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RESEARCH ARTICLE

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Trees in African drylands can promote deep soil and groundwater recharge in a future climate with more intense rainfall

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Abstract

Tropical regions are likely to experience more intense rainfall events in the future. Such an increase in rainfall intensities will affect soil and groundwater recharge, with potential consequences for millions of people. However, little is known about the impact of tree cover on soil and groundwater recharge under higher rainfall intensities. Here, we investigated the effect of tree cover and rainfall intensity on soil water drainage in an agroforestry parkland in West Africa. We collected soil water drainage from lysimeters located at 50 and 150 cm depth in both small and large open areas among trees, which represent contrasting degrees of tree cover, and analyzed a subset of water samples for $\delta^{18}O$ and $\delta^{2}H$ to gain insights into the mechanisms of water flow within the soil profile. We found that under high rainfall intensities (>20 mm d^{-1}), the median daily soil water drainage amount at 150 cm was 13 times higher in the small compared with the large open areas, whereas at 50 cm, there were no significant differences. Low rainfall intensities (<10 mm d^{-1}) resulted in little soil water drainage both at 50 and 150 cm depth, regardless of canopy opening size. The isotopic signature of soil water drainage suggested less evaporation and a higher degree of preferential flow in small compared with large open areas. Our results suggest that maintaining or promoting an appropriate tree cover in tropical African drylands may be key to improving deep soil and groundwater recharge under a future climate with more heavy rainfall.

KEYWORDS
drylands, groundwater recharge, intense rainfall, macropores, tree cover, water stable isotopes

1 | INTRODUCTION

Climate change projections based on global climate models suggest an increase in the frequency of heavy precipitation events during the 21st century over most areas of the globe, especially in high latitudes and tropical regions (Seneviratne et al., 2012). An increase in the recurrence of extreme meteorological events such as heavy rainfall can alter ecosystem functioning and eventually trigger ecosystem regime shifts, which, in turn, can have large impacts on ecosystem services (Jentsch & Beierkuhnlein, 2008; Knapp et al., 2008; Scheffer & Carpenter, 2003). More heavy rainfall events could theoretically lead to enhanced recharge of soil and groundwater (Knapp et al., 2008; Owor, Taylor, Tindimugaya, & Mwesigwa, 2009), but it could also result in more overland flow and a higher occurrence of downstream flooding (Döll & Flörke, 2005). Whether more intense rainfall events translate into more recharge or greater overland flow is primarily regulated by the physical and hydraulic properties of soils, which, in turn, are strongly affected by land cover and land use. Within the context of adaptation to climate change, it is therefore highly relevant to investigate the potential impacts of the projected increase in the frequency of heavy rainfall events on soil water dynamics in relation to land cover and land use. This is particularly important in drylands, where water scarcity places critical constraints on primary production and livelihood opportunities.

In semiarid West Africa, rainfall is characterized by a high spatial, intra- and inter-annual variability (Lebel, Taupin, & Damato, 1997; Nicholson, 1995, 2013). Annual rainfall is concentrated in a single, relatively short, rainy season that may occur between April and October (Nicholson, 1995). Rainfall intensities are inherently high, and a large proportion of the annual rainfall falls during very intense storms (Zipser, Cecil, Liu, Nesbitt, & Yorty, 2006). For instance, observations across the region indicate that 25% of the total annual rainfall falls at intensities above 30 to 90 mm h^{-1} (Charreau, 1971; Hoogmoed, 1981; Hoogmoed & Stroosnijder, 1996; Lebel, Taupin, & Damato, 1997). Soils in the semiarid tropics, and in semiarid West Africa in particular, are typically sensitive and vulnerable to degradation, which is mainly a result of their low structural stability, especially when soil organic matter inputs are low (Bationo, Kihara, Vanlauwe, Waswa, & Kimetu, 2007; El-Swaify, Singh, & Pathak, 1983; Hoogmoed, 1983; Hoogmoed & Stroosnijder, 1984; Lal, 1996). The prevalence of high rainfall intensities, coupled with the physical characteristics of these soils, frequently leads to the formation of soil crusts on the soil surface. These crusts reduce water infiltration capacity, resulting in enhanced overland flow and limited soil and groundwater recharge (El-Swaify et al., 1983; Hoogmoed, 1983; Hoogmoed & Stroosnijder, 1984), which can negatively affect primary production, local water supplies, ecosystem services, and the livelihoods of local people. This situation can be further exacerbated in the future, as regional climate models for West Africa predict an increase in the number of extreme wet rainfall days by the middle and end of the 21st century (Ibrahim, Karambiri, Polcher, Yacouba, & Ribstein, 2014; Sylla, Nikiema, Gibba, Kebe, & Klutse, 2016; Vizy & Cook, 2012). Moreover, some of these projections suggest that the period around the onset of the rainy season will experience the most substantial changes in daily precipitation, with a delay of the rainy season and an increase in the intensity of very wet events (Ibrahim et al., 2014; Sylla et al., 2015). This, in turn, points to a greater risk of both drought and flooding events at the onset of the rainy season (Sylla et al., 2015; Sylla et al., 2016). Therefore, in semiarid West Africa, the combination of increasing rainfall intensities and degradation-prone soils may put future groundwater resources at risk.

Tree cover has a strong influence on soil and groundwater recharge through the alteration of various components of the hydrological cycle, including interception, transpiration, soil infiltration, and preferential flow (Brauman, Freyberg, & Daily, 2012; Fan, Oestergaard, Guyot, & Lockington, 2014; Le Maitre, Scott, & Colvin, 1999). In a recent study conducted in semiarid West Africa, we found that moderate tree cover enhances soil and groundwater recharge (Ilstedt et al., 2016). This is largely attributable to the critical role trees play in improving soil infiltrability and preferential flow, mainly by enhancing macroporosity through root and faunal activity (Bargués Tobella et al., 2014). However, considering the projected increase in extreme rainfall events, we were interested in investigating the specific impact of tree cover on soil water dynamics under different scenarios of rainfall intensity. In semiarid West Africa, tree cover notably declined in response to the droughts in the 1970s and 1980s (Gonzalez, 2001; Gonzalez, Tucker, & Sy, 2012; Hiernaux et al., 2009; Maranz, 2009; Vincke, Diedhiou, & Grouzis, 2010; Wezel & Lykke, 2006). More recently, an increase in tree cover on farmlands, mainly linked to farmer managed natural regeneration practices, has been observed throughout the region (Haglund, Ndjeunga, Snook, & Pasternak, 2011; Reij, Tappan, & Smale, 2009; Sendzimir, Reij, & Magnuszewski, 2011; Tougiani, Guero, & Rinaudo, 2009). Knowing how changes in tree cover, either climate or human-induced, will affect soil and groundwater recharge under different scenarios of rainfall intensity is vital to plan sound strategies for adaptation to climate change. Moreover, this information would be of great interest for ongoing large-scale tree-based landscape restoration programs in this region, such as the African Forest Landscape Restoration Initiative (AFR-100) or the Great Green Wall of the Sahara and the Sahel Initiative.

