Estimation of seasonal water use of *Faidherbia albida* (Delile) A.Chev. in a Sahelian agroforestry parkland

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Description of the subject. *Faidherbia albida* is recognized as a promising agroforestry species. In agroforestry systems, tree water use (TWU) dynamics is a key component of its impacts on associated crop yield and the water balance. Little is known about *F. albida* water uptake while an estimation of the ecosystem water balance is crucial in the context of climate change.
Objectives. The aim of this study is to assess *F. albida* water use along a year and the implication of tree size, season and phenology.
Method. Five mature trees were selected in an agroforestry parkland in the groundnut basin near Niakhar village in Senegal to monitor sap flow. Tree water use (TWU) or (Q) was calculated and climate conditions, soil water content and leaf phenological phases were also continuously recorded.
Results. Results revealed a significant TWU variability between rainy and dry seasons and between leaf phenological stages. The maximal water use values were observed in the first part of the dry season between December and January, when the trees are in full leaf, with large between-tree variability, from 118 to 261 l·tree^{-1}·d^{-1}. The TWU slowly decreased during the dry season and reached minimal values during the leafless phase which takes place during the rainy season.
Conclusions. The average annual water use was estimated at about 40,000 l·tree^{-1}·year^{-1}, *i.e.* 27 mm·tree^{-1}·year^{-1}, which represents 5.3% of 2019 annual rainfall (513 mm). The significant relationship of TWU with leaf phenological phases ($R^2 = 0.81$) supports the possibility that a simple model can estimate the tree water use.
Keywords. Dryland, phenology, sap, density, transpiration.

Utilisation saisonnière de l'eau par l'arbre *Faidherbia albida* (Delile) A.Chev. dans un parc agroforestier du Sahel
Description du sujet. *Faidherbia albida* est reconnue comme une espèce agroforestière prometteuse. Dans les systèmes agroforestiers, la dynamique de l'utilisation de l'eau par arbre (TWU) est une composante essentielle de son impact sur le rendement des cultures associées et sur le bilan hydrique. On sait peu de choses sur l'absorption d'eau du *F. albida*, alors qu'une estimation du bilan hydrique à l'échelle écosystémique est cruciale dans le contexte du changement climatique.
Objectifs. L'objectif de cette étude est d'évaluer l'utilisation de l'eau du *F. albida* pendant une année et déterminer l'implication de la taille de l'arbre, de la saison et de la phénologie.
Méthode. Cinq arbres matures ont été sélectionnés dans un parc agroforestier dans le bassin arachidier à côté du village de Niakhar, au Sénégal, pour y effectuer les mesures de flux de sève. Le flux total par arbre (Q) ou TWU a été calculé et l'enregistrement des paramètres climatiques, de la teneur en eau du sol et des différentes phases phénologiques effectué.
Résultats. Les résultats ont révélé une variabilité significative de TWU entre la saison des pluies et la saison sèche et les stades de feuillaisons. Les valeurs maximales d'utilisation de l'eau ont été observées dans la première partie de la saison sèche, entre

261 l·arbre⁻¹·jour⁻¹. La variation de TWU était faible pendant la saison sèche, puis a atteint des valeurs minimales pendant la phase sans feuilles qui a lieu pendant la saison des pluies.

Conclusions. La consommation d'eau moyenne annuelle a été estimée à environ 40 000 l·arbre⁻¹·an⁻¹, soit 27 mm·arbre⁻¹·an⁻¹, ce qui représente 5,3 % des précipitations annuelles de 2019 (513 mm). La relation significative entre la consommation d'eau et les phases de feuillaison ($R^2 = 0,81$) suscite la possibilité d'un modèle simple qui permettrait d'estimer l'utilisation de l'eau par les arbres.

Mots-clés. Zone sèche, phénologie, densité, sève, transpiration.

1. INTRODUCTION

Faidherbia albida (Delile) A Chev. is a multipurpose tree in Sub-Saharan Africa providing many ecosystem services to rural populations (Hirai, 2017; Ereso, 2019; Sileshi et al., 2020; Lu et al., 2022). *Faidherbia albida* is a leguminous tree that belongs to the Fabaceae family and Mimosoidea sub-family (Santiago & Lambert, 2010). *Faidherbia albida* is leafless during the rainy season, which reduces competition with associated rainfed crops for water, nutrients and light in West African agroforestry parklands. Because it improves soil fertility ("fertility island" effect), it also substantially increases associated crop yield under its canopy (Louppe, 1990; Bayala et al., 2012; Sida et al., 2018; Roupsard et al., 2020; Clermont-Dauphin et al., 2023). Accordingly, tree density in *F. albida* parklands is an important determinant of associated crop production. However, estimation of the optimal density of trees requires understanding the patterns of the water flows, and specially the vegetation water use component. Unlike most of the other agroforestry trees species, *F. albida* is considered as a phreatophyte species that only uses a little amount of annual rainfall. Roupsard et al. (1999) estimated tree water use of a *F. albida* parkland cover in a Sudanese agroforestry parkland at about 4% of the total annual rainfall. This particular advantage in the Sudanese savanna may be different under drier areas within different local climate conditions and tree density.

