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Changes in Certain Paddy Soil Properties under Perforated Sheet Pipe as Subsurface Shallow Drainage

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Abstract

Certain soil properties are expected to change under subsurface shallow drainage. This study focuses on the use of sheet pipes originally developed for use in Japan approximately 40 years ago. However, limited research on the said sheet pipes necessitates further study. To investigate the changes in soil properties in a field where a sheet pipe has been installed, soil samples were collected from drainage stream sites in the field—upstream, midstream, and downstream—at specific distances from the sheet pipe (0 m, 1 m, and 2 m) and soil depths (10 cm, 25 cm, and 45 cm), both before and after rice cultivation. In only one rice cropping, we found no significant impact caused by the sheet pipe on some soil properties, except for larger pores. We observed larger mesopores portions (MePs) at distances of 0 m and 1 m from the sheet pipe in deeper soil layers (at depths of 25 cm and 45 cm). Although this study found no significant differences in macropores (MaPs), MePs could lead to the development of MaPs and cracks and could improve drainage characteristics in the future.

Discipline: Agricultural Engineering
Additional key words: conductivity, mesopores, physical properties, saturated hydraulic, sheet pipe

Introduction

Global agricultural production has been aiming at adapting to climate change and producing more crops while effectively and sustainably managing water. Agricultural drainage, including surface and subsurface drainages, removes excess water from flooded land and provides better environments for crops. Parsinejad & Akram (2018) proposed that drainage is one of the main elements of integrated water management for climate-adaptive solutions.

Improvements in soil water storage and increases in percolation or permeability with conventional tile or mole drains have been reported (Blann et al. 2009, Fausey 2005, Skaggs et al. 1994). However, only few papers have showed that conventional drainage impacts soil characteristics such as soil bulk density (BD), aggregation, compaction, macroporosity, soil salinity, pH, and cation exchange capacity (Vopravil et al. 2017, Wealge et al. 2019). Moreover, water table reduction and increases in air-filled capacity, saturated hydraulic conductivity, and water-holding capacity were studied using such drainage technologies (Tiwari & Goel 2017, Schwab et al. 1985). Most studies have focused on topsoil with a heavy texture and the spacing of deep drains and mainly compared adjacent soils with nonmole or tile drainage. Thus, limited literature has explained the long-term effects of such drainage on crop yield and soil physical properties (Wesström et al. 2008).

In a deep drainage study, Francis & Morton (1991) not only claimed that subsurface gravel mole drainage did not affect drainage through less surface infiltration and soil water content but also observed more root extension from upper layers to near the drainage. Subsurface shallow drainage is expected to offer more benefits in accelerating drainage compared with deep drainage (Oosterbaan 2017). Therefore, more research must be conducted on subsurface shallow drainage such as sheet pipe.

Sheet pipe was developed approximately 40 years ago and is mainly installed in the western part of Japan. Sheet pipe was typically installed at soil depths of 40 cm-50 cm with close spacing (4 m-8 m). These settings have been settled in empirical ways. Compared with

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other conventional drains, sheet pipe has one significant advantage of not requiring transitional materials (JASPiP 2014) such as gravel and straw; thus, sheet pipe is considered a cost-effective and environmentally friendly technique. The limited previous studies on paddy fields with heavy texture soils found that installing sheet pipe had some benefits in reducing waterlogging and the electrical conductivity (EC) of drained water (Setiawan et al. 2019). Moreover, our previous study reported the long-term impacts of sheet pipe on some paddy fields (Soe et al. 2019).

However, research on the drainage function of sheet pipe and its impact on soil properties remains inadequate. For instance, it remains unclear where the drainage water passes through, and the why and how aspects of the sheet pipe function have yet to be clarified. Moreover, when will these impacts appear after installation is still uncertain. Hence, this study investigated the changes in certain paddy soil properties as a short-term impact under newly installed sheet pipe during a single rice cropping. For that purpose, we studied the properties of soil collected from stream sites (upstream, midstream, and downstream) with sheet pipe installed in the field at specific distances from the sheet pipe (0 m, 1 m, and 2 m) and soil depths or layers (10 cm, 25 cm, and 45 cm), both before and after rice cultivation.

