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1. Executive summary

This delivery reports on the analysis of soil water regime and the influence of trees and shrubs om this process. The presence of trees and shrubs in crop and pasture fields (agroforestry) is highly promoted to buffer climatic variability and water constraint in dry areas (Van Noordwijk et al. 2014). It is assumed that they will positively influence the soil water regime through; i. long term effects on soil properties such as as density/porosity, infiltration and water retention and ii. short term effects by changing the water balance components as preferential infiltration along coarse roots, soil evaporation, water uptake, water table recharge, root hydraulic redistribution, surface soil water availability for crops. The objectives of the task were to analyse these potential effects, and to provide inputs for modeling tree influence at different scales (WP4 & WP7).

The approach combines large scale collection of indicators in agroforestry systems of farmer fields in Burkina, Mali and Sénégal and in depth studies using innovative devices in the Faidherbia Flux site of Sénégal.

The data analysis is still running but several key results have been obtained:

- Improvement of soil bulk density (decrease) and water infiltration (increase) are generally observed close to trees and shrubs. However the difference may be slight and variable between sites and systems. The decrease or buffering of crop water stress at tree proximity is evidenced but also variable.
- For short term effects on the water balance, several insights were observed in Faidherbia-Flux site:
  - Preferential infiltration along coarse roots after stemflow
  - Tree water use reach up to 300 l/day per individual, with seasonal course highly related to the inverted phenology. Despite annual water use estimated about 40 000 L/tree, it represents only 5 to 10% of the annual rainfall when the relatively low tree density is taken into account. Knowing the benefits on crop productivity, this suggest the interest of increasing tree density without risk for the water resource.
  - However the estimated recharge of the water table as assessed through isotopes signature is low and of similar order than tree water use. Hence an increase of tree density could have a significant impact on recharge and related constraints such as salinity.
  - For the first time, root hydraulic redistribution has been evidenced under Faidherbia albida tree. The daily water increment at night can reach up to 1% at 100 cm soil depth. However the phenomenon appears heterogeneous both in space and time. GPR scanning revealed that all the area of the field is colonized by tree superficial roots even 20 m from trees and mainly located between 40 and 140 cm with an average around 90 cm.
- Knowing that root hydraulic redistribution has also been evidenced in the past on several sahelian species of the project as *A. tortilis*, *P. reticulatum* and *G. senegalensis*, our results with Faidherbia trees confirm the generality of the process and points out the interest in taking into account this mechanism in future modeling works.

The results and experiences also provide some methodological insights:

- The impact of innovative tools or applications to understand processes (sap flow measurements with TIMFLOW prototype, automatic infiltrometer, georadar) but with practical limitation to extend in many fields

- The observation of the large tree root colonization in open spaces of agroforestry systems, which somehow challenges the approach comparing plots close and far from trees reveal the tree effects. Moreover, processes that occurred right under tree or shrubs collar as preferential infiltration seen by GPR, cannot be catched by classical measurements.
- Importance (and difficulty) of modelling hydrodynamics in sandy soils
- Validation of the multi-scale and parallel approach adopted in this project which combines simple indicators collection in the different sites, and comprehensive in-depth study of underlying processes in selected instrumented test sites.

2. Soil water regime and tree impacts

2.1 Infiltration

2.1.1 Influence of shrubs and trees and pruning management

Surface soil water properties

In Burkina Faso, in Saria and Yilou sites, measurements of infiltration rates in the presence of *Piliostigma reticulatum, Guiera senegalensis*, or under ligneous material mulch, were conducted throughout the project and indicated that infiltration enhancement vs control was more pronounced under mulch conditions.

In Saria site in farmers' fields for instance, soil under shrub pruning or with mulching appears more porous, with higher water infiltration rate than control (Table 1). Results on visual estimation of soil structure (VESS) or aggregate stability by slack test show same trend in improvement close to tree/shrub showing a correlation between maintenance of soil structure and infiltration (Bazongo et al. 2024).

Treatment	Stability aggregates surface (0-2cm)	Stability aggregates soil (2-10cm)	VESS score 1-5 (lower = better)	Infiltration rate ml.min^{-1}
P. reticulatum high stand	6,00 ± 0,00 a	6,00 ± 0,00 a	2,75 ± 0,55 ab	25,14
P. reticulatum coppiced	5,84 ± 0,69 a	6,00 ± 0,00 a	2,63 ± 0,32 ab	34,90
G. senegalensis coppiced	5,63 ± 1,06 a	6,00 ± 0,00 a	2,53 ± 0,39 ab	30,33
Mixed mulch	5,67 ± 0,71 a	6,00 ± 0,00 a	2,31 ± 0,19 b	39,05
Control	5,05 ± 1,70 a	4,95 ± 1,76 ab	2,81 ± 0,44 a	24,04
P-value	0,1482	0,003746	0,02564	

Table 1: Infiltration and soil structure indicators measured in farmers' fields in Saria, Burkina Faso

In the Yilou site, on farmers' fields, we also analysed infiltration properties under different shrub or tree densities. Soil infiltration rate increases with density of shrubs (dominated by *Piliostigma reticulatum*), being higher in plots with 400-600 shrubs.ha^{-1} (369 ± 63 ml.min^{-1}) than density of 30-100 shrubs.ha^{-1} (201 ± 43 ml.min^{-1}). In tree parklands (dominated by *Vitellaria paradoxa*) infiltration rate was also found higher in

average with density of 15-30 trees.ha^{-1} of *Vitellaria paradoxa* (79.5 ± 7.5 ml.min-1) than with density of 3-15 trees.ha^{-1} (61.6 ± 4.2 ml.min-1).

In a different context, in Kamboinsé research station, where plots have been kept since 2014 with different and controlled densities of the shrub *Piliostigma reticulatum* which are coppiced and mulched each year during cropping season, we also tested the impact of shrub density on water infiltration rates in the different plots. Two types of tillage were conducted in this setup: seeding into zai pits or direct seeding (minimum tillage).

In Figure 1 we clearly see that increasing shrub densities tends to increase water infiltration rates, both under zai or direct seeding tillages (Gnissien 2024).

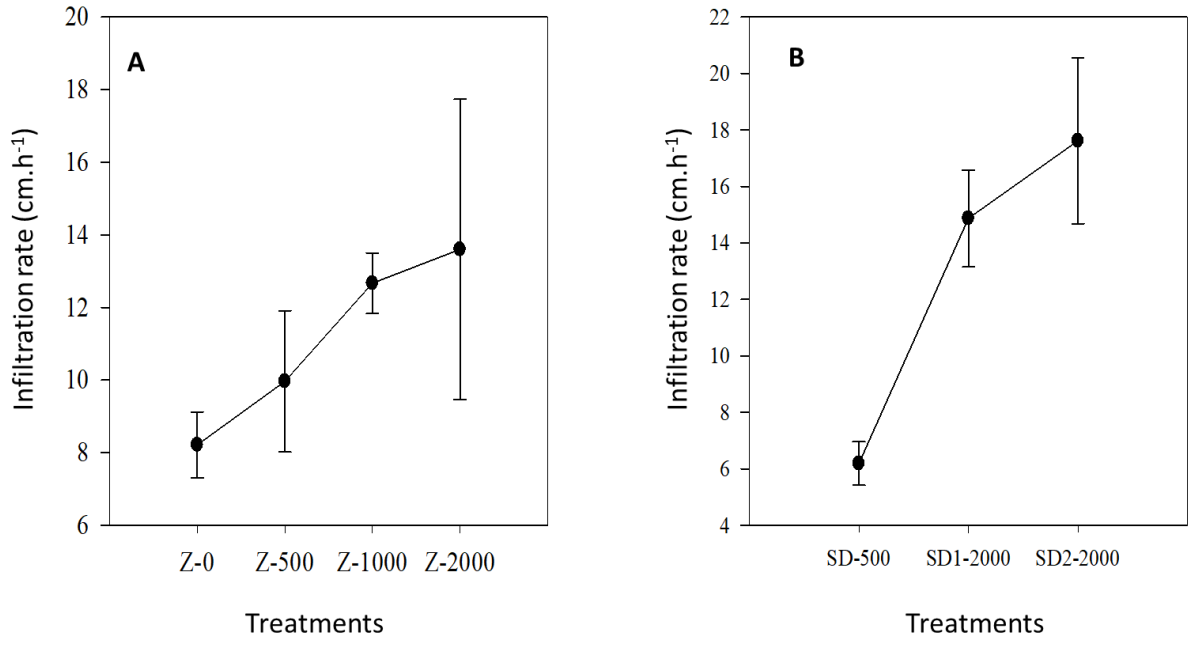


Figure 1: Effect of shrub density (0, 500, 1000 or 2000 stands per ha) on infiltration rates measured in the Kamboinse station plots, conducted either under zai seeding (Z - A) or direct seeding (SD - B).

In Mali as well, we tested the effects of mulching prunings of *Guiera senegalensis* J. L. Gmel, Piliostigma reticulatum (DC.) Hochst and Gliricidia sepium Jacq. Walp (during 3 years at 2.5t/ha) on soil water infiltration rates. The lowest rate was recorded on the plot with no prunings (control) at 0.16 cm/min., and the highest on the plots with Guiera senegalensis prunings and Gliricidia sepium prunings at 0.22 cm/min. for both (Figure 2).

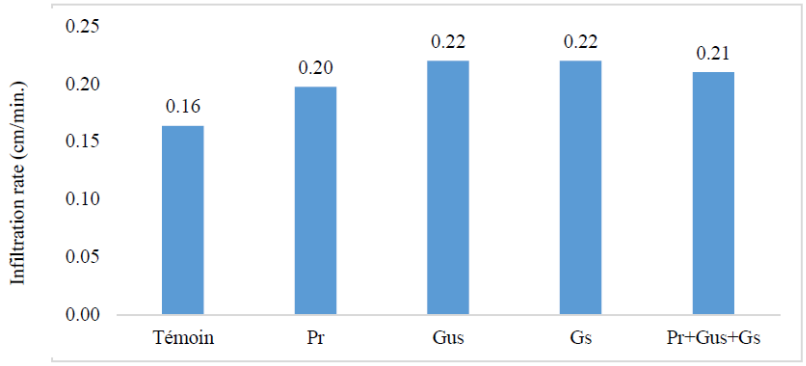


Figure 2. Effect of mulching prunings of shrubs on soil infiltration rate in Mali. Témoin=Control, Pr=Piliostigma, Gus=Guiera, Gs=Gliricidia

In Sénégal, the effects of Faidherbia tree on soil surface hydraulic properties, has been analyzed in farmer fields studied by WP4 around Niakhar. The sampling included 20 trees distributed in 3 villages: Sanghaie (8 trees), Sob (6 trees), Diohine (6 trees), balanced between not pruned and pruned (no mulching), with 2 plots per tree (under and far of crown) and 5 replications per plot (automatic infiltrometers). Finally, 200 infiltrations measurements were performed between November and December 2023. The soils were sampled (0-15 cm) for measurement of initial water content before each infiltration (200) and for soil texture and bulk density for each plot (40). The data were analyzed using the BEST method.



Figure 3. a) Location of infiltration plots around Sob village; b) automatic infiltrations close to tree. W. Faye et al. 2024.

Globally, these various measurements indicated that the soil density was lower under tree (1.47 versus 1.52, $P<0.001$). Conversely, the tree management (pruning) had no significant effect (Figure 4).

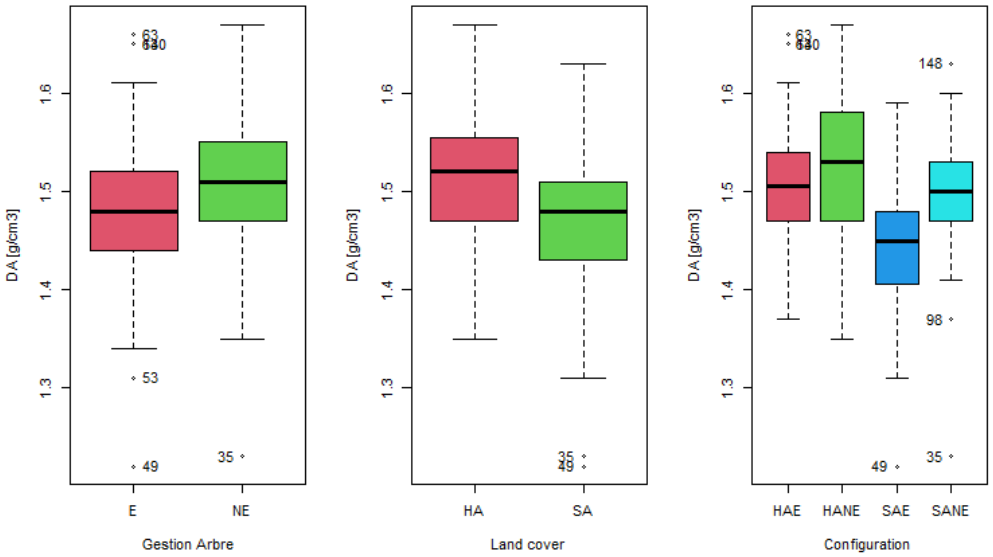


Figure 4. Soil bulk density according tree management, pruned(E) / not pruned (NE) and land cover, far to tree (HA)/close (SA).

