NRC Research Press

ARTICLE

Soil conditions in the “donga” soils in subhumid zone in West Africa

Julien Avakoudjo, Félix Kouelo Alladassi, Valentin Kindomihou, Tobi Moriaque Akplo, Mahugnon Socrate Agonvinon, Guillaume Lucien Amadji, and Brice Sinsin

Abstract: Water erosion threatens large areas around the world. “Donga” is one of the witnesses of gully erosion in northern Benin, which induces serious threats to the natural habitats. This study was conducted to evaluate soil moisture content in different donga types (“microdongas”, “mesodongas”, and “megadongas”) and its variation at different topographic levels. The thermogravimetric soil moisture measurement technique was used for moisture estimation on saturated and unsaturated soil. Data were analyzed through analysis of variance test and *t* test with SAS software. The results showed that soil moisture content varied according to donga types. On unsaturated soil, higher difference (2.75%, $p = 0.0328$) was obtained in mesodongas at the middle followed by megadongas at the middle (2.6%, $p = 0.034$). On saturated soil, higher difference was obtained in mesodongas at the upstream (6.51%, $p < 0.0001$) at downslope (4.55%, $p = 0.0032$) and in the middle (4.32%, $p = 0.0328$) followed by microdongas at the upstream (2.25%, $p < 0.0001$). The findings in this paper should be useful to researchers looking for soil moisture information in subarid and subhumid zone at different topographic levels to develop afforestation strategies based on species that can make the best use of soil water.

Key words: soil erosion, soil moisture, donga, topographic level, Benin.

Résumé : L’érosion hydrique menace de grandes régions, partout dans le monde. Les “dongas”, sorte de ravines dans le nord du Bénin, témoignent du sérieux danger que pose ce type d’érosion pour les habitats naturels. Les auteurs ont entrepris d’évaluer la concentration d’eau dans le sol de différents types de donga (“microdongas”, “mésodongas” et “mégadongas”) et la façon dont elle varie avec le niveau topographique. La technique thermogravimétrique employée pour doser l’eau dans le sol a permis d’estimer la teneur en eau du sol, saturé ou pas. Les données ont ensuite été traitées par analyse de la variance et avec le test de Student sur un logiciel SAS. Les résultats indiquent que la teneur en eau du sol varie avec le type de donga. Quand le sol n’est pas saturé, l’écart le plus important (2,75 %, $p = 0{,}0328$) a été relevé au centre des mésodongas, puis au centre également des mégadongas (2,6 %, $p = 0{,}034$). Quand le sol est saturé, l’écart le plus important survient au sommet des mésodongas (6,51 %, $p < 0{,}0001$), au bas de la pente (4,55 %, $p = 0{,}0032$) et au milieu de celle-ci (4,32 %, $p = 0{,}0328$). Viennent ensuite les microdongas, au sommet de la ravine (2,25 %, $p < 0{,}0001$). Cet article devrait aider ceux qui cherchent à en savoir plus sur la teneur en eau du sol selon le niveau topographique, dans les régions semi-arides et subhumides, en vue d’échafauder une stratégie de boisement en fonction des espèces capables de tirer le maximum de l’eau présente dans le sol. [Traduit par la Rédaction]

Mots-clés : érosion du sol, teneur en eau du sol, donga, niveau topographique, Bénin.

Received 27 October 2020. Accepted 12 April 2021.

J. Avakoudjo, V. Kindomihou, and B. Sinsin. Laboratory of Applied Ecology, Faculty of Agronomic Sciences, University of Abomey-Calavi, Abomey-Calavi, BP 526, Cotonou, Bénin.

F. Kouelo Alladassi, T.M. Akplo, and M.S. Agonvinon. Laboratory of Soil Microbiology and Microbial Ecology, Faculty of Agronomic Sciences, University of Abomey-Calavi, BP 711, Abomey-Calavi, Bénin.

G.L. Amadji. Laboratory of Soil Sciences, Faculty of Agronomic Science, University of Abomey-Calavi, Abomey-Calavi, BP 526, Cotonou, Bénin.

Corresponding author: Julien Avakoudjo (email: julioavak@gmail.com).

Can. J. Soil Sci. **00:** 1–9 (0000) dx.doi.org/10.1139/cjss-2020-0137

Introduction

Soil moisture is the temporary storage of water within a shallow layer of earth's upper surface as compared with the total amount of water available throughout the globe (Engman 1991; Srivastava et al. 2006). The importance of precise soil moisture information is well understood in various fields like agriculture, hydrology, meteorology, environmental studies, etc (Pavan et al. 2018). Inadequate availability of water in the soil is the main obstacle to agricultural production, making it the primary limiting factor to the achievement of high agricultural productivity over the years (Rossato et al. 2017). In addition, extreme variability in climatic conditions also influences agricultural productivity; i.e., in some years, the water supply to plants is sufficient to achieve high crop yields, whereas in other years, inadequacy can lead to total loss of crops (Antonino et al. 2000). Soil moisture is very dynamic, both temporally and spatially; therefore, its continuous monitoring is necessary. W National Park is located in the drier zone in subhumid region of Benin. The main feature of the subhumid region is low rainfall as usual in the Sudanian biogeographical region (Barbosa et al. 2015; Barbosa and Lakshmi Kumar 2016; Marengo et al. 2016). The social implications related to low rainfall were pointed out in Paredes et al. (2015) and may be ranged into four types: (*i*) meteorological, when precipitation is far below the normal; (*ii*) hydrological, when the river flow cannot attend to demands of a given system of water management; (*iii*) agricultural, when there is not enough moisture in the soil for the development of a crop at any stage of growth; (*iv*) socioeconomic, when there is reduction of the availability of water, and this causes damage and impacts to the population. Agricultural drought is due to water deficiency in soil and consequent water stress to plants, causing the reduction in the biomass production (Rossato et al. 2017). Therefore, the consequences are more acute in the cropping systems located in the "donga" zones (Avakoudjo et al. 2014). In fact, the dongas are catastrophic situations of soil degradation featuring a vast depression without being a watershed (absence of watercourses). This occurs due to erosion and soil collapse and the phenomena of soil subsidence and slumpflation (McCarthy et al. 2001; Tooth et al. 2002; Toko and Sinsin 2008). Thus, the assessment of soil moisture condition, the estimation of soil water content, and the effects of donga type (according to their size) and topography on this parameter are relevant and are important information associated with a decline in agricultural yield. Although recent studies on land-use in the W National Park in Benin and its surroundings have shown an increase in agriculture fields (more than 10 times the initial area from 1972 to 2008) (Avakoudjo et al. 2014), it is still necessary to identify the toposequences favorable to agriculture in donga areas in order to implement effective water and soil management practices. Soil water content is important in agronomic, hydrological, and meteorological processes at all spatial scales (Pavan et al. 2018). It plays a key role in water stress detection and irrigation management. Information of soil moisture can also be used as an indicator for the prediction of natural disasters, such as drought and flooding, and environmental changes, such as dust storms and erosion (Pavan et al. 2018).