Materials and methods

Polyethylene plastic perforated sheet pipe with distinct tiny pores (approximately 1 mm in diameter, 532 holes m^{-1}) and weighing 17 kg per 100 m was installed in a paddy field at Takedatsu, Kunisaki City, Oita Prefecture, Japan, on April 3, 2018. The experimental field (measuring 0.32 ha) is located 0.36 m above sea level in a closed embankment to prevent the intrusion of seawater. This land was reclaimed approximately 40 years ago and has recently been used for the cultivation of rice as fodder. Prior to cultivation in 2018, 20 tons of gypsum and 200 kg of manure per hectare were applied. Table 1 summarizes the time schedule.

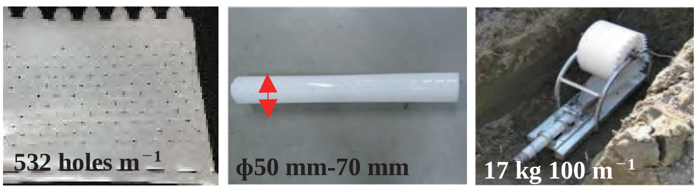
On average, there was a 4-m gap between the installed sheet pipe along a 0.1% slope in the field. The installation process required first cutting up the land with a ripper mounted on a bulldozer and then installing perforated sheet pipe at a depth of 40 cm (Fig. 1 (a)). This flat plastic sheet could be transformed into a pipe measuring 70 mm in diameter when installed in the field using a mole drainer (Fig. 1 (b)). The drain outlet was closed at the end of July in 2018 (during the growth period).

The first soil sampling was performed on April 4, 2018, one day after the installation of the sheet pipe. The second sampling was later performed after rice harvesting on November 25, 2018.

A total of 27 soil samples representing the stream sites with the sheet pipe (upstream, midstream, and downstream) were collected at three soil depths (10 cm, 25 cm , and 45 cm) in triplicates. A visual and soil hardness investigation revealed a compacted plow layer at a depth of 15 cm-20 cm. We collected soil samples from different soil layers as follows: 10 cm as disturbed topsoil, 25 cm as undisturbed topsoil, and 45 cm as undisturbed subsoil, with 100 cm^3 sampling cores for undisturbed soil and approximately 500 g of disturbed soil. For the second sets, 81 soil samples representing the same state as the first sampling plus three additional distances from the sheet pipe (0 m, 1 m, and 2 m) were collected after harvesting. Both disturbed (500 g) and undisturbed soils with 100 cm^3 cores were collected. The average temperatures during soil sampling were 17.1°C (first sampling) and 12.1°C (second sampling).

Field infiltration was analyzed with a DIK-4201 cylindrical intake rate meter at distances of 10 m and 30 m from the drain outlet after sheet pipe installation (at the first soil sampling) and after one rice cropping

(a) Installing sheet pipe in the field



(b) A roll of perforated sheet and a mole drainer

Source: https://jaspip.jp/siryou/

Fig. 1. General features of perforated sheet pipe and its installation in the field

