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Research Article

Agricultural Expansion-Induced Infiltration Rate Change in a West African Tropical Catchment

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Land use and land cover in the Dano catchment is characterized by a rapid conversion from seminatural vegetation (fallow) to agriculture (cropland). The study compares both the saturated (K_s) and the unsaturated (K_h) hydraulic conductivities under cropland and fallow in the catchment to gain insights into the effect of the current land use on soil water dynamics. Hydraulic conductivity was measured under forty-two (42) pairs of adjacent cropland-fallow plots using a Hood infiltrometer. K_s, K_h, bulk density, and soil texture were further compared using a paired two-tailed Student's t-test ($p = 0.05$). The results showed that both K_s and K_h are highly variable irrespective of the land use type (coefficient of variation > 100%). The results also showed that K_s was significantly higher (1.16-fold on average) under fallow compared to cropland. As for K_h, the results showed that, from −2 cm to zero tension heads (h), K_h under cropland and fallow is not significantly different; however, as the supplied tension decreases up to the saturation state, K_h under fallow becomes statistically higher compared to cropland. No significant difference was found between soil textures and bulk density under cropland and fallow meaning that the observed differences of K_s and K_h under cropland and fallow were caused by land use and not preexisting difference in texture. These results suggest an increasing risk of erosion, soil fertility reduction, and flood in the catchment because of agricultural land expansion.

1. Introduction

Hydraulic conductivity (K) is a key hydraulic property determining water flow in the soil. It is an essential input for hydrological process analysis and simulation, as well as for crop models. K is potentially influenced by several factors including the topography, soil type and parent material, vegetation, land use, and seasonal change [1–6]. The combination of these factors makes K a highly variable soil physical property, and measured values may considerably vary for a particular soil [7]. A comprehensive understanding of K variability and the contribution of influencing factors thus remain a challenge. However, this understanding is a prerequisite to comprehend any hydrological system behavior, improve infiltration process representation in different applications, and to develop management strategies within agricultural and hydrological systems.

Many studies have increased the understanding of K variation due to (i) soil texture (e.g., [6, 8–11]), (ii) land use and land cover change [1, 3, 12], (iii) soil type [13, 14], (iv) agricultural practices [15, 16], etc. However, insights gained from the effect of agricultural practices (tillage, crop pattern, and fallow duration) on K variation have proved to be context specific. This is consistent with a literature review by Strudley et al. [17] which concluded that the results of the reviewed studies are so contradictory that hardly a general rule can be drawn when comparing the effects of agricultural practices on soil hydraulic properties. Indeed, agricultural management induced-infiltration change may be overshadowed

by its high natural spatial and temporal variability of K [15, 17]. Therefore, many authors (e.g., [17]) suggest that research to determine the impact of agricultural management options on the hydraulic conductivity should consequently be designed in a manner to consider the effect of dominant factors affecting soil hydraulic properties such us the soil type, soil local heterogeneity, and topography.

To exclusively quantify the differences in the soil hydraulic conductivity caused by forest conversion to spontaneous grass, Pirastru et al. [4] followed an approach based on the comparison of adjacent forest-grass fields. In this way, they minimized the potentially confounding factors in order to interpret differences in soil hydraulic conductivity as a function of land use alone. To rule out other influencing factors and assess the influence of land use change on soil hydraulic properties, Zimmermann et al. [18] compared native forest, pasture, and trees plantation located on homogenous soil units. Adjacent plots comparison approach was also followed by Pirastru et al. [19] to investigate on soil hydraulic properties and subsurface hydrological dynamics under maquis and grass, as did Agnese et al. [20] to compare native forest and pasture. Although findings achieved by these authors and many others (e.g., [21, 22]) might differ, they underline the importance of considering homogenous soil units to overcome the influence of dominant factors (e.g., soil type and topography) affecting K while assessing the impact of land use and land cover change on soil infiltration.