In coherence with bulk density, the water infiltratration (saturated conductivity Ks) was found higher close to tree (0.176 against 0.133 mm/s, P <0.001 Figure 5)

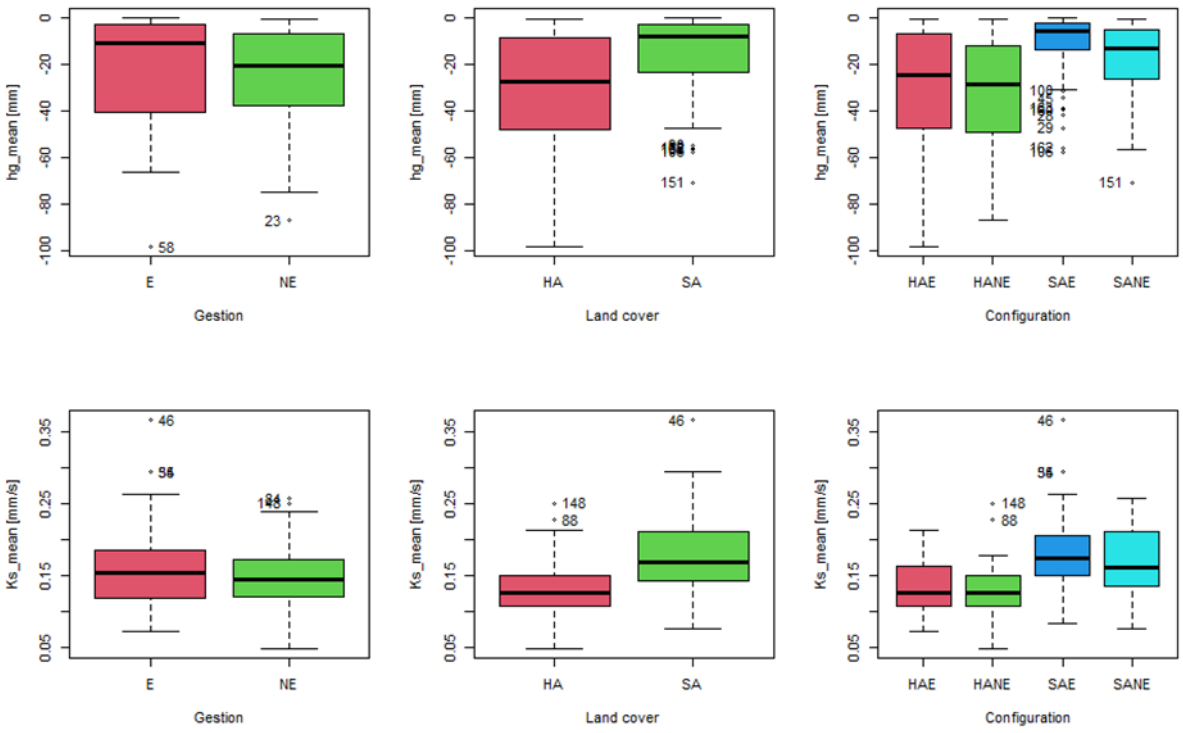


Figure 5. hydraulic parameters at saturation, scale of water pressure (Hg) and hydraulic conductivity (Ks) according tree management, pruned (E) or not (NE), and land cover, far to tree (HA) or close (SA).

Between sites/villages, there were no significant differences in terms of average hydraulic conductivity (Figure 6). A large variability of Ks was noticed in the field and also within plots in these very sandy soils (90 % Sand).

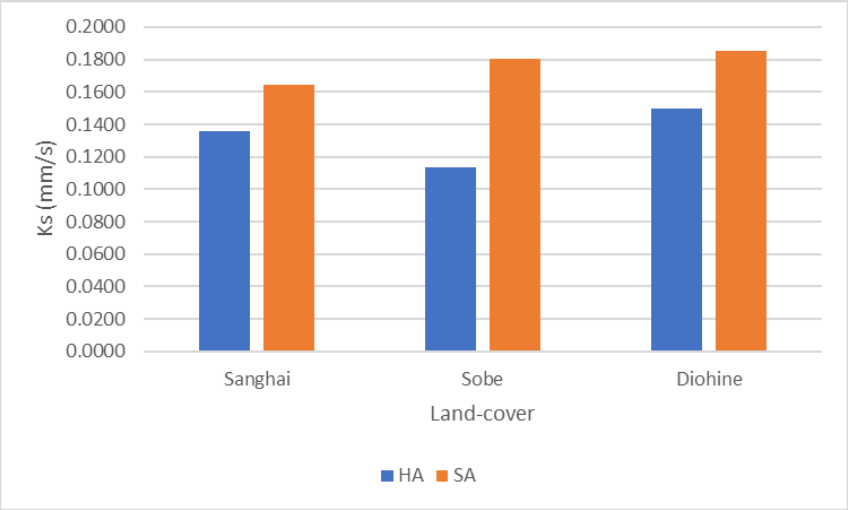


Figure 6. Hydraulic conductivity at saturation according sites/villages.

Also in Sénégal, in Faidherbia Flux station at Sob, similar trend has been observed with 6 plots and 3 measurements time (June, October, December 2022). The results showed a trend of slightly higher infiltration and saturated hydraulic conductivity (Ks) in plots closed to trees but no significant differences likely due to not enough replication versus variability (Figure 7).

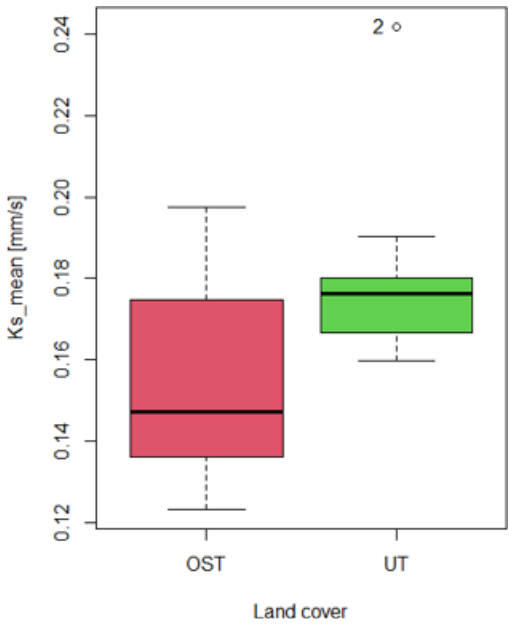


Figure 7. Saturated hydraulic conductivities measured in plots outside trees (OST) and under trees (UT) in Sob Faidherbia Flux site (W. Faye et al., EGU 2023)

Soil water dynamics and profiles

Differences in infiltration rates induced by tree presence of mulch treatment are expected to influence soil water dynamics during the season. As an example to illustrate this, **in Mali**, in the Koulikoro site, the effect of ligneous material mulch application on soil moisture content under sorghum crop has been assessed by classical gravimetric method (Figure 8).

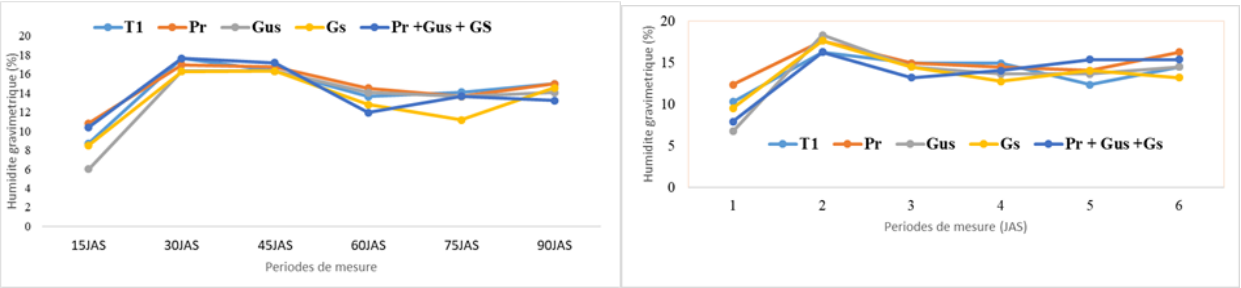


Figure 8. Soil water content at 20 cm depth (left) or 40 cm depth (right) in control conditions (T1) or in the presence of mulch from *Piliostigma reticulatum* (Pr), *Guiera senegalensis* (Gus), *Gliricidia sepium* (Gs) or a combination of 3, at different days after sowing (JAS).

Very interestingly, lower-than-control water content in top horizon and higher-than-control in deep horizon in observed under mulch during the three first sampling dates, an effect which tends to vanish afterwards. This is coherent with a better infiltration under mulch in the beginning of the rainy season.

In a different context, the effect of a shea tree (*Vitellaria paradoxa*) agroforestry system on soil moisture and maize (*Zea mays*) production potential was tested in the Sudanian zone of Mali. The experiment was conducted in the Zoumanana-Diassa area, in the village of Nagnassoni (11.5200 N; 005.657 W, 351 m). We tested the combination of distance to tree and wind exposure on water profile evolution throughout the season (Figuire 9).

Measurements were taken twice a week from the time the tubes were installed until the corn was harvested. The water available to plants across the soil profile (i.e. every 10 cm to the maximum tube depth) was calculated as the difference between the soil water content measured at a given time across the profile and the soil water content at the wilting point.

The main results obtained from monitoring water profiles show that at the surface (10 cm depth), soil water content is variable and influenced by the rainfall regime. Soil water content in the opposite direction to the wind and at the tree crown boundary (Sens_Opp_V_LH) is fairly high until August, followed by rapid drying out from September onwards. On the other hand, soil water content is at its highest at the surface of the canopy and in the direction of the prevailing wind (Sens_V_LH_) in October, when maize completes its vegetative cycle. Soil water content decreases towards the end of the season, drying out more rapidly at the crown edge than at the surface (10 cm deep).

Interestingly, at depth (60 cm and +1m), the trend is for higher soil water content at the crown edge (under tree influence) than outside the crown. At the end of the season, water dries out more quickly outside the canopy than at the canopy edge at soil depth. These results further illustrate the effect of tree on preferential water infiltration and storage.

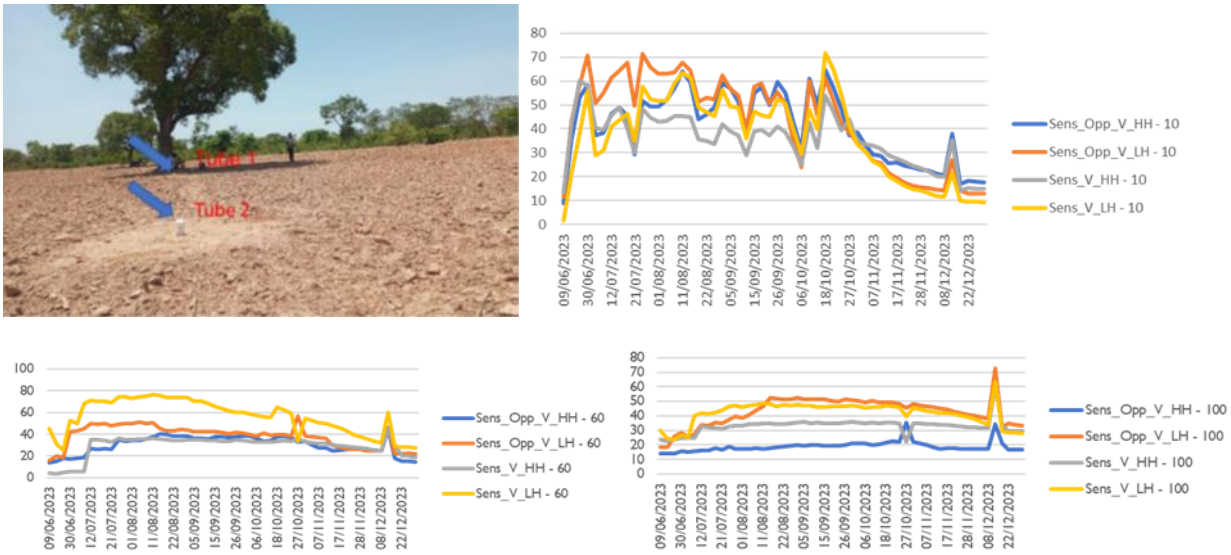


Figure 9. Soil moisture measurement across the rainy season with 4 tubes inserted to 1.60 m depth with the following characteristics: tube 1, installed at the edge of the shea tree crown/shoot and following the prevailing wind direction (Sens_V_LH); tube 2, installed at twice the radius of the crown/tree in the direction of the prevailing wind (Sens_V_HH);- tube 3, installed at the limit of the crown/tree crown of the shea tree and in the opposite wind direction (Sens_Opp_V_LH); tube 4, installed at twice the radius of the crown/shoot in the opposite direction to the wind (Sens_Opp_V_HH). Results at 10cm, 60cm and 1m depth are shown.