Stable isotopes of water provide relevant information about residence times and mixing of water along the soil profile, recharge processes, and deep soil water origin (e.g., Barnes & Turner, 1998; Gat, 1971; Gat & Tzur, 1967; Gazis & Feng, 2004; Landon, Delin, Komor, & Regan, 2000; Mathieu & Bariac, 1996; Sprenger, Leistert, Gimbel, & Weiler, 2016; Zhang et al., 2017). In this study, we use the line conditioned excess (lc-excess; Landwehr & Coplen, 2004), which allows discriminating waters that have undergone significant nonequilibrium evaporation from waters whose isotopic composition resembles that of local precipitation, to differentiate between preferential and matrix flow. Under preferential flow, a fraction of the infiltrating water moves rapidly along preferred pathways in the vadose zone and is thus subject to little evaporation losses, resulting in higher (i.e., less negative) lc-excess values of soil water at depth. In contrast, under matrix or uniform flow, water infiltrating into the ground moves slowly throughout the soil matrix and is thus more exposed to evaporation, leading to lower (i.e., more negative) lc-excess values of soil water. We therefore propose that lc-excess of mobile soil water can help identify the dominant mechanism of water flow through the vadose zone, which builds on the approach used by Hasselquist, Benegas, Roupsard, Malmer, and Ilstedt (2018) in a shade grown coffee agroforestry system in Costa Rica.

In this study, we evaluated how tree cover affects soil water dynamics in relation to rainfall intensity in a dryland agroforestry system in Burkina Faso. We hypothesized that (a) increased rainfall intensities will result in greater soil water recharge and deep soil water drainage in small compared with large open areas among trees (i.e., higher vs. lower tree density areas), and (ii) soil water drainage collected at deeper depths in small open areas has undergone less evaporative enrichment (i.e., higher lc-excess values) compared with water collected in large open areas, indicating greater preferential flow in small open areas.

2 | MATERIAL AND METHODS

2.1 | Study site description

The study was carried out in Saponé (12° 04′ 48” N, 1° 34′ 00” W), a rural municipality located in central Burkina Faso, West Africa (Figure 1). The landscape in the study area is characterized by an open tree layer consisting of scattered multipurpose trees. Agricultural crops are grown under and among trees. These cultivated woodlands are locally known as agroforestry parklands and constitute the most predominant farming system in semiarid West Africa, covering extensive areas of land (Boffa, 1999; Kessler, 1992). *Vitellaria paradoxa* C.F. Gaertn. is the dominant tree species in the agroforestry parklands of Saponé and West Africa at large (Bayala et al., 2015; Bayala, Teklehaimanot, & Ouedraogo, 2002; Bazié, 2013; Boffa, 1999; Breman & Kessler, 1995; Lovett & Haq, 2000). Other common tree species in the study area include *Adansonia digitata* L., *Parkia biglobosa* (Jacq.) G. Don, *Lannea microcarpa* Engl. & K. Krause, *Khaya senegalensis* (Desv.) A.Juss., *Sclerocarya birrea* (A. Rich.) Hochst., *Terminalia laxiflora* Engl., *Azadirachta indica* A.Juss., *Acacia nilotica* (L.) Delile, *Diospyros mespiliformis* Hochst. ex A.DC., *Ficus gnaphalocarpa* (Miq.) Steud. ex Miq., and *Tamarindus indica* L. Average tree density in the study area was 21 trees ha^{-1} but ranged between 4 and 62 trees ha^{-1}. Tree canopy cover estimated from satellite images on 20 plots of dimensions 100 × 50 m ranged between 3% and 21%. Tree diameter at breast height averaged 45 cm, and average tree ground projected area estimated from canopy diameter was 67 m^2. The most common agricultural crops grown in the study area are pearl millet, sorghum, cowpea, and groundnuts. The cropping season starts between May and July, depending on the onset of the rainy season, and harvesting generally takes place in November. Livestock is allowed to graze in the fallows all year around and in the agricultural fields only during the dry season, once they have been harvested.

Mean annual precipitation at Ouagadougou, which is located 30 km north from the study area, was 790 mm year^{-1} from 1952 to 2014, ranging between 570 and 1189 mm yr^{-1} (Direction de la Météorologie du Burkina Faso). The aridity index was 0.38 for the period from 1974 to 2003, and thus, the climate can be classified as semiarid (UNEP, 1992). Rainfall is unimodal, with the rainy season occuring between April and October, and the majority (~70%) of the total annual rainfall being concentrated between July and September. During the dry season, which runs from November to March, mean monthly rainfall is below 10 mm. Roughly 50%, 25%, and 10% of the total annual rainfall recorded in Ouagadougou between 1979 and 1994 fell at intensities above 30, 55, and 100 mm h^{-1}, respectively (Hoogmoed & Stroosnijder, 1996).

The study area lies within a peneplain at 310–325-m a.s.l and is characterized by a fairly flat topography, with slopes ranging between 1% and 2%. The dominant soils in the study area have been classified as *sols ferrugineux tropicaux lessivés* according to the local soil classification system (CPCS, 1967), corresponding to *Ferric Lixisols* (FAO-ISRIC-ISSS, 1998) or *Alfisols* (Soil Survey Staff, 2006). They have low nutrient content (Jonsson, Ong, & Odongo, 1999) and sandy clay and sandy loam textures.

2.2 | Sampling design

The experiment was originally designed to estimate changes in groundwater recharge as a function of tree cover (Ilstedt et al.,

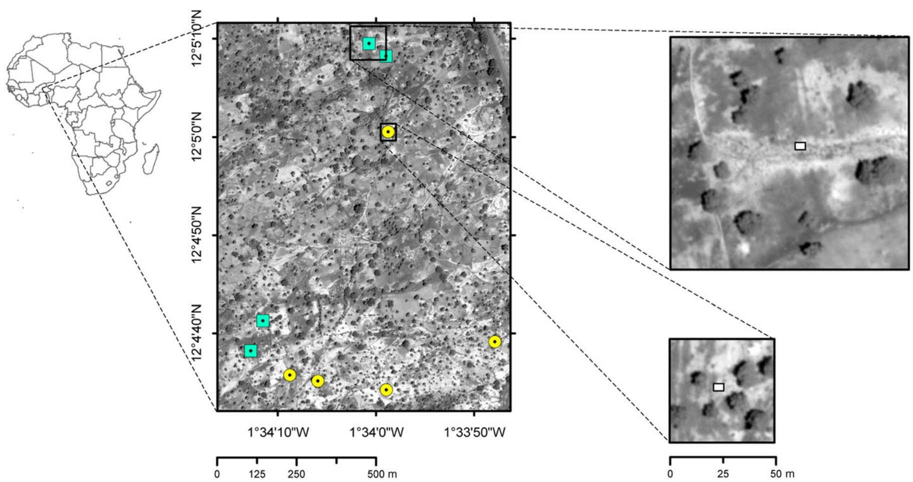

FIGURE 1 Overview of the study area and sampling locations in Burkina Faso, West Africa. Satellite image (Panchromatic WorldView-2 image from 18 July 2012) of the study area showing the nine sampling locations, four corresponding to large open areas (blue squares), and five to small open areas (yellow dots). Enlargements of a large and a small open area are also shown. In each sampling location, soil water drainage was collected at depths of 50 and 150 cm in a soil pit located at the center of the open area (white box) [Colour figure can be viewed at wileyonlinelibrary.com]

2016). We selected two classes of sampling locations in order to span a range of tree densities: small and large open areas (i.e., canopy free areas or gaps among trees; Figure 1). Based on the observed range in size of open areas within the study site, small and large open area classes were defined as having a radius (i.e., distance from the center of the open area to the nearest tree stem) below and above 20 m, respectively. During 2009, we sampled a total of eight open areas, four large, and four small, and in 2010, we included an additional small open area (see Table 1 for information about replicates). This additional small open area was included in 2010 because we observed that there were two lysimeters located in small open areas that malfunctioned during the sampling period in 2009 (see the section on field sampling for details). The selected small and large open areas had a radius of 6–13 and 22–30 m, respectively. Small open areas were 459 m^2 on average, whereas large open areas were 4,158 m^2, nearly one order of magnitude larger. The soils within the study area are rather homogeneous, and there were no differences on soil type or main soil properties such as soil texture between large and small open areas. The selected open areas were all cultivated with pearl millet or sorghum during the study period (rainy seasons 2009 and 2010). Isolated shrubs can be found in the open areas, but these are rare because farmers typically cut them before sowing.