In Sub-Saharan agroforestry systems, long term studies on tree water use dynamics are still scarce (Roupsard et al., 1999; Do et al., 2008). Especially, little is known about seasonal *F. albida* water use in Sahelian areas. As climate change impacts local precipitation patterns and water resources, complex water use strategies may be at play, especially for phreatophyte plant species. Intergovernmental panel on climate change (IPCC, 2021) expects deep changes in plant phenological cycles, with increase in photosynthesis, air vapor pressure deficit, and plant transpiration in Sub-Saharan tropical forests (Massmann et al., 2019; Adeyemi et al., 2020). In the Senegalese Sahel not only drier climate conditions but also soil salinization may be combined to affect *F. albida* water use (Faye et al., 2020). To optimize the management of *F. albida*, it is therefore important to better understand how this species responds to its local environmental conditions. Moreover, understanding *F. albida* contributions to the evapotranspiration component of the hydrologic cycle in agroforestry systems is crucial to optimize current and future management strategies of these systems according to current and future changes in soil water availability.

Several approaches are used to evaluate tree water use (Granier, 1985; Do et al., 2011). In this study, we used the xylem sap flow measurements to evaluate *F. albida* water use because it is an indicator of plant water use. It is a light-intrusive method that has been applied in many ecosystems and particularly in semi-arid woody species (Roupsard et al., 1999; Compaoré, 2006; Bayala et al., 2008; Do et al., 2008; Van den Bilcke et al., 2013; Awessou et al., 2017). We aim at quantifying *F. albida* water use during the rainy and the dry seasons in a *F. albida* agroforestry parkland in the Senegalese Sahel. Specifically, leaf phenology, tree transpiration dynamics, and their contribution to the water balance are investigated.

2. MATERIALS AND METHODS

2.1. Study site

This study was conducted from April 2019 to December 2020 in the intensive measurement "*Faidherbia* flux" site (Lat. N: 14°29'44.916" Long. W: 16°27'12.851") equipped with a 30 m tower for micro-meteorological sensors and the estimation of the Eddy covariance fluxes. The site is located in a 15 ha agro-silvo-pastoral *F. albida* parkland in the Peanut Basin at Sob village near Niakhar, in the West central ecoregion of Senegal (Tappan et al., 2004). The climate is semi-arid and Sudano-Sahelian in a sandy ferruginous tropical soil type (Tappan et al., 2004). Air temperatures average 29.8 °C and annual precipitation is about 600 mm with substantial inter annual variations ranging between 400 and 800 mm since 1960s (Lalou et al., 2019; Faye et al., 2020). Rainy season lasts four months between June and September. The study area is located less than 20 m above the sea level. Tree canopy is dominated by *F. albida* with a density of 6.8 tree·ha⁻¹ (Lericollais, 1972; Roupsard et al., 2020). For decades, it has been the object of permanent agro-silvo-pastoral practices

to feed the high densities of the Serer population (50 to 70 inhabitants·km⁻² in 1950 and around 300 today) (Pélissier, 1966; ANSD, 2023).

2.2. Plant material and device

We sampled five adults *F. albida* of representative sizes ranging between 31 and 66 cm of diameter at breast height (**Table 1**) on which sap flow was monitored.

The transient thermal dissipation (TTD) method with single probe was applied with a cyclical heating of 10 min or 600 s every 30 min (Do et al., 2011; Nhean et al., 2019).

The interpolation of temperatures before heating provides the baseline temperature. The temperature signal is the temperature increase after 600 s (T600). We assumed that the flux was reaching zero value each night and thus corresponds to the maximal temperature ($T600_0$) recorded in the night. The thermal index related to sap flux density (K1) is calculated using the following formula:

$$K1 = \frac{T600_0 - T600}{T600} \tag{1}$$

Single Granier needles with standard tip of 20 mm were used (UP Germany, Ibbenbüren) with a heating power of 200 mW. We applied the multispecies linear calibration provided by Isarangkool Na Ayutthaya et al. (2010):

$$SFD = 12.95 \times K1 \tag{2}$$
($n = 276$, $R^2 = 0.88$, RRMSE = 24.1%)

where SFD is the sap flux density expressed in Ldm⁻²·h⁻¹. Probes were inserted into the sapwood at breast height. Trunk observations and preliminary coring showed in the area a xylem depth around 12 cm whatever the trunk diameter with an empty or decaying wood heart. The xylem was divided into four bands of 3 cm width. Four to six probes, according to tree diameter, were inserted at different azimuths (east, west, north, south) in the outer band where the sap flux densities are usually the highest (**Figure 1**). The radial profile of sap
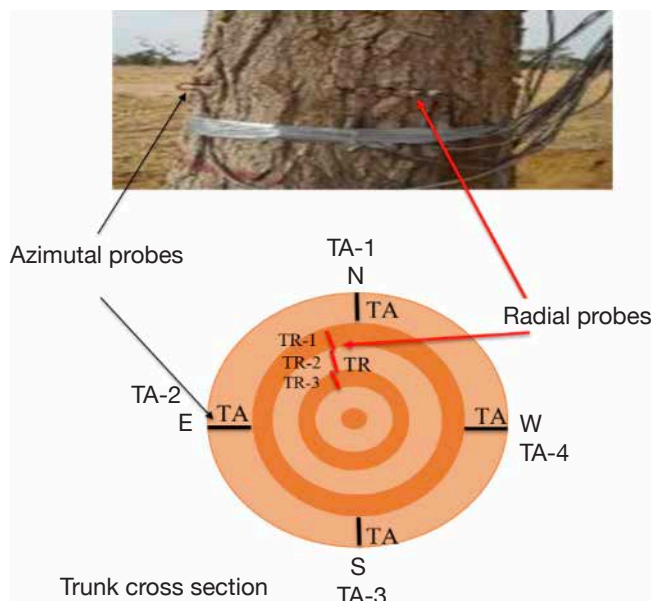

