Characteristics of soil hydraulic conductivity in natural forest, agricultural land, and green open space area

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Abstract. Soil hydraulic conductivity is one of the important soil characteristics that determine the amount and proportion of water that will be infiltrated into the soil column and that which flows as surface runoff. It is strongly influenced by soil porosity and characteristics that affect soil porosity such as soil texture and structure, soil organic matter content, land management, and plant canopy cover density. This research is aimed to identify the character of soil hydraulic conductivity in different land uses namely forest, agricultural land, and green open space areas. The results showed that: a) forest conversion into agricultural land led to the decline of soil quality, so that the conversion of forest land into agricultural land decreased the soil hydraulic conductivity; b) forest canopy cover density affected the soil quality and soil hydraulic conductivity, where high density canopy cover had higher value of soil hydraulic conductivity; c) Situgede tourism forest had the lowest soil hydraulic conductivity as compared to other forest types; d) soil hydraulic conductivity in conservation agriculture was higher than those in intensive annual crop land and Situgede tourism forest, and it's not significantly different from the soil hydraulic conductivity in low density forest canopy; and e) soil hydraulic conductivity in green open spaces area were strongly determined by the naturalness of landscape and human intervention level on its formation and management, where the University of Indonesia urban forest and Lembah Gurame city park which function as ecotourism areas had lower soil hydraulic conductivity as compared to Grand Forest Park.

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INTRODUCTION

Conversion of forest land into agricultural areas and its subsequent conversion into settlements and other developed areas is currently an unavoidable phenomenon in various regions of Indonesia. This conversion has led to a decrease in forest area and conversely encouraged an increase in agricultural land and settlement areas, which in turn causes an imbalance in the regional water system and could trigger hydrometeorological disasters such as floods and landslides.

Reduction of canopy cover of permanent vegetation due to linear loss of forest cover causes a progressive decrease in rainfall interception and increases the amount of rainwater that falls directly on the soil surface, which then encourages greater surface runoff and soil erosion (Hidayat *et al.*, 2007). The decreasing organic matter originating from litter and twigs is directly correlated with the lower soil organic matter content and the lower soil biological activities. The lower soil biological activities, especially those of meso and macro soil fauna causes a limited amount of macropores in the soil column. Widianto *et al.* (2004) showed that forest conversion into monoculture coffee in Lampung causes changes in soil characteristics in the form of a decrease in organic matter content and amount of soil pores. Decreasing soil organic matter content also causes the decline of soil aggregates stability and increases soil bulk density. The resultant of these processes leads to a lower ability to transmit water into the soil (decrease soil water storage) and increase the amount of surface runoff flowing into the river.

To maintain the balance of ecosystem dynamics and environmental quality in urban areas, development of green open spaces such as city parks and urban forests has been currently initiated. Besides improving microclimate conditions, developing green open space was also intended to increase the water infiltration into soil columns so that it is expected to slightly help control surface flow in an urban area. The research is aimed at studying the soil hydraulic conductivity characteristics and other soil physical properties that affect it in different land-use types, namely natural forest, tourism forest, agricultural land (unirrigated farmland, cacao plantations, annual crops with intensive and conservation management), and green open space areas.

METHOD

Research Locations and Time

The research was done in four locations, namely: a) Nopu Village (Palolo Sub District, Donggala, Central Sulawesi); b) Dramaga Research Forest (DRF I) (Bogor, West Java); c) Dramaga Research Forest and Cikabayan Experimental Field Faperta IPB (DRF II) (Bogor, West Java), and d) Green Open Space (GOS) area of Depok City (West Java). The research was conducted from August-December 2005 (Nopu Village), February-June 2016 (DRF I), and February-June 2019 (DRF II and GOS of Depok City).

Data Collection

Equipment and Materials

The equipment being used in this research was a simple permeameter, auger hole, Global Positioning System, stopwatch, pressure and membrane plate aparatus, pippetes, burret, erlenmeyer, and other tools to determine the soil characteristics with laboratory analysis. The other equipment was stationery, computer and HP android with GLAMA (Gap Light Analysis Mobile App) Software. The materials being used were undisturbed soil sample, disturbed soil sample, H_2O_2, HCl, Natrium Pyrophosphate, Ferroin 0.025 M, $K_2Cr_2O_7$ 1 N, concentrated H_2SO_4, $FeSO_4$ 0.5 N, aqua dest, and water to measure soil hydraulic conductivity in the field.