In **Senegal**, at the Faidherbia Flux site, the soil water content also tends to be higher close to trees in rainy season (Diongue et al. EGU 2021, Figure 10).

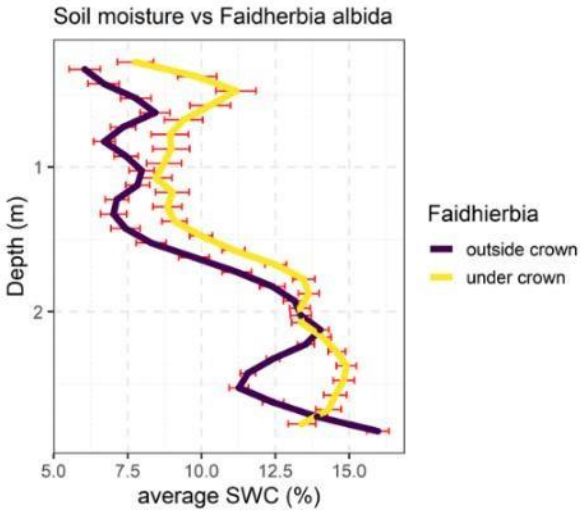


Figure 10: Change in average soil moisture content (SWC) (%) with depth (m) outside and under the crown of *F. albida*. TDR pico probe, 6 Tecanat access 3 m tubes.

Manual Beerkan versus automated infiltrometer

Soil infiltration rates were measured with the Beerkan method illustrated below, which is light and easy to apply and is also used in the Biofunctool kit. In Senegal, we have also tested an automated Beerkan setup in order to intensify the data acquisition for more in-depth studies.

To test the performance of Beerkan manual measurement versus automatic infiltrometer in these sandy soils, an extensive comparison has been made at the soil surface (Lassabatère et al. EGU 2024). The results show similar infiltration parameters and supports the interest of Beerkan manual measurement when easy setup is required such as in Biofunctool.

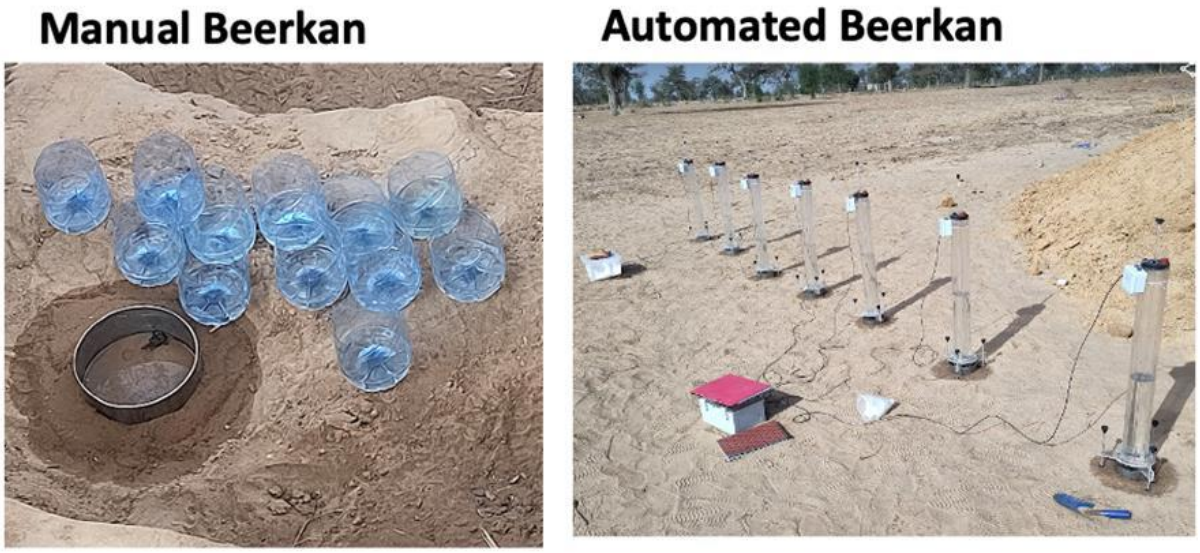


Figure 11: Photo of the material used in the classical Beerkan method (left), and automated setup tested in Senegal (right)

2.1.2 Preferential infiltration after stemflow

A specificity of rainfall capture under trees and shrubs is the fact that a substantial amount of water intercepted by the crown reaches the soil by sliding on the trunk, which is called stem flow, and can generate preferential infiltration along collar and vertical coarse roots. An experiment of simulated stem flow was performed dry season (December) 2022 in Faidherbia-Flux site. The infiltration of 40 L in two pulses has been followed by ground penetrating radar (GPR) around a Faidherbia tree and monitored over time on a grid set (Figure 12). Such a protocol allows to reconstruct water content in 3D and its temporal evolution. The data provided evidence of deep preferential infiltration along collar and proximal roots (S. Talla et al. EGU 2023). This infiltration is spatially very narrow, just under the tree, and difficult to catch by classical measurements « close to the tree ». Such a phenomenon significantly increases infiltration in agroforestry plot and should be taken into account.

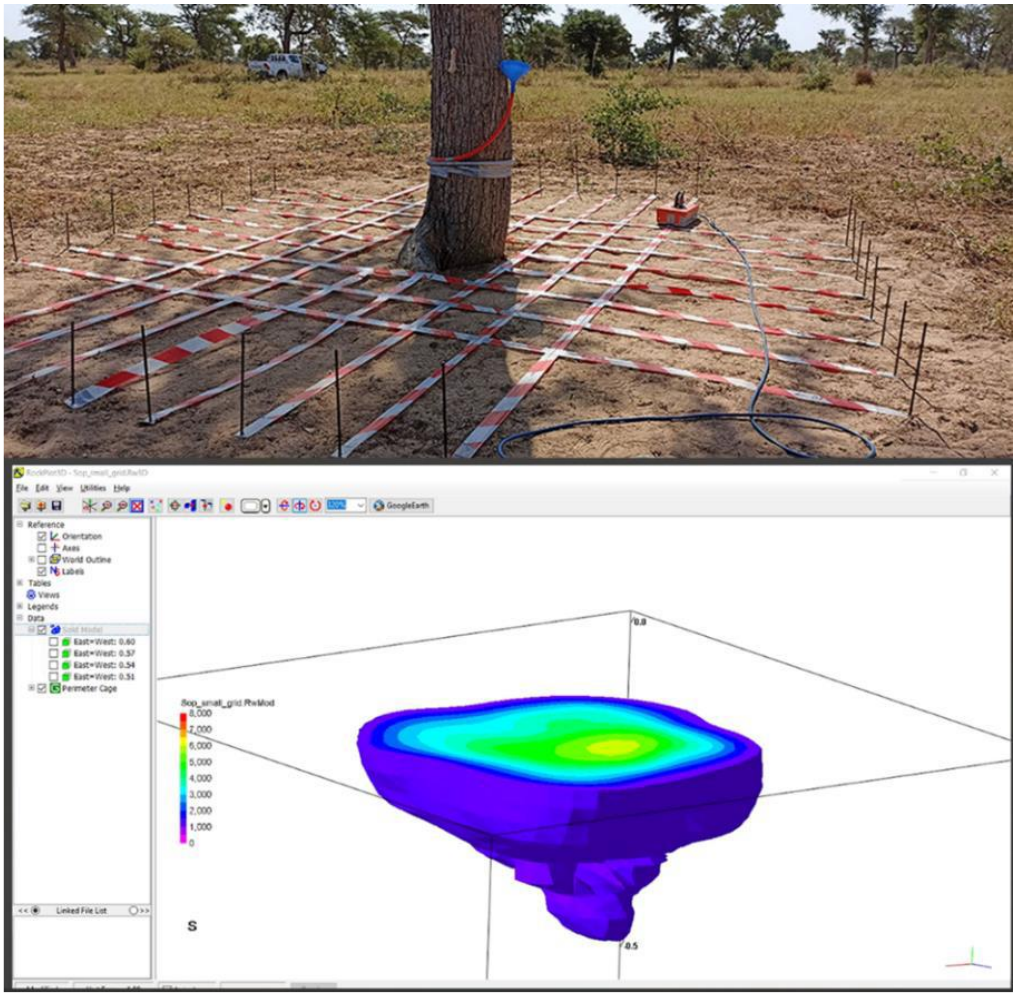


Figure 12: Ground penetrating radar time-lapse analysis of water infiltration experiment in Sob Faidherbia Flux site (S. Talla et al., EGU 2023), showing preferential infiltration along main root axis

2.2. Root hydraulic redistribution

The root hydraulic redistributions (RHR) are one of the expected effects of trees and shrubs on surface soil surrounding crops, particularly in dry conditions. RHR is a passive water movement through roots induced by a gradient of soil water potential between roots located in wet soil horizon to roots located in a dry horizon. The most known case is the hydraulic lift. This process could provide beneficial agronomic effects by increasing surface soil water availability for crops, but is particularly difficult to detect. Its existence has been shown with *Piliostigma reticulatum* and *Guiera senegalensis* in the Sahel but never with *Faidherbia albida* trees. We have investigated this phenomenon in Faidherbia-Flux site by looking for both 1) reverse flow in lateral roots (i.e. towards the soil) and 2) soil water content increase in the night with the « Hydroseve » experimental equipement.

2.2.1 Roots location

As a phreatophytic species, Faidherbia tree is assumed to have bimorphic root system with superficial lateral roots and deep tap roots down to the water table which should facilitate hydraulic lift. In Faidherbia Flux site, deep root scanners set up in wells confirmed the location of fine roots just above the water table 5 m deep. Surface soil Samplings showed the location of FA roots in the 30-150 cm depth horizon even 20 m far from trees (Siegvaart et al. 2023).

To have a complete picture, a ground penetrating radar (GPR) has been used in partnership with LEHNA laboratory of Lyon (T. Winiarski et al.) to map coarse roots over the Faidherbia-Flux site. From 23/06 to 01/07/2023 an intensive experiment applied a GPR with 400 MHz antenna over an area of 240 m x 130 m with 10x10 m crossing lines (Fig.13a). A Msc Student (Mame Diarra Fall) advised by Axel Tcheheumeni Djanni (UCAD) is completing the data analysis. First results (25 transversal profiles) shows 1) a maximum depth of measurement about 3 m according the radar configuration; 2) 3 soil layers, with an intermediate layer between 1 and 2.5 m of higher density with changing depth according the slope and 3) many detected roots (coarse roots, > 2 cm of diameter) even far from trees, even in locations estimated "out of tree influence" (Fig.13b), and vertically preferentially located above the intermediate soil layer, with a root average depth of 0.9 m. These results confirm and extend the previous results from destructive samplings. The importance of the field colonization by surface lateral roots is a new insight which should change our view of the area of tree influence.