Furthermore, various procedures—field and laboratory—are used to determine the hydraulic conductivity, and each involve a wide range of instruments and solutions. Many studies [23–25] highlighted the dependency of the K value on the determination method. The laboratory methods are conducted in a more controlled environment and are generally considered very reliable though sample taking, and transportation might introduce an error factor. Field methods of K measurements may also be subject to some bias. Fodor et al. [26] reported that field measurement of K may lead to air bubbles entrapped in the soil due to the advancing wetting front and results in a field hydraulic conductivity that may be underestimated. Alagna et al. [27] compared six infiltration techniques and concluded that they provided similar estimates of K even if the methods were not perfectly equivalent due to different soil disturbances. Overall, field measurement methods of K are considered to be more representative of soil water conditions [5, 7, 28]. Therefore, the current study adopted a field measurement method.

The abovementioned studies consistently show that land use change potentially alters soil hydraulic conductivity. Furthermore, they underline that changes of soil hydraulic conductivity associated with the conversion from natural vegetation to agriculture depend on the local context (crop types, management practices, etc.). Very few field investigations concerning hydrological processes were made in the tropical African subhumid zones. A very limited number of studies have performed comparative investigations on K values between different land use types. Croplands have progressively replaced natural vegetation and fallow areas in the Dano catchment during the past decades [29]. The influence of such a land use dynamics on soil hydraulic conductivity has not yet been investigated. It is hypothesized that cropping and fallowing/natural vegetation differently influence soil hydraulic conductivity and that a decrease of natural vegetation and fallow for the benefit of cropland might modify soil water dynamics and consequently change the hydrological behavior of the catchment. The objective of this study is to determine—at the plot level—the saturated and unsaturated hydraulic conductivities under cropland and fallow/natural vegetation and gain insights into regarding the land use and land cover change impact on soil water dynamics in the Dano catchment.

2. Materials and Methods

2.1. Study Area and Sampling Design. The investigations were carried out in the Dano catchment (Figure 1). The Dano catchment is in the Southwest Region of Burkina Faso and covers an area of approximately 195 km^2. The catchment is located in the Sudanese climate zone; thus, it is characterized by (i) the alternation of two seasons including a dry season of 6 to 7 months (November to April) and a rainy season of 5 months (May to October) and (ii) woody, arboraceous, or scrubby savannah vegetation type. Average annual temperatures in the catchment area are around 27°C for average monthly temperatures between 24°C and 32°C with an average annual rainfall over the last 10 years of 958 mm [29]. The main soil groups in the catchments include Gleysols, Cambisols, Lixisols, Stagnosols, Leptosols, and Plinthosols (the latter represents about 73.1% of the area) [31].

The infiltration tests were performed on adjacent plots: one in a cropland and its other counterpart in a fallow area following transect lines. The transect lines were defined in collaboration with the *Soil Science and Soil Ecology* working group of the university of Bonn. This group produced the local soil map of the Dano catchment. In their approach, they defined lines to ensure an even coverage of the study area. The infiltration plots were performed on those transect lines (Figure 1). To account for local soil heterogeneity, for a given pair of cropland-fallow adjacent plots, the distance between plots was kept as close as possible (0 to 3 m), and three infiltration tests were carried out per plot. The saturated hydraulic conductivity K_s and the unsaturated hydraulic conductivity K_h values for each plot are calculated as the geometric mean of three replicated infiltration tests. The procedure of adjacent plot selection was repeated forty-two times throughout the catchment, which yielded a set of 42 plots in croplands and related 42 (counterparts) in fallow areas. The infiltration test thus compares a paired sample of the two land use types. The test was carried out in the period of August to October 2012, corresponding to the crop development and midseason stages, i.e., 6 to 8 weeks after ploughing during the rainy season.