Collection of Soil Samples

The research was conducted on deep solum Inceptisols soil (the solum thickness >75 cm). In sub-group categories, the soil was classified as Typic Eutrudept (Nopu Village) and Typic Dystrudept (DRF I, DRF II, and GOS of Depok City). Soil samples were taken in triplo from topsoil (0-20 cm) and subsoil (20-40 cm) that consists of undisturbed and disturbed soil samples. Soil samples were taken from selected land-use types. Land use types were analyzed using Quickbird imagery for Nopu Village (Central Sulawesi) and SPOT 6 imagery (Lapan, 2016) for DRF 1, DRF II, and GOS of Depok City (West Java). The density of vegetation canopy cover on DRF I, DRF II, and GOS of Depok City were analyzed using GLAMA application on an android device. The density of canopy cover was classified using the Forestry Department criteria (1992, in Komara, 2008), which was categorized as high (canopy cover >70%), medium (40-70%), and low (<40%).

Measurement of Soil Hydraulic Conductivity

The soil hydraulic conductivity was measured adjacent to the soil sampling point using a simple permeameter with a falling head permeameter approach. The measurements were conducted in the top soil layer (0-20 cm) by recording the rate of water level decrease in the permeameter tube until the decrease in water level reached a constant value (Hidayat *et al.*, 2014).

Data Analysis

Soil samples of each layer were analyzed in a laboratory to obtain the value of soil texture, soil organic matter content, total soil pores, soil water content, and pore size distribution (Table 1).

Table 1 Type and method of soil analysis

No	Analysis Type	Analysis Method
1	Soil texture	pippetes
2	Soil organic matter content	walkley and black
3	Total soil pores	gravimetry, bd, and bjp calculation
4	Soil water content	gravimetry
5	Pore size distribution	pressure/membrane plate apparatus

The data obtained from measuring soil hydraulic conductivity in the field is used to calculate the soil hydraulic conductivity value using formula:

$$K = \frac{\{\ln(\frac{h}{r} + [\left(\frac{h}{r}\right)^2 + 1]^{\frac{1}{2}}) - 1)\}\, Q}{2\pi h^2}$$

Description:

K : hydraulic conductivity (cm/hour)

h : height of water level (cm)

r : tube radius (cm)

Q : discharge (AxV) (cm^3/hour)

A : permeameter tube area (cm^2)

V : constant rate of water decline at saturation condition (cm/hour)

π : 3.14

RESULTS AND DISCUSSION

Soil Texture

Soil texture is defined as the relative proportion of soil particle fractions (sand, silt, clay). Soil texture is one of the permanent soil physical characteristics and is highly correlated with the parent material. It takes a huge effort to be able to change soil texture so that land-use changes don't affect the soil texture (Table 2).

Table 2 Average values of soil texture (0-40 cm)

No	Research location	Texture			
		Sand (%)	Silt (%)	Clay (%)	Texture Class
1	Nopu (Central Sulawesi)	49.6	34.8	15.4	Loam
2	DRF I (West Java)	10.9	18.0	71.1	Clay
3	DRF II (West Java)	7.5	15.0	77.5	Clay
4	GOS of Depok City	8.1	13.1	78.8	Clay

Soil Organic Matter Content

Land use type affects the soil organic matter content. Its content is strongly related with the amount of litters and crop residues being produced in each land use type. Forest has the highest thickness of litter, so it has the highest content of soil organic matter (Figure 1). Forest conversion into agricultural land causes a decrease in litter thickness on the soil surface (Hairiah *et al.*, 2004).
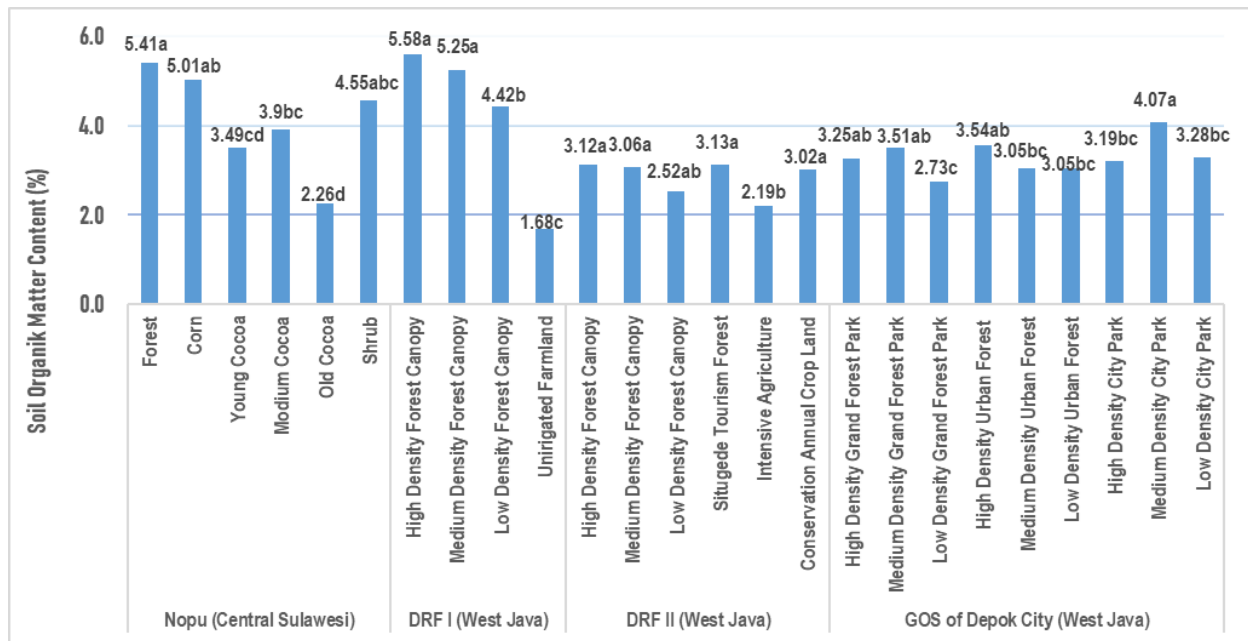