(at the second soil sampling). In the laboratory, the soil texture (% sand, silt, and clay) was analyzed using the pipette method and classified as per the US Department of Agriculture (USDA) procedure. Soil moisture content was measured using the gravimetric method. Saturated hydraulic conductivity was measured with a Daiki permeameter (DIK-4050) using the falling head method. In this study, *K*s (cm s^{-1}) value was converted into a logarithmic value (−log *K*s). The soil organic matter (OM) content (%) was determined using the ignition loss method with a muffle furnace (ADVANTEC KL-160) and calculated from the difference of the dried weight at 105°C and 550°C divided by the dried weight at 105°C × 100. Soil BD was analyzed using the dry core method (Rowell 1994). The soil–water characteristic curves, which were used to formulate three prediction trends at lower suction values, S shape, and higher suction values, were drawn using the hanging column method for lower suction values (−10 to −150 cm) and the centrifuge method (KOKUSAN 2750) for higher suction values (pF = negative logarithm for height of water column in centimeter; 2.4-4.2). The Young–Laplace equation was then applied together with these three prediction trends to calculate the pore size distribution. In this study, > 50 µm pore size was classified as a MaP and 0.5 µm-50 µm pore size as a MeP (Lal & Shukla 2004). Plant available moisture (PAM) was calculated to find the difference between pF 2.0 and pF 4.2 (Lal & Shukla 2004). The units of all pores were cm^3 cm^{-3}. The HORIBA HM-20p pH meter and HORIBA ES-14 conductivity meter were used to measure soil pH and EC (µS m^{-1}) in 1:5 deionized water. Total carbonate (total CO_3) was measured using volumetric analysis (Rowell 1994). Disturbed soil samples were used to determine soil texture and analyze OM, pH, and EC.

Statistical analyses, such as Pearson's correlation, linear regression analysis, analysis of variance (ANOVA), F-test, a multicollinearity test, and formulating an adjusted R^2 test, were conducted using SPSS 15. All means were compared to identify the changes under the installed sheet pipe before and after rice cropping at the stream sites at specific distances from the sheet pipe at all soil depths, with a least significant difference of 5%.

Table 1. Time schedule

Activity	Timing (2018)
Installation of sheet-pipe	April 3
Soil sampling (before rice cultivation)	April 4
Land preparation	April 12
Rice planting	April 15
Closure of drainage	July 18
Harvesting	November 10
Soil sampling (after rice cultivation)	November 25

Results

1. General properties of soils

As shown in Table 2, the soil texture in the study field was sandy loam in the upper two layers (10 cm and 25 cm) and loamy sand in the deeper layer (45 cm). Although the soil pH at a soil depth of 10 cm was not different from that of 45 cm, the EC and total CO_3 (%) values at a soil depth of 45 cm were higher than those in the upper two layers.

The basic intake rate at a 2-m distance from the sheet pipe after rice cropping showed a slightly higher trend than that at a 2-m distance before rice cropping (Table 3).

2. Changes and differences in soil physical properties

Figure 2 shows the changes and differences in certain soil properties (N = 27, 3 × 3 × 3). A one-way ANOVA was carried out for all factors—rice cropping, distance, streamlines, and soil depth (layer)—for the 27 soil samples. There was a significant difference, on average, for rice cropping ($P < 0.01$). For streamline, the averages of BD, OM, −log *K*s (saturated hydraulic conductivity), and MaPs were significantly different. Moreover, for soil depth, the averages of BD, OM, and MePs were significantly different. For MeP, there is a significant difference among rice cropping, distance, and soil depth.

In this study, "change" refers to changes caused by rice cropping, whereas "difference" refers to the differences among stream lines, distance, and soil depths.

Table 2. General characteristics of soils

Soil Depth	Sand (%)	Silt (%)	Clay (%)	Soil Texture (USDA 1994)	pH (H_2O 1:5)	EC (µS cm^{-1})	Total CO_3 (%)
10 cm	75.5 (± 1.3)	15.2 (± 2.1)	13.3 (± 1.7)	Sandy loam	6.7 (± 0.2)	58.9 (± 9.9)	5.2 (± 1.5)
25 cm	74.2 (± 4.6)	13.2 (± 4.5)	12.6 (± 1.4)	Sandy loam	6.6 (± 0.3)	76.6 (± 16.7)	5.9 (± 1.1)
45 cm	81.6 (± 1.4)	9.7 (± 1.6)	8.7 (± 1.0)	Loamy sand	6.7 (± 0.2)	79.7 (± 15.5)	6.5 (± 2.3)

* Numbers in parentheses denote standard deviations.
Number of disturbed samples = 108 (27 before + 81 after rice cropping)

Figures 2 (a) and (b) show the changes and differences in the average BD and OM. At all soil depths, the average BD decreased, whereas the average OM increased after rice cropping in comparison with before rice cropping. The average BD at a 2-m distance from the sheet pipe through the soil layers decreased from 1.42 g cm^{-3} (before rice cropping) to 1.35 g cm^{-3} (after rice cropping). In contrast, the average OM through the soil layers increased from 1.5% (before rice cropping) to 3.2% (after rice cropping).