In the center of each open area, we excavated a soil pit with surface dimensions of 1.5 × 2 m. In each soil pit, soil water drainage (Healy, 2010, also referred to as mobile or percolating soil water) was collected at 50 and 150 cm depth using passive fiberglass wick lysimeters adapted from those described by Zhu, Fox, and Toth (2002). We choose an installation depth of 50 cm for the shallow lysimeters to sample the soil water drainage immediately below the root layer. This was based on the observation that, in the study area, most of the fine roots of *V. paradoxa* (the dominant tree species) and crops are concentrated in the uppermost 50 cm of the soil (Bayala, Teklehaimanot, & Ouedraogo, 2004). Deep lysimeters were installed at 150 cm depth as this was a good compromise between the ideal situation of going deeper, and what it was practically feasible in the field given that soil pits needed to be dug manually and water drainage collected from the lysimeters by hand on a daily basis. In comparison with normal zero-tension pan lysimeters, passive fiberglass wick lysimeters have a greater drainage collection efficiency, which can approach 100% (Zhu et al., 2002). A total of 16 (8 sampling locations × 2 sampling depths per location) and 18 (9 × 2) lysimeters were installed in 2009 and 2010, respectively. The lysimeters had a collection surface of 30 × 40 cm and were placed in a rectangular cavity carefully excavated on the wall of the soil pit, with the collection surface in close contact with the ceiling of the cavity. Water collected in the lysimeters was stored in closed plastic tanks connected to the lysimeter collection plate through a hose. The tanks were located inside the soil pits, and the pits were covered with an iron sheet to avoid direct precipitation and further reduce evaporation of collected water. For more details about the construction and installation of the lysimeters, see Ilstedt et al. (2016). In each sampling location, one 2-L rain gauge was mounted at 1.5 m height near the center of the open area.

TABLE 1 Number of sampling locations (total, large open areas, and small open areas) and specific sampling periods in which soil water drainage was collected by lysimeters placed at 50 and 150 cm depth in an agroforestry parkland in semiarid Burkina Faso, West Africa, during 2009 and 2010

	Sampling locations			
Year	Total	Large	Small	Sampling period
2009	8	4	4	Jul. 9–Oct. 29 (excluding Aug. 27 and Sept. 2)
2010	9	4	5	Jul. 1–Aug. 13[a]

Note. Days in which the groundwater table was above 2 m depth are excluded from the sampling periods.

[a]Despite the lysimeters and rainfall gauges were installed 1 Jul., there was no rainfall or soil water drainage until 8 Jul.

2.3 | Field sampling

Soil water drainage and rainfall volumes were manually recorded daily, in the early morning, during the rainy seasons in 2009 and 2010. However, the actual sampling periods of soil water drainage were reduced due to some soil pits being filled with water during certain days or longer periods. Thus, we only considered data from days where the water table was below 2 m depth in all soil pits (Table 1). Some lysimeters malfunctioned during the study period. Out of a total of 16 and 18 lysimeters in 2009 and 2010, we were unable to collect soil water from two and one lysimeters, respectively, due to poor contact between the lysimeter collection surface and the soil matrix.

Immediately after recording the volume of soil water drainage gathered in each lysimeter, a subsample of this water was collected for isotopic analysis. Water samples were stored in airtight polyethylene vials, and the vial lid was sealed with parafilm. Vials were then placed in a fridge at 4°C until isotopic analysis.

2.4 | Lab analyses

A subset of soil water drainage samples collected from lysimeters were analyzed for $\delta^{18}O$ and $\delta^{2}H$. We selected a total of 15 sampling periods, which corresponded to a two to three-day period following a rainfall event (Table 2). The length of the period was typically of 3 days, but in the case that a new rainfall event occurred during the third day, the period was shortened to 2 days. The selection of the periods was based on two criteria: (a) that the periods were regularly distributed throughout the main sampling periods in 2009 and 2010

TABLE 2 Selected periods for $\delta^{18}O$ and $\delta^{2}H$ analysis of soil water drainage samples collected in an agroforestry parkland in semiarid Burkina Faso, West Africa, during the rainy season in 2009 and 2010

Year	Period
2009	Jul. 9–Jul. 11; Jul. 17–Jul. 18; Jul. 22–24; Aug. 1–2; Aug. 9–10; Aug. 17–19; Sept. 10–11; Sept. 13–15
2010	Jul. 8–10; Jul. 11–13; Jul. 17–19; Jul. 20–22; Jul. 23–25; Jul. 30–Aug. 1; Aug. 11–13

and (b) that the majority of the lysimeters collected soil water drainage within the time period. This last criterion restricted our analyses to periods following rainfall events with intensities above 10 mm d^{-1}. For each sampling time period, we created a bulk lysimeter water sample based on the relative volume of water collected during each specific day.

We analyzed the isotopic composition of bulk lysimeter water samples by isotope ratio infrared spectroscopy (IRIS) on a Picarro L2130-i cavity ring-down laser spectrometer coupled with an A0211 high-precision vaporization module (Picarro Inc., Sunnyvale, CA, USA). Raw isotope ratios (δ^{18}O and δ^{2}H) were corrected for drift and memory effects and normalized to the Vienna Standard Mean Ocean Water (VSMOW) scale following the procedures proposed by van Geldern and Barth (2012). A total of four in-house reference water samples were used to correct and normalize the raw data and for quality control. In-house reference waters had been calibrated against three International Atomic Energy Agency standard materials, the VSMOW, the Greenland Ice Sheet Precipitation, and the Standard Light Antarctic Precipitation. The estimated measurement precision, based on repeated analyses of control samples, was ±0.04‰ for δ^{18}O and ±0.23‰ for δ^{2}H. Isotope ratios are expressed according to the standard delta notation in parts per mil (‰) relative to the VSMOW (Coplen, 1996):

$$\delta^{*} = \left(\frac{R_{sample}}{R_{VSMOW}} - 1\right) \times 1000,$$

where δ^{*} represents either δ^{18}O or δ^{2}H, and R is the heavy to light isotope ratio ($^{18}O/^{16}O$ or $^{2}H/H$).