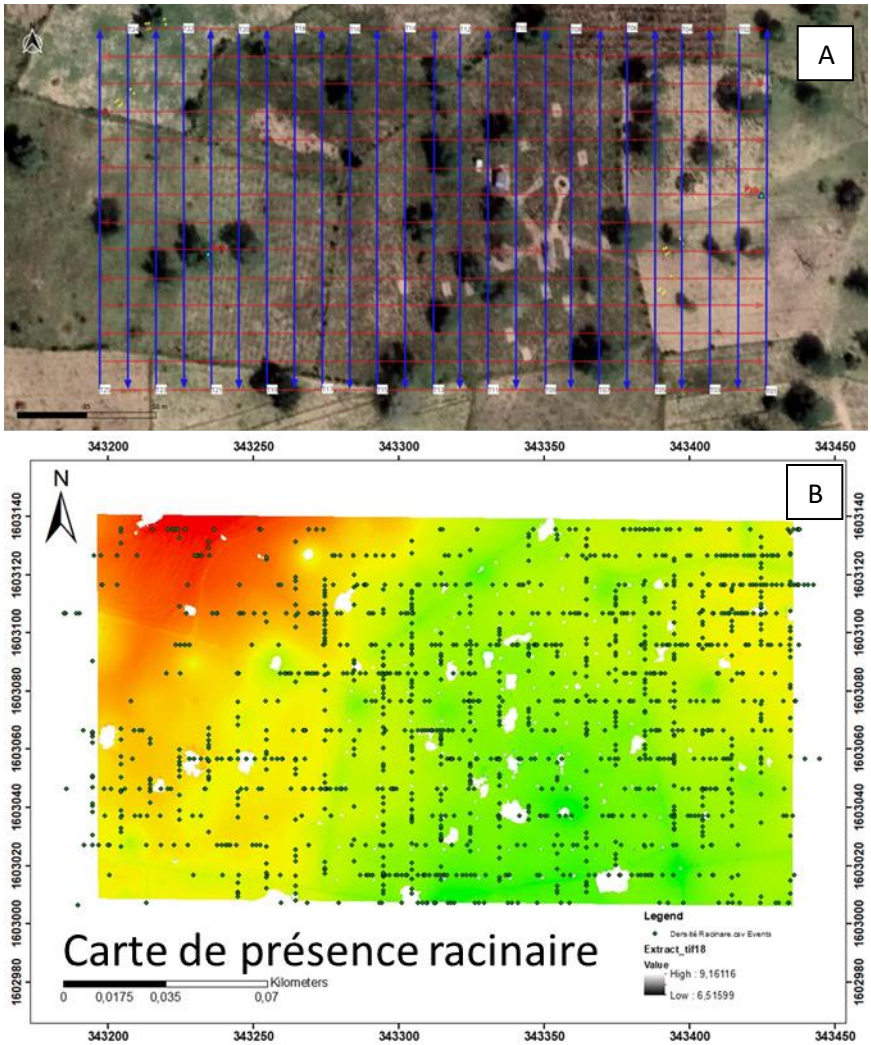


Figure 13. Mapping of coarse roots detected by GPR in Faidherbia Flux site. A) 10x10m grid of scan lines over an area of 240x130 m area; B) Map of coarse roots (>2 cm diameter) detected above 3 m depth. The white shades are tree crowns (Mame Diarra Fall 2024).

2.2.2 Root Reverse flow assesment

Measurement by thermal dissipation needles

To measure the intensity and flow direction in proximal roots, we used the Transient Thermal Dissipation (TTD) signal (Do et al. 2002, 2011) with a physical harmonic solution based on Fourier analysis (De Sousa et al. 2020) and applied to a three needles configuration (Fig.14) The whole experimental design includes 5 trees with 4 proximal roots equipped per tree (2 lateral/horizontal and 2 tap/vertical roots).



Figure 14. Sapflowmeter probes inserted in a proximal lateral root of Faidherbia albida. Three needles configuration with one central heater (Granier type needle) and two surrounding thermocouples 8mm apart.

In lateral roots, the results in dry season generally showed a progressive decrease of positive intensity (I.e. flux towards trunk), annulation and appearance of small negative values (i.e. flux towards soil) as in Figure 15 below.

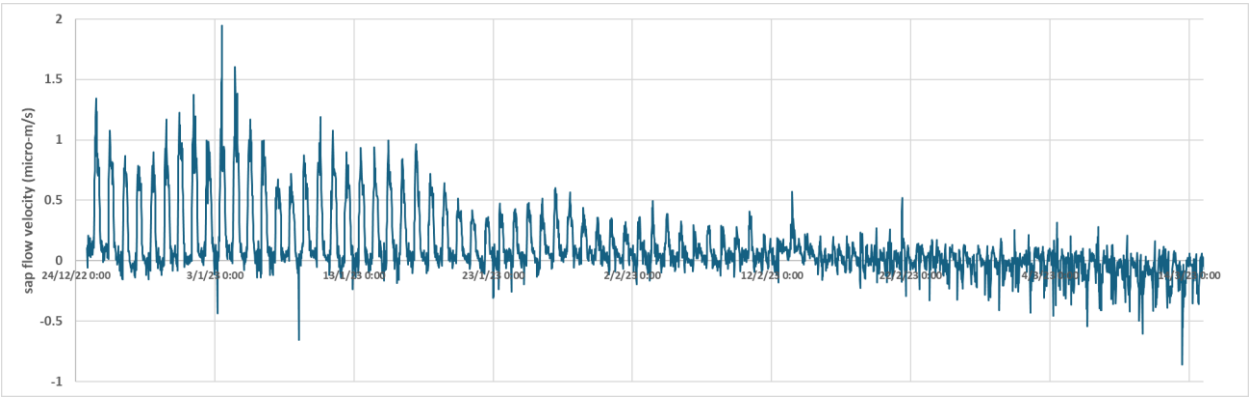


Figure 15. Seasonal course of sap flow velocity (mm/s) measured by directional TTD with harmonic solution in proximal lateral root of Faidherbia albida in dry season (December to March), corresponding to the previous Figure.

This observation of reverse flow in roots supports the existence of hydraulic redistribution in Faidherbia albida tree. However the values are small and of variable intensity between lateral roots and above all the sign of the flux strongly relies on the zero flux reference which is recorded every night from the maximum signal. However, this assessment is not very accurate and based on hypotheses which can be challenged.

Measurement by non-invasive TIMFLOW prototype

The assessment of zero flow without cutting the stem or knowing the exact thermophysical properties of the system is a dilemna for all current methods of sap flow measurement.

To assess zero and negative flow, we have developped a new mobile device without invasive needles which combines heat pulse from a microwave antenna and an infrared camera to follow the heat dissipation according space and time. The plot of the peak position of the heat wave versus time allows to estimate the heat velocity which is directly related to the sap flow velocity. The prototype TIMFLOW has been published in January 2024 (Louche et al. 2024). After several testing, its successful use in dry season 2024 has confirmed the existence of reverse flow in the proximal lateral roots of Faidherbia (Fig. 16).

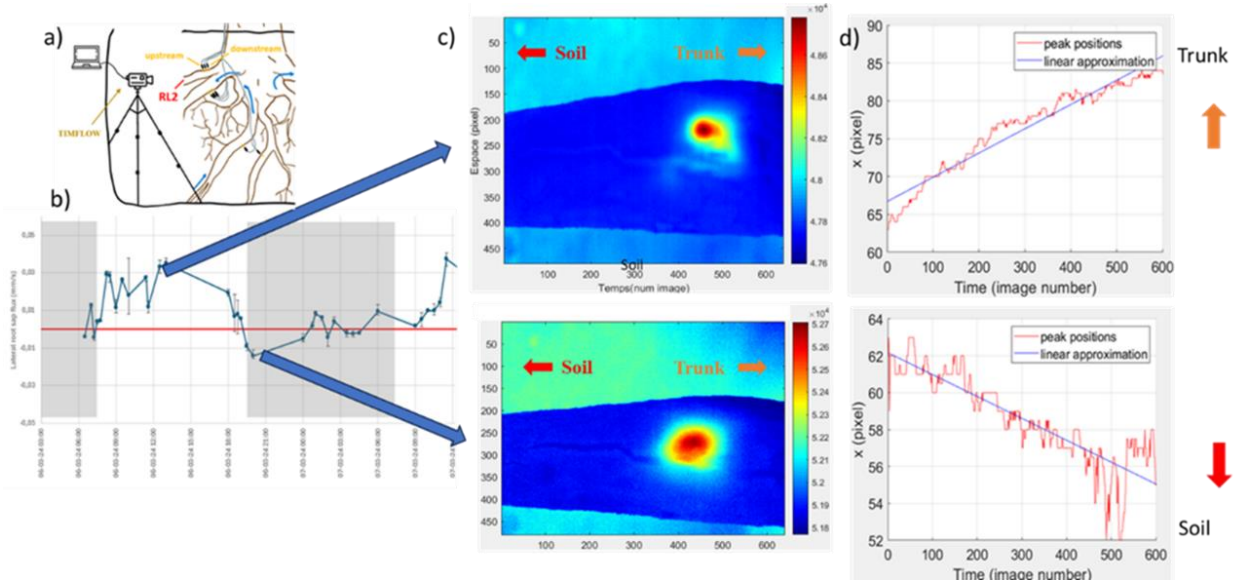


Figure 16. Daily dynamics of the heat pulse velocity induced by sap flow in a lateral root of Faidherbia albida using the TIMFLOW device in March 2024. a) experimental scheme, b) daily kinetic of the heat pulse velocity with negative phases in the night (towards the soil); c) thermal imaging after heat pulse; d) regression of heat pulse peaks to calculate velocity (S. Fauconnier et al. 2024)

The assessment of reverse flow in lateral root by two independent methods strengthens this result.

2.2.3 Nighttime Water release in soil

The study of potential water release by roots in soil within 24 h cycle was investigated by different approaches: profiles of automatic probes of soil humidity (CS655) and soil water potential (TEROS21) set up in 3 wells down to the water table, mobile TDR probe (TRIME pico) in access tubes, and gravimetric measurement after soil coring at three depths (20 and 60 cm with 3 replications, 100 cm without replications) in 3 zones with different situations (under tree cover, out of tree cover). The signals of dielectric probes appeared correlated to temperature at the intra-daily scale and did not reveal reliable trends. Only the gravimetric measurements showed significant changes in several situations (Fig. 17).

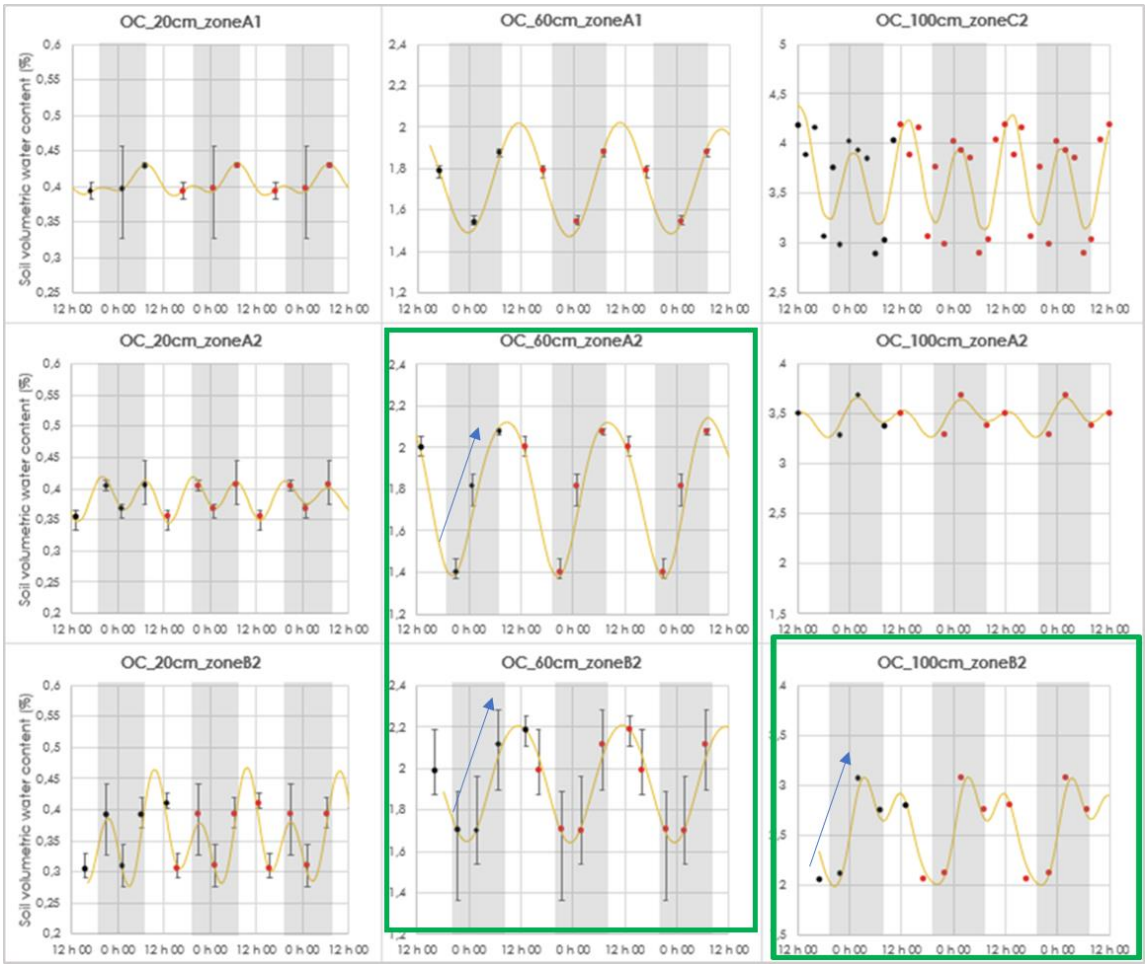


Figure 17. Soil volumetric water content fluctuations over 24 h (black dots) within "out of cover" (OC) situation measured by gravimetric methods across different zones and depths. Red points are extrapolated over three days and approximation using Inverse Discrete Fourier Transform. Grey areas represent nighttime periods. The numbers next to each zone denote the measurement campaign. S. Fauconnier et al. 2024.