Figure 1 Content of soil organic matter in each land use type in Nopu Village (Central Sulawesi), DRF I, DRF II, and GOS of Depok City ($\alpha= 0.05$)

Nopu (Central Sulawesi)

Conversion of forest land into agricultural land led to a decrease in soil organic matter content. Forests are usually encroached by a slash and burn system to be planted with the annual crop, especially corn or other annual crops. The annual crop is planted for a few years as long as the plant production is still good enough. When annual crop production has declined drastically, farmers usually start to grow plantation crops, especially cocoa. Some farmers allow ex-annual cropland changes into shrub and bushland to be reused as agricultural land in the next period (after 7-10 years).

Compared to forest land, soil organic matter content decreased by 7.4% in corn land, 35.5% in young cocoa, 27.9% in medium age cocoa, and 58.2% in old cocoa. This is in line with the research result of Sabaruddin *et al.* (2001) and Kuimi *et al.* (2016), which showed that the conversion of natural forest into annual cropland causes a significant decrease in soil organic matter content. In the temperate area, the loss of organic carbon due to agricultural activity can reach 30% (Murty *et al.*, 2002), and in a tropical area, the loss is greater as a result of the faster decomposition rate of organic matter. Weed elimination when caring for the plant in young cocoa leads to a reduction in weeds and litter that serve as a source of soil organic matter. Pruning of non-productive branches and burning of litter under old cocoa plants led to a very significant decrease in soil organic matter content. Burning the litter is usually done because most farmers assume that cocoa litter is the habitat of cocoa pests and diseases, such as helopeltis and fruit flies. Thus, forest conversion into agricultural land cause change in soil physics, chemical properties, and biological characteristics (Viollete *et al.*, 2009).

Dramaga Research Forest I (DRF I)

Soil organic matter content decreased with the decreasing cover of the forest canopy. Soil organic matter content in high-density forest canopy, which was 5.58% decreased to 5.25% in the medium density forest canopy, 4.42% in low-density canopy forest, and 1.62% in unirrigated farmland. Soil organic matter content varies with vegetation type (Shapkota and Kafle, 2021), and vegetation density (Menyailo *et al.*, 2022). Compared to the high-density forest canopy, soil organic matter content in unirrigated farmland exhibited a drastic decrease of 69.9%. The decrease was caused by no more litter, branches, and plant residues which serve as sources of organic matter, and by intensive soil tillage, which will in turn accelerate the decomposition of organic matter and loss of organic matter from the land surface due to soil erosion.

Dramaga Research Forest II (DRF II)

Although the litter in Situgede Tourism Forets (STF) is always swept away and removed out from STF site, the content of soil organic matter in STF was slightly higher as compared to other forests. It was caused by the open condition of the forest floor with sufficiently high humidity (due to forest canopy), which encourages the growth of moss with sufficient thickness on the surface soil, which in turn contributes to the maintenance of soil organic matter content. The interesting result is the soil organic matter content in conservation agriculture (3.02%) which is not significantly different from the soil organic matter content in forest land (2.52-3.13%). The return of all plant litter and weeds as mulch and the application of minimum soil tillage practices contribute positively to maintaining and increasing soil organic matter content in conservation agriculture.