2.5 | Data analysis

The analysis of the effect of rainfall intensity and tree cover on soil water drainage was limited to two main sampling periods in which we had data on soil water drainage from all sampling locations (Table 1). We classified daily rainfall events during these two periods into three intensity classes: <10, 10–20, and >20 mm d^{-1}. The specific intensity cutoffs were chosen in order to have a similar frequency of rainfall events within each class when considering the two sampling periods (rainy seasons in 2009 and 2010). For each date on which a rainfall event was recorded, we calculated the mean soil water drainage amount collected at 50 and 150 cm depth and the mean difference between the amounts of rainfall and drainage collected at 50 cm depth, for both large and small open areas.

In order to analyze the effect of rainfall intensity and opening size on the degree of evaporation of soil water drainage, and thereby on the degree of preferential flow, we calculated the lc-excess of bulk lysimeter water samples collected at both 50 and 150 cm depth as follows (Landwehr & Coplen, 2004):

$$\text{lc} - \text{excess} = \delta^{2}\text{H} - a\,\delta^{18}\text{O} - b,$$

where a and b are the slope and y-intercept of the local meteoric water line (LMWL), respectively. In this study, we used the LMWL from Barogo, an area located ~85 km northeast of our study site, which has the following equation (Mathieu, 1993):

$$\delta^{2}\text{H} = 7.73\,\delta^{18}\text{O} + 7.8.$$

This LMWL, which expresses the relationship between δ^{2}H and δ^{18}O of meteoric waters, was computed for rains which were not affected by evaporation (Mathieu & Bariac, 1996), and is close to other LMWLs within the Sudano-Sahelian zone of West Africa (Ceperley, 2014; Dakouré, 1999; Gourcy, Aranyossy, Olivry, & Zuppi, 2000; Mbonu & Travi, 1994).

During nonequilibrium evaporation, the isotopic composition of water is affected by kinetic fractionation. Due to the disproportional relative impact that kinetic fractionation processes have on oxygen compared with hydrogen isotopes, nonequilibrium evaporation results in evaporation lines with slopes below eight (Barnes & Allison, 1988; Barnes & Turner, 1998; Kendall & Caldwell, 1998). Thus, water that has undergone nonequilibrium evaporation will plot below and towards the right of the LMWL in a dual-isotope plot (Figure 2). As evaporation proceeds, the heavier isotopes (^{2}H and ^{18}O) become progressively enriched in the liquid phase, and thus, the remaining water will increasingly deviate from the LMWL (Kendall & Caldwell, 1998). Lc-excess directly indicates the offset of a water sample from the LMWL, with values close to zero indicating no or little evaporative fractionation, whereas more negative values indicate a higher degree of evaporative isotopic enrichment (Landwehr & Coplen, 2004).

For each time period in which soil water drainage was analyzed (Table 2), we calculated the mean daily rainfall intensity for the set of days within the period in which rainfall was recorded.

Statistical analyses were performed in Minitab 17 statistical software (Minitab Inc., State College, Pennsylvania, USA). Mann–Whitney

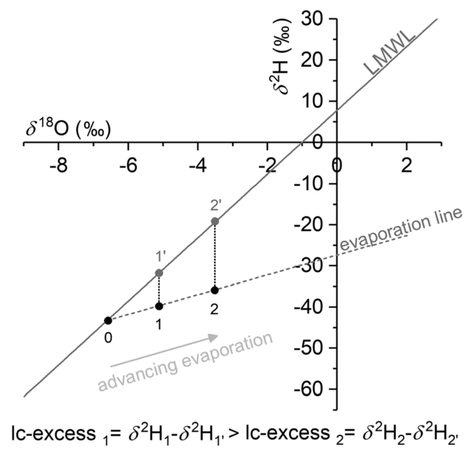

FIGURE 2 Representation, in the δ18O–δ2H space, of the Local Meteoric Water Line (LMWL) and meteoric water that has undergone different degrees of evaporation. As evaporation proceeds, water with an original isotopic composition described by point 0 becomes more enriched in the heavier isotopes and moves progressively towards the right along the evaporation line. Thus, water represented by 2 has undergone more evaporation compared with water represented by 1; this is also shown by a more negative lc-excess value for 2 compared with 1

test was used to test the following hypotheses: (a) accumulated soil water drainage at 50 and 150 cm depth at the end of the two sampling periods in 2009 and 2010 was higher for the small compared with the large open areas;(b) for a given daily rainfall intensity class, daily soil water drainage collected at 50 and 150 cm depth was higher for small compared with large open areas; (c) daily soil water drainage collected at 50 and 150 cm depth was higher for higher daily rainfall intensities; (d) lc-excess values of soil water drainage were lower (i.e., more negative) for samples collected in the large compared with small open areas. We observed that large open areas received the first soil water drainage at 150 cm depth following the onset of the rainy season later than small open areas. In 2010, large open areas did not receive any soil water drainage at 150 cm depth until July 14, whereas in 2009, it was not until August 1. Thus, to make reasonable comparisons between large and small open areas, data on lc-excess values of soil water drainage collected at 150 cm depth corresponding to those periods in which no data were available from large open areas (i.e., previous to August 1, 2009, or July 14, 2010) were excluded from the analysis. In addition to testing these hypotheses, we also looked at the linear relationship between lc-excess values of soil water drainage collected at 50 and 150 cm depth, which we believe can provide valuable insights into the mechanisms of soil water flow. Specifically, we argue that slope coefficients close to one are indicative of preferential flow, as this would imply that the isotopic composition of mobile soil water at 150 cm depth resembles that of mobile soil water at 50 cm depth. In contrast, slopes below one would indicate more negative lc-excess values of mobile soil water collected at 150 cm depth compared with 50 cm depth, suggesting a higher prevalence of matrix flow. The significance level was set to 0.05 for all statistical tests.

3 | RESULTS

3.1 | Overview of the two analyzed periods

Daily rainfall amounts were notably higher in 2010 compared with 2009 (Figure 3). During the study period in 2009, 46% of the daily rainfall events were <10 mm, whereas only 30% and 24% of them were 10–20 and >20 mm, respectively. In contrast, in 2010, more than half of the daily rainfall events (57%) were >20 mm, and only 14% and 29% were 10–20 mm and <10 mm, respectively. Accumulated rainfall for the entire 2009 study period was 534 mm, whereas in 2010, it was only 413 mm. Of this total rainfall amount, 18%, 34%, and 48% corresponded to daily rainfall events <10, 10–20, and >20 mm, respectively in 2009, whereas in 2010, 90% of the total accumulated rainfall corresponded to >20-mm daily rainfall events and only 4% and 6% to <10 and 10–20-mm rainfall events, respectively.

In general, cumulative soil water drainage was higher in the small compared with the large open areas (Figure 3). Although there were no significant differences at 50 cm depth, median accumulated soil water drainage collected at 150 cm depth was greater in the small compared with large open areas (25 and 0.04 mm, respectively, in the first five sampling weeks in 2009, P = .05; 35 and 12 mm in 2010, P = .09). At the end of the sampling period in 2009, median accumulated soil water drainage at 150 cm was nearly twice as high in small compared with large open areas (91 and 50 mm, respectively, P = .03).