In the study area, serious economic and environmental problems related to dongas and soil erosion become recurrent (Avakoudjo 2016). Local communities must cope with a considerable decrease in their productivity and incomes resulting in a rapid depletion of soils, as the watersheds are still out of protection against water and wind erosion (MEPN 2010).

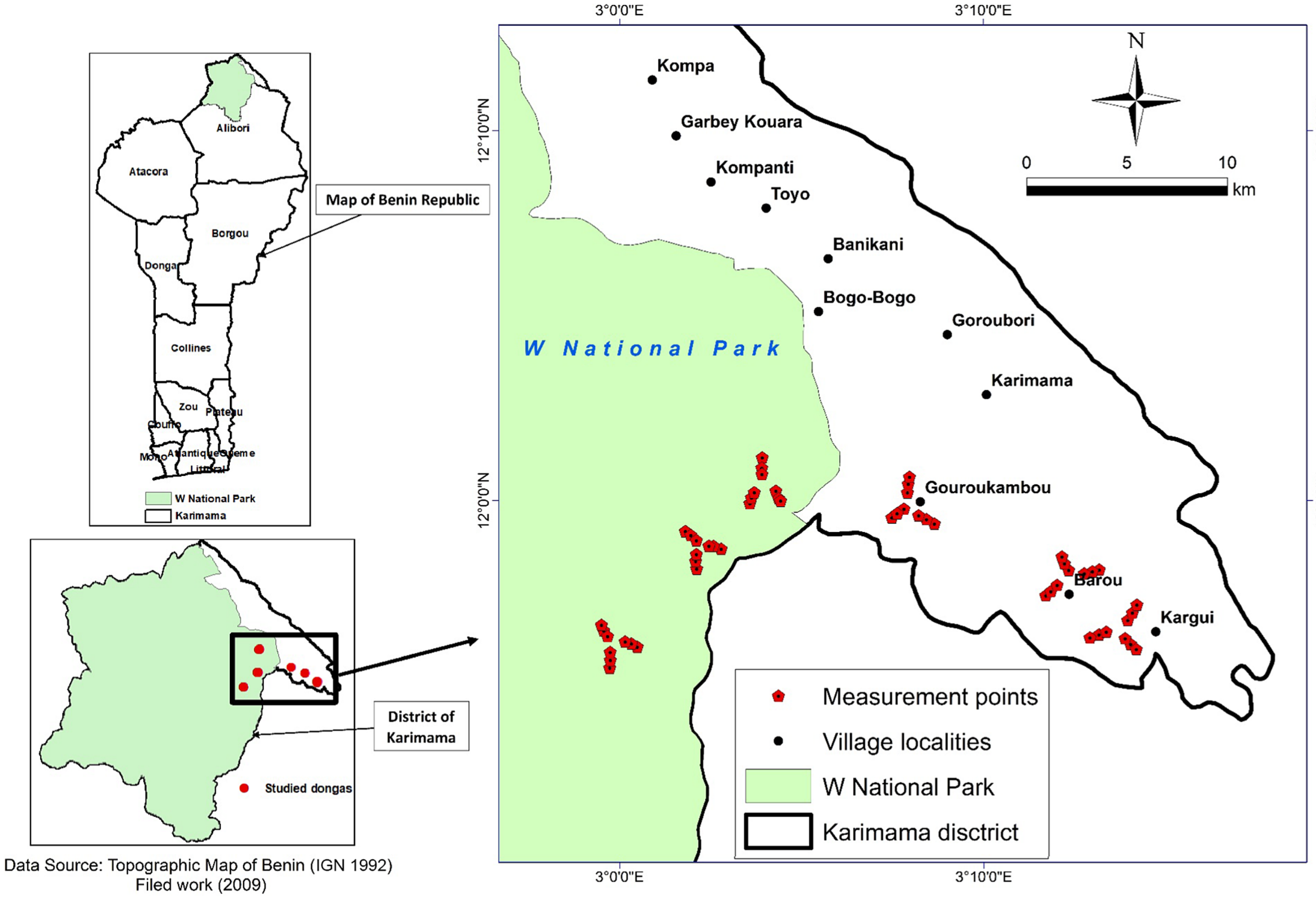
There are various methods to assess soil moisture status. In the present study, soil moisture was estimated by point measurements using gravimetric method. This method involves taking a soil sample from the field determining the weight of water contained in this soil sample, relative to the weight of dry soil. The present study used the gravimetric method to evaluate soil moisture content in different donga types ("microdongas", "mesodongas", and "megadongas") and its variation at different topographic levels (upslope, middle, and downslope) in the subhumid zone of Benin.