GOS of Depok City

Soil organic matter content decreased in line with decreasing density of vegetation canopy cover in Grand Forest Park (GFP) and Urban Forest of the University of Indonesia (UFUI), but the influence was not clearly seen in Lembah Gurame City Park (LGCP). On LGCP land, the highest organic matter content was obtained in medium-density canopy cover (4.07%), which was slightly higher than those in high-density canopy cover (3.19%) and low-density canopy cover (3.28%). LGCP is one of the ecotourism areas in Depok City, which cause visitor intervention in the distribution of organic waste in various places so that the effect of canopy cover on the soil organic matter content becomes less visible.

Total Porosity and Soil Pore Size Distribution

Land use type indirectly influences soil porosity and pore size distribution through its effect on the increase in soil organic matter content (Figure 1) and improvement in soil aggregate stability. Soil organic matter plays an important role as a cementing agent for soil particles to form a larger and more stable aggregate, which in turn can increase total soil porosity and soil macropores (very fast drainage pores, fast drainage pores, and slow drainage pores) (Table 3).

Nopu (Central Sulawesi)

Land use type affected only very fast drainage pore (VFDP), but did not affect total soil porosity, fast drainage pore (VDF), and slow drainage pore (SDF). Forest conversion into young cocoa plantations led to a 71.04% decrease in VFDP, where VFDP in the forest land of 17.40% decreased to 5.04% in young cocoa land. Decrease of soil organic matter content as a result of forest conversion into young cocoa land (Figure 1) causes loss of soil aggregate stabilizer material. The instability of soil aggregate caused the amount of VFDP to decrease and change into a smaller pore size. Total soil porosity and drainage pores are relatively high on forest area compared to agricultural land due to relatively high content of organic matter and soil fauna activity in decomposing organic matter in the soil (Bizuraho *et al.*, 2018).

Table 3 Total porosity and pore size distribution of soils in the research locations

Type of Land Use	Total Porosity (%)	Drainage Pore (%)	VFDP (%)	FDP (%)	SDP (%)
Nopu (Central Sulawesi)					
Forest	59.12	32.35a	17.40a	7.15	7.80
Corn	58.74	28.26ab	11.23bc	7.52	9.51
Young cocoa	54.21	23.76b	5.04d	7.66	11.05
Medium age cocoa	58.36	27.94ab	8.21cd	13.14	6.59
Old cocoa	56.35	27.04ab	9.53bc	10.97	6.54
Shrub	55.97	27.22ab	12.50b	7.09	7.63
Dramaga Research Forest I (West Java)					
High density forest canopy	62.79a	16.77ab	6.80	4.42	2.86a
Medium density forest canopy	63.96a	21.96a	9.18	6.92	3.61a
Low density forest canopy	60.98a	13.04b	4.53	4.19	1.29b
Unirrigated farmland	56.05b	16.46ab	8.26	2.38	1.36b
Dramaga Research Forest II (West Java)					
High density forest canopy	63.14a	21.25a	4.82a	10.50a	2.82a
Medium density forest canopy	61.44ab	16.97abc	2.50ab	6.56ab	2.49ab
Low desnsity canopy forest	60.15bc	15.38bc	3.03ab	4.19b	1.68abc
Situgede tourism Forest	60.69abc	15.51bc	5.04a	4.57b	1.70abc
Intensive agriculture	58.52c	14.76c	0.72b	4.18b	0.83c
Conservation agriculture	60.80abc	20.73ab	2.63ab	6.34ab	1.40bc
Green Open Space of Depok City (West Java)					
GFP*-high canopy cover	66.81a	20.67	5.17	6.62b	8.89a
GFP-medium canopy cover	66.27a	29.88	10.62	12.50a	6.76ab
GFP-low canopy cover	66.64a	24.89	5.17	14.36a	5.36ab
UFUI*-high canopy cover	56.13ab	12.95	6.48	4.60b	1.88b
UFUI-medium canopy cover	46.01b	10.87	5.02	3.90b	1.95b
UFUI-low canopy cover	50.91ab	13.9	5.85	2.96b	5.14ab
LGCP*-high canopy cover	54.08ab	21.47	11.39	5.69b	4.39ab
LGCP-medium canopy cover	57.57ab	14.02	8.59	3.10b	2.33b
LGCP-low canopy cover	56.18ab	22.57	13.81	2.89b	2.89b

Note: UFUI: Urban Forest of University of Indonesia; GFP: Grand Forest Park; LGCP: Lembah Gurame City Park; VFDP: Very fast drainage pore; FDP: Fast drainage pore; SDP: Slow drainage pore