The gap between the cumulative curves of rainfall and soil water drainage at 50 cm depth was larger in 2010 than in the equivalent 5-week period in 2009 (Figure 3). Total accumulated rainfall in 2010 was 413 mm, nearly double as much as for the equivalent period in

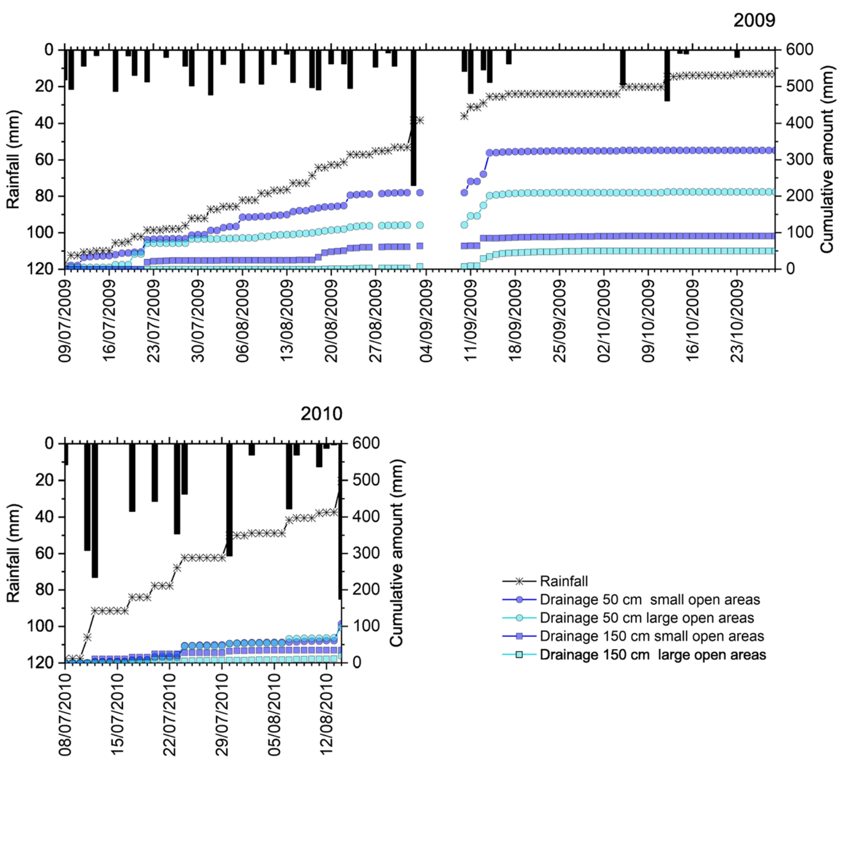

FIGURE 3 Daily rainfall amounts (bars) and cumulative curves of rainfall and soil water drainage for the two analyzed periods in 2009 and 2010 in an agroforestry parkland in Burkina Faso, West Africa. Cumulative soil water drainage curves depict the median value for small (dark blue) and large (light blue) open areas at 50 (circles) and 150 cm (squares) depth [Colour figure can be viewed at wileyonlinelibrary.com]

2009, which was 236 mm. However, median accumulated soil water drainage at 50 cm depth was higher in 2009 than in 2010 (157.9 and 95.5 mm for 2009 vs. 61.3 and 68.3 mm for 2010, for small and large openings, respectively).

3.2 | Effect of rainfall intensity and opening size on the amount of soil water drainage

Regardless of rainfall intensity, there were no significant differences in the amount of daily soil water drainage collected at 50 cm depth between the small and large open areas (Figure 4a). When rainfall intensity increased from <10 to 10–20 mm d^{-1}, both large and small open areas received significantly more water at 50 cm depth, with median daily soil water drainage amounts about 11 and five times higher, respectively. In small open areas, increasing rainfall intensity from 10–20 to >20 mm d^{-1} led to four times higher median daily soil water drainage amounts collected at 50 cm depth, whereas in large open areas, such increase in rainfall intensity did not have any significant impact on the amount of soil water drainage at this depth.

The amount of soil water drainage collected at 150 cm depth was significantly higher in the small compared with the large open areas under rainfall intensities of 10–20 and > 20 mm d^{-1}, with up to 13 times higher median daily soil water drainage amounts, but not for intensities <10 mm d^{-1} (Figure 4b). In large open areas, daily rainfall intensity did not influence the daily amount of soil water drainage collected at 150 cm depth, whereas daily soil water drainage collected in small open areas increased significantly when rainfall intensity increased from <10 to 10–20 mm d^{-1}.

The difference between the amounts of daily rainfall and daily soil water drainage collected at 50 cm depth was not significantly different between small and large open areas (Figure 4c). In both small and large open areas, increasing rainfall intensity from <10 to 10–20 mm d^{-1} resulted in more water being lost before reaching 50 cm depth. In contrast, increasing rainfall intensity from 10 to 20 to >20 mm d^{-1} only lead to significantly higher losses in large open areas.

3.3 | Effect of rainfall intensity and opening size on the lc-excess values of soil water drainage

The lc-excess values of soil water drainage collected at 50 cm depth were not different between small and large open areas (Figure 5a). However, in general, lc-excess values of soil water drainage collected at 150 cm depth were higher (i.e., less negative) in small compared with large open areas. This difference was significant under rainfall intensities of 10–20 mm d^{-1} and nearly significant under intensities >20 mm d^{-1} (Figure 5b). Raw data on $\delta^{18}O$, $\delta^{2}H$, and lc-excess for all bulk lysimeter water samples corresponding to the different sampling periods considered in the analysis can be found in Table S1.

Under rainfall intensities >20 mm d^{-1}, mean lc-excess values of soil water drainage collected at 150 cm depth were positively related to those of soil water drainage collected at 50 cm during the same time period (Figure 6); this was true for both small (lc-excess $_{SO,150\ cm}$ = 1.2 lc-excess $_{SO,50\ cm}$ + 0.5, R^2 = 0.50, P = .05) and large open areas (lc-excess $_{LO,150\ cm}$ = 0.8 lc-excess $_{LO,50\ cm}$ − 2.9, R^2 = 0.76, P = .02). In contrast, under rainfall intensities of 10–20 mm d^{-1}, there was no relationship between mean lc-excess values of soil water drainage collected at 150 cm depth and those collected at 50 cm depth in large open areas (lc-excess $_{LO,150\ cm}$ = 0.2 lc-excess $_{LO,50\ cm}$ − 10.8, R^2 = .04, P = .80), whereas in small open areas, the relationship was nearly significant (lc-excess $_{SO,150\ cm}$ = 1.1 lc-excess $_{SO,50\ cm}$ + 1.36, R^2 = 0.54, P = .06), with a slope close to one.

4 | DISCUSSION

Findings from this study indicate that tree cover, daily rainfall intensity, and the interaction between the two strongly influenced soil water dynamics in an agroforestry parkland in semiarid West Africa. We found that at high rainfall intensities, small open areas of less than 13 m in radius have more than 10-fold higher amounts of deep soil water drainage than open areas that are larger than 22 m in radius, suggesting that tree cover has a positive effect in enhancing deep percolation under more intense rainfall events. Irrespective of the size of the open area, there was little recharge of deep soil water at low rainfall intensities (<10 mm d^{-1}), which is consistent with limited amounts of soil water drainage collected at 50 cm depth in both large and small open areas. In contrast, daily amounts of soil water drainage collected at 150 cm were significantly higher in small compared with large open areas both under 10–20 and >20-mm d^{-1} rainfall intensities. When rainfall intensity increased from <10 to 10–20 mm d^{-1}, only small open areas received significantly more water at 150 cm despite that both large and small open areas had significantly larger amounts of soil water drainage at 50 cm depth. Taken together, these results suggest that (a) increased rainfall intensities do not necessarily result in greater recharge of deep soil water, and more importantly, (b) tree cover plays a decisive role in enabling deep soil water drainage under increased rainfall intensities.