For streamline after rice cropping, the average BD of the upstream site (1.39 g cm^{-3}) was slightly larger than those of the downstream site (1.33 g cm^{-3}). After rice cropping, the OM content at 25 cm depth was larger than that at 10 cm depth.

Figures 2 (c)-(f) show the changes and differences of −log *K*s, MaP, MeP, and PAM at each distance, streamline, and soil depth before and after rice cropping.

Although −log *K*s generally decreased after rice cropping, MaP, MeP, and PAM almost increased compared with that before cropping at all depths. After rice cropping, the average −log *K*s decreased from the upstream to the downstream site. For soil depths, the average value of −log *Ks* at 45 cm depth was the minimum.

A large portion of MeP increased near the sheet pipe downstream. The average MeP was 0.23 cm^3 cm^{-3} at 25 cm depth and 0.21 cm^3 cm^{-3} at 45 cm depth.

The increases in MaP and MeP at a 2-m distance at 25 cm and 45 cm soil depth after rice cropping were different from those at a 2-m distance before rice cropping. Moreover, the average MaP and MeP at 45 cm depth at the downstream site increased from 0.03 + 0.14 cm^3 cm^{-3} (2-m distance before rice cropping) to 0.03 + 0.24 cm^3 cm^{-3} (0-m distance after rice cropping).

Saturated hydraulic conductivity and MaPs mostly increased with the conventional subsurface drainage in paddy fields (Talukolaee et al. 2018).

Table 3. Comparison of infiltration test before and after rice cropping

Expression	2-m JAISP (before)			2-m ISP (after)		
	10 m from outlet	30 m from outlet	Average	10 m from outlet	30 m from outlet	Average
Basic Intake rate (mm h^{-1})	2.9	5.9	4.4	4.9	12	8.5

2-m JAISP denotes testing at a 2-m distance from the sheet pipe just after installation before rice (fodder) cultivation.
2-m ISP denotes testing at a 2-m distance from the installed sheet pipe after rice (fodder) harvesting.

3. Relationship between the soil properties and saturated hydraulic conductivity

Figure 3 shows the relationship between saturated hydraulic conductivity (−log *K*s) and some soil properties before and after rice cropping for each depth (N = 36, 9 [before] + 27 [after]), as well as regression lines.

The larger the −log *K*s, the larger the BD but the smaller the OM, MaP, MeP, and PAM for all depths. For rice cropping, BD decreased, whereas OM, MaP, MeP, and PAM increased for all soil depths. The largest R^2 was between −log *K*s and OM (0.74-0.81), followed by BD (0.65-0.78).

4. Average soil properties according to each factor

According to multiple comparisons (27 treatments), the average soil properties (N = 3) at the same streamline under different distances from the sheet pipe, and soil depths after rice cropping were statistically different. There was a clear difference between soil depths, and the soil characteristics of the deeper depth were different from those of the shallow ones. For example, the BD at 45 cm depth was different from that at 10 cm and 25 cm depth under the same stream site and distance. However, only MeP at a 0-m distance at 45 cm depth downstream was larger in the deeper depth. A large average value of MeP was found in the deeper depth, especially in the downstream site.

Discussion

After a single rice cropping, changes and differences in BD, OM, and −log *K*s (Fig. 2 (a), (b), (c)) were observed. Smaller BD and larger OM were found even at the deeper layers (25 cm and 45 cm) at the downstream site after rice cropping. At the shallow depths, the intrusion of rice roots induced a reduction in BD. However, these changes were caused not only by rice roots and sheet pipe installation but by many management practices, including rice cropping management practices such as manuring, land cultivation, and water management. BD and OM were also associated with −log *K*s (Fig. 3 (a) and (b)). Ultimately, no significant impacts caused by the use of sheet pipe could be identified.

