (30)	124	125	12
		30 (17)	148	148	19
	No impact	0	23	178	—
		0	7	178	—
BD	Impacted	112 (63)	66	66	8
		127 (71)	51	51	8
	No impact	161 (90)	17	17	11
		123 (69)	55	55	15
		96 (54)	82	82	25

Total amount of rainfall equals 178 cm^3 for one-hour duration. The numbers in parenthesis under runoff column are the percentage of the total amount of rainfall.

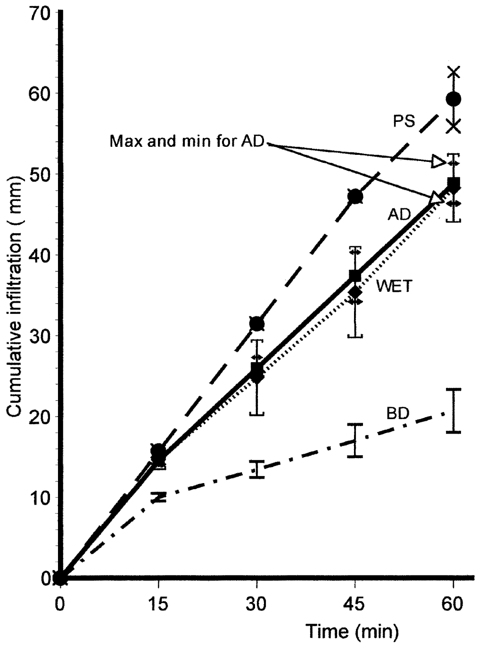

Fig. 2 (a) Cumulative infiltration of Hokudai soil with raindrop impact at different soil conditions.

total rainfall for the two replicates.

There were clear differences in the final infiltration rates (the infiltration rate in the fourth interval, between 45 and 60 min of rainfall duration) between no-raindrop impact and raindrop impact treatments. In the no raindrop impact the final infiltration rates for five of the eight samples were unchanged. The difference in final infiltration rate between no- and with raindrop impact was least in BD (0.11 cm/hr) and the highest difference in final infiltration was in WET (1.49 cm/hr) and followed by AD (1.42 cm/hr). Since the samples of the no-impact and impacted had the same initial conditions, the difference observed in the final infiltration rate was attributed to the raindrop energy. This result supports the studies conducted by Agassi *et al.* (1985) and Keren (1990). They showed that the final infiltration rate with the high-energy rain was much lower than the corresponding rate with the low-energy rain.

3.1.2 Biei soil

In case of the no raindrop impact of Biei, there was a 100% infiltration of the total rainfall in WET and PS treatments. However, runoff was observed in BD and AD treatments. Runoff in BD started 19 min for two replicates and 12 min for the third one after the start of rainfall and for AD runoff started after 16 min. The BD had 24, 64, 73% of runoff of the total rainfall for the three replicates and AD had 11 and 18% of runoff of the total rainfall as shown in Table 4. Infiltration rate in BD decreased at an early stage then became constant during the rest of the rainfall duration. The decrease in infiltration of AD with no raindrop impact must be attributed to slaking effect which makes the soil aggregates disintegrate easily and forms a less porous surface and as a result runoff occurred. This disintegration might possibly occur in all dry treatments as AD, PS and BD, however, the effect was high in AD. Assuming equal disintegration occurred between AD and PS, PS's relatively big pores were possibly large enough to infiltrate the total rainfall while AD have impeded the infiltration due to clogging of small pores between the aggregates.

For the raindrop impact as shown in Fig. 2 (b), runoff was observed in WET and PS as well as an increase of runoff in AD which was clearly shown in Table 4. Cumulative runoff was high in BD samples followed by WET, AD and PS. However, cumulative infiltration shown in Fig. 2 (b) had similar trends with Hokudai as shown in Fig. 2 (a).

For both soils the difference in final infiltration rate between the no- and with raindrop impact treatments was relatively high in WET and AD followed by PS while BD had negligi-

Table 4 Hydrological conditions during rainfall of Biei soil

Type of soil		Runoff (cm^3) (%)	Stored (cm^3)	Infiltrated (cm^3)	Time to runoff (min)
AD	Impacted	82 (46)	96	96	16
		65 (37)	113	113	15
		43 (24)	135	135	16
	No impact	32 (18)	146	146	15
		20 (11)	158	158	17
PS	Impacted	34 (19)	144	144	22
		48 (27)	106	130	28
	No impact	0	178	178	—
		0	178	178	—
WET	Impacted	55 (31)	123	123	20
		108 (61)	70	70	20
	No impact	0	178	178	—
		0	92	178	—
BD	Impacted	130 (73)	48	48	7
		115 (65)	63	63	8
	No impact	114 (64)	64	64	19
		42 (24)	136	136	19
		130 (73)	48	48	12

Total amount of rainfall equals 178 cm^3 for one-hour duration. The numbers in parenthesis under runoff column are the percentage of the total amount of rainfall.