As expected, higher rainfall intensities resulted in more soil water drainage overall. At 50 cm depth, this was particularly pronounced when rainfall intensity increased from <10 to 10–20 mm d^{-1}, both in the small and large open areas. This is in agreement with previous observations indicating that in arid and semiarid environments, only heavy rainfall events contribute significantly to the recharge of soil and groundwater, whereas small rainfall events result in no or little percolation (Barnes, Jacobson, & Smith, 1994; Gee & Hillel, 1988; Mathieu & Bariac, 1996; Owor et al., 2009; Small, 2005; Taylor et al., 2013). However, when rainfall intensity increased from 10–20 to >20 mm d^{-1}, only small open areas received significantly larger amounts of water at 50 cm depth. This suggests that, in small open areas, higher rainfall intensities lead to enhanced recharge of soil water. In contrast, increasing rainfall intensities in large open areas did not result in higher soil water recharge but likely led to more infiltration-excess overland flow. Further studies are needed to better understand the specific threshold in rainfall intensity above which

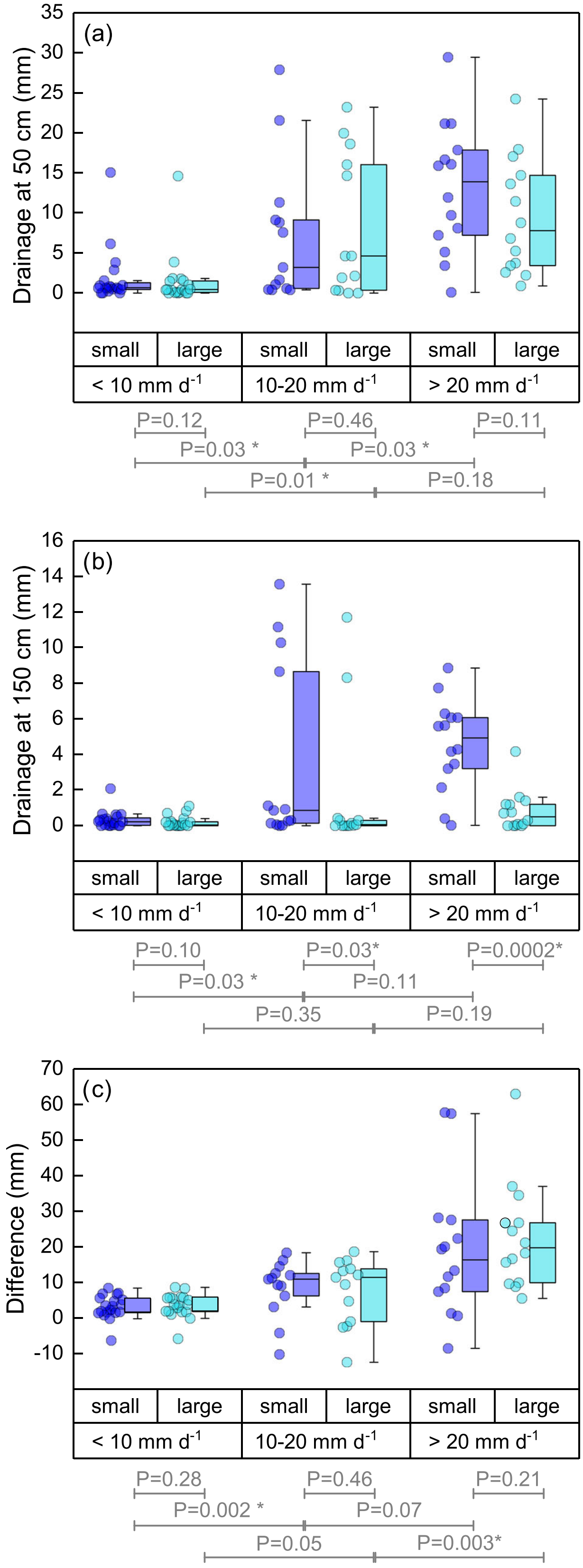

FIGURE 4 Box plots and individual data points of soil water drainage collected at 50 and 150 cm depth (a,b) and of the difference between rainfall amount and drainage collected at 50 cm depth (c), in small (dark blue) and large (light blue) open areas under the three specified classes of daily rainfall intensity (<10, 10–20, >20 mm d^{-1}). The three lines in the box plot show the first quartile, the median, and the second quartile. Whiskers extend to the outermost data point that falls within 1.5 box lengths (interquartile range). *P* values for the Mann–Whitney test are shown at the bottom of each panel [Colour figure can be viewed at wileyonlinelibrary.com]

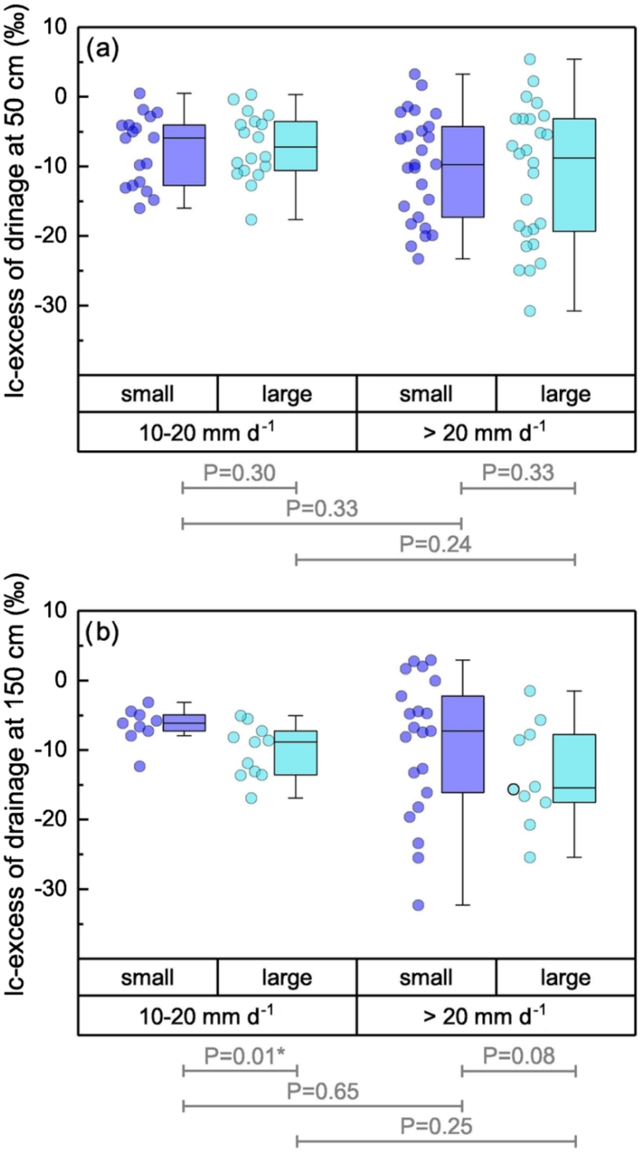

FIGURE 5 Box plots and individual data points of lc-excess of soil water drainage collected at 50 (a) and 150 (b) cm depth in small (dark blue) and large (light blue) open areas under the two studied classes of daily rainfall intensity (10–20 and >20 mm d^{-1}). The three lines in the box plot show the first quartile, the median, and the second quartile. Whiskers extend to the outermost data point that falls within 1.5 box lengths (interquartile range). *P* values for the Mann–Whitney test are shown at the bottom of each panel [Colour figure can be viewed at wileyonlinelibrary.com]

