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Research Article
Hydrodynamic Assessment of Soils under Continuous Cultivation in the Savannah Zone, North of Côte d'Ivoire

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Abstract
Background and Objective: Efficient use of water by crops is essential in the savannah areas in the North of Côte d'Ivoire. Therefore, the agricultural exploitation of soils in these areas requires a better knowledge of the hydric constraints of crops. This study aimed to assess the hydrodynamic characteristics of soils and the water constraints faced by crops in the Tiangakaha, Nibolikaha and Napalakaha villages, in the North of Côte d'Ivoire. **Materials and Methods:** Soil samples were taken and analyzed in the laboratory for texture and organic matter content. Bulk density was determined by the cylinder method. After measuring water infiltration into the soil by the Muntz method, samples were taken to determine the soil water contents and reserves. The ANOVA was done, using the R software, to compare data between the villages and to perform the Newman-Keuls test at the 5 p.c. level. **Results:** The soils of Tiangakaha and Nibolikaha areas were permeable, while that of Napalakaha was very permeable. The easily usable water reserves (EUR) were higher (14.25 mm) in the 0-20 cm layers in Napalakaha and lower (9.58 mm) in Tiangakaha soils. In the 20-40 cm layers, the EUR of Nibolikaha was greater (16.06 mm) than that of Tiangakaha (10.71 mm). **Conclusion:** The potential for using soil water reserves by crops was lower in Tiangakaha, where the soil is silty, with the highest bulk density.

Key words: Hydraulic conductivity, water reserve, soil, potential evapotranspiration, Côte d'Ivoire

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Climate change often results in the more frequent advent of extreme climatic phenomena, such as flooding, drought, winds speed, etc. It causes isohyets to move from North to South which, consequently, causes a modification of the ecological setting[1,2]. It also negatively affects agriculture, mostly in developing countries[3].

In addition to its role in anchoring plants through the rooting systems, soil provides plants with nutrients and stores water essential for their growth and development. These nutrients are assimilated by plants after they have been dissolved in soil water[4]. Climate change, causing rainfall variability in space and time, leads to rainfall deficits in areas deemed to be more watered and worsens in more or less arid areas. This consequently results, firstly in a water deficit during the growing cycles and seconds possible drying out of watercourses which can be used to renew the soil water reserves through irrigation.

The Northern part of Côte d'Ivoire experiences a long period of drought each year, resulting in a water deficit greater than 700 mm[5], which hinders agricultural output. This situation compromises food security and makes the populations, living in this part of the country, vulnerable. Thus, in the hope of allowing crops to complete their cycles, possibly with adequate water supply, the bottom slopes are often used for cropping by women, who have the responsibility of feeding their family. Unfortunately, the long dry season always ends up drying outcrops, leaving people to face severe food short age and therefore resilience[6].

The objective of this study was to assess the hydrodynamic characteristics and the hydric constraints of soils under continuous cultivation in the tree village areas.

MATERIALS AND METHODS

Study area: The study was carried in February, 2017 in Tiangakaha, Nibolikaha and Napalakaha village sites, in the North of Côte d'Ivoire (Department of Korhogo), whose respective geographical coordinates are 05°32'19.4''W and 09°19'47.1''N, 05°26'11.9'' W and 09°24'49.9''N and 05°24'47.3''W and 09°25'46,3'' N. The soils of these localities are Ferralsols, Lixisols and Gleysols[6]. The climate is Sudanese and tropical subhumid. It is characterized by two seasons: a dry season (November-May) and a rainy season (June-October). The average annual rainfall varied between 1100 and 1230 mm, with an average annual temperature of 26.7°C[7]. The vegetation is grassy and wooded savannah characterized by scattered trees and shrubs, with a canopy density in the order of 25-35 p.c.

Physical and chemical characterization of soils: Soil samples were obtained, in composite, from 5 elementary samples taken from the 0-20 and 20-40 cm layers in each plot covering areas of 0.47, 0.50 and 0.78 ha in Tiangakaha, Nibolikaha and Napalakaha villages, respectively. Soil texture was obtained through sedimentation analysis using the Robinson-Kohn pipette method and the textural triangle to determine soil textural class. Bulk density was determined by the cylinder method. Organic carbon content was determined using the Walkley and Black method. Organic matter was determined by multiplying the carbon content by 1.724[8,9].