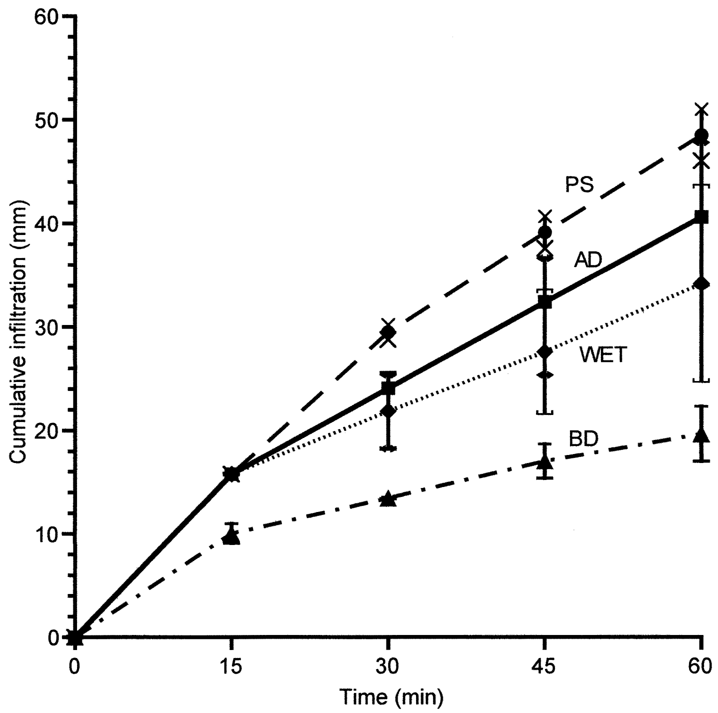

Fig. 2 (b) Cumulative infiltration of Biei soil with raindrop impact at different soil conditions.

ble difference. For those samples that all the amount of rainfall was infiltrated into the soil during the no-raindrop impact (in five of the eight cases as shown in Tables 3 and 4), it can be said that there was no surface crust formation.

From the above facts we can conclude that the rainfall energy was the main reason for the occurrence of surface runoff or decline of final infiltration rate by activating the formation of crust. From our visual observation, this happened by the breakage or disruption of the soil aggregates by the raindrop impact resulted in rearrangement of the soil particles into smoother, denser and relatively smaller aggregates.

3.2 Effect of soil initial conditions and its impact on surface crusting

The responses for the raindrop impact were different for different initial conditions. The change in the ratio of infiltration rate between the no- raindrop impact and raindrop impact treatments was expressed as $e_i=(i_o-i)/i_o$, where i_o and i are the infiltration rates at 15 minutes interval for the no- and with raindrop impact treatments, respectively. In Hokudai soil, as shown in Fig. 3, BD had its maximum value of e_i at the first 15 min-period. Furthermore, the time to runoff for both no- and with raindrop impact was observed by 15 min except one case (Table 3), indicating raindrop impact being earlier to appear. Nevertheless, e_i of BD at 45 to 60 min period was about 5% as shown in Fig. 3, which was small. The effect of crusting, though little, happened during the first 15 min period. The highest value of e_i was observed in AD and WET which was 23 and 24% respectively. In PS, e_i remained nil until 45 min then increased to 6%. There was no runoff until the last 10 min. It is clear from the graph that the impact of raindrop was low in PS for Hokudai.

Biei soil had higher e_i in WET and AD and least e_i in BD like Hokudai soil as shown in Fig. 4. For PS, e_i was quite significant (23%) only

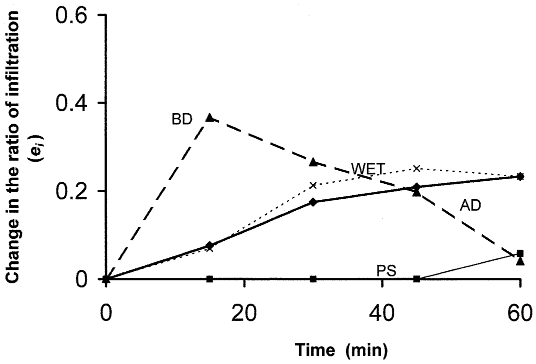

Fig. 3 Change in the ratio of infiltration rate between no- and with raindrop impact soils of Hokudai.