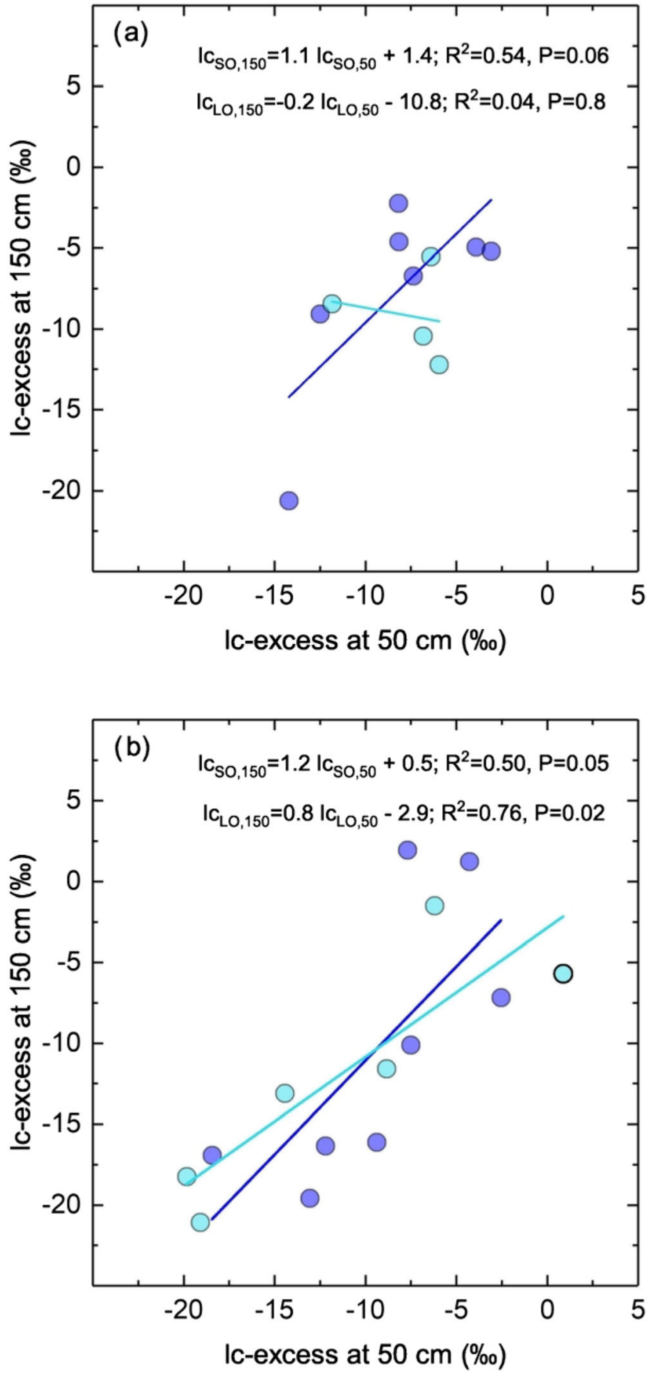

FIGURE 6 Scatterplots of mean lc-excess values of soil water drainage collected at 50 versus 150 cm depth under rainfall intensities of 10–20 (a) and >20 mm d^{-1} (b) in small (dark blue) and large (light blue) open areas. The lines show the fitted linear relationship for each group [Colour figure can be viewed at wileyonlinelibrary.com]

more intense rainfalls do not contribute to increasing soil water recharge and how this threshold is affected by tree cover.

But, what is the specific role of tree cover in enhancing deep soil water drainage? In most soils, the recharge of soil and groundwater occurs via a two-domain flow process, that is, both through the soil matrix and through macropores (Beven & Germann, 2013). When water flow occurs primarily via matrix flow, the recharge process is typically slow. In contrast, water flow along macropores, also known as preferential flow, is much faster and leads to deeper water drainage (Hendrickx & Flury, 2001). In a previous study in the same study area, we found that the degree of preferential flow decreased with increasing distance to the nearest tree stem and that it was higher in small compared with large open areas (Bargués Tobella et al., 2014). This is likely the result of trees increasing macroporosity through the combined effect of litter inputs, root and faunal activity, and microclimate (Bayala et al., 2006; Belsky, Mwonga, Amundson, Duxbury, & Ali, 1993; Dunn, 2000; Greene, 1992; Mordelet, Abbadie, & Menaut, 1993). In the same study area, Bayala et al. (2006) found that soil carbon content was higher under trees than in the adjacent open areas and demonstrated that this was because of the contribution of trees to soil organic matter through increased litter inputs. Along the same lines, and also within the same study area, Joelsson (2012) found that bulk density increased with increasing distance to the closest tree, whereas topsoil organic carbon and subsoil macroporosity decreased with increasing distance. Macropores, such as root and faunal channels, serve as pathways for the preferential flow of water through the vadose zone (Beven & Germann, 2013; Bromley, Brouwer, Barker, Gaze, & Valentin, 1997; Devitt & Smith, 2002). Therefore, the degree of preferential flow will often decrease gradually as one moves from the vicinity of a tree towards an open area further away from the influence of trees, in particular in the case of funneled preferential flow, which occurs around the base of tree stems where stemflow concentrates (Fan, Baumgartl, Scheuermann, & Lockington, 2015; Fan, Scheuermann, Guyot, Baumgartl, & Lockington, 2015; Johnson & Lehmann, 2006). The radius of influence of individual trees on enhancing preferential flow will largely depend on their root system and canopy architecture, in particular on the radial extent of their lateral roots. In Burkina Faso, roots of *Sarcocephalus latifolius*, a native tree of West Africa, were found up to a distance of 20 m from the trunk (Kaboré, Hahn, Hien, & Nacro, 2015). In drylands, it has been estimated that the canopy-to-rhizosphere radius ratio can be as low as 1/10 (Lejeune, Tlidi, & Lefever, 2004). It is thus very likely that in our study area, tree roots extend well beyond the canopy edge of trees into the open areas, which would explain why small open areas (radius 6–13 m) have a higher degree of preferential flow compared with large ones (radius 22–30 m).