Dramaga Research Forest (DRF I and DRF II)

Land use and crop canopy density affected the total porosity and drainage pore of soil. Linear Reduction of crop canopy cover density caused a decrease of soil organic matter content (Figure 1) which in turn would decrease the total porosity and drainage pore of soils. Loss of soil organic matter and intensive tillage caused reduction of total soil porosity in unirrigated farmland by more or less 10.7% as compared with forest area (DRF I), where total porosity in unirrigated farmland was 56.05%, which was lower than total soil porosity in forest area (62.79%). On the other hand, soil in conservation agriculture had total porosity that was not

significantly different from that of the medium density forest canopy and had a drainage pore that was similar to that of dense forest canopy cover. Conservation tillage can increase total soil porosity (Tangyuan *et al.*, 2009).

Green Open Space of Depok City

Physically, vegetation cover and soil condition on GFP in Depok City have not been much affected by human intervention, and it was in contrast with the condition of UFUI and LGCF. Although the influence of GOS was not significant, soil on GFP tended to have higher total porosity and drainage pore as compared to CFUI and LGCP. Human intervention that was significant on land formation process (cut and fill, and mixing of soil materials) in LGCP and the use of LGCP as a recreation park caused the influence of vegetation canopy cover density on total soil porosity and drainage pore of the soil, to be invisible.

Soil Hydraulic Conductivity

Soil hydraulic conductivity is defined as the ability of soil to infiltrate water into soil column, both horizontally and vertically, in saturated and unsaturated conditions. The ability of soil to transmit the water is influenced heavily by soil porosity and pore size distribution, as well as other factors which affect soil pore distribution, such as soil texture and soil organic matter content. Land use type affects soil organic matter content (Figure 1), as well as soil porosity and soil pore distribution (Table 3), so that land use type will affect soil hydraulic conductivity. Soil hydraulic conductivity decreases logarithmically with increasing time (duration) and soil water content.

Nopu (Central Sulawesi)

The pattern of soil hydraulic conductivity in forest and agricultural land is presented in Figure 2a. Under condition of soil moisture content ±30-35%, the average value of initial hydraulic conductivity of forest land was 43.7 cm/h, which was much higher than the average initial hydraulic conductivity in corn land (25.2 cm/h), shrub and bush land (19.1 cm/h), young cocoa (12.9 cm/h), medium age cocoa (13.1 cm/h), and old cocoa (11.0 cm/h) (Figure 2b).
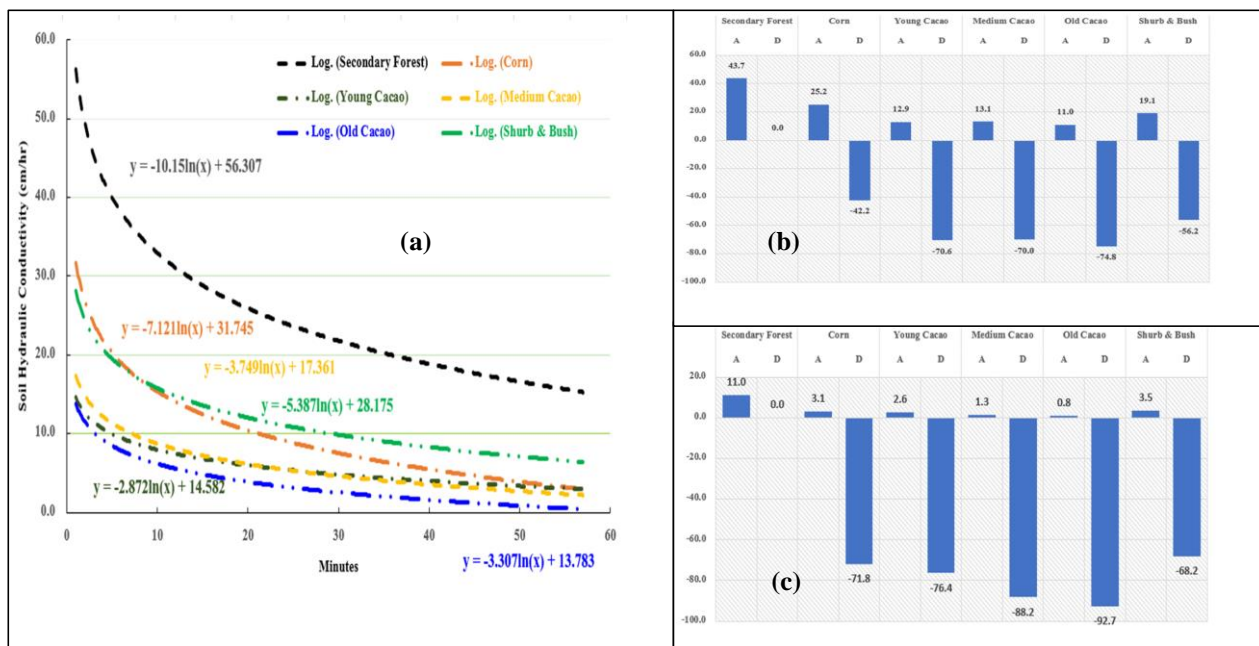