2.2. Measuring Methods. A Hood infiltrometer [32, 33] was used for the purposes of this study (Figure 2). The Hood

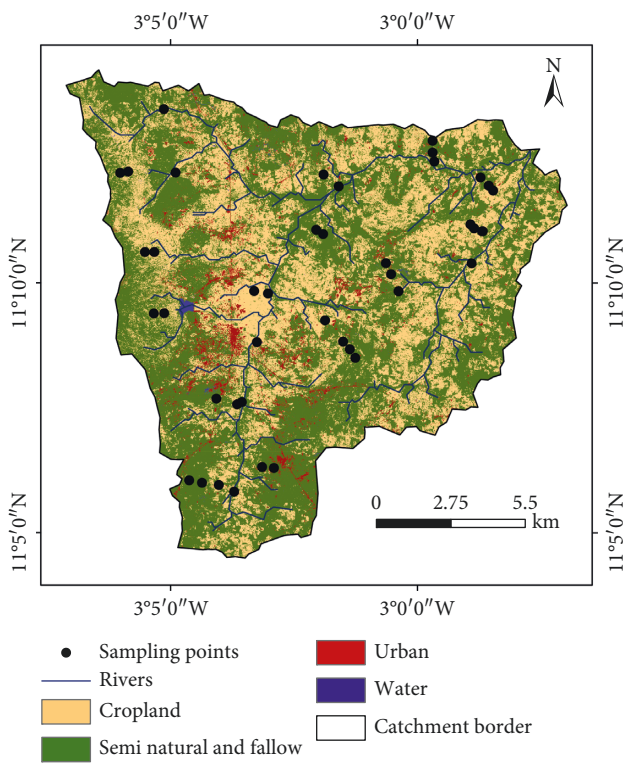

Figure 1: Location of sampling points within the Dano catchment. Each sampling point refers to two adjacent cropland and fallow plots. Land use map is after Forkour [30].

infiltrometer is a tension infiltrometer for measuring both soil surface field K_s and K_h. Among the advantages of the method are the *in-situ* measurement of soil hydraulic conductivity, the minimizing of soil disturbance, and the possibility to observe the air entry points during the measurement. Infiltration with the Hood infiltrometer starts from a closed hood about three-quarters filled with water and standing on the ground. The control of the hydraulic pressure head in the water volume under the hood is made by adjusting the intake pipe immersion depth in the bubble tower. The difference of height at the U-tube manometer and the water level in the standpipe indicates the applied pressure head under the hood. The applied hood had a radius of 16 cm. Under both fallow and cropland, the vegetation was shortened when necessary to allow a proper installation of the hood. Saturated fine sand was consistently used to seal the edge of the hood against the soil up to an outer ring. During measurement, the hydraulic head is progressively decreased starting from the value zero up to the air entry point. The infiltration rates were recorded for a pressure head of $h \approx 0$, followed by constant stairs of 0.5 cm in the pressure head imposition (i.e., −0.5, −1.5, and −2 cm). At $h < -3$ cm, the number of measurements reduced, and measurements were measured only where possible. The leakage rate (ΔZ/unit time) was measured on the infiltration reservoir. The flow rate was reported (for ΔZ on the infiltration reservoir = 1 cm) when an apparent steady state was reached.

Several procedures are available for calculating the hydraulic conductivity from the measured raw data [26]. However, hydraulic conductivity from the steady-state infiltration in this study was estimated according to Wooding [35] as reported in the instructions manual coming along with the Hood infiltrometer [34]. The theoretical principle underling the Hood infiltrometer is summarized in equations (1–5).

Hydraulic conductivity K_h is a function of water pressure head h in the soils [36]:

$$K(h) = K_s \exp(\alpha^* h), \tag{1}$$

where K_s ($L \cdot T^{-1}$) is the saturated hydraulic conductivity, h (L^{-1}) is the water head, and α is an empirical fitting parameter.

Under steady state and based on equation (1), Wooding [35] found the following approximate solution for the infiltration rate from a shallow circular pond of radius r:

$$Q(h) = \pi r^2 K_s \exp(\alpha h_o)\left(1 + \frac{4}{\pi r \alpha}\right), \tag{2}$$

where $Q(h)$ is the steady flow rate ($L^3 \cdot T^{-1}$) under a given supply potential h_o (L).

K_s and α are the only unknowns from equation (2). They can be either solved by making measurements at a fixed water tension with multiple disc radii or inversely making measurements with a fixed disk radius at multiple water tensions. The latter was applied in this study.