That small open areas have a higher degree of preferential flow means that a larger portion of the infiltrating soil water moves faster through the soil profile and, thus, penetrates more rapidly to deeper soil depths. This could explain why small open areas received more water both at 50 and 150 cm depth when rainfall intensity increased. In contrast, in large open areas, which are further away from the influence of trees, soil water flows mainly through matrix or uniform flow and, thus, penetrates slowly through the soil profile. This would, in turn, explain why in large open areas the observed increase in the amount of soil water drainage collected at 50 cm depth in response to higher rainfall intensities did not have a significant impact on deep soil water drainage. This argument is consistent with our results on lc-excess values of soil water drainage collected at 150 cm depth, which were lower (i.e., more negative) for large compared with small open areas. These results indicate that deep soil water drainage collected in the large open areas had undergone more evaporation, which, in turn, might suggest that in large open areas, water flows slowly through the vadose zone (i.e., matrix flow) and is thus more subject to evaporation. These findings are in accordance with a previous study conducted in the same area, which indicated that, following the onset of the rainy season, smaller open areas received deep soil water drainage earlier than larger open areas (Ilstedt et al., 2016). Thus, the contrasting flow mechanisms between small and large open areas can lead to differences in the time needed for infiltrating water to reach deep soil layers, which, in turn, can explain the observed differences in the amount of deep soil water drainage. In a study in semiarid West Africa, Mathieu and Bariac (1996) showed that preferential flow along macropores was the dominant groundwater recharge process in the Barogo basin and estimated that it accounted for ~70% of the total groundwater recharge. Our findings agree with those of Mathieu and Bariac (1996) and moreover suggest that, in conditions typical of the semiarid tropics, macropores are needed to enable the recharge of deep soil water under increased rainfall intensities. In the absence of macropores, more intense rainfall events could lead to increased recharge of topsoil water, but since matrix flow is a slow process, a large fraction of this water will likely return to the atmosphere as evaporation and never contribute to deepwater drainage, especially if evaporation increases as a result of global warming.

Because trees and associated soil fauna enhance macroporosity and preferential flow (Bargués Tobella et al., 2014), maintaining and promoting a moderate tree cover might be a good strategy to improve deep soil and groundwater recharge under a future climate with more frequent heavy rainfall events. However, tree cover should not be too high; otherwise, transpiration and interception losses from trees would counteract any beneficial effects they might have on deep soil and groundwater recharge (Feng et al., 2016; Ilstedt et al., 2016; Liu et al., 2018; Tian et al., 2017). In the same study area, we found that there is an optimum tree cover that maximizes groundwater recharge, which reflects the balance between the positive and negative effects of trees. The optimum tree cover represents a threshold below which increasing tree cover leads to improved groundwater recharge, whereas above this threshold, more trees result in reduced water yields (Ilstedt et al., 2016). In water-limited environments, understanding the potential thresholds in the relationship between tree cover and water availability is critical. In China's semiarid Loess Plateau, Feng et al. (2016) estimated the threshold at which additional revegetation in the area will cause a shortage in the water supply for human activities. Additionally, they found that this threshold could be significantly reduced in the future due to climate change and increased water withdrawals and called for a better match of species and planting density in large-scale restoration programs. In line with the growing awareness of the important relationship between tree cover and groundwater recharge, more research is needed to better understand how this relationship will change in response to projected changes in rainfall intensity. Furthermore, other factors affecting the overall water balance through either evapotranspiration, soil infiltration, or water flow in the vadose zone should also be considered. Some of these factors include local conditions related to climate, seasonality, geology, topography, soils, and land use history. Other relevant factors are those that are derived from or can be influenced by management practices, for instance, tree species composition, tree age, and spatial distribution, understory vegetation cover, tree pruning, and livestock control (e.g., Bayala et al., 2002; Dierick & Hölscher, 2009; Savadogo, Sawadogo, & Tiveau, 2007; Sun, Lü, Wang, Hu, & Fu, 2015; Tian et al., 2017; Vertessy, Hatton, Reece, O'sullivan, & Benyon, 1997).

The slope coefficients of the regression between lc-excess values of daily soil water drainage collected at 50 and 150 cm depth provided some further insights into the mechanisms of water flow in the soil. As mentioned earlier, we argue that slopes close to one suggest the occurrence of preferential flow, whereas slopes close to zero would indicate a dominance of matrix flow. Using this assumption, it appears that under rainfall intensities of 10–20 mm d^{-1}, preferential flow occurred in small open areas but not in large ones. Moreover, our results indicate that rainfall intensities >20 mm d^{-1} activated the occurrence of preferential flow in large open areas, although this did not result in significant increases in soil water drainage amounts. A possible explanation for this is that in large open areas, where there are only a few macropores, very high rainfall intensities are needed to activate water flow along these macropores, as less intense rainfalls will be easily retained in the soil matrix. However, since the number of macropores is small in large open areas, they do not have a substantial impact on the amount of soil water drainage. Thus, the slope coefficients method proposed in this study provides information about the flow mechanisms of the water draining at specific soil depth but not about the dominant flow mechanism of the entire volume of infiltrating water or the drainage amounts.

More intense rainfall resulted not only in an overall increase in soil water drainage collected at 50 cm depth but also in larger differences between the amount of rainfall and the amount of soil water drainage collected at 50 cm depth. This suggests that heavy rains enhance the occurrence of overland flow, also known as surface runoff. Very heavy rains might have a limited effect on recharging soil water and, instead, contribute proportionally more to overland flow. Therefore, it is likely that rain falling beyond a certain intensity threshold has a disproportionally lower impact on replenishing soil water than that falling at moderate intensities. This would explain why median accumulated soil water drainage at 50 cm depth was lower for the sampling period in 2010 than in the equivalent 5-week period in 2009, despite that accumulated rainfall during the sampling period in 2010 was nearly twice as great as in the equivalent sampling period in 2009. During the sampling period in 2010, the total accumulated rainfall was 413 mm, and 84% of this corresponded to daily rainfall events above 30 mm, whereas in the equivalent period in 2009, the total accumulated rainfall was 236 mm, and daily rainfall intensities were always below 30 mm d^{-1}. The area between the cumulative curves of rainfall and drainage at 50 cm was larger for the sampling period in 2010 than for the equivalent period in 2009, which supports the idea that very heavy rainfall events lead to more overland flow and proportionally less recharge of topsoil water. Infiltration-excess overland flow is a common phenomenon in semiarid West Africa, in particular when forest or woodlands have been converted to other land uses such as cropland or pasture (Favreau et al., 2009; Lal, 1996). Soil degradation following deforestation might be so severe as to induce a regime shift from a state in which most incident rainfall infiltrates into the soil to a new state in which overland flow dominates. A greater occurrence of overland flow can lead to more erosion and floods (Giertz, Junge, & Diekkrüger, 2005; Mahe et al., 2010), which, in turn, can reduce crop yields and deteriorate the quality of surface waters. Strategies for adaptation to climate change should, therefore, seek to minimize the occurrence of overland flow by enhancing water infiltration into the soil. Water harvesting techniques such as contour stone bunds can be effective for this purpose (Reij et al., 2009). In addition, maintaining or establishing scattered trees on agricultural land can be beneficial as well, as trees in these environments can act as water harvesters (Bargués Tobella et al., 2014), thereby enhancing deepwater percolation.

Climate change projections indicate that West Africa will experience an increase in the number of extreme rainfall events in the 21st century (Sylla et al., 2016; Vizy & Cook, 2012). Results from our study suggest that tree cover is key not only to making this an opportunity to increase soil and groundwater recharge but also to avoiding escalated land degradation. If tree cover is absent, there is a higher risk for rainfall to be lost either through evaporation or overland flow. In contrast, when trees are present, rainfall is more likely to infiltrate into the soil and contribute to deep soil and groundwater recharge.

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CONFLICT OF INTEREST

The authors declare no conflict of interests.

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