Materials and Methods

Study area

The study was carried out in the subhumid zone of Africa in the Sudanese dry zone of Benin in the Karimama district. It extends from 11°26′00″ to 12°25′00″ north in latitude and from 2°48′00″ to 3°05′00″ east in longitude (Fig. 1). It is bounded to the north by the Niger River, to the south-west by the Banikoara district, to the south-east by the Kandi district, to the east by the Malanville district, and to the eest by Burkina-Faso. It covers 6102 km^2 of which 92.3% (5085 km^2) is occupied by the W National Park and 16.67% (1017 km^2) for the land-use areas. It is located in the dry Sudanian zone with two contrasting seasons: a rainy season from May to September and a dry season from October to April. The 30 yr annual average precipitation is 900 mm. The temperatures undergo significant variations with an annual average of 28 °C. The relief is a vast granito-gneissic peneplain dominated by a few hills (Viennot 1978). The geological substratum of the area is composed of quartzites, basic rocks, mica schists, schists, granites, gneisses, and sandstone (Szaniawsky 1982). The soils are raw minerals, little evolved, tropical ferruginous, and gley minerals. The hydrographic network brings together the Mékrou (410 km) and Alibori (338 km). In addition to these large rivers, there are small ones connected in many places along their course. The plant formations encountered correspond mainly to wooded shrub savannas, islands of riparian forests, and dense dry forests (Adomou 2005). The main crops grown by

Fig. 1. Studied area and location of measurement points in dongas. [Colour online.]



Data Source: Topographic Map of Benin (IGN 1992)
Filed work (2009)

local populations of the study area are sorghum/millet, rice, and maize (PDREGDE 2013; INSAE 2016, 2017).

To compare the soil moisture content of the donga upstream with middle and downstream values, we randomly selected three sites both in the W National Park and its periphery (farmland or surrounding areas). Donga sizes were taken into account, and soil moisture content was measured in the microdongas (donga depth ≤ 1 m), mesodongas (1 m < donga depth ≤ 3 m), and megadongas (donga depth > 3 m). Sampled Dongas and characteristics are given by Table 1, and the location of studied dongas and measurement points is in Fig. 1.

Methodology

Soil moisture content was collected in two ecosystems (*i*) the W National Park as a protected area (control) and (*ii*) surrounding areas (farmland). Soil moisture content was collected from three donga types, specifically (*i*) microdongas (donga depth above ground surface ≤ 1 m), (*ii*) mesodongas (1 m < donga depth ≤ 3 m), and (*iii*) megadongas (donga depth > 3 m), at three topographic levels (upstream, middle, and downslope). There were three repetitions in each donga. A total of 54 sites were selected within land-use areas in Karimama district and the W National Park (27 sites each), with site selection broken down as follows for the land-use areas: (*i*) Kargui land-use area (9 sites), (*ii*) Baru land-use area (9 sites), and (*iii*) Gouroukambou land-use area (9 sites). Global positioning system was used to collect the coordinates of those selected sites. The collected coordinates were used for map creating with ArcGIS version 10.5 software (Esri 2016) using the topographic map of Benin (IGN 1992).

Soil moisture content was estimated by point measurement using gravimetric method on unsaturated and saturated soil. The tests and surveys were carried out from April to November 2009. The direct measurement of soil property is done in the field and by analyzing soil sample under laboratory condition. Thus, before the soil moisture test at donga upstream, middle, and downstream, the soil was sampled with the density cylinder to assess unsaturated soil moisture content. After, saturated soil was sampled to assess saturated soil moisture. Gravimetric method is the only direct way to assess soil moisture (Johnson 1962; Reynolds 1970). This method involves taking a soil sample from the field, accurately weighing it, completely drying it out in an oven (i.e., at 105 °C until a constant dry weight), re-weighing the dry sample, determining the weight of water contained in a soil sample, relative to the weight

Table 1. Sampled dongas (gullies) location and characteristics.

Characteristics of donga	DP$_1$	DP$_2$	DP$_3$	DT$_1$	DT$_2$	DT$_3$
Location	W Park	W Park	W Park	Gouroukambou land-use area	Baru land use area	Kargui land use area
Geographic coordinate						
Longitude (E)	03°04′27″	03°03′19″	03°00′36″	03°08′08″	03°11′47″	03°13′39″
Latitude (N)	11°59′59″	11°59′30″	11°56′26″	11°57′49″	11°56′23″	11°55′22″
Depth (m)						
Mim	1.20	0.25	0.81	1.48	0.25	0.20
Max	4.20	1.22	2.53	4.20	1.10	2.71
Mean diameter (m)	171	62	176.3	103	191.2	430
Donga type						
Class	>3 m	≤1 m	1 m < depth ≤ 3 m	>3 m	≤1 m	1 m < depth ≤ 3 m
Type	Megadonga	Microdonga	Mesodonga	Megadonga	Microdonga	Mesodonga
Upstream slope (%)	4.5	5.0	6.5	4.25	4.0	3.75
Middle slope (%)	4.0	3.0	4.5	3.0	2.75	3.0
Downstream slope (%)	2.0	1.0	4.0	1.5	1.5	2.0

Note: DP, Donga in the W National Park; DT, Donga in the land-use areas.

of dry soil. The moisture contained in the soil is measured in terms of percentage (eq. 1).

$$(1)\qquad \%\,\mathrm{SM} = 100 \times \frac{\mathrm{Ww} - \mathrm{Dw}}{\mathrm{Ww}}$$

where % SM is the soil moisture content, Ww is the wet weight of soil, and Dw is the dry weight of the soil.