Nighttime increases were noticeable, reaching +0.5 % at 60 cm and +1.0 % at 100 cm. Integrated in water stock for the 0-100 cm layer these increases may correspond to 1 mm/day depending situations, which corresponds to substantial impact compared to the components magnitude in the water balance. However these punctual measurements revealed large heterogeneity in space and in time and are difficult to extrapolate for reliable quantification without specific approach.

2.3. Water balance

The water balance assessment relies on the estimation of its different components: the soil water stock, the inputs as infiltration (rainfall-runoff) and the output as soil evaporation, trees and crops water use and drainage or ground water recharge.

The global water balance as measured in Sénégal by the Faidherbia Flux tower by eddy correlations and related set up has been described in the WP4 reports and deliverables. The report here mainly focused on the tree water relations followed by the "Hydroseve" equipements.

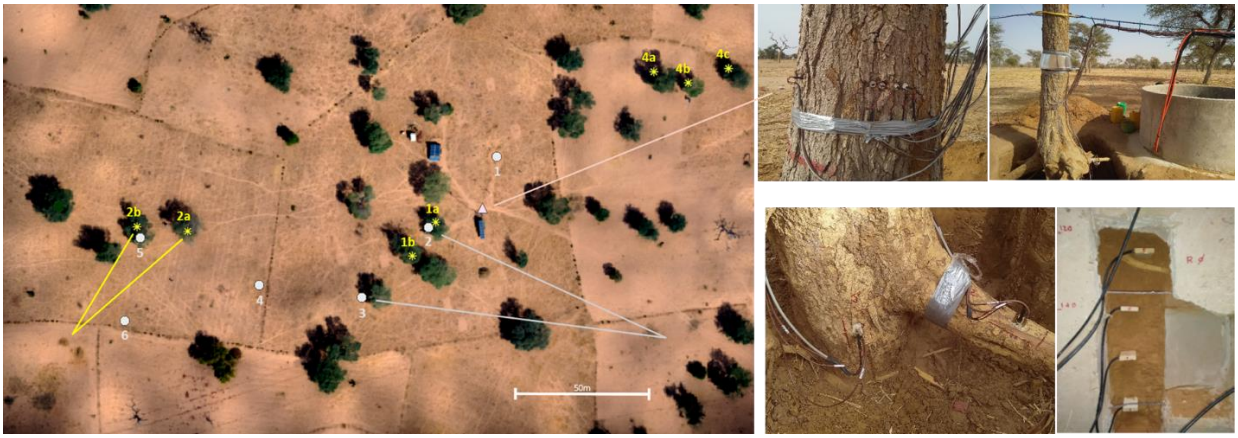


Figure 18. View of the Hydroseve set up of soil-tree water measurements in Faidherbia Flux Senegal site. With equipment of water measurements in soil (humidimeters, tensiometers and piezometers, 3 wells and 20 access tubes) and trees (sapflowmeters and humidimeters, 7 trees, trunks and roots). 150 automatic probes at 30 s time recording.

Data of soil water content and sap flow from 2019 to 2024 are available in Faidherbia Flux data base for soil water balance and modelling of WP4&WP7.

2.3.1 Tree water use

Measured xylem sap flow mainly represents tree water use, i.e. tree water uptake from the soil, induced by leaf transpiration and neglecting internal exchange due to tree water reserves.

Recorded Sap flows since 5 years illustrated a closed relationship with the inverted phenology of Faidherbia trees (Diouf 2020, Sarr et al. 2023, see Figure 19). Flux are minima in the rainy season but not null suggesting tree water reserve in play. They abruptly increase at the start of dry season with tree leaf flush and a sharp decrease of 0-2m soil water stocks. The sap flow maxima are reached between December and January. The values decrease towards the dry season with different shapes according year. The most abundant rainy season of 2022 with 824 mm is followed by a more belly shape suggesting a sensitivity of Faidherbia water use to rainfall variability despite it phreatophytic habit.

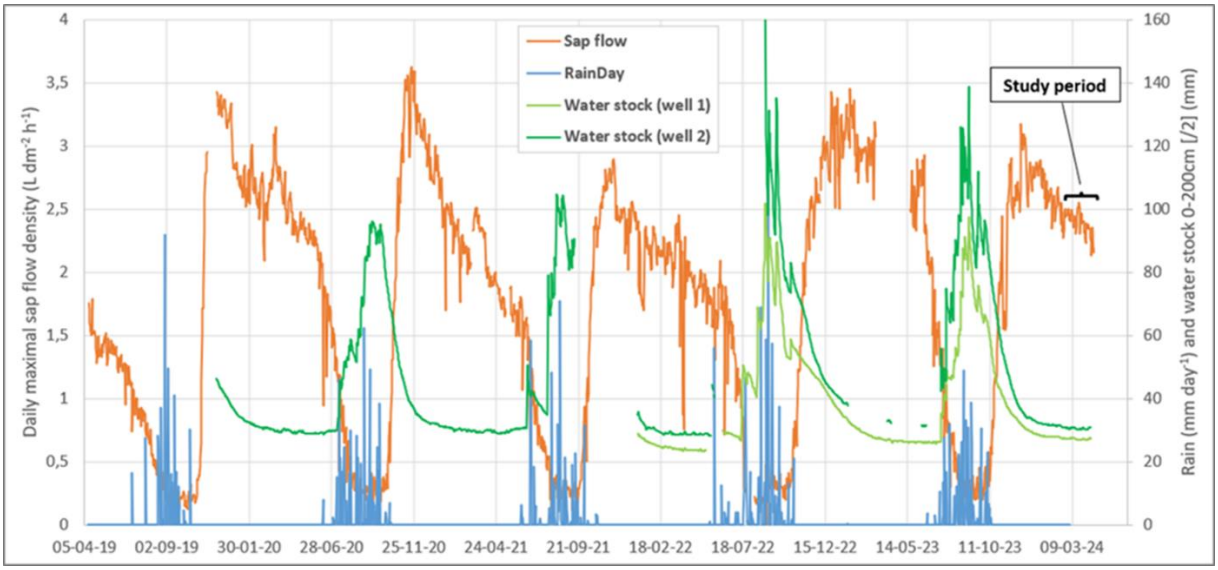


Figure 19. Seasonal course of tree daily maximum sap flow density (average of 7 trees), rainfall (blue) and 2 m depth water stocks (green) at Faidherbia Flux site. The outlined study period in 2024 corresponds to the intensive study of hydraulic redistribution by S. Fauconnier.

The low water use in rainy season confirmed the reduced competition by *Faidherbia albida* for water with crops. The maxima in dry season correspond to individual tree water use ranging from 100 to 300 Ld^{-1} according tree size.

The average annual water use is estimated around 40 000 L $tree^{-1}$ which is obviously large but the conversion at the scale of the soil area provides a modest 27 mm y^{-1} due to the relatively low tree density of 6.8 tree ha^{-1} measurer on a large scale. Just around the Faidherbia Flux tower, the tree density climbs up to 12.9 tree ha^{-1}. However in all cases these water use represents only between 5 to 10 % of annual rainfall. Knowing the positive effect of Faidherbia tree on crop productivity, a first conclusion would be to suggest an increase of tree density without risk for the soil water resource.

2.3.2 Soil Hydraulic parameters

First, soil hydraulic parameters in Faidherbia-Flux station were evaluated down to 2 meters by pedotransfert functions (PTFs) based on measurements of soil density, texture and carbon content, and by inverse estimation from the Hydrus-1D water balance model using Faidherbia-Flux data (Diongue et al.2022, Table 2). In both cases, the parameters are based on the Vangenuchten soil hydraulic model (1980).

Table 4. Comparing soil hydraulic parameters using various methods found in the Sahelian literature and in the present study. Values in parentheses are minimum and maximum values. θ_r is the residual water content, θ_s is the saturated water content, α and n are empirical shape parameters, K_s is the saturated hydraulic conductivity, and l is the tortuosity.

Methods	θ_s (cm^{-3} cm^{3})	α (cm^{-1})	n (-)	K_s (cm h^{-1})	Reference
In situ analysis (field drainage, infiltration test)	[0.28–0.40]	0.024	2.5	[0.4–0.9]	(Vachaud *et al.* 1978, Rockström *et al.* 1998)
PTFs	[0.36–0.40]	[0.020–0.024]	[2.7–4.1]	[6.1–7.3]	(Manyame *et al.* 2007, Abaker *et al.* 2018, Bogie *et al.* 2018)
	[0.32–0.48]	[0.036–0.124]	[1.5–2.3]	[0.4–14.6]	This study
Model calibration (SISPAT, SISPAT-RS, SWIM)	[0.27–0.30]	-	[2.1–3.7]	[0.2–24.5]	(Braud *et al.* 1997, Gaze *et al.* 1997, Braud 1998, Demarty *et al.* 2004, Velluet *et al.* 2014)
Inverse estimation (HYDRUS- 1D)	[0.27–0.23]	0.040	[3.7–2.8]	[0.3–0.4]	(Šimůnek *et al.* 1998)
	[0.29–0.45]	[0.006–0.020]	[1.8–2.4]	[2.1–5.3]	This study

Table 2. Soil Hydraulic parameters according Vangenuchten model from sahelian literature and Diongue et al. 2022 (table 4 in this study).

The estimations were completed by measurement in laboratory on undisturbed samples taken in the field at different locations and depth (down to 2.5m) in Faidherbia Flux site by combining the evaporation method (Hyprop) and measurement with psychrometer (WP4C) in the dry part of the retention curves (SAK. Faye et al. CID 2024). The results demonstrate a significant variability according depth and field location which has to be taken into account (Fig 20). Moreover, they show that the monophasic model of Vangenuchten (1980) which is commonly used in integrated models is not the most appropriated to simulate the dry part of curves in this sandy soil. The best fits were obtain with the bi-phasic model of Fredlung and Xing (1994).