This study also found a large portion of larger pores (MaP + MeP). Despite the clear increases in MeP at soil depths of 25 cm and 45 cm, there were no clear increases in MaP (Fig. 2 (d) and (e)). In particular, a large portion of MeP was found at the downstream site of 0-m distance and a depth of 45 cm (Table 4).

Larger pores normally develop from the soil surface because of natural drying. However, this study found increases in MeP at deeper layers, with MaP development not being clear. This is not normal. It seems feasible to understand that under the opening conditions of the sheet pipe end (outlet), the air was ventilated or moved into the sheet pipe, especially near the drainage outlet (i.e., downstream). We could expect the air intrusion and drying near the drainage outlet to induce MeP development.

In our previous long-term study, increases in MeP were clear (Soe et al. 2019), but in this study, an increase in MeP was distinct. The sheet pipe used in this study lasted only seven months, whereas those used in our previous long-term study lasted 7 and 12 years.

These larger pores are responsible for the movement of water (Eusufzai & Fujii 2012). The sheet pipe was apparently responsible for MeP development, a sign regarding the transition of MaP development. It is widely

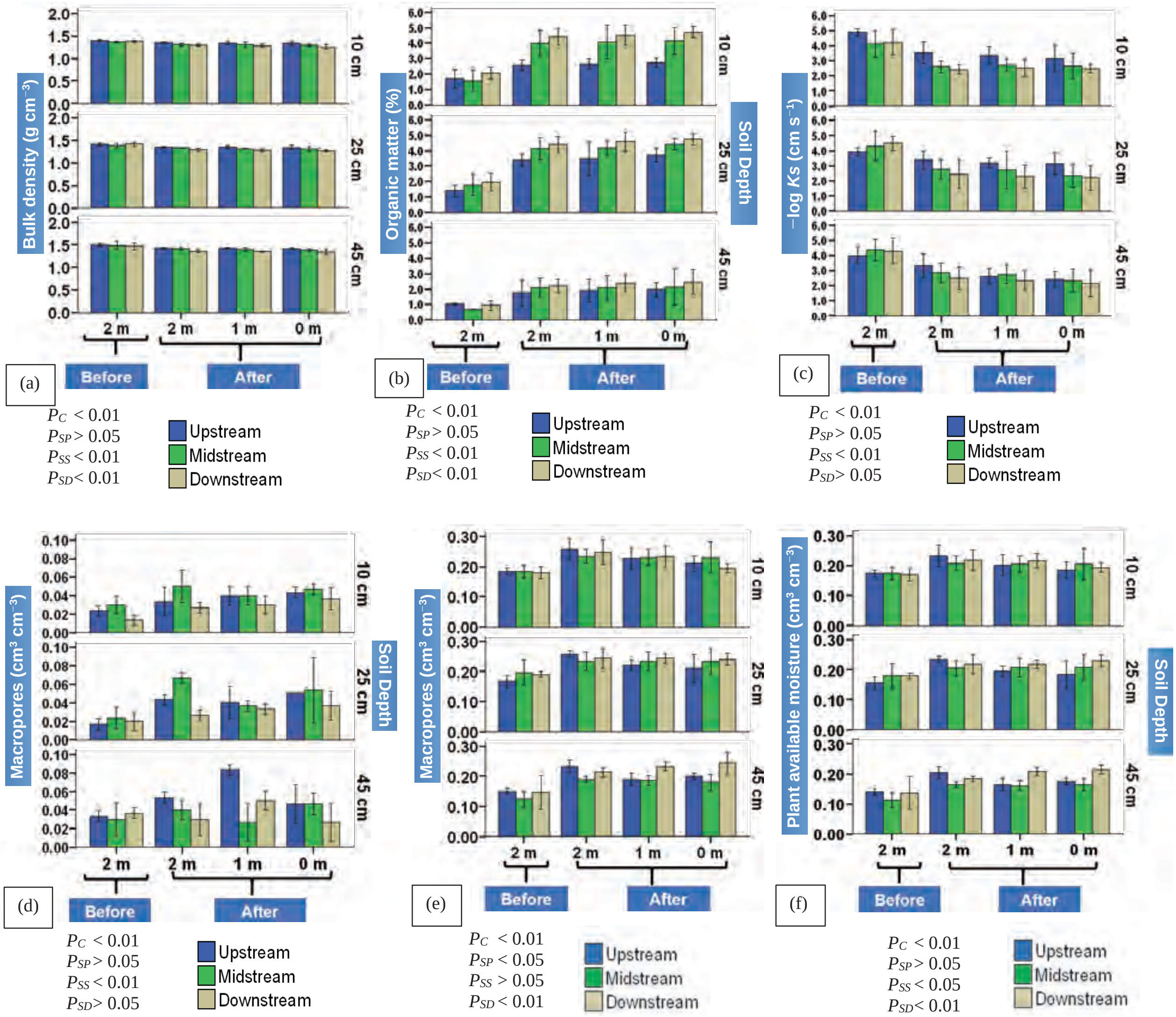


Fig. 2. Changes and difference in a) soil bulk density (g cm^{-3}), b) soil organic matter (%), c) saturated hydraulic conductivity (−log *K*s), d) macropores (cm^3 cm^{-3}), e) mesopores (cm^3 cm^{-3}), and f) plant available moisture (cm^3 cm^{-3}) at different soil depths, stream sites, and sheet pipe distances during rice cropping

Before: before rice cultivation, After: after rice cultivation

Error bars express standard deviations.

Pc< 0.01 means that changes in soil properties during a rice cropping are statistically highly significant at *P*< 0.01.

Psp< 0.05 means that changes in soil properties regarding distances from the sheet pipe are statistically significant at *P*< 0.05.

Pss< 0.01 means that changes in soil properties under different stream sites are highly statistically significant at *P*< 0.01.

Psd< 0.01 means that changes in soil properties at different soil depths shows highly statistically significant at *P*< 0.01.