Statistical analyses

Statistical analyses were performed with SAS version 9.4 software (SAS Institute, Inc. 2013). The data were first checked for normal distribution using Shapiro–Wilk's test (D'Agostino and Stephens 1986). An analysis of variance (ANOVA) test was computed according to general linear model procedure when Shapiro–Wilk's test was significant ($p > 0.05$). To determine the effects of type of donga and topography on the soil moisture content, an ANOVA test was carried out. For each investigated area, the model included the effect of type of donga and topography and the interaction between the two. Mean comparisons were made using least significant difference (LSD) test. A t test for independent samples was performed to compare the means of soil moisture content obtained in the W National Park and its surrounding area for each donga type and topography level. Significant differences were declared using 5%.

Results

Effect of the type of donga on soil moisture in the study areas

Soil moisture in saturated and unsaturated soils varied in different types of dongas in the W National Park as well as in its surrounding area. Table 2 shows data on the mean soil moisture content for different types of donga in the W National Park and its surrounding area on saturated and unsaturated soil. In the W National Park, the highest soil moisture contents were recorded on the unsaturated soil with mesodonga (4.21%) and microdonga (3.30%) compared with megadonga (2.28%) (LSD = 1.01**). In converse, the highest soil moisture content was recorded with mesodonga (20.71%) for the saturated soil. As far as the surrounding area is concerned, the highest soil moisture content was recorded with megadonga (4.32%), whereas the lowest value was obtained with mesodonga (2.16%). However, mean soil moisture content was the same in mesodonga (15.58%) and megadonga (16.15%) and different from the recorded values (18.67%) in microdonga (LSD = 1.53**).

Effect of the topography on soil moisture in the study areas

Table 3 shows data on the mean soil moisture content of the soil at different toposequence. Significant difference was observed on unsaturated and saturated soil in the W National Park (respectively LSD = 1.01** and LSD = 1.57***) and in its surrounding areas (respectively LSD = 0.95*** and 153***).

For unsaturated soil, the mean soil moisture contents are not significantly different at upstream (2.56%) and middle (3.53%) in the W National Park, but they are significantly different to values recorded at downstream (3.70%). While in land-use areas recorded values at upstream (2.76%) were different from values at downslope (3.68%) in donga upstream.

For saturated soil, the mean soil moisture content recorded at the upstream (19.30%) in upstream dongas is different from values recorded at the middle (17.69) and the downstream (18.38%) in W National Park. In the

Table 2. Comparison of the mean soil moisture content in different type of dongas in study areas.

	Soil moisture content on unsaturated soil (%)		Soil moisture content on saturated soil (%)	
Types of donga	W National Park	Land-use areas	W National Park	Land-use areas
Microdonga	3.30 ± 0.38a	2.98 ± 0.17b	19.12 ± 0.68b	18.67 ± 0.74a
Mesodonga	4.21 ± 0.42a	2.16 ± 0.15b	20.71 ± 0.54a	15.58 ± 0.48b
Megadonga	2.28 ± 0.27b	4.32 ± 0.54a	15.55 ± 0.48c	16.15 ± 0.41b
LSD	1.01^{**}	0.95^{***}	1.57^{***}	1.53^{**}
CV (%)	29.56	39.23	22.46	23.96
R^2	0.51	0.14	0.23	0.16

Note: LSD, least significant difference; CV, coefficient of variation. For each column, means with the same lowercase letter are not significantly different according to the LSD test. * *p* value significant at 5%; ** *p* value significant at 1%; *** *p* value significant at 0.1%.

Table 3. Comparison of the mean soil moisture content in saturated and unsaturated soils according to the topography in study areas.

	Soil moiture content on unsaturated soil (%)		Soil moiture content on saturated soil (%)	
Topography	W National Park	Land-use areas	W National Park	Land-use areas
Upstream	2.56 ± 0.28b	2.76 ± 0.14b	19.30 ± 0.61a	15.25 ± 0.53b
Middle	3.53 ± 0.38ab	3.02 ± 0.23ab	17.69 ± 0.70b	17.29 ± 0.59a
Downstream	3.70 ± 0.45a	3.68 ± 0.17a	18.38 ± 0.59ab	17.87 ± 0.60a
LSD	1.01^{*}	0.95^{**}	1.57^{*}	1.53^{**}
CV (%)	29.56	39.23	22.46	23.96
R^2	0.51	0.54	0.23	0.16

Note: LSD, least significant difference; CV, coefficient of variation. For each column, means with the same lowercase letter are not significantly different according to the LSD test. * *p* value significant at 5%; ** *p* value significant at 1%; *** *p* value significant at 0.1%.

surrounding area, the mean soil moisture content recorded at the upstream (15.25%) is different from values recorded at the middle (17.29) and the downslope (17.87%). Higher mean variation (CV = 39.23%) was observed in land-use areas on unsaturated soil.

Variation of the soil moisture content through the toposequence of each type of donga

The combined effect of donga types and topography on the soil moisture content was analyzed. Table 4 shows data on the mean of soil moisture content into the soil at different toposequences in different donga types. In the microdongas (depth of the donga ≤ 1 m) of the W National Park, soil moisture content decreased according to the toposequence. Indeed, the lowest soil moisture was obtained at the top of the slope (1.85%). Conversely, the highest average (4.45%) was obtained at the bottom of the slope in the W National Park. In the land-use area, the average soil moisture content (2.05%) at the top of the slope was found to be significantly lower than the average values recorded at the middle (3.69%) and bottom of the slope (3.19%) on unsaturated soil.