Hydrodynamic characterization of soils: Water infiltration into soil measurements at the three sites was made using the Muntz method. A device of three identical dual ring in filter meters, each composed of a measuring ring and a guard ring was used[10]. The infiltration points were covered with a tarpaulin at the end of the tests to prevent water evaporation. Forty-eight hours later, soil samples were taken in the 0-20 and 20-40 cm layers to determine soil moisture at field capacity. Thus, the weight water and the soil moisture at the permanent wilt point were determined, respectively, using the following Eq.[11,12]:

$$\omega_{fc} = \left(\frac{M_{ss}}{M_s} - 1\right) \times 100$$

$$\omega_{pw} = \frac{\omega_{fc}}{1.84}$$

Where:

ω_{fc} = Mass of water at field capacity
ω_{pw} = Mass of water at permanent wilt point
M_{ss} = Mass of soil sample
M_s = Mass of dry soil

The easily usable water reserves (EUR) of the soils was determined from useful water reserves (UR) using the following Eq.[13,14]:

$$UR = DB(\omega_{fc}-\omega_{pw})z$$

$$EUR = \frac{2}{3}UR$$

Where:

BD = Bulk density
z = Soil layer thickness
ω_{fc} = Mass of water at field capacity
ω_{pw} = Mass of water at permanent wilt point

Duration of depletion of the easily usable water reserves: The data of the potential evapotranspiration were provided by the Ivorian Airport and Meteorological Exploitation and Development Company (SODEXAM). The duration of EUR depletion was determined using the following Eq.[15]:

$$t = \frac{EUR}{PET_j}$$

Where:

t = Duration of depletion (days)
EUR = Easily usable water reserve (mm)
PET_j = Potential daily evapotranspiration (mm)

Statistical analysis: Analysis of variance (ANOVA)was applied to data.Soil water content data were compared between the villages using the R software, version 3.5.1. The groups of homogeneous means were formed using the Newman-Keuls test at the 5 p.c. level.

RESULTS

Soil characteristics: The highest bulk density (1.58 and 1.63 g cm^{-3}) of the 0-20 and 20-40 cm layers, respectively were obtained with the Tiangakaha soil and the lowest (1.42 and 1.52 g cm^{-3}) in the Napalakaha soil. Both soil layers are silty at Tiangakaha. In Nibolikaha and Napalakaha soils, the 0-20 cm layers are sandy loam and clayey loam, respectively, while the 20-40 cm soil layers are clayey loam and clayey. The soils of the three villages were found to be poor in organic matter. However, the highest organic matter contents (1.82 and 1.33 p.c.), from the 0-20 and 20-40 cm layers respectively were recorded at Napalakaha. The lowest organic matter contents were obtained at Tiangakaha (1.36 p.c.) in the 0-20 cm layer and at Nibolikaha (1.05 p.c.) in the 20-40 cm layer (Table 1).

Saturated hydraulic conductivityof soils: The evolution of the hydraulic conductivity of the soils (Fig. 1) has a biphasic appearance at the three village sites. Hydraulic conductivity, first, decreased more rapidly during the first 30 min and more slowly during the 120 min period before stabilizing. The soils of Nibolikaha and Tiangakaha were permeable with saturated hydraulic conductivity (Ks) values varying between 9.13 and 11.60 cm h^{-1} and between 15.60 and 17.93 cm h^{-1}respectively.

Table 1: Soil physical characteristics and organic matter at the three sites

		Villages		
Parameters	Layer (cm)	Tiangakaha	Nibolikaha	Napalakaha
Bulk density (g cm^{-3})	0-20	1.58 ± 0.06^{a}	1.49 ± 0.03^{ab}	1.42 ± 0.08^{b}
	20-40	1.63 ± 0.09^{a}	1.56 ± 0.5^{a}	1.52 ± 0.04^{a}
Texture	0-20	Silty	Sandy loam	Clayey loam
	20-40	Silty	Clayey loam	Clayey
Organic matter (p.c.)	0-20	1.36	1.50	1.82
	20-40	1.13	1.05	1.33

Means followed by the same letter, in the same line, do not differ significantly according to the Newman-Keuls test at the 5 p.c. level

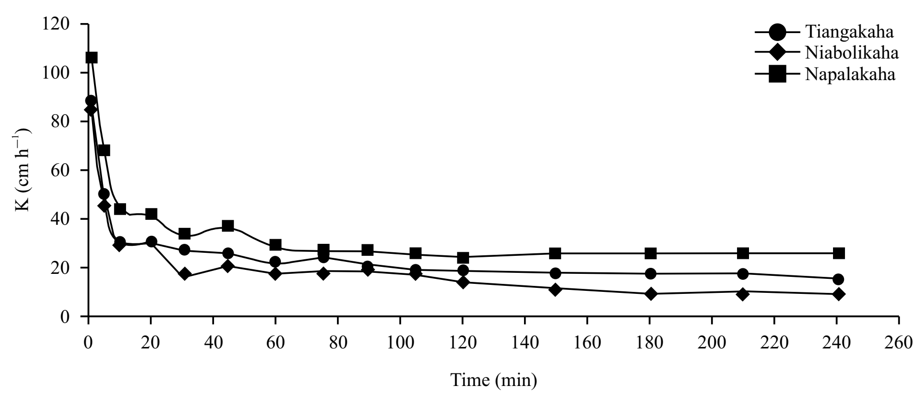

Fig. 1: Evolution in time of the hydraulic conductivities of the soils at the three sites