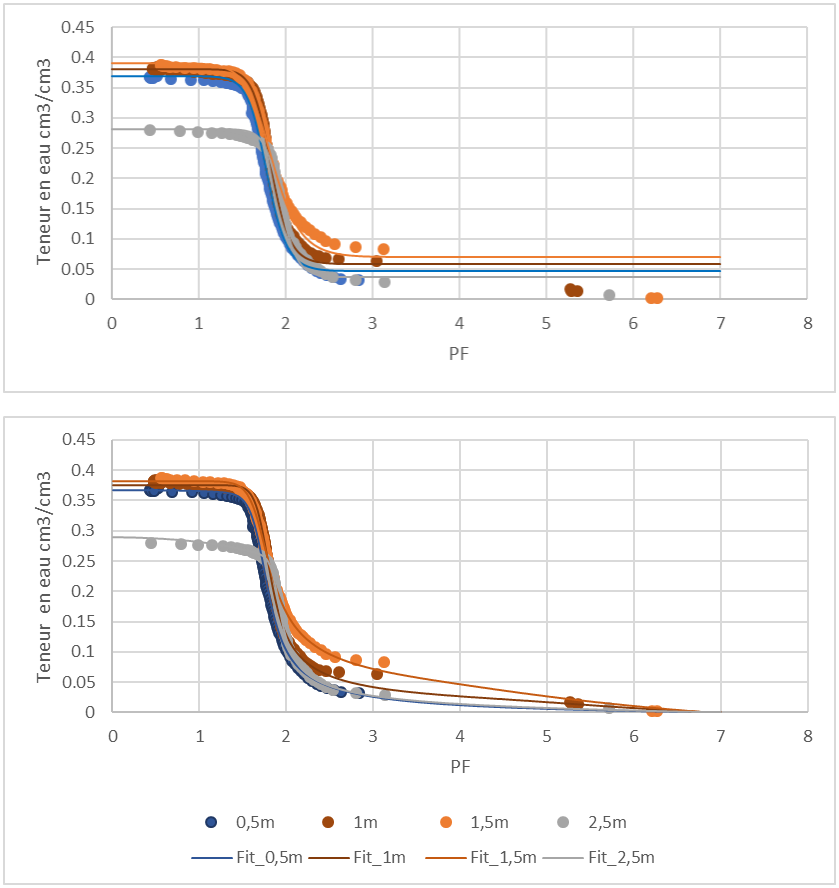


Figure 20. Soil water retention curves at different depths in Niakhar sandy soil (dots) and best fits according the models of A) Vangenuchten (1980) and B) Fredlung and Xing (1994), (S. Faye et al. 2024)

Both in the field and in laboratory soil volumetric humidity at 0.01 cm^3/cm^3 or 1% are regularly measured in this soil and the fits by Vangenuchten model cannot predict values below 0.03 cm3/cm3. Field capacity in sandy soils is usually estimated around pF2. The correspondances at pF2 in the retention curves of Figure 20 provides an acceptable range of water content between 0.1 and 0.15 cm3/cm3 for Field Capacity according depth.

The estimations of saturated hydraulic conductivity were displayed over a huge range of magnitude according methods: 0.1 cm h^{-1} in at 0.5 m and 0.01 cm h^{-1} at 1.5m in the laboratory experiment (S. Faye), to [2.5-5.3 cm h^{-1}] by water balance inversion (D. Diongue) and 55 cm h^{-1} by soil surface infiltration and BEST method (W. Faye). Indeed, the consequence on modeling should not be the same. The estimate from soil surface infiltration appears too high compared to previous field drainage experiment in Dior soil (Vachaud et al. 1978).

2.3.3 Soil evaporation and ground water recharge

In Sénégal, at Faidherbia flux site, stable-isotope approache(^{18}O) has been used to evaluate the components of the water balance (evaporation, transpiration, groundwater recharge) and their variability under canopy and outside canopy to decipher the tree influence along seasons (Diongue et al. 2023).

The isotopic signature separates two soil horizons: the shallow soil water horizon down to 170 cm with a complex signature under several influences (infiltration, evaporation, root hydraulic redistribution) and the deep soil water horizon with a very stable signature which is closer to the one of rainfall than to the one groundwater (Fig. 21). There is little influence of the distance to the tree on the profiles and by consequences on the components of the water balance. The large lateral and vertical soil exploration by the Faidherbia tree roots is likely involved. Despite sandy soil, the evaporation front reaches important depth as 40 cm. The existence of hydraulic lift challenges the interpretation of isotopic signatures and should likely increase the soil evaporation in dry season.

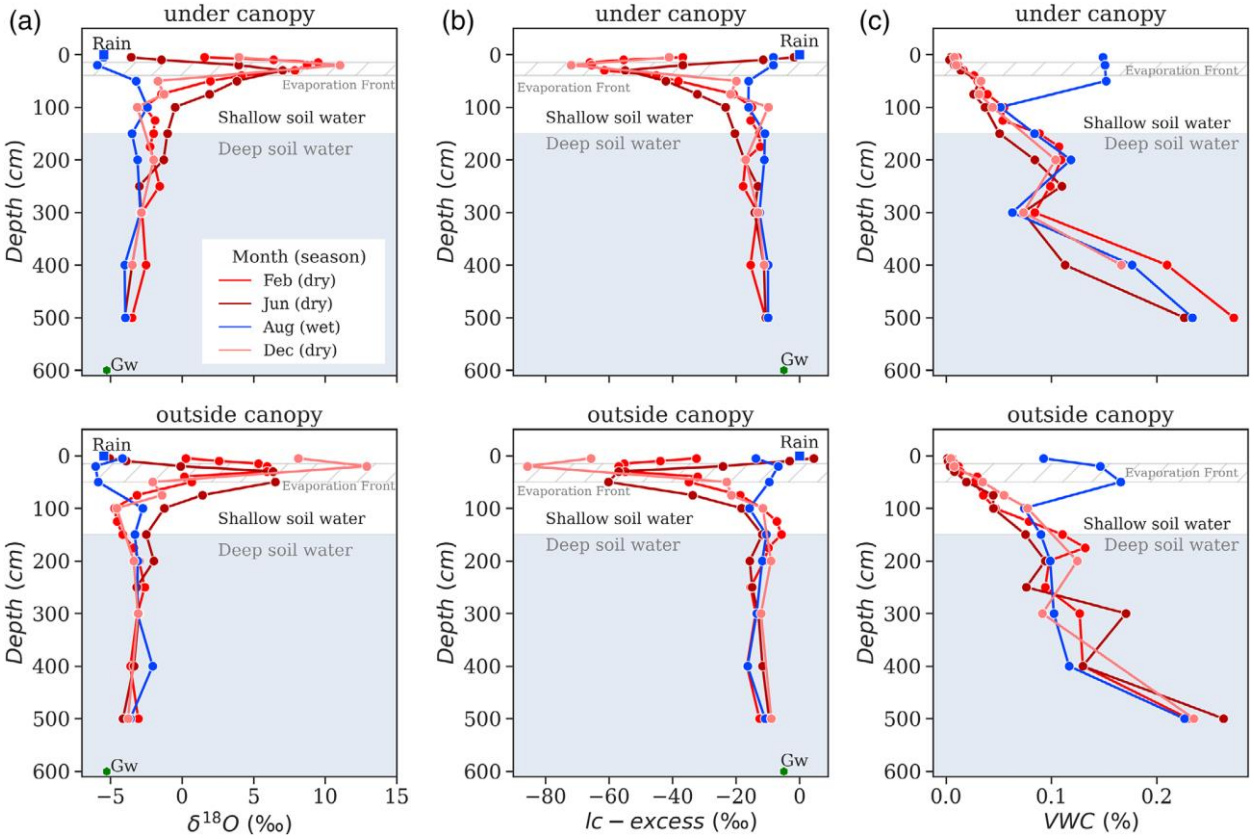


Figure 21. Profiles at the upper slope location in the Faidherbia-Flux station at Sob, of (a) soil water isotopic ratio ($\delta^{18}O$), (b) lc-excess, and (c) soil volumetric water content (VWC) for the indicated sampling months (seasons) under and outside the canopy of Faidherbia albida. Hatched areas indicate the evaporation-front depth intervals. Shaded grey areas represent the separation between the shallow and the deep soil water. In (a) and (b), the blue square indicates the amount-weighted mean composition of rainfall (rain) at the soil surface, and the green hexagon shows the mean isotopic composition of groundwater (Gw) at a depth of around 600 cm (Diongue et al. 2023).

The mean annual groundwater recharge has been estimated using stable isotope measurements and models (Figure 22). The annual groundwater recharge would be between 2 and 7 mm yr^{-1}, which represents around 1% of rainfall. This value is low and suggest that the main recharge of the water table (showing a 1 m seasonal amplitude on average) is coming through preferential pathways or lateral flow

mouvement as by infiltration in the edges of temporary ponds, not by the soil matrix. However, we may notice that according tree water use magnitude, an increase of tree density would likely impact the already low ground water recharge through the soil matrix. Knowing the soil and water salinity in the depth in Niakhar zone, the consequences of any recharge reduction should be studied with caution.

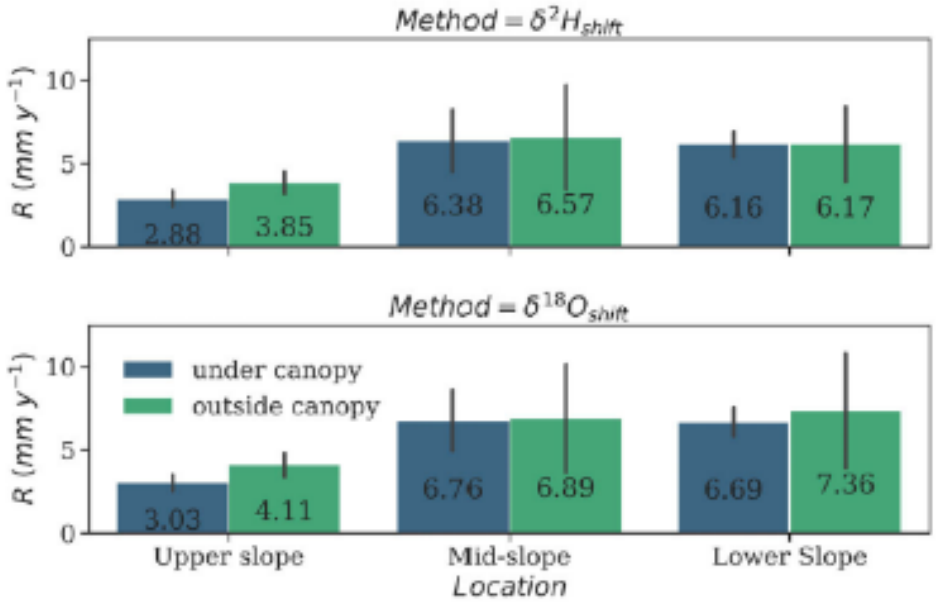


Figure 22. Mean annual groundwater recharge of the CT aquifer underneath and outside tree canopies at Faidherbia Flux Site, based upon analyses of the δ^2H_{shift} and $\delta^{18}O_{shift}$. Error bars show the standard deviation associated with each sampling period (February, June, and December). (Diongue et al., 2023a

2.3.4 Tree and Crop water stresses

Plant water stress is an indicator of induced water regime by trees for crops but also for trees themselves according climatic and seasonal conditions

In Burkina Faso, measurements of predawn leaf water potential were performed in experiments in Saria area (Figure 23). Indeed, predawn plant water potential tends to equilibrate with soil water potential as a result of stomatal closure during the night, and is therefore an indicator of the soil water status in the active roots area. Locally made hydraulic membrane pressure chambers were used for these measurements, as they are of low cost and do not need compressed gas logistics. The results showed that presence of shrub (Piliostigma or Guiera) consistently increased water potential in nearby sorghum when compared to crop outside of any shrub influence (Control). Application of shrub prunings as mulch had similar effects. This is in good agreement with previous observation of higher water contents in the area surrounding trees and shrubs.

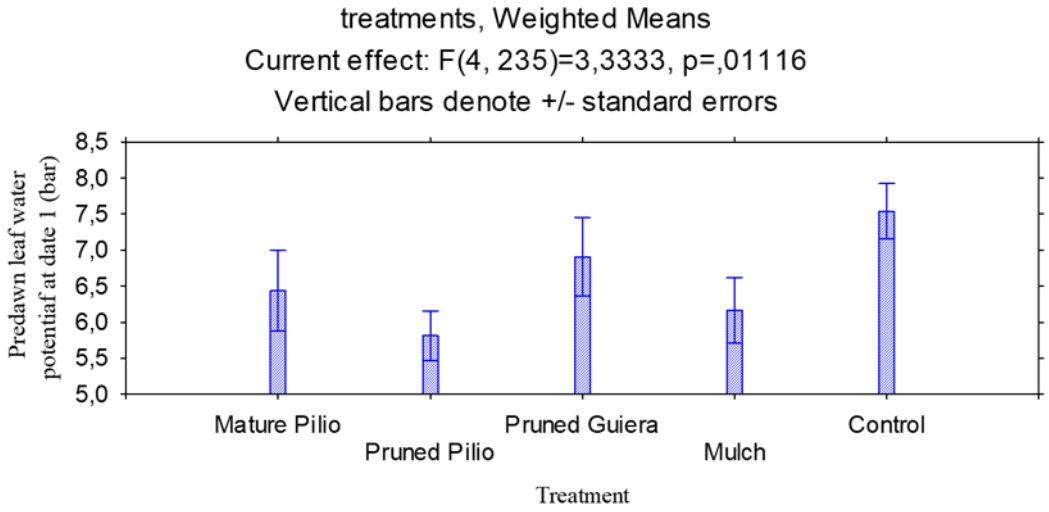


Figure 23: Predawn leaf water potential (bar) measurements in sorghum crops out of influence of shrubs (Control) or under the presence of *P. reticulatum* or *G. senegalensis* shrub, with different management options (pruned, unpruned (mature), mulched).