On saturated soil, a similar trend was observed. The highest soil moisture was recorded downstream (20.92% in the W National Park and 21.25% in the land-use areas). In the mesodongas (1 m < depth of donga ≤3 m), the soil moisture content at the upstream (3.73%) and bottom downstream (3.60%) was the same but different from the values recorded in the middle (5.29%) on unsaturated soil in the W National Park. In the land-use areas, the highest moisture values were recorded at upstream and middle (2.31% and 2.54%, respectively). Soil moisture at saturation did not significantly vary through toposequence at both the W National Park and land-use areas. In the megadongas (donga depth > 3 m), the average soil moisture values recorded at the three topographic levels are the same in both ecosystems for unsaturated soil. Conversely, soil moisture at saturation significantly varied through toposequence in W National Park. Soil moisture saturation is lower in the middle (13.59%) in megadongas compared with recorded values at upstream (16.87%) and downstream (16.19%) (LSD = 2.22^{*}).

Results of Student's *t* test on the soil in the saturated and unsaturated soil

Table 5 shows the comparison of the average soil moisture in the W National Park and its surrounding

Table 4. Comparison of the mean of soil moisture content of the soil through the toposequence in different type of dongas in the study areas.

		Soil moisture on unsaturated soil (%)		Soil moisture on saturated soil (%)	
Types of donga	Topography	W National Park	Land-use areas	W National Park	Land-use areas
Microdonga	Upstream	1.85 ± 0.90b	2.05 ± 0.91b	17.85 ± 1.62ab	15.60 ± 1.36b
	Middle	3.60 ± 2.46ab	3.69 ± 1.06a	18.59 ± 3.86b	19.17 ± 5.01a
	Downstream	4.45 ± 3.40a	3.19 ± 1.20a	20.92 ± 4.81a	21.25 ± 4.66a
LSD		1.79*	0.71*	1.03**	3.36*
CV (%)		81.27	35.84	25.19	26.89
R^2		0.14	0.30	0.57	0.19
Mesodonga	Upstream	3.73 ± 1.72b	2.31 ± 1.02ab	20.81 ± 1.01a	14.30 ± 1.19a
	Middle	5.29 ± 1.77a	2.54 ± 1.14a	20.89 ± 4.07a	16.57 ± 4.06a
	Downstream	3.60 ± 1.27b	1.62 ± 1.04b	20.43 ± 1.98a	15.88 ± 1.12a
LSD		1.04*	0.71*	NS	NS
CV (%)		22.28	49.72	19.42	22.38
R^2		0.36	0.12	0.10	0.07
Megadonga	Upstream	2.09 ± 1.56a	4.60 ± 5.15a	16.87 ± 2.16a	16.49 ± 3.42a
	Middle	2.22 ± 2.28a	4.82 ± 4.20a	13.59 ± 4.54b	16.12 ± 3.29a
	Downstream	2.54 ± 2.27a	3.56 ± 2.27a	16.19 ± 2.76a	15.84 ± 2.60a
LSD		NS	NS	2.22*	NS
CV (%)		40.54	43.78	21.31	19.36
R^2		0.18	0.19	0.16	0.08

Note: LSD, least significant difference; CV, coefficient of variation; NS, nonsignificant. For each column, means with the same letter are not significantly different according to the LSD test. * *p* value significant at 5%; ** *p* value significant at 1%; *** *p* value significant at 0.1%.

Table 5. Comparison of the difference of mean soil moisture content on unsaturated and saturated soil at different slope and donga types.

Types of donga	Topography	W National Park	Land-use areas	Difference	*p* value
Soil moisture on unsaturated soil (%)					
Microdonga	Upstream	1.85 ± 0.90	2.05 ± 0.91	−0.20	0.0678
	Middle	3.60 ± 2.46	3.69 ± 1.06	−0.09	0.0974
	Downstream	4.45 ± 3.40	3.19 ± 1.20	1.26	0.0595
Mesodonga	Upstream	3.73 ± 2.72	2.31 ± 1.02	1.42	0.077
	Middle	5.29 ± 3.77	2.54 ± 1.14	2.75	0.0328
	Downstream	3.60 ± 2.27	1.62 ± 1.04	1.98	0.0458
Megadonga	Upstream	2.09 ± 1.56	4.60 ± 5.15	−2.51	0.0269
	Middle	2.22 ± 2.28	4.82 ± 4.20	−2.60	0.034
	Downstream	2.54 ± 2.27	3.56 ± 2.27	−1.02	0.0661
Soil moisture on saturated soil (%)					
Microdonga	Upstream	17.85 ± 1.62	15.60 ± 1.36	2.25	<0.0001
	Middle	18.59 ± 3.86	19.17 ± 5.01	−0.58	0.0661
	Downstream	20.92 ± 4.81	21.25 ± 4.66	−0.33	0.4353
Mesodonga	Upstream	20.81 ± 1.01	14.30 ± 3.19	6.51	<0.0001
	Middle	20.89 ± 2.07	16.57 ± 1.06	4.32	0.0328
	Downstream	20.43 ± 1.98	15.88 ± 1.12	4.55	0.0032
Megadonga	Upstream	16.87 ± 2.16	16.49 ± 3.42	0.38	0.3501
	Middle	13.59 ± 1.54	16.12 ± 1.29	−2.53	0.0401
	Downstream	16.19 ± 2.76	15.84 ± 2.60	0.35	0.0688

land-use area. It appears that whatever the level of the toposequence (upstream, center, and downstream), the unsaturated soil moisture content obtained for the microdongas of the W National Park is statistically equal to those obtained values in the land-use area. In mesodongas, the center and downstream have significantly higher moisture content on unsaturated soils in the W National Park than its surrounding area. In contrast, megadongas have a lower soil moisture content in the W National Park than its surrounding land-use area on unsaturated soil.

Concerning the moisture content of saturated soils, it was found that in the upstream of microdongas, there is a higher moisture content in the W National Park compared with the surrounding area (difference = 2.25; $p < 0.0001$). On saturated soil, the difference between the soil moisture content in the center and downstream in the W National Park and land-use area was not significant. In contrast, the soil moisture content on saturated soil in the mesodongas of W National Park is higher than the obtained values in the surrounding land-use areas at upstream, center, and downstream.