The application of equation (2), for neighboring values of water tensions (h_1, h_2), gives (note that in this study the difference of the pressure head between h_1 and $h_2 = 0.5$ cm)

$$\begin{aligned} \frac{Q_1}{\pi r^2} &= K_s \exp(\alpha h_1)\left(1 + \frac{4}{\pi r \alpha}\right), \\ \frac{Q_2}{\pi r^2} &= K_s \exp(\alpha h_2)\left(1 + \frac{4}{\pi r \alpha}\right). \end{aligned} \tag{3}$$

And by the means of division, α can be derived as follows:

$$\alpha = \frac{\ln(Q_1/Q_2)}{h_1 - h_2}. \tag{4}$$

Finally, the hydraulic conductivity for h_1 is given by

$$K(h_1) = \frac{(Q_1/\pi r^2)}{1 + (4/\pi \alpha r)}. \tag{5}$$

2.3. Soil Physical and Chemical Properties. Alongside the infiltration measurement test, undisturbed topsoil (1–10 cm) core samples and disturbed topsoil samples were collected for laboratory analyses. The undisturbed soil samples were taken using stainless steel sample rings following the drop hammer method on leveled soil horizons. The core cylinders were 250 cm^3 volume, i.e., 4 cm and 5 cm in radius and height, respectively. The samples were collected on 50% of the infiltration test plots, i.e., 21 disturbed

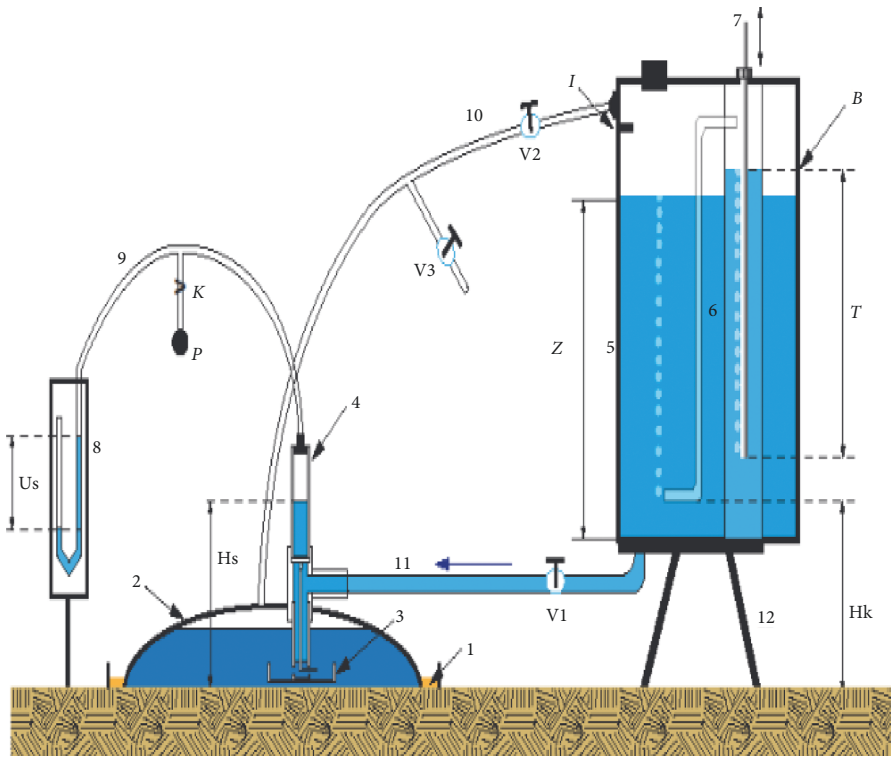

Figure 2: Schematic setup of the Hood infiltrometer [34]. (1) Fine sand sealing; (2) plastic hood; (3) buffer vessel; (4) standpipe; (5) infiltration reservoir; (6) bubble tower; (7) air intake pipe; (8) U-tube manometer; (9) hose connection 1; (10) vent pipe; (11) hose connection 2; (12) stand. *B*: filling level of the bubble tower; Hk: distance between soil surface and air outlet; Hs: water level in the standpipe; *I*: the maximum filling level of the infiltration reservoir; *K*: valve for cutting off the pipette ball; *P*: pipette ball; *T*: immersion depth of the air intake pipe; Us: height difference at the U-tube manometer; V1: valve for separating the water volumes; V2: valve for separating the air volumes; V3: valve for pressure adjustment; *Z*: filling height of the infiltration reservoir.