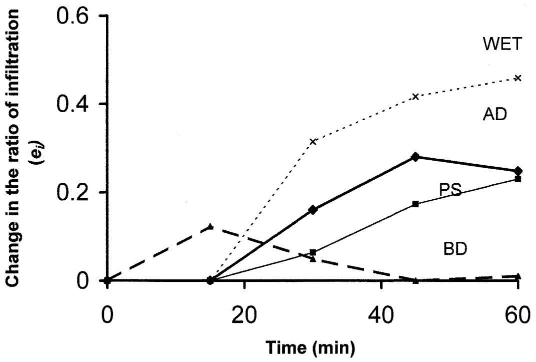

Fig. 4 Change in the ratio of infiltration rate between no- and with raindrop impact soils of Biei.

less by 2% from AD. Unlike Hokudai soil, PS of Biei had high value of e_i, which indicated that Biei soil is more vulnerable to crust formation.

From this we can say that WET, for both Hokudai and Biei, seems to be affected as much as AD. However, combining all factors like time to runoff, total infiltration, amount drained water, *ei* and the saturated hydraulic conductivity (to be discussed in following section), gives the true picture of the crusting effect and its process. In Hokudai soil, WET and AD treatments had almost similar infiltration until the termination of the rainfall as shown in Fig. 2 (a) whereas AD had early time to runoff as shown in Table 3. In case of Biei, the effect of initial moisture content was high as it affects PS sample almost equally to AD unlike Hokudai. From the tensiometer reading, however, infiltration did not reach 5 cm depth in all replicates of AD while it reached 10 cm depth in PS and WET. This is an indication that AD was more vulnerable to the formation of crust.

Though the two types of soils belong to the same clay loam texture category, the impact of rainfall had different responses. Biei soil was more affected by the raindrop impact in all treatments.

PS was included in the present study to evaluate the effects of aggregate size with respect to porosity and wash-in effect. Our hypothesis was that as the aggregate size crumbled, the smaller size particles would be washed-in and cumulative infiltration becomes low and *ei* becomes high in PS compared to AD. However, the result did not meet our hypothesis. Cumulative infiltration of PS was higher than AD for both soils as shown in Fig. 2 (a) and (b). There was slow disturbance on the surface of PS from the observation and this was clearly seen in Hokudai soil. Two factors should be taken into consideration for the reason why PS had less disturbances than AD. The first factor is that the change in porosity due to the effect of raindrop impact and the second factor is the strength of the raindrop energy to break the aggregate size. Either the raindrop energy to break the bigger aggregates was not strong enough or the change in porosity from the initial pore volume due to raindrop impact was less in PS assuming the raindrop energy had equal effect in both AD and PS treatments. In this study, the wash-in mechanism was not confirmed either through our results or our visual observations.

In case of BD, the difference between the no- and with raindrop impact treatments was low and it was not quite clear to explain the crust formation using the infiltration rate of the soil. Nevertheless, the time to runoff was early in the raindrop impact treatment that can give an indication of earlier formation of crust than the no-raindrop impact treatment. Furthermore, e_i showed an earlier difference, indicating the evidence of the effect of the raindrop impact (Fig. 3 and 4).

There was an apparent difference in infiltration rate as well as time to runoff between the two soils. Biei soil has a less infiltration capacity and faster to generate runoff. This is an indication of the fact that Biei soil was more susceptible to crust formation, which must be due to its low organic matter, high silt, low porosity and high bulk density of the soil.

3.3 Changes in saturated hydraulic conductivity

Hydraulic conductivity of the surface crust was evaluated using Darcy's law in stratified soil. Hydraulic conductivity of two layered soil is expressed as (July and Horton, 2004),

$$L_t/K_{tot}=L_{cr}/K_{cr}+L_n/K_n \quad (1)$$

where L_t, L_{cr} and L_n are total length of the soil column, thickness of the crust and length of soil under the crust (L_t-L_{cr}), respectively. K_{tot} and K_n are saturated hydraulic conductivity of the raindrop impacted and no-raindrop impacted samples which were measured immediately after the rainfall was over, and K_{cr} is saturated hydraulic conductivity of the crusted layer. The crusted length (L_{cr}) was measured after careful removal of the loosened particles from the subsurface layer and determined as 2 mm after measuring several samples of crusts by vernier caliper.

Saturated hydraulic conductivities of the crusted layer (K_{cr}) for Hokudai soil decreased in the order of four for WET, two for PS and one for AD and BD compared to the no- raindrop impact soil (K_n) as shown in columns 2 and 3 of Table 5. The impedance caused by the formation of crusted layer appears to be high in WET and least in BD. It can be said that Hokudai soil is easily disrupted by raindrop energy when wet than dry. The bondage between particles seemed to become hard when dry and more energy is needed to break aggregates into pieces. Thus, K_{cr} of WET was lower than that of AD. To further verify this idea, a study should be done with high raindrop energy like high rainfall intensity and/or big raindrop size.

For Biei soil, K_{cr} decreased in the order of four for AD, three for PS and WET, and two for BD compared to K_n as shown in columns 2 and 3 of Table 5.