Figure 2 Soil hydraulic conductivity characteristics in forest and agricultural land (Nopu, Central Sulawesi)

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In saturated condition, the higher hydraulic conductivity was found in forest area (11 cm/h), followed by shrub land (3.5 cm/h), corn land (3.1 cm/h), young cocoa (1.3 cm/h), and old cocoa (0.8 cm/h) (Figure 2c). Compared to forest area, saturated hydraulic conductivity in old cocoa drastically decreased 92.7%. Saturated hydraulic conductivity is strongly correlated with soil pore size distribution, especially the very fast drainage pore (Table 3). Forest land has higher hydraulic conductivity, which was associated with the high amount of macropore (drainage pore) (Beven and Germann, 2013) and the continuity of macropores (Archer *et al.*, 2013) due to macrofauna activities and plant root decay in the soil. Forest conversion into agricultural land led to a significant decrease in soil hydraulic conductivity (Figure 2).

Dramaga Research Forest (DRF I and DRF II)

The soil in DRF has a clay texture with a clay proportion of ±71.1-77.5%, which was different from soil in Nopu site with loam texture and clay content of ±15.4% (Table 1). Therefore, soil hydraulic conductivity in DRF was lower as compared with those in soils of Nopu forest areas. This is in line with Mainuri and Owino (2013) research results which showed that soil hydraulic conductivity decreased with increasing clay content. The highest soil hydraulic conductivity was obtained in the high-density forest canopy, followed by the medium-density forest canopy, low-density forest canopy, annual conservation cropland, Situgede Tourism Forest, and intensive annual cropland (Figure 3).

Compared to the high-density forest canopy, soil hydraulic conductivity in the medium-density forest canopy exhibited a decrease of about ±18.8% (initial hydraulic conductivity) and ±19.1% (saturated hydraulic conductivity) (Table 4). The decline was even more drastic, which were respectively, about 29.0% and 38.9% (low canopy forest), and 64.9% and 52.6% (Situgede Tourism Forest). The largest decrease was found in intensive annual cropland, which was 86.0% (initial hydraulic conductivity) and 84.5% (saturated hydraulic conductivity). Conservation annual cropland showed better performance where the decrease of hydraulic conductivity was ±48.2% (initial hydraulic conductivity) and 41.2% (saturated hydraulic conductivity). Conservation tillage by conducting soil tillage and weed clearing in accordance with crop needs (minimum tillage) and maintaining crop residue as a mulch contribute something to maintaining better soil hydraulic conductivity, whose values were not significantly different from those of low-density forest canopy. Although still forest-vegetated, visitor intervention in Situgede Tourism Forest causes the soil hydraulic conductivity be lower than those of conservation agriculture.
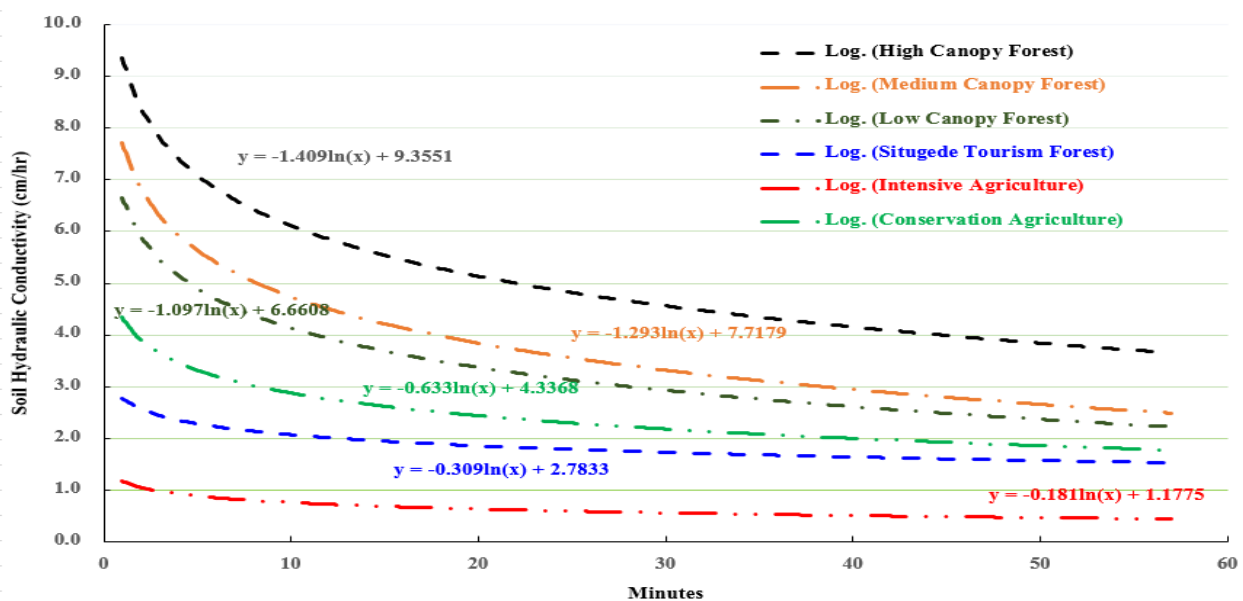