samples and 21 undisturbed soil cores for each land use type. The bulk density was determined by dividing the oven-dry mass of the core soil by its volume, and the coarse particles content was determined by passing the sample through a 2 mm diameter sieve. The texture analysis was carried out by a combination of wet sieving (sand fractions) and sedimentation (silt and clay fraction) [37], and *soil organic carbon (SOC)* content was determined by elemental analysis [38, 39].

2.4. Statistical Analysis of the Collected Data. Soil hydraulic conductivity is generally reported to be a log-normally distributed property [7, 40] and thus needs to be transformed in order to be normally distributed. The Shapiro–Wilk test for normality was performed to determine whether the infiltration data were normally distributed, for the purpose of a transformation, in order to conduct variance analysis on conductivity data. A paired two-tailed Student's *t-test* was performed on the normal distributed data set to test the statistical difference of K_s and K_h and texture between cropland and fallow.

3. Results and Discussion

3.1. Saturated Hydraulic Conductivity under Cropland and Fallow. The Shapiro–Wilk test indicated a nonnormal distribution of saturated hydraulic conductivity values, consistently with the result reported by several authors [41–43]. Therefore, the logarithm-base 10 of the data was calculated, and the resultant $\log K_s$ showed a normal distribution (Table 1 and Figure 3).

The $\log K_s$ shows a relatively low *CV*, 13.65% and 24.17% for fallow and cropland, respectively, indicating uniformity in the distribution of $\log_{10} K_s$. The mean value of K_s for both cropland and fallow correspond to the high infiltration class [7]. However, both land use types presented single K_s values ranging from very low to very high class.

Besides the effect of factors like topography, a wide range of sand content and soil type/group that affects K_s under both land use types, two elements can underline the high dispersion of K_s under fallow: (i) the difference in the age of the fallow areas under investigation (between 1 and 5 years) and (ii) the fallowing practice (technic). As highlighted by Miranda et al. [44], the both total porosity and macroporosity increase with the extension of the fallowing period, leading to an increase in hydraulic conductivity. Bush fallow or natural regrowth, as commonly done in the catchment, leads to the development of a diversity of plants species on the fallow areas. Different fallowing periods associated with herbaceous plants of different species may have led to the wide variation of K_s within the fallow sample.

Similarly, the variation of K_s under cropland can specifically be attributed, on the one hand, to the difference of

Table 1: Descriptive statistics of $\log_{10} K_s$ for cropland and fallow ($n = 42$).

Variable	Land use	Mean (cm/d)	CV (%)	SWilk p value
$\text{Log}_{10} K_s$	Cropland	2.32	24.17	0.30
	Fallow	2.60	13.65	0.39

CV: coefficient of variation; *SWilk p* value: Shapiro and Wilk skewness significance test p value; n: sample size.