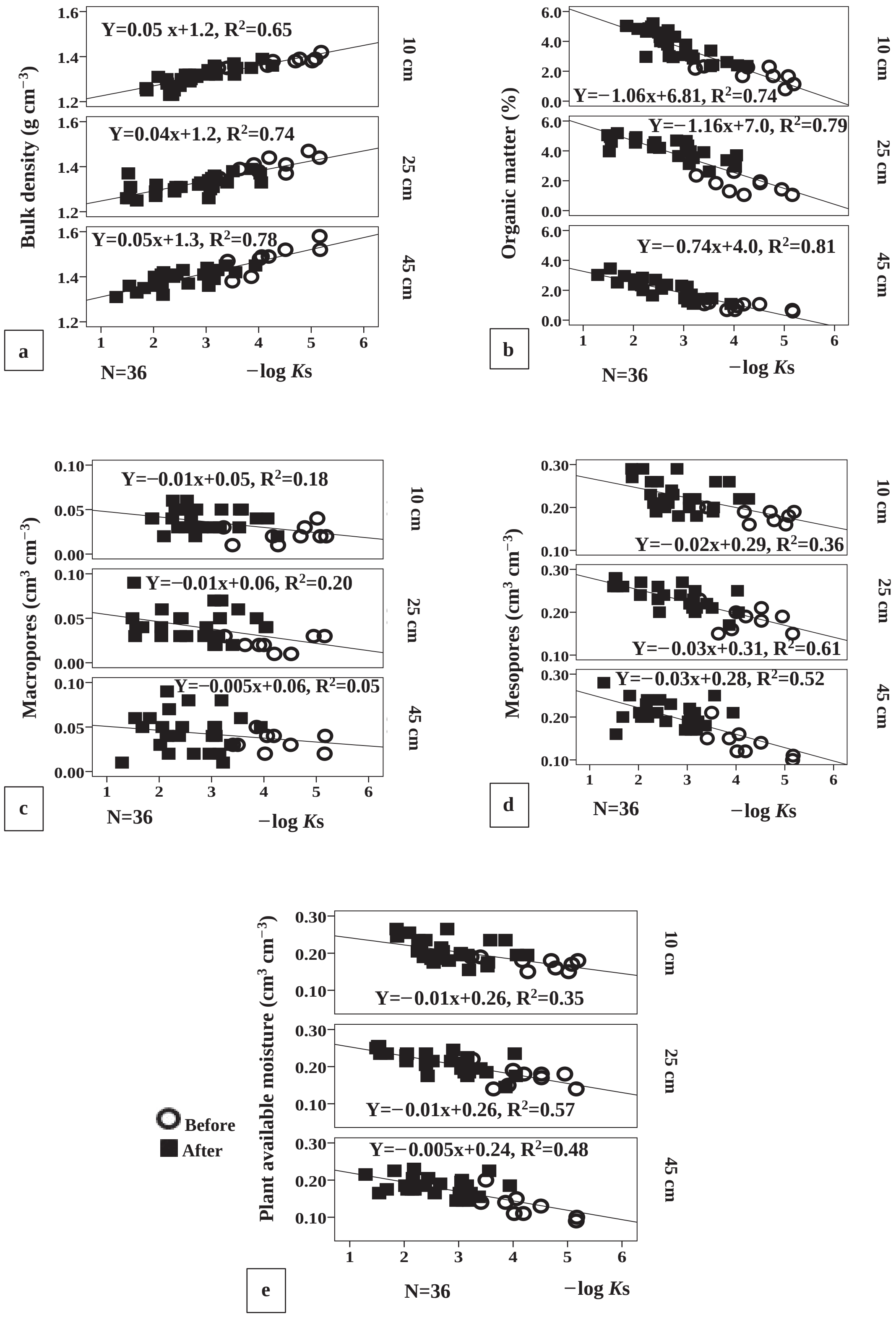


Fig. 3. Relationships between saturated hydraulic conductivity (–log *K*s) and a) soil bulk density, b) soil organic matter (%), c) macropores ($cm^3\ cm^{-3}$), d) mesopores ($cm^3\ cm^{-3}$), and e) plant available moisture ($cm^3\ cm^{-3}$)

Before: before rice cultivation, After: after rice cultivation

Regression equations are shown for each soil property. x means –log *K*s and Y means each soil property such as BD ($g\ cm^{-3}$), OM (%), MaPs ($cm^3\ cm^{-3}$), MePs ($cm^3\ cm^{-3}$), and PAM ($cm^3\ cm^{-3}$).

known that MaPs develop in several years (Eigendbrod 2003). Tabuchi (1968) also referred to the generation of cracks in paddy soils under traditional drainage as a function of dryness that takes several years.

Conclusion

This study investigated the changes in some soil properties under installed sheet pipe, one of the subsurface drainage technologies, in a paddy field regarding the stream sites of the drainage, the distance from the sheet pipe, and soil depths (layers) during rice cropping. During only one rice cropping, we could find no significant impacts caused by the sheet pipe on some soil properties, except for larger pores. We observed larger MeP portions at distances of 0 m and 1 m from the sheet pipe at deeper soil layers (25 cm and 45 cm), especially at the downstream site. Although the differences in MaPs in this study were not significant, MePs could lead to the development of MaPs and cracks as well as improved drainage characteristics in the future. An increase in MePs in this study was assumed to be a transition state of small cracks or MaPs. Therefore, the spatial distribution of cracks or MaP under installed sheet pipe must be clarified, and these developing rates and periods should be investigated as part of future studies.