Figure 3 The pattern of soil hydraulic conductivity in forest and agricultural land (Dramaga, Bogor)

Table 4 Characteristics of soil hydraulic conductivity in forest and agricultural land (Dramaga, Bogor)

Soil Hydraulic Conductivity	HCF		MCF		LCF		STF		IA		CA	
	A	D	A	D	A	D	A	D	A	D	A	D
Initial Value	7.3	-	5.9	-18.8	5.2	-29.0	2.6	-64.9	1.0	-86.0	3.8	-48.2
Saturated Value	3.0	-	2.5	-19.1	1.85	-38.9	1.43	-52.6	0.47	-84.5	1.78	-41.2

Note: HCF: High canopy forest; MCF: Medium canopy forest; LCF: Low canopy forest; STF: Situgede tourism forest; IA: Intensive agriculture; CA: Conservation agriculture; A: Actual; D: Difference

Green Open Space of Depok City

GOS is a land that stretches quite extensively and is overgrown with many plants and trees, both naturally and deliberately planted, and equipped with facilities that support the function of GOS. The main functions of GOS are as the lung of a city or region (due to an increase in carbon dioxide absorption and oxygen production), reducing the temperature, increasing coolness, and dampening noise. In addition, the development of GOS is also aimed at maintaining land availability for water infiltration areas and balancing the natural environment for community convenience and welfare.

Soil hydraulic conductivity in GOS of Depok City is strongly influenced by the naturalness level of the landscape and human intervention in the development and functioning of the GOS. On relatively natural landscapes such as GFP, the soil hydraulic conductivity is higher as compared to UFUI and Lembah Gurame City Park (LGCP) (Figure 4). GFP of Depok City is a natural preservation area for the collection of plant and animal species so that the condition is still relatively natural, and access to the area is also relatively restricted. On the other hand, UFUI and LGCP were developed as GOS with fairly easy accessibility and also functioned as ecotourism areas.