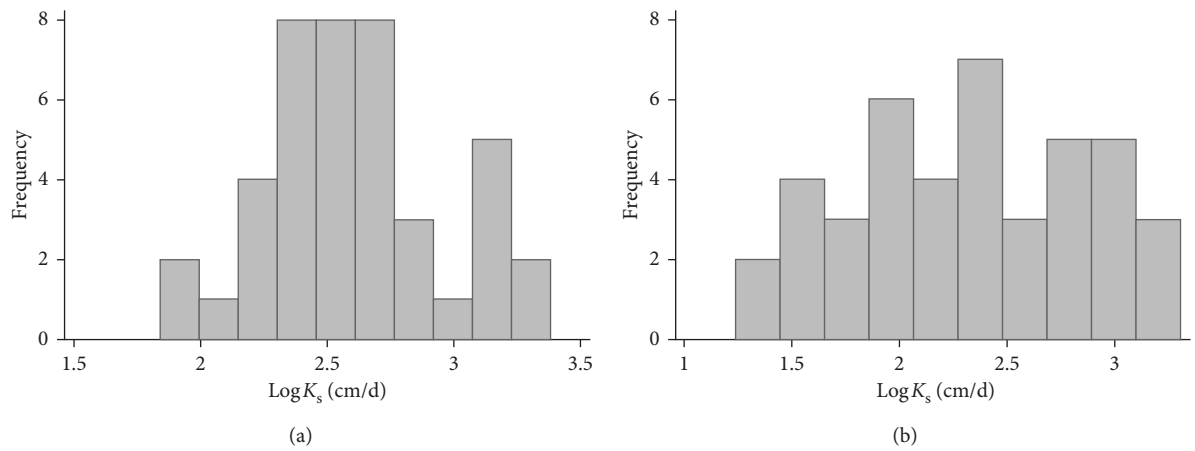

Figure 3: Histograms of $-\log_{10}$ transformed saturated hydraulic conductivity under fallow (a) and cropland (b) ($n = 42$).

crop species under cultivation in the infiltration plots. The investigated croplands were mainly composed of sorghum, cotton, maize, cowpea, and groundnut, each with a specific cropping calendar. The difference in the cropping calendar further implies different crop development stages. Alletto and Coquet [41] highlighted the root development stage as a K_s temporal variation factor under cropland. On the other hand, variation of K_s under cropland can be explained by the ploughing of croplands. All investigated fields were tilled. Tillage is known to have a transient effect on K_s. The saturated hydraulic conductivity generally increases immediately after tillage due to an increase in water-conducting mesopores and macropores but decreases afterward due to settlement and consolidation of the soil [16, 43]. Osunbitan et al. [45] noticed that, eight weeks after tillage, K_s under cropland could decrease to a rate lower than K_s under land use without tillage. The infiltration tests were performed over a relatively long period (about two months, Section 2.1), implying that different crop development stages were under investigation. Moreover, the crops fields were ploughed at different periods. Differences of the crop type, development phase, and date of plough, as the above authors, may explain the observed high dispersion of K_s under cropland.

Figure 4 suggests that saturated hydraulic conductivity is generally higher under fallow compared to cropland. The paired two-tailed Student's *t-test* shows that there is a difference between $\log K_s$ under cropland and $\log K_s$ under fallow (p *value* $= 0.007$). These results are in line with the conclusion of several studies [18, 46] dealing with land use and land cover change impact on the saturated hydraulic conductivity that is a decreasing hydraulic conductivity with increasing land use intensity (i.e., a conversion from natural vegetation to crop). However, the distribution of the considered sample between different crops, especially crop association (Table 2), limits investigating the sole effect of crop types on K_s. Furthermore, as 90% of the sampled points were located on Plinthosols (the dominant soil group), one could not perform a consistent investigation on the effect that soil type had on the difference between K_s under cropland and fallow. Nevertheless, the results overall evidence that K_s is significantly higher under fallow compared to cropland, suggesting a difference in the soil macroporosity under the two land use types.

Macropores have a larger influence on the hydraulic conductivity at saturation than mesopores even though they generally occupy a much smaller fraction of total soil porosity [16, 47, 48]. Iovino et al. [49] found contribution of micropores to unsaturated flow to be relatively more important in tilled soil than in natural ones. Conversely, close to saturation, flow in the natural, nontilled soils concentrates in a relatively small number of large macropores. Macropores under fallow and natural vegetation are primarily formed by (i) biological activity of earthworms, ants, and termites [3], and (ii) plant roots [48, 50]. Under ploughed cropland, macropores are formed by (i) the rearrangement of the solid phase by a tillage tool, (ii) plant roots, and (iii) to a lesser extent by earthworms [51–54]. Benjamin [50] reported macroporosity to be reduced under cropland as compared to fallow and other natural vegetation types due to earthworm and termite populations abundance under the latter compared to cropland. Tillage is furthermore a punctual operation with a transient effect on porosity increment; however, tillage-induced disturbance is reported to have a detrimental impact on preexisting macropores and earthworm and termite population abundance [51–54]. Against this trend of increasing infiltration rate with