In the Faidherbia parklands of the Niakhar area, such positive effect of tree vicinity on millet predawn leaf water potential was also observed. In the figure 22 below, extracted from Clermont-Dauphin et al. (BASE 2023 which gathers data from 68 plots scattered in 5 villages, we can see that predawn water potential is higher in millet plots close to the tree than in open areas, both at beginning of rainy season and at flowering stage (Figure 24a, b). This translates into less water stress as illustrated by midday water potential (Figure 24 c,d) and this effect is particularly strong at the critical flowering stage. This is certainly one of the key determinants of the enhancement of grain and straw yields which is observed close to the tree in the majority of plots (Figure 22 e,f).

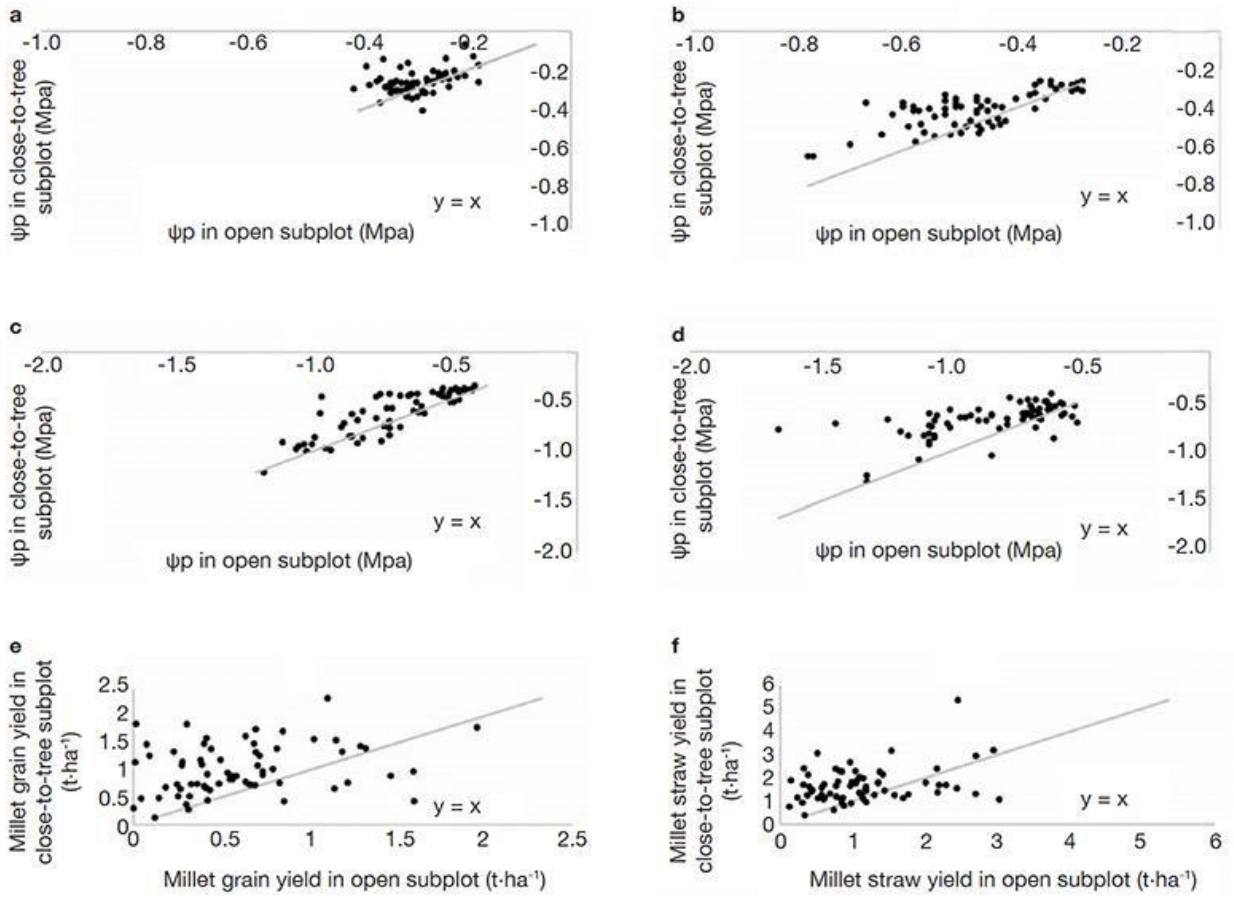


Figure 24. Pairwise comparisons of the following variables measured in open and close-to-tree subplots of five villages of central Senegal: **a, b.** Predawn leaf water potential of millet before and after millet flowering respectively; **c, d.** midday leaf water potential of millet before and after millet flowering respectively; **e, f.** millet grain and straw yield respectively. In a, b, c, d, each point is average of four repetitions collected in 68 pairs of subplot. In e, f, each point is from a 8 m² sampling area located in the center part of each subplot.

For Faidherbia trees in Niakhar, a moderate but significant water constraint was indicated by a decrease of predawn leaf water potential from -0.24 MPa in starting dry season (November-December) to -0.50 MPa in February despite the access to water table (Kh. Diouf 2020).

The dynamics of the reference canopy stomatal conductance at low air vapour pressure deficit of 1 kPa (no air dryness constraint) deduced from sap flow measurement (Phillips and Oren 1998) also supports a significant soil water constraint in mid dry season (February) compared to December with a 50% reduction (Do et al. 2022). The use of drone infrared thermography was also tested in Sénégal to catch indication of water status and transpiration regulation of trees and plants on a large scale versus soil water regime. Stomatal regulation under constraint increases leaf temperature by decreasing the cooling effect of transpiration. The quantification of canopies temperature through infrared imaging has required several sensitive methodological steps. But at the end, with the illustration of Figure 25, the results provide convincing information of existing variability between individual and between time.

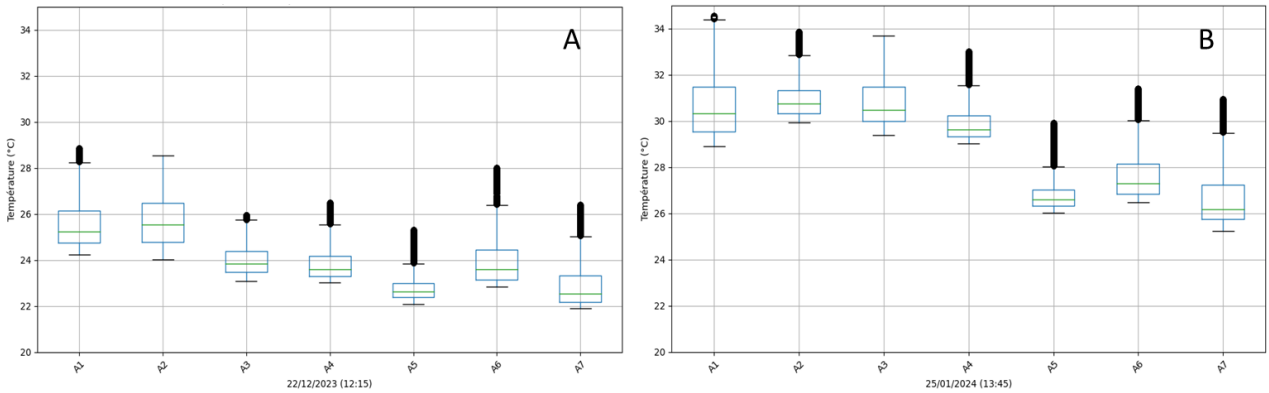


Figure 25. Midday canopy temperature of 7 Faidherbia trees in Faidherbia Flux site of Niakhar Sénégal as indicated by drone infrared thermography in end of December (A) and in end of January (B). Box-plots are descriptive of canopy pixels variation. (Mouhammed Dia et al. CID 2024).

The results also suggest an increasing water stress in the end of January versus December. However they were first results currently deepened by a second MsC 2 student.

2.3.5 Modelling

An expected output of all the previous detailed quantifications in Faidherbia Flux was to provide soil and plant water parameters to run integrated dynamic models at different scales which are taking into account tree effect (WP4, WP7). The work has started with HYDRUS, MAESPA and ORCHIDEE. The work with Hydrus (soil focus) is the more advanced with three publications, already used in previous interpretation of soil water parameterization (Diongue et al. 2022) and quantification of soil water balance components taking into account tree effects (Diongue et al. 2022, 2023a, 2023b). However substantial differences in results according modeling approaches and measurements suggest to focus on the quantification and modeling improvement of several processes as preferential infiltration, soil water retention and conductivity, soil evaporation and root hydraulic redistribution. Indeed, none of the current models applied is taking into account preferential infiltrations and root hydraulic redistribution. The inclusion of such processes is a priority of future modeling works.

2.4. General concluding remarks

Data obtained throughout the project at this stage, gathering several techniques to understand tree and shrub effects on soil water dynamics and several locations, yielded some consistent trends.

First of all, vicinity of trees or shrubs induced improvements of soil structure and porosity, inducing a general decrease in soil bulk density and increase in water infiltratration close to trees and shrubs. In some sites, this beneficial effect further induced a decrease or buffering of crop water stress at tree proximity. However, the differences between tree/shrub-influenced and control situations are variable between sites and systems and not always significant.

Concerning short term effects on the water balance and closer analysis of underlying processes, several insights were noticed in Faidherbia-Flux site, most of the being evidenced for the first time in the Faidherbia/crop system. Rain water preferential infiltration along coarse roots after stemflow was evidenced under the trees. Tree water use could also be estimated and reach up to 300 l/day per individual, with seasonal course highly related to the inverted phenology of Faidherbia. Despite annual water use estimated about 40 000 L/tree, it represents only 5 to 10% of the annual rainfall when the relatively low tree density is taken into account. Knowing the benefits of tree on crop productivity, this may suggest an

interest in increasing tree density without major risk for the water resource availability. However the estimated recharge of the water table as assessed through isotopes signature is low and of similar order than tree water use by the system. Hence an increase of tree density could have a significant impact on recharge and by the way possibly on related constraints such as salinity.

For the first time, root hydraulic redistribution has been evidenced under Faidherbia albida tree. The daily water increment at night can reach up to 1% at 100 cm soil depth. The phenomenon appears heterogeneous both in space and time. GPR scanning revealed that all the area of the field is colonized by tree superficial roots even at 20 m of trees and mainly located between 40 and 140 cm with an average around 90 cm: this distribution may have a major impact on hydraulic distribution, and also on tree/crop synergies or competition for resources. Knowing that root hydraulic redistribution has also been evidenced in the past on several sahelian species of the project as *A. tortilis*, *P. reticulatum* and *G. senegalensis*, our results with Faidherbia trees confirm the generality of the process and points out the interest in taking into account this mechanism in future modeling works.

The results and experiences developed in SustainSahel also provided some methodological advances which brought new insights in Sahelian systems. The impact of innovative tools or applications to assess water dynamics governing processes (sap flow measurements with TIMFLOW prototype, automatic infiltrometer, georadar) was significant in better understanding the Faidherbia/crop system where these tools have been implemented; it also revealed the harshness of conducting these field studies properly, which limits practical possibilities to extend to a diversity of fields. An other surprising observation brought by the use of GPR technology was that of the large tree root colonization in open spaces of Faidherbia-agroforestry systems, which somehow challenges the approach comparing plots close and far from trees to reveal the tree effects. Moreover, processes that occurred right under tree or shrubs collar as preferential infiltration seen by GPR, cannot be catched by classical measurements « close to tree ». Developments in soil water retention curves analysis on undisturber samples further stressed the importance and difficulty of modelling hydrodynamics of sandy soils.

All in one, these results validated the multi-scale and parallel approach adopted in this project, which combines simple indicators collection in the different sites, and comprehensive in-depth study of underlying processes in selected instrumented test sites, as a way to better appreciate influence if ligneous species on water dynamics and on crop response, in a variety of situations.

3. Dissemination activities related with the Deliverable

3.1 Peer-reviewed publications

2024. Louche H., A. Penarier, Ph. Nouvel, B. Clair, C. Coillot, F.C. Do, 2024. A new approach combining microwave heat pulse and infrared thermography for non-invasive portable sap flow velocity measurement. ***Agricultural and Forest Meteorology*** 347 (2024) 109896. https://doi.org/10.1016/j.agrformet.2024.109896

2023. Clermont Dauphin Cathy, N'Dienor M., Leroux L., Ba H.S., Bongers F., Jourdan C., Roupsard O., Do Frédéric, Cournac Laurent, Seghieri Josiane. (2023). Faidherbia albida trees form a natural buffer against millet water stress in agroforestry parklands in Senegal. *Biotechnologie, Agronomie, Société et Environnement*, 27 (3), en ligne [14 p.]. ISSN 1370-6233.