Due to the biophysical condition of the ecosystem, which was still well maintained, GFP of Depok City had a quite high soil hydraulic conductivity and was not significantly different from the secondary forest in DRF. Instead, soil hydraulic conductivity in UFUI and LGCP experienced a significant decrease of about 86.7% and 83.3% for initial hydraulic conductivity; 62.91% and 40.42% for saturated hydraulic conductivity (Figure 5), respectively. This explicitly shows that GOS in the form of urban forests and city parks has not been able to support its function as a water infiltration area in the city.
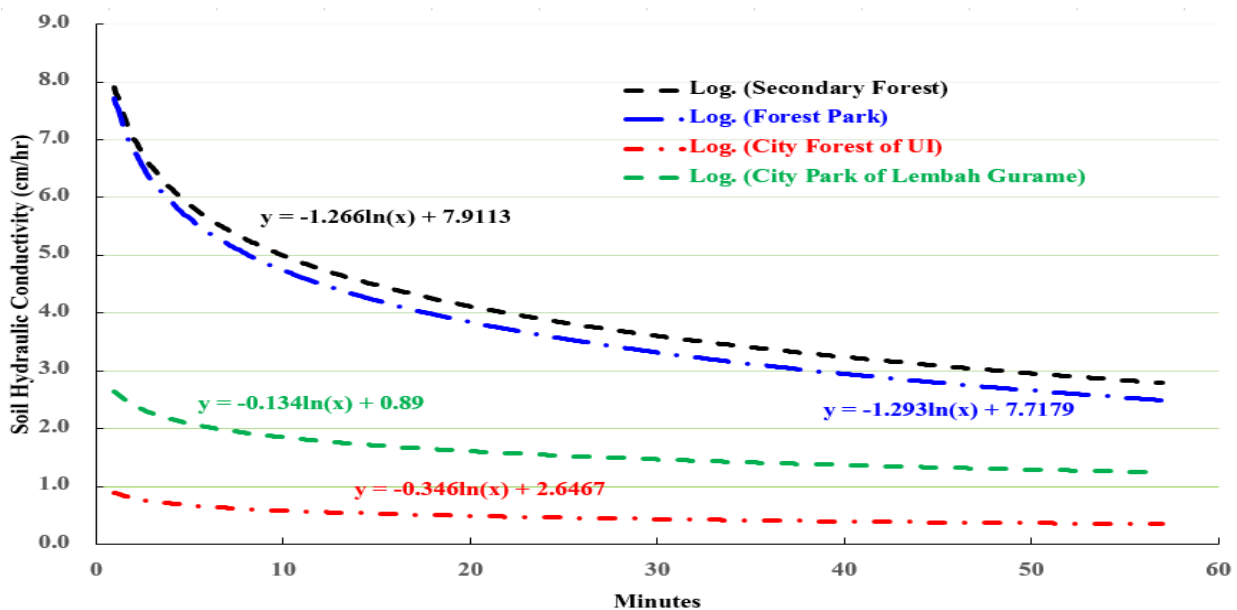

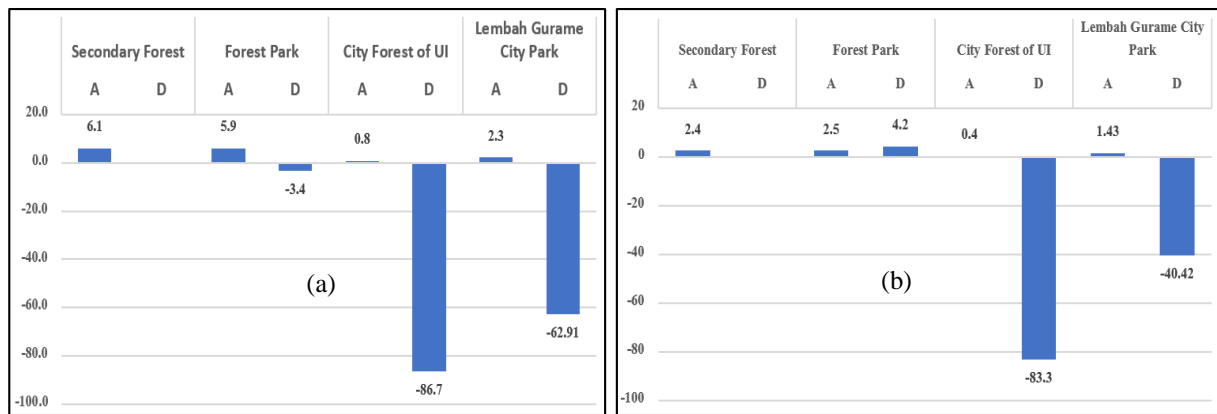Figure 4 Soil hydraulic conductivity pattern in GOS of Depok City

Figure 5 Soil hydraulic conductivity characteristics in GOS of Depok City: (a) initial hydraulic conductivity, and (b) saturated hydraulic conductivity

CONCLUSIONS

Forest conversion into agricultural land causes deterioration of soil quality, such as a decrease of soil organic matter and soil porosity and changes in pore size distribution, so that the conversion will decrease soil hydraulic conductivity. The density of forest canopy cover affects soil quality and soil hydraulic conductivity. Forest with high-density canopy cover had the highest soil hydraulic conductivity as compared with medium and low-density forest canopy. Situgede Tourism Forest had the lowest soil hydraulic conductivity as compared to the other forest types.

Soil hydraulic conductivity in conservation agriculture was higher than that in intensive agriculture and Situgede tourism forest, and the value was not significantly different from soil hydraulic conductivity in low-density canopy forest. Soil hydraulic conductivity in GOS was strongly influenced by the naturalness of the landscape and human intervention level, both in GOS development and management. UFUI and LGCP, which functioned as ecotourism areas had lower soil hydraulic conductivity than that in GFP. Development of GOS in the form of urban forests and city parks has not been able to support its function as a water infiltration area in the city.

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