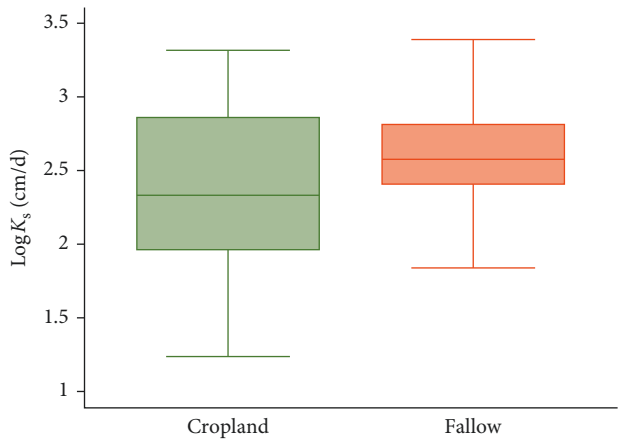

Figure 4: Boxplot comparison of saturated hydraulic conductivity ($\log K_s$) on cropland and fallow.

Table 2: Descriptive statistics of the K_s (cm/d) per crop type ($n = 42$).

Crop type	n	Mean	SD	Minimum	Maximum
Cotton	3	54.64	57.46	17.27	120.8
Cowpea	4	158.87	159.5	50	395.97
Groundnut	4	49.23	29.15	28.76	92.46
Maize	4	362.81	270.1	175.71	760.16
Sorghum	27	583.93	563.09	33.05	2048

Cowpea and groundnut are additionally associated with sorghum and maize in intercropping.

increasing biological activity, Jouquet et al. [55] reported that termite sheetings breakdown generate structural crusts which reduce the infiltration rate under fallow. Mettrop et al. [56] also report a reduction of the infiltration rate due to termite activity in northern Burkina Faso.

Field observations during the infiltration test attested a root density much higher under fallow compared to cropland. The decomposition of roots and subsequent formation of root channels may contribute to the higher macroporosity under fallow. No comparative investigation on the earthworm, termite, ant, etc. population density was carried out; however, the systematic annual ploughing of croplands suggests that the fauna activity might be lower under cropland compared to fallow areas.

3.2. Unsaturated Hydraulic Conductivity. Unsaturated hydraulic conductivity was derived from the infiltration rate measurements. At supplied tension heads (h) below -2 cm, unsaturated hydraulic conductivity under cropland and fallow was found to be not statistically different (p *value* $= 0.05$). As the supplied tension decreases up to the saturation state, the hydraulic conductivity under fallow becomes significantly higher compared to cropland (Table 3). This ascertains that differences of hydraulic conductivity between fallow and cropland become greater towards saturation as reported by Kelishadi et al. [57] (Figure 5). The result supports the idea that the difference in the hydraulic conductivity between fallow and cropland is indeed associated with the difference of macroporosity as suggested in Section 3.1. Under high water tension (h), whilst water predominantly flows through the soil matrix no difference between land use types is noted. This ascertains that matrix conductivity is quite similar under the different land use types. However, toward saturation, when water starts flowing into soil macropores, significant differences are observed between the land use types, implying a predominant function of soil macropores.

3.3. Soil Properties and the Hydraulic Conductivity. The *t-test* shows no significant difference between the textures of different land use types and denotes that the observed difference of hydrological conductivity was caused by land use and not preexisting difference in texture (Table 4). The comparison of bulk density and soil carbon content under the two land uses shows a similar trend. These results suggest that the difference of K_s between cropland and fallow is unlikely to be attributable to the initial arrangement and size in soil pore. Several decades of cultivation the Dano catchment combined with the shortening of fallowing periods do not allow a consequent organic matter accumulation in the topsoil even under fallowing. The rapid rotation between cropland and fallow tends to even the soil texture and organic matter content in the catchment.

4. Conclusion

Through the comparison of saturated and unsaturated hydraulic conductivity, the study exhibited that, for the same land use type (cropland or fallow), the infiltration rate is a highly variable parameter in the Dano catchment. However,

Table 3: Summary of statistics for the $\log_{10}$ of unsaturated hydraulic conductivity with increasing water tension ($n = 42$).