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We owe deep gratitude to Dr. Tetsuro Fukuda (chairperson of the Japan Sheet Pipe Promotion Association) and Mr. Kozo Arita (a landowner in Takedatsu, Kunisaki City, Oita Prefecture) for helping us smoothly conduct the field experiments. We are also thankful toward our laboratory members who helped during the difficult times involving soil sampling and during the field study. Finally, we would like to note that this study would not have been possible without the financial support of the Japan International Cooperation Agency.

Table 4. Average of some soil characteristics (Streamline, distance, and depth)

Stream site	Distances	Soil depths (cm)	BD	−log Ks	OM	MeP	MaP	PAM
up	0	10	1.3367 B	3.1700 A	2.7367 B	0.2097 A	0.0433 A	0.2036 B
		25	1.3467 B	3.1400 A	3.7267 A	0.2100 A	0.0500 A	0.2187 B
		45	1.4200 A	2.4100 B	1.9500 C	0.1993 A	0.0467 A	0.2516 A
	1	10	1.3400 b	3.3667 a	2.6600 b	0.2267 a	0.0400 b	0.2645 a
		25	1.3500 b	3.1600 a	3.4800 a	0.2200 a	0.0400 b	0.1793 b
		45	1.4233 a	2.6333 b	1.9033 c	0.1900 b	0.0833 a	0.1559 c
	2	10	1.3433 β	3.5433 α	2.5733 β	0.2567 α	0.0333 ϒ	0.2530 β
		25	1.3533 β	3.3633 α	3.3900 α	0.2567 α	0.0433 β	0.2840 α
		45	1.4267 α	3.3133 β	1.7467 ϒ	0.2333 β	0.0533 α	0.2302 ϒ
mid	0	10	1.2933 H	2.6467 G	4.1467 G	0.2300 G	0.0467 H	0.2325 H
		25	1.3133 H	2.3333 G	4.4033 G	0.2333 G	0.0533 G	0.2205 H
		45	1.3900 G	2.3333 G	2.1200 H	0.1800 H	0.0467 H	0.2580 G
	1	10	1.3100 Y	2.7200 X	4.0767 X	0.2300 X	0.0400 X	0.2048 Y
		25	1.3167 Y	2.7100 X	4.1733 X	0.2333 X	0.0367 X	0.2266 X
		45	1.4000 X	2.7467 X	2.0800 Y	0.1867 Y	0.0267 Y	0.2345 X
	2	10	1.3067 z	2.6100 x	4.0100 x	0.2333 x	0.0500 y	0.2046 z
		25	1.3333 y	2.7633 x	4.1467 x	0.2333 x	0.0667 x	0.2267 y
		45	1.4167 x	2.8600 x	2.1033 y	0.1900 y	0.0400 z	0.2570 x
down	0	10	1.2567 q	2.4967 p	4.7267 p	0.1927 q	0.0367 p	0.2353 p
		25	1.2767 q	2.2033 p	4.7400 p	0.2400 p	0.0367 p	0.2236 pq
		45	1.3467 p	2.1767 p	2.4767 q	0.2433 p	0.0267 q	0.2138 q
	1	10	1.2867 e	2.5333 d	4.5167 d	0.2333 d	0.0300 e	0.2468 d
		25	1.2833 e	2.2833 d	4.5700 d	0.2433 d	0.0333 e	0.2335 d
		45	1.3567 d	2.3433 d	2.3800 e	0.2333 d	0.0500 d	0.2109 e
	2	10	1.3000 E	2.4233 D	4.4067 D	0.2467 D	0.0267 D	0.2279 E
		25	1.2967 E	2.4467 D	4.4133 D	0.2433 D	0.0267 D	0.2485 D
		45	1.3633 D	2.4967 D	2.2000 E	0.2133 E	0.0300 E	0.1893 F

BD: Bulk Density (g cm^{-3}), Ks: Hydraulic conductivity (cm s^{-1}), OM: Organic Matter content (%), MaP: Macro-pores (cm cm^{-3}), MeP: Meso-pores (cm cm^{-3}), and PAM: (Plant Available Moisture, cm^3 cm^{-3}), respectively.

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