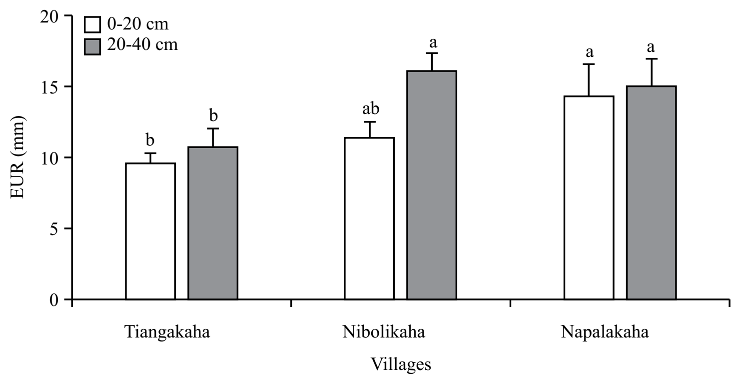

Fig. 2: Variation of the easily usable water reserves of soils depending on the depth at the three sites

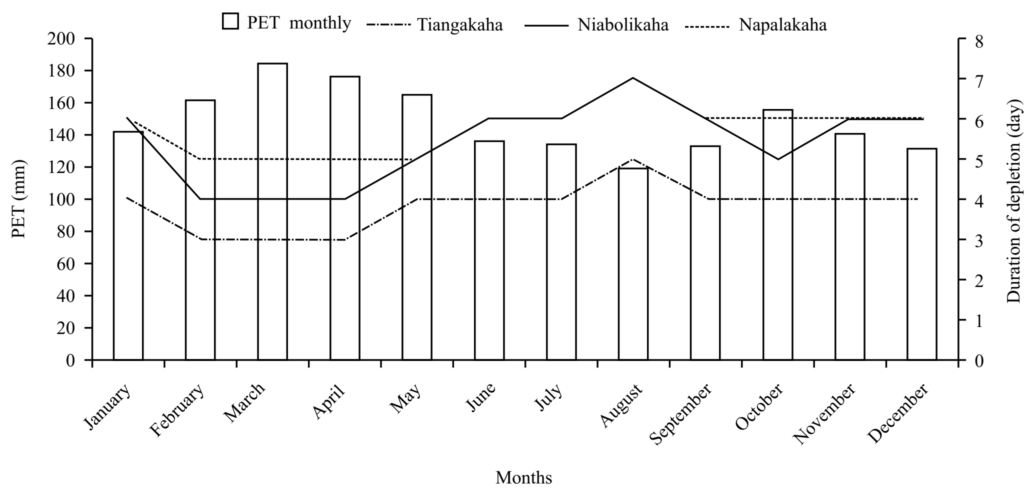

Fig. 3: Monthly evolution of the potential evapotranspiration (PET) and the duration of depletion of the soil EUR at the three sites

That of Napalakaha, having Ks value between 25.60 and 26.27 cm h^{-1}, was very permeable. Statistical analysis of hydraulic conductivities at saturation shows significant differences ($p<0.05$) between soils.

Soil water reserves: The 0-20 cm soil layers of Napalakaha gave the highest easily usable water reserve (14.25 mm), while the lowest (9.58 mm) was obtained at Tiangakaha. In 20-40 cm layers, the soil of Nibolikaha had the highest easily usable water reserve (16.06 mm) and Tiangakaha the lowest (10.71 mm) (Fig. 2). The statistical analysis revealed significant differences ($p<0.05$) between the water reserves in the soil layers.

Potential use of easily usable soil water reserves (EUR) by crops: At Tiangakaha, the highest duration of depletion of the soil EUR (5 days) was recorded in August and the lowest (3 days) in February, March and April. In Nibolikaha, the soil water reserve lasted up to 7 days in August, while in February, March and April, it depleted within 4 days. As for Napalakaha, the maximum duration of EUR depletion was also observed in August (7 days) and the minimum (5 days) in February, March, April and May (Fig. 3). The maximum duration was 7 days and was observed in Nibolikaha and Napalakaha in August. The EUR runned out faster (3 days) in Tiangakaha during February, March and April.