2023. Diongue D.M.L, G. Brunetti, C. Stumpp, F.C. Do, O. Roupsard, D. Orange, W. Faye, S. Sow, C. Jourdan, S. Faye. A probability framework for assessing the hydrological impact of Faidherbia albida in an arid area of Senegal. ***Journal of Hydrology*** 622(8) :129717. DOI : 10.1016/j.jhydrol.2023.129717

2023. Diongue D.M.L, C. Stumpp, O. Roupsard, D. Orange, F.C. Do, S. Faye. Estimating water fluxes in the critical zone using water stable isotope approaches in the Groundnut and Ferlo basins of Senegal. ***Hydrological Processes*** 37(1). DOI : 10.1002/hyp.14787

2023. Sarr M.S., K. Diouf , A. Rocheteau, O. Roupsard, D. Orange, C. Jourdan, I. Diedhiou, J. Seghieri, F.C. Do, 2023. Estimation of seasonal water use of Faidherbia albida (Del.) A. Chev in a Sahelian agroforestry parkland. Biotechnology, Agronomy, Society and Environment, 27(3), 196-204. DOI 10.25518/1780-4507.20512

2022. Diongue D. M. L, O. Roupsard, F. C. Do, C. Stumpp, D.Orange, S. Sow, C. Jourdan and S. Faye. Evaluation of parameterisation approaches for estimating soil hydraulic parameters with HYDRUS-1D in the Groundnut Basin of Senegal. ***Hydrological Sciences Journal*** 67(15). DOI : 10.1080/02626667.2022.2142474

2020. Faye W, Fall AN, Orange D, Do F, Roupsard O, Kane A, 2020. Climatic variability in the Sine-Saloum basin and its impacts on water resources: case of the Sob and Diohine watersheds in the region of Niakhar. *PIAHS*: Hydrological processes and water security in a changing world, 383, 391-399; doi: 10.5194/piahs-383-391-2020. https://piahs.copernicus.org/articles/383/index.html

2020. Faye W, Fall AN, Orange D, Fleury L, Do F, Jourdan C, Roupsard O, Kane A, 2020. Characterization of surface water-groundwater relations in an agrosystem with strong climatic constraints in the central-western groundnut basin : case of the Sob and Diohine watersheds in the Niakhar OPSE (Senegal). *Climat et Développement*, 2020, 29 : 36-46. (ISSN 1840-5452)

3.2. Communications in conferences

2024. Lassabatere L., D. Yilmaz, W. Faye, D. Orange, H. Aroui, D.M.L. Diongue, S-M. Saint-Louis, T. Winiarski1, B. Mourier, R. Angulo-Jaramillo1, S. Di Prima7, O. Roupsard, and F. C. Do. Manual versus Automated Beerkan run for characterizing the hydraulic properties of sandy soil in Senegal's Sahel. EGU General Assembly 2024 (oral com.)

2023. Diongue D.M.L., C. Stumpp, O. Roupsard, F.C. Do, D. Orange, C. Jourdan, S. Faye. Do the water table stable isotopes (18O, 2H) give insight into the hydrological impact of agroforestry systems ? The case of Faidherbia albida parklands in the Senegalese groundnut basin. 9th Friend-Water Global Conference, 25-29 September 2023, Dakar , Senegal, Oral com. ST1.

2023. Talla S., W Faye, G. Fernandez, L. Lassabatere, R. Angulo-Jaramillo, O. Roupsard, S. Di Prima, F.C. Do. Evaluating stemflow infiltration through time-lapse ground-penetrating radar surveys on a

Faidherbia albida tree in Senegal's Sahel. EGU2023, 14-19 April, Vienna, Austria & Online (oral com.).

2023. Faye W., Orange D., Do F.C., Jourdan C., Roupsard O., Fall A.N., Kane A., Di Prima S., Angulo-Jaramillo R., Lassabatère L., 2023. Caracterizing soil hydraulic properties using best method in a semi-arid agrosystem parkland (the peanut basin of Senegal). 9th Global FRIEND-Water Conference, UNSECO, PHI, IAHS, IRD, Dakar, UCAD, 5-10 June 2023.

2023. Faye W., D. Orange, S. Talla, F. Do, C. Jourdan , O. Roupsard, A. Faty, A. Niang, A. Kane, S. Di Prima, R. Angulo Jaramillo, L. Lassabatère. Spatio-temporal analysis of soil surface hydraulic properties in a semi-arid agroforestry system of the Senegalese groundnut basin. EGU2023, 14-19 April, Vienna, Austria & Online (oral com.)

2022. Roupsard O., W. Faye, S. Sow, D.M.L. Diongue, D. Orange, F.C. Do, C. Jourdan, C. Stumpp, S. Faye. Inverted phenology of Faidherbia albida paced with the dynamics of the water table. 5th World Agroforestry Congress, July 17-20, Quebec city, Canada (oral com.)

2022. Do F.C., M.S. Sarr, K. Diouf, S. Sow, D. Diongue, A. Rocheteau, I. Diedhiou, J. Seghieri, G. Le Maire, O. Roupsard, 2022. Faidherbia albida transpiration and canopy conductance in a reference agroforestry system of West Africa. 5th World Agroforestry Congress, July 17-20, Quebec city, Canada (oral com.)

2022. Diongue D.M.L, F.C. Do, C. Stumpp, D. Orange, C. Jourdan, S. Sow, S. Faye, O. Roupsard. 2022. Comparing the performances of pedotransfert functions with inversely estimated soil hydraulic parameters in a deep cultivated Sahelian soil using HYDRUS-1D. EGU 2022, 23-27 May, Vienna, Austria & Online (oral communication).

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2020. Faye W., A.N. Fall, D. Orange, F. Do, C. Jourdan , O. Roupsard, A. Kane, 2020. Caractérisation des relations eau de surface eau souterraine dans un agrosystème à fortes contraintes climatiques du centre ouest du bassin arachidier : cas des bassins versants de Sob et de Diohine dans l'OPSE de Niakhar (Senegal). « 4th International conference hydrology of African large river basins » Friend/UNESCO/International Hydrological Program. Cotonou, Bénin 24-28 November 2020.

3.3 Posters in conferences

2024 Bazongo B., Clermont-Dauphin C., Hien M., Yelemou B. Influence des modes de gestion des arbustes sur la quantité du carbone labile et la vitesse d'infiltration de l'eau dans les parcelles culture du sorgho en zone nord soudanienne du Burkina Faso. 4ième Conférence internationale sur l'Intensification Durable des sols et agroécosystèmes en Afrique (CID 2024). 23-25 avril 2024, Dakar, Sénégal (poster S2-15)

2024. Dia M., A.H. Niang, S.M. Diène, A.A. Diouf, A. Audebert, O. Roupsard, M. Gueye & F.C. Do, 2024. Analyse thermographique infrarouge d'un parc à Faidherbia albida par imagerie drone. 4ième Conférence internationale sur l'Intensification Durable des sols et agroécosystèmes en Afrique (CID 2024). 23-25 avril 2024, Dakar, Sénégal (poster S4-16).

2024. Faye S. A. K., D.M. Diongue, H. Aroui, L Lassabatère & F.C. Do, 2024. Variabilité des propriétés hydrodynamiques des sols dans un parc agroforestier à Faidherbia albida – application de la méthode d'évaporation en laboratoire. 4ième Conférence internationale sur l'Intensification Durable des sols et agroécosystèmes en Afrique (CID 2024). 23-25 avril 2024, Dakar, Sénégal (poster S3-50).

2024. Mbaye A.A., I. Diop & F.C. Do, 2024. Automatisation du traitement des données de flux de sève pour le boitier autonome TTD+. 4ième Conférence internationale sur l'Intensification Durable des sols et agroécosystèmes en Afrique (CID 2024). 23-25 avril 2024, Dakar, Sénégal (poster S4-17).

3.4 PhD related

2024. Faye Lamine (2024-2027). Redistributions hydrauliques racinaires dans le système agroforestier à Faidherbia albida : existence, intensité et consequence sur la disponibilité en eau et les composantes du bilan hydrique du sol. ED Eau et Usage de l'Eau, UCAD de Dakar, Bourse IRD/ARTS, Directeur principal de these F.C.Do. Soutenance prévue en 2027.

2023. Talla Saidou (2023). Flux de sève et relations hydriques sol-arbre dans le parc agroforestier à Faidherbia albida: apport de l'analyse numérique et des mesures thermiques et électromagnétiques innovantes. ED Maths et Informatique, ESP/UCAD. Bourse IRD/ARTS, Directeur principal de these FC. Do. Résiliée au 15/01/2024.

2023. Diongue Djim (2020-2023). Partitionnement des flux d'eau dans le continuum sol-plant-atmosphère en milieu semi-aride – Apport de la modélisation et des approches isotopiques dans le Bassin arachidier et le Ferlo. Doctorat UCAD Edeque. Bourse UCAD et Ohmi Téssékéré. Co-encadrant avec comme encadrant principal O. Roupsard. Soutenue le 25/02/2023 (prix 2023 de la meilleure thèse de doctorat du Sénégal décerné par l'académie des sciences et techniques du Sénégal).

2021. Faye Waly, 2017-2021. Ecohydrologie du bassin arachidier (cas de Niakhar): dynamique de l'infiltration et modélisation hydrologique des aquifères superficiels dans un espace sylvopastoral. UCAD (Univ. Dakar); Bourse Ambassade de France au Sénégal. Dir. Sc.: Alioune Kane, Orange D., Awa Niang Fall.`Soutenance: Décembre 2021.

2024. Gnissien Moussa - Effets des modes de gestion des parcs agroforestiers sur les propriétés physico-chimiques et biologiques des sols et les rendements des cultures en zones nord-soudanienne et subsahélienne du Burkina Faso. Thèse soutenue le 5 Septembre 2024 à l'université Nazi Boni, Bobo Dioulasso, Burkina Faso

3.5 MSc related

2024. Fall Mame Diarra, 2024. Localisation des racines grossières et structures du sol par géoradar de surface dans un parc agroforestier à Faidherbia albida. M2 UCAD Geophysique, Dakar, Sénégal. Soutenance prévue juillet 2025.

2024. Mbaye Abdoul Aziz, 2024. Réalisation d'un package de traitement automatique des données de flux de sève obtenues avec la méthode à dissipation thermique transitoire. M2 ESP/UCAD Big Data &Intelligence Artificielle. Dakar, Sénégal. Soutenu le 11/11/2024.

2024 Faye Serigne Abdou, 2023. "Variabilité verticale des propriétés hydrodynamiques (conductivité et retention) dans un sol sableux suppose homogène". M2 UCAD Hydrogéologie, Dakar, Sénégal. Soutenance prevue fin 2024.

2024. Fauconnier Sébastien, 2023. Ecohydrology of a Sahelian woody species: Faidherbia albida. Assessing root hydraulic redistribution in the agroforestry parkland of Sob, Senegal. M2 Faculté des bioingénieurs, Université catholique de Louvain, 2024 (soutenu le 29/08/2024). Prom. : Vincke, Caroline ; Do, Frédéric. http://hdl.handle.net/2078.1/thesis:48229. Prix CERA 2024 du meilleur mémoire de la section Sciences de l'Environnement et des Forêts de l'UCL.

2024. Dia Mohammed. "Analyse temporelle de la température du couvert de Faidherbia albida à partir d'image thermographique infra-rouge aéroportée". M2 UCAD Informatique, Image, Modélisation, Dakar Sénégal. Soutenu le 20/07/2024.

2021 Masse Lucien. "Etude expérimentale et modélisation thermomécanique de la mesure de flux de sève par imagerie thermique". Rapport de stage de M1, Polytech Montpellier

2020. Majzels Achille. "Modélisation numérique du lien entre la vitesse d'une onde de chaleur et la vitesse du flux de sève dans les végétaux" Projet Industriel de Fin d'Etude (PIFE), Polytech Montpellier.

2020. Diouf Khalisse. Evaluation de la transpiration par mesure du flux de sève chez l'espèce agroforestière *Faidherbia albida* dans un site semi-aride du basin arachidier au Sénégal. Mémoire de fin d'études d'ingénieur agronome, ENSA de Thiès.

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