Discussion

Soil erosion is one of the major forms of land degradation in the world (Nanna 1996; Sohan and Lal 2001). Land degradation in the study area is mostly characterized by the phenomena of natural soil erosion and collapse known as dongas (McCarthy et al. 2001; Toko 2005; Toko and Sinsin 2008). Dongas are large, steep-walled depressions without direct contact with a stream (McCarthy et al. 2001; Toko 2005; Avakoudjo 2016). Deforestation activities, to acquire land for cultivation, are the major anthropogenic causes of land degradation in land-use areas with a strong impact on natural resources (Baruti 2004). Water availability is useful for crop and plant development. Soil moisture and its availability to support plant growth is a primary factor in farm productivity (Pitts 2016), and our results showed that soil moisture content varied with different types of donga in the W National Park and land-use areas for both unsaturated and saturated soils. Donga size influences soil moisture content in the study area. Vegetation cover is denser in the W National Park than in the surrounding land-use areas. In the W National Park, trees retain water around the roots, whereas in the surrounding land-use areas, vegetation is destroyed for crops. These conditions are conducive to water and nutrient erosion and low soil moisture content. In the W National Park, vegetation cover is dense than land-use area, with no tree cover. These conditions are favorable to erosion of water and nutrients and low soil moisture content. Analyzing soil moisture variation, Rong et al. (2017) showed that cultivated watersheds have greater temporal and spatial heterogeneity in soil moisture and that soil moisture in cultivated watersheds has important implications for the adoption of appropriate tillage measures for agriculture. Similarly, this study found that the soil condition, whether water saturated or not, influences the moisture content of the soil. When the soil is saturated, the soil pores are saturated with water, and the soil moisture content is at its maximum. Water can no longer infiltrate the soil and will run off. Therefore, the influence of the soil moisture content will be more noticeable on unsaturated soil. On unsaturated soil, the soil moisture content is the same in the microdongas and mesodongas and different from the values recorded in the megadongas of the W National Park, whereas the soil moisture content is the same in the microdongas and mesodongas of the surrounding land-use area and different from the values recorded in the megadongas.

The size of the donga significantly influences the soil moisture content in the study area. The amount of soil water that can be stored and its availability to plants both depend on the type of soil (Pitts 2016). Microdongas are signs of gully erosion characterized by the stripping of soil and nutrients to a depth of 1 m (depth ≤ 1 m), whereas mesodongas range in depth from 1 to 3 m (1 m < depth ≤ 3 m) and megadongas are deeper (depth > 3 m) (Avakoudjo et al. 2018). Soils are subject to extensive stripping of surface horizons. This results in exposure of the underlying horizon with a fine texture (clay) and massive structure (Diatta 1978; Avakoudjo 2016). These very impermeable clays and the underlying horizons promote hypodermic flow causing the collapse of the surface horizons with a sandy texture (Diatta 1978). Rong et al. (2017) noted that clay and sand levels are major factors controlling soil moisture on farms. In the study area, it was noted that on unsaturated soil, soil moisture content is the same in microdongas and mesodongas and different from the values recorded in megadongas. In deeper dongas (megadongas), the soil moisture content value is lower in W National Park and higher in its surrounding area. These results obtained in the W National Park are consistent with those of Rong et al. (2017) who showed that under the influence of high evaporation, soil moisture in the topsoil was significantly lower than that in the subsoil, which is contrary to those obtained in the surrounding land-use areas. Numerous studies on factors influencing soil moisture content have shown that it is influenced by vegetation cover (Fu et al. 2003), topography (Cantón et al. 2004; Ersahin and Brohi 2006; Qiu et al. 2001), and soil properties (Famiglietti et al. 1998; Gómez-Plaza et al. 2001). The combined effect of donga size (type) and topography showed a significant effect on soil moisture content at different topography levels in the W National Park and the surrounding land-use areas on saturated and unsaturated soil in microdongas (depth ≤ 1 m), on unsaturated soil only in mesodongas (1 m < depth ≤ 3 m) and on saturated soil only in the W National Park in megadongas (depth > 3 m). These results showed that in the microdongas and mesodongas in the W National Park and in its surrounding land-use areas on unsaturated soil, topography influences soil moisture content. This influence is only found in the saturated soils of the mesodongas in the W National Park. Restoration actions can therefore be carried out in these degraded areas both in the W National Park and in the land-use zone at different levels of topography, and attention should be paid to the dynamics of the unsaturated zone in relation to the vegetation (Séguis et al. 2004).

Species that can be planted in these microdongas and mesodongas will benefit from soil moisture at the top of the slope, in the middle, and at the bottom of the slope on unsaturated soils. At the periphery of the dongas, vegetation is lacking (Avakoudjo, 2008). The presence of glacis or impluvium (Roose et al. 2010) at the periphery of the dongas (ravines) at the top of the slope means that actions will be more intensive in the middle and bottom of the slope. Water and nutrients escape from this impluvium that cannot be cultivated, and plants will benefit from the nutrients eroded from upstream to downstream of these degraded areas. Studies on temporary and seasonal variations in soil moisture at the top, middle, and bottom of the slopes and their driving causes can help to build better reforestation and rehabilitation strategy for these vast degraded areas called dongas (ravines).