Initially dry samples showed extremely lower K_{cr} than WET. PS and AD had similar K_{cr} values after the raindrop impact. Runoff occurred for Biei AD with no-raindrop impact, which indicates that the soil was easily disrupted even in the absence of raindrop impact. Effect of initial soil moisture content on K_{cr} was very different between Hokudai and Biei soils.

The ratios of hydraulic conductivity of the whole column of the raindrop impacted to that of no-raindrop impacted (K_n/K_{tot}) were 2 times for AD and BD, 8 times for PS and 300 times for WET for Hokudai. While for Biei, the ratios were 27, 10, 1.33 and 10 times for AD, WET, BD and PS, respectively. The effect of the crusted layer on the whole soil profile was high in WET, followed by PS and low in AD and BD for Hokudai. Unlike Hokudai the impact on the whole profile was high in AD, followed by PS and WET and low in BD for Biei.

Table 5 Average Hydraulic conductivity of Hokudai and Biei soils after rainfall

Type of soil		K_{cr} $\times 10^{-3}$ (cm/s)	K_n $\times 10^{-3}$ (cm/s)	K_{tot} $\times 10^{-3}$ (cm/s)
AD	Hokudai	1.21	62	35
	Biei	0.0165	27	1
PS	Hokudai	1.75	800	100
	Biei	0.0171	100	10
WET	Hokudai	0.056	890	3.6
	Biei	3.08	1770	180
BD	Hokudai	0.0108	5.9	3.3
	Biei	0.0355	8	6

Where K_{cr} is the hydraulic conductivity of crusted layer, K_n is the hydraulic conductivity of the no-impacted column and K_{tot} is the Hydraulic conductivity of the whole column of raindrop impacted

4. Conclusions

Four different treatments for Hokudai and Biei soils were examined to investigate the effect of raindrop impact on the crust formation by comparing with no-raindrop impact. The two soils used as well as the treatments for each soil had shown different responses against the no-raindrop and raindrop impacts. The following conclusions can be drawn regarding the effect of raindrop impact on the treatments, soil type and the formation process of crust.

1. Results of the no- and with raindrop impact indicated that raindrop energy was the main factor for the formation of surface crusting on bare soil. This result agrees with Boiffin (1986), McIntyre (1958) and Nishimura *et al.* (1993).

2. However, processes of crust formation by raindrop impact investigated from water movement were different among the treatments. The crust was formed earlier for high bulk density (BD) treatment. Infiltration rates of air dried (AD) and wet (WET) treatments decreased with time by raindrop impact. In large aggregate (PS), cumulative infiltration was the highest among the treatments. The small aggregates had higher impact. Similar results were found by Farres (1978).

3. PS was prepared to check the wash-in effect. Contrary to the expectation there were no washed-in particles observed in our study. Chen *et al.* (1980) has similar outcome. However, other authors (McIntyre, 1958 ; Nishimura *et al.*, 1993) have found wash-in effect.

4. Even though it could not show us the extent of formation, the time to runoff or ponding became an indication of formation of crusting in cases of WET, AD and PS.

5. In Hokudai soil, hydraulic conductivity of crust layer (K_{cr}) of AD was high compared to that of WET indicating that aggregate became more stable with decreasing soil water. While in Biei, AD had the lowest K_{cr} followed by PS and WET. The main reason for this can be the strength of the aggregates at different moisture contents, that is, Hokudai soil had high bondage between particles when dry and Biei soil particles had strong bondage when wet. Thus, Biei soil aggregates were easily disintegrated during rainfall when dry. In addition, the infiltration capacity of Biei soil was low compared to Hokudai soil and the values of K_{cr} decreased drastically in dry samples of Biei soil. Thus, it can be said that Biei soil was more susceptible to crust formation and surface runoff when dry.

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雨滴の衝撃が表面クラスト形成に与える影響

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要　　旨

北海道の 2 種の粘土質ローム土である北大と美瑛を用い，雨滴の衝撃がクラスト形成過程に与える影響を室内実験により明らかにした。処理区として風乾（AD），湿潤（WET），大団粒（PS）および高乾燥密度（BD）を用意した。降雨強度が 63 mm h^{-1} の降雨装置により，高さ 170 cm より雨滴を 1 時間与えた。最終の浸入速度は，PS＞AD＞WET＞BD の順であり，雨滴エネルギーの影響は団粒径の小さな AD と WET が団粒径の大きな PS に比べて大きかった。クラスト形成による透水係数の低下は大きい順に北大では WET＞PS＞AD＞BD の順であり，湿潤試料よりも乾燥試料の団粒が安定であった。一方，美瑛では透水係数の低下は大きい順に AD＞PS＞WET＞BD の順であった。美瑛では乾燥することにより透水係数が大きく低下し，浸入量も北大よりも小さかった。

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