Water tension (cm)	$\text{Log}_{10} K_h$ under cropland			$\text{Log}_{10} K_h$ under fallow			Cropland vs *fallow t-test p* value
	Mean	95% CI		Mean	95% CI		
−0.1	2.29	2.11	2.46	2.57	2.46	2.68	0.0078
−0.5	2.16	1.98	2.34	2.43	2.32	2.54	0.0096
−1	2.00	1.81	2.18	2.26	2.14	2.37	0.0186
−1.5	1.83	1.63	2.04	2.09	1.95	2.22	0.0417
−2	1.67	1.44	1.90	1.91	1.75	2.07	**0.0853**
−2.5	1.51	1.25	1.77	1.74	1.55	1.93	0.1482
−3	1.34	1.05	1.64	1.57	1.34	1.79	0.2229
−5	0.69	0.26	1.13	0.88	0.51	1.25	0.511
−10	−0.93	−1.76	−0.10	−0.84	−1.58	−0.09	0.8674

CI: confidence interval; *n*: sample size.

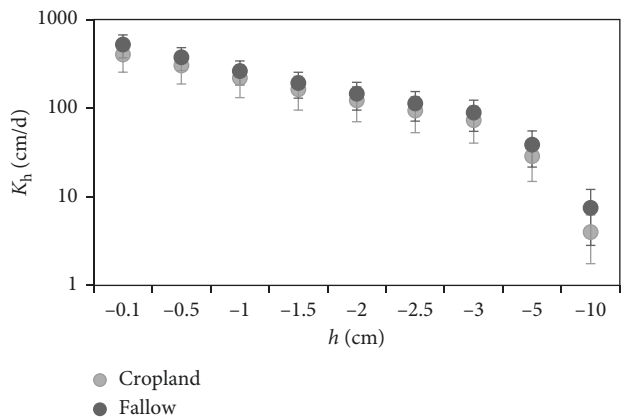

Figure 5: Mean and 95% confidence interval of unsaturated hydraulic conductivity (K_h) estimated from field measurement with increasing water tension under cropland and fallow.

Table 4: Soil texture, coarse particles, and bulk density under cropland and fallow at the investigated plots.

Variable	Cropland					Fallow					Cropland vs Fallow *t*-test *p* value
	Mean	SD	Minimum	Maximum	*n*	Mean	SD	Minimum	Maximum	*n*	
Sand (%)	37.75	8.83	21.05	53.47	21	35.59	10.38	14.69	51.26	21	0.4709
Clay (%)	20.58	9.31	4.69	37.34	21	22.08	7.12	13.77	34.86	21	0.5622
Bulk density (g/cm^3)	1.43	0.12	1.24	1.75	21	1.42	0.14	1.14	1.60	21	0.9042
Coarse particles (%)	43.21	27.73	0.88	84.96	21	53.21	29.38	0.00	89.70	21	0.2636
SOC (%)	1.39	0.63	0.33	3.39	21	1.47	0.64	0.18	2.75	21	0.6795

Sample distribution per soil type: Plinthosol = 71%; Cambisol = 9%; Lixisol = 9%; Stagnosol = 9%.

the adjacent plots comparison approach as performed in the study reveals significant differences of K_s and K_h for water tension lower than −2 cm between cropland and fallow. This difference was attributed to abundant macropores under fallow compared to cropland. Soil macroporosity appears to be reduced under cropland as suggested by the measurements of the unsaturated hydraulic conduction at a different water tension. Therefore, ploughing and other farming activities are likely to negatively affect soil pore size and arrangement.

The results further indicate that a decrease in soil infiltration following a conversion from fallow to cropland is not influenced by texture and depend only on the soil structure that, to some extent, is dependent on land use. As shown in the study, both cropland and fallow areas had very comparable textural composition, bulk density, and organic matter content. Overall, land conversion from fallow to cropland in the Dano catchment shows—at the plot scale—a potential to increase infiltration excess overland flow and consequently exacerbate surface runoff generation which could lead to more erosion, loss of soil fertility, or flood in the catchment.

Data Availability

The data set applied in the study is available on request to the corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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