Conclusion

In this paper, gravimetric methods such as point measurement methods were used to estimate soil moisture content. Donga sizes and topography influence soil moisture content. Mean soil moisture content in the W National Park is lower in megadongas (depth > 3 m) and higher in its surrounding land-use areas on the same donga on unsaturated soil. In microdongas (depth ≤ 1 m), soil moisture content at different levels of topography was significantly different on saturated and unsaturated soil in the W National Park and its surrounding land-use areas. In mesodongas (1 m < depth ≤ 3 m), soil moisture content at different levels of topography was significantly different on unsaturated soil in the W National Park and its surrounding areas, whereas in megadongas (depth > 3 m), soil moisture contents at different level of topography have significant difference on saturated soil in the W National Park. Restoration actions could be carried out in these degraded areas particularly in the land-use areas at different levels of the topography, and attention must be paid on the dynamics of the unsaturated zone in relation to vegetation cover in an agroforestry system. Species that can be planted in these degraded areas will benefit from soil moisture in the upstream, middle, and downslope on unsaturated soils. This study points out that vegetation cover is a key factor to mitigate soil degradation in dry areas.

References

Adomou, C.A. 2005. Vegetation Patters and Environnemental gradients in Benin Implications for biogeography and conservation. Ph.D. Thesis, Wageningen University, Wageningen. 133 p.

Antonino, A.C.D., Sampaio, E.V.S.B., Dall'Olio, A., and Salcedo, I.H. 2000. Water budget in a soil with food crops in the semi-arid region of northeast Brazil. Rev. bras. eng. agríc. ambient. **4**, 29–34. doi:10.1590/S1415-43662000000100006.

Avakoudjo, J. 2008. Dégradation des terres et réhabilitation des écosystèmes dégradés au Nord du Bénin : Étude de cas du Parc National du W et des terroirs riverains dans la Commune de Karimama (Bénin). Master's thesis, Université d'Abomey-Calavi. 68 p.

Avakoudjo, J. 2016. Evaluation des « dongas » : Processus, Gestion et Possibilités de mise en valeur dans la commune de Karimama au Nord du Bénin. Thèse de Doctorat en Sciences Agronomiques, Université d'Abomey-calavi, Bénin. 258 p.

Avakoudjo, J., Mama, A., Toko, I., Kindomihou, V., and Sinsin, B. 2014. Dynamique de l'occupation du sol dans le Parc National du W et sa périphérie au nord-ouest du Bénin. Int. J. Biol. Chem. Sci. **8**(6): 2608–2625. doi: doi:10.4314/ijbcs.v8i6.22.

Avakoudjo, J., Toko, I., Kouelo, A.F., Kindomihou, V., Amadji, G.L., and Sinsin, A.B. 2018. Typologie des dongas et effet de l'érosion hydrique sur l'acidité et la teneur en matière organique des sols à Karimama au nord-ouest du Bénin. Revue de Géographie du Bénin Université d'Abomey-Calavi (Bénin), Volume thématique. pp. 22–42.

Barbosa, H.A., and Lakshmi Kumar, T.V. 2016. Influence of rainfall variability on the vegetation dynamics over Northeastern Brazil. J. Arid Environ. **124**: 377–387. doi:10.1016/j.jaridenv.2015.08.015.

Barbosa, H.A., Lakshmi Kumar, T.V., and Silva, L.R.M. 2015. Recent trends in vegetation dynamics in the South America and their relationship to rainfall. Nat. Hazard. **77**: 883–899. doi:10.1007/s11069-015-1635-8.

Baruti, J.H.M. 2004. Study of soil moisture in relation to soil erosion in the proposed Tancitaro Geopark, Central Mexico: a case of the Zacandaro sub-watershed. Master's thesis, International Institute for geo-information Science and earth observation Enschede, The Netherlands. 104 p.

Cantón, Y., Solé-Benet, A., and Domingo, F. 2004. Temporal and spatial patterns of soil moisture in semiarid badlands of SE Spain. J. Hydrol. **285**: 199–214. doi:10.1016/j.jhydrol.2003.08.018.

D'Agostino, R.B., and Stephens, M.A. (eds.). 1986. Goodness-of-fit techniques. Marcel Dekker, New York, NY, USA.

Diatta, S. 1978. Etude pédologique de quelques périmètres irrigués du bassin du fleuve Gambie (Sénégal Oriental). Centre national de Recherches Agronomiques de Bambey, Institut sénégalais de Recherches Agronomiques. pp. 1–31.

Engman, E.T. 1991. Applications of microwave remote sensing of soil moisture for water resources and agriculture. Remote Sens. Environ. **35**(2–3): 213–226. doi:10.1016/0034-4257(91)90013-V.

Ersahin, S., and Brohi, A.R. 2006. Spatial variation of soil water content in topsoil and subsoil of a Typic Ustifluvent. Agric. Water Manage. **83**: 79–86. doi:10.1016/j.agwat.2005.09.002.

Environmental Systems Research Institute, Inc. (Esri). 2016. Argis 10.5. Copyright © 1995–2016. Esri, Redlands, CA, USA. pp. 92373–8100.

Famiglietti, J.S., Rudnicki, J.W., and Rodell, M. 1998. Variability in surface moisture content along a hillslope transect, Ratttlesnake Hill, Texas. J. Hydrol. **210**: 259–281. doi:10.1016/S0022-1694(98)00187-5.

Fu, B.J., Wang, J., Chen, L.D., and Qiu, Y. 2003. The effects of land use on soil moisture variation in the Danangou catchment of the Loess Plateau, China. Catena, **54**: 197–213. doi:10.1016/S0341-8162(03)00065-1.

Gómez-Plaza, A., Martínez-Mena, M., Albaladejo, J., and Castillo, V.M. 2001. Factors regulating spatial distribution of soil water content in small semiarid catchments. J. Hydrol. **253**: 211–226. doi:10.1016/S0022-1694(01)00483-8.

IGN. 1992. Fond Topographique du Bénin. Cotonou, République du Bénin.

Johnson, A.I. 1962. Methods of measuring soil moisture in the field. Geological Survey Water-Supply Paper 1619-U.

Marengo, J.A., Torres, R.R., and Alves, L.M. 2016. Drought in Northeast Brazil — past, present, and future. Theor. Appl. Climatol. **20**: 1–12. doi:10.1007/s00704-016-1840-8.