DISCUSSION

The trends in hydraulic conductivities were similar in soils from the three sites. This trend decreased over time before reaching a constant value at saturation, which differed from soil to soil. Indeed, at the start of infiltration, water quickly penetrated into the soil, through macro-pores, filling the meso and micro-pores. When the latter two pores were filled, the water flowed at a constant speed in the macro-pores, thus giving the soil saturated hydraulic conductivity (Ks). These results corroborate with previous studies[10,14], which stipulated that the hydraulic conductivity follows a curve whose equation is of the type K = f (t), which can be broken down into two parts: the first translated into a transient regime in which the hydraulic conductivity decreased over time and the second corresponded to a permanent regime, where it becomes constant. This trend was also obtained in another study[13,16], whose dKostiakov's, Philip's, Horton's and Green Ampt's infiltration models. The soil of Napalakaha, whose layers are clayey loam and clayey in texture was more permeable than the others, which have a silty and sandy loam texture. This is due to both its relatively high organic matter content and its low bulk density. This shows that when soil is provided with organic matter, it has a better structure and therefore is light, thereby resulting in better water circulation. That is why, biochar amendment increases soil permeability by at least one order of magnitude, reduces tortuosity by 20-30 p.c. and results in more uniformly distributed pore water velocities from a change in the geometry of soil pores[17]. The Ks decreases in coarse-textured soils and increases in fine-textured soils following biochar application[18]. Water circulation improves more in the case of slash-and-burn cultivation because of an increase in soil porosity, following organic matter burning out by fire[10]. In addition, the combination of cover crops with no-tillage improves water infiltration[19]. However, alkaline irrigation water increases the net negative charges on the clay particles of the soil and thereby the number of exchangeable cations, clay particles dispersion and a movement of the dislodged particles into the pores, thus resultinginKsreduction[20].

The easily usable water reserves of the soils of Napalakaha and Nibolikaha are higher than those of Tiangakaha in the two layers because of higher organic matter contents. This organic matter associated with clay has increased the water retention capacity of the Napalakaha and Nibolikaha soils. These results support the study[16] showed that the water retention capacity of soil is greater in layers with high organic matter content. In addition, the easily usable reserves of the soil increased with depth. This trend depends on soil texture because the 0-20 cm layers of the sites have silty, sandy loam and clayey loam textures, while the 20-40 cm layers are silty, clayey loam and clayey. Thus, the 20-40 cm layers are better provided with finer elements than the upper layers. Indeed, the higher the content of the fine particles of a soil, the higher is its water retention capacity and hence, its water reserve. This corroborates the work done[21], which showed that the easily usable water reserves of soils differ according to soil texture, increasing from sandy to clayey soils. Thereby, the soil coarse element content, even calcareous concretions[22], decreases its water reserve. But, after tilling a soil, its total porosity gradually decreases with time and depth. That becomes relatively stable, with an increase in soil water holding capacity due to the reduction in effective porosity and the development of residual porosity[23,24].

Maximum duration of 7 days of depletion of the easily usable soil reserves in Nibolikaha and Napalakaha and 5 days in Tiangakaha was obtained in August, while the minimum duration was 4 days in Nibolikaha and Napalakaha and 3 days in Tiangakaha in February, March and April. The Tiangakaha soil, therefore, depleted faster than the Nibolikaha and Napalakaha soils. Indeed, the temperature is lower in August. In these conditions, the soil water evaporates less and the plants transpire little so, evapotranspiration is low. Soil reserves are slowly used, which explains the long duration of their depletion, while the dry season occurs in February, March and April when the temperature is high. Therefore, since evapotranspiration is high, the water reserves are quickly depleted, hence the shorter duration in water use by crops, especially at the Tiangakaha site. However, depletion of soil water by evapotranspiration mainly occurs within the 0-2 m soil layer, suggesting negligible root water uptake below this depth[25]. It should be noted that the proportion of water loss through transpiration is greater than that through evaporation[26]. In addition, in slash-and-burn cultivation after an intense fire, soil moisture content is significantly highest during the first cultivation period, before being lower than that of the soil without burning during the second period[10].

CONCLUSION

It appeared that the soils of Tiangakaha and Nibolikaha were permeable, while that of Napalakaha was very permeable. However, the soils water reserves of Nibolikaha and Napalakaha sites were higher and increased with depth. Consequently, the potential for using these reserves was greater in Nibolikaha and Napalakaha than in Tiangakaha soils, where the soil is silty and has a higher bulk density, both in the rainy season and in the dry season. This means that more important provisions are necessary to meet the water needs of crops in this latter village.

SIGNIFICANCE STATEMENT

This study revealed the water supply capacity of plants through the soils of Tiangakaha, Nibolikaha and Napalakaha villages, which may be beneficial to the farmers of these localities. It will help to discover critical areas of soil hydrodynamic that many researchers have not been able to explore, before. Thus, a new theory on soil water availability for plants can be found.

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