McCarthy, T.S., Tooth, S., Brandt, D., Hancox, P.J., and Kendall, G.J. 2001. Controls on late quaternary river channel and alluvial fan activity in the semi-arid Steelpoort region. Mpumalanga Northern Province, South Africa. South African J. Geol. http://www.aber.ac.uk/rivers/staff/tooth.htm.

MEPN. 2010. Etude de référence de l'état de dégradation des terres des sols dans les communes de Ouaké, Banikoara, Karimama, Kpomassè, Ouèssè, et Ségbana. Programme Spécial de reboisement et de restaurationdes terres (PSRT). Rapport Cabinet Golf Expertises, 60 p.

Nanna, S. 1996. A geo-information theoretical approach to inductive erosion modelling based on terrain mapping units, dissertation. Wageningen Agricultural University, Wageningen, Netherlands. 162 p.

National Institute of Statistical and Economical Analysis (INSAE). 2016. Cahier des villages et quartiers de ville du département de l'Alibori (RGPH-4, 2013). 26 p.

National Institute of Statistical and Economical Analysis (INSAE). 2017. Analyse globale de la vulnérabilité et de la sécurité alimentaire (AGVSA). Rapport. 179 p.

Paredes, F.J., Barbosa, H.A., and Guevara, Y.E. 2015. Análisis espacial y temporal de las sequías en el nordeste de Brasil. Agriscientia, **32**: 1–14. doi:10.31047/1668.298x.v32.n1.16552.

Pavan, K.S., Dheeraj, K., Hari, S., and Srivastava, P.P. 2018. Assessment of different methods for soil moisture estimation: a review. J. Remote Sens. GIS, **9**(1): 57–73. doi:10.37591/jorsg.2018.v9i1.105.

PDREGDE. 2013. Etudes techniques pour le développement de petits périmètres irrigués dans la plaine alluviale du fleuve Niger à Karimama et à Malanville. Etude d'impact environnemental et social. Rapport définitif. 129 p.

Pitts, L. 2016. Monitoring soil moisture for optimal crop growth. Observant. https://observant.zendesk.com/hc/en-us/articles/208067926-Monitoring-Soil-Moisture-for-Optimal-Crop-Growth#soil%20moisture%20basics [22 Feb. 2019].

Qiu, Y., Fu, B.J., Wang, J., and Chen, L.D. 2001. Soil moisture variation in relation to topography and land use in a hillslope catchment of the Loess Plateau, China. J. Hydrol. **240**: 243–263. doi:10.1016/S0022-1694(00)00362-0.

Reynolds, S.G. 1970. The gravimetric method of soil moisture determination. J. Hydrol. **11**(3): 258–273. doi:10.1016/0022-1694(70)90066-1.

Rong, L., Duan, X., Feng, D., and Zhang, G. 2017. Soil moisture variation in a farmed dry-hot valley catchment evaluated by a redundancy analysis approach. Water, **92**: 1–16. doi:10.3390/w9020092.

Roose, E., Sabir, M., and Laouina, A. 2010. Gestion durable de l'eau et des sols au Maroc Valorisation des techniques traditionnelles méditerranéennes. IRD Edition, 117–193.

Rossato, L., dos Santos Alvalá, R.C., Marengo, J.A., Zeri, M., do Amaral Cunha, A.P.M., Pires, L.B.M., and Barbosa, H.L. 2017. Impact of soil moisture on crop yields over brazilian semiarid. Front. Environ. Sci. **5**: 73. doi:10.3389/fenvs.2017.00073.

SAS Institute Inc. 2013. Base SAS 9.4 procedures guide: statistical procedures, 2nd ed. SAS Institute Inc., Cary, NC, USA.

Séguis, L., Galle, S., Peugeot, C., Kamagate, B., and Robain, H. 2004. Caractérisation des processus hydrologiques sur le super-site de la Donga Haut bassin de l'Ouémé (Bénin), ORE AMMA-CATCH. Atelier Expérimentation et Instrumentation. INSU-Météo France-IFREMER, Paris 23-24 mars 2004. https://www.researchgate.net/publication/ 282171074.

Sohan, W., and Lal, S. 2001. Extraction of parameters and modelling soil erosion using GIS in a grid environment. Paper presented at the 22nd Asian Conference on Remote Sensing, 5–9 Nov., Singapore.

Srivastava, H.S., Patel, P., and Navalgund, R.R. 2006. How far SAR has fulfilled its expectation for soil moisture retrieval. Asia-Pacific Remote Sensing Symposium. 641001–641001-12.

Szaniawsky, H. 1982. Développement des parcs nationaux : Plan directeur du Parc National du W du Niger. Rapport technique 3 PNUD/FAO, Rome, 98 p.

Toko, I. 2005. Savannah'grassland productivity in relation with natural soil subsidence and slumpflation (dongas) in the W National Park. M.sc. thesis, at Departement of Geography of Abomey-Calavi University, 88 p.

Toko, I., and Sinsin, B. 2008. Les phénomènes d'érosion et d'effondrement naturels des sols (dongas) du Parc national du W et leur impact sur la productivité des pâturages. Sécheresse, **19**(3): 193–200. doi:10.1684/j.sec.2008.0145.

Tooth, S., McCarthy, T.S., Hancox, P.J., Brandt, D., Buckley, K., Nortje, E., and McQuade, S. 2002. The geomorphology of the Nyl River and floodplain in the semi-arid Northern Province, South Africa. S. Afr. Geograph. J. **84**: 226–237. doi:10.1080/03736245.2002.9713774.

Viennot, M. 1978. Carte pédologique de reconnaissance de la République Populaire du Bénin à 1/200 000 feuille de Kandi-Karimama. ORSTOM Note explicative 66(9): 55 p.