Figure 1. Sapflowmeter set up in trunks at breast height of the five *Faidherbia albida* trees (E: east, S: south, O: west, N: north, TA: azimutal probes, TR: radial probes) — *Installation de l'appareil du flux de sève à hauteur de poitrine des troncs des cinq arbres de* Faidherbia albida *(E : est, O : ouest, N : nord, S : sud, TA : sondes azimutales, TR : sondes radiales).*

flux density was assessed on the North azimuth with three additional probes located in the middle of each band of the inner xylem. The outer value was taken as reference and the radial profiles provided decreasing coefficients which were applied to the average outer SFD to calculate a weighted SFD. An aluminum foil collar was placed around the probe's installation section of the stem to avoid direct solar radiation.

2.3. Phenology monitoring

Leaf phenology was assessed according to Grouzis & Sicot (1980): visual observations were made every 10 days even during the rainy season, when *F. albida* loses its leaves completely. These following stages were considered:
0. leafless;
1. leaf buds opening;
2. start of leaf expansion on 10-50% of branches;

Table 1. Biometric characteristics of sampled *Faidherbia albida* (Fa) — *Caracteristiques biométriques des* Faidherbia albida (Fa) *échantillonnés*.

Tree characteristic	Fa5	Fa4	Fa27	Fa28	Fa46
Diameter at breast height (cm)	40.1	47.8	56.6	66.8	31.2
Mean bark thickness (mm)	14.5	20.1	18.6	16.6	16.6
Sapwood area (dm²)	9.5	12.0	15.4	19.2	6.0

3. leaves fully expanded on more than 50% of branches;
4. start of leaf senescence as indicated by color change on less than 50% of branches;
5. all leaves senescent or fallen on more than 50% of branches.

Each of these phenological stages was converted in percentages that is estimated visually for each tree and then averaged.

2.4. Soil water content monitoring

The volumetric soil water content was measured at 15, 35, 55, 75, 95, 115, 135, 155, 175 and 195 cm using automated Time Domain Reflectometers (TDR, type CS616, Campbell, USA, Logan), which were installed horizontally and calibrated with gravimetric water content and bulk density data.

The devices were connected to a CR1000 data logger (Campbell Sc, USA, Logan). The measurements were automatically recorded every 30 min. The soil water storage expressed in mm is obtained from the following expression:

$$R = Hv \times Z \qquad (3)$$

where Hv is the volume humidity of the soil (%) and Z, the soil depth (dm).

2.5. Calculation of transpiration

The water use per tree (Q) was calculated by multiplying the weighted SFD by the sapwood area. The values were averaged between trees to yield a mean flow for an "average" tree. Such a flow is assumed equal to water use or transpiration by neglecting change in water storage. Hourly sap flows were cumulated over 24 h to calculate daily transpiration in Lday^{-1}. To obtain convert in mm, the later value was divided by the average soil area per tree, estimated with the density of 6.8 trees·ha^{-1}.

2.6. Data recording and analyses

Meteorological data (relative humidity, photosynthetic active radiation [PAR], rainfall) were automatically measured and recorded every 30 min by the Eddy Flux Tower at 20 and 2 m heights. The vapor pressure deficit, VPD (KPa), is the difference between saturation vapor pressure (es) and partial vapor pressure (e) VPD (kpa) = es (kpa) - e (kpa) computed from air temperature T (°C) and relative humidity RH (%). Statistical analyses were performed using JMP Pro software, version 13.0. and homogeneity of the variances was tested with the Shapiro-Wilk normality and Bartlett test, respectively. If significant differences of analysis of variance were demonstrated, multiple comparisons were performed, using a Tukey Honestly Significant Difference (HSD) approach.

3. RESULTS

3.1. External and radial profile of sap flux density

During full leaf foliage in April 2019, the average external sap flux density reached 2 Ldm^{-2}·h^{-1} for tree Fa27 and Fa28 and 1 Ldm^{-2}·h^{-1} for tree Fa5 and Fa46. Between 12th and 15th April, the dynamics was the same between trees (**Figure 2a**). The SFD diurnal dynamics, both axial and radial, follow the PAR dynamics (**Figure 2b**). The analyses of variance showed significant differences of external sap flux density and radial profile between trees ($p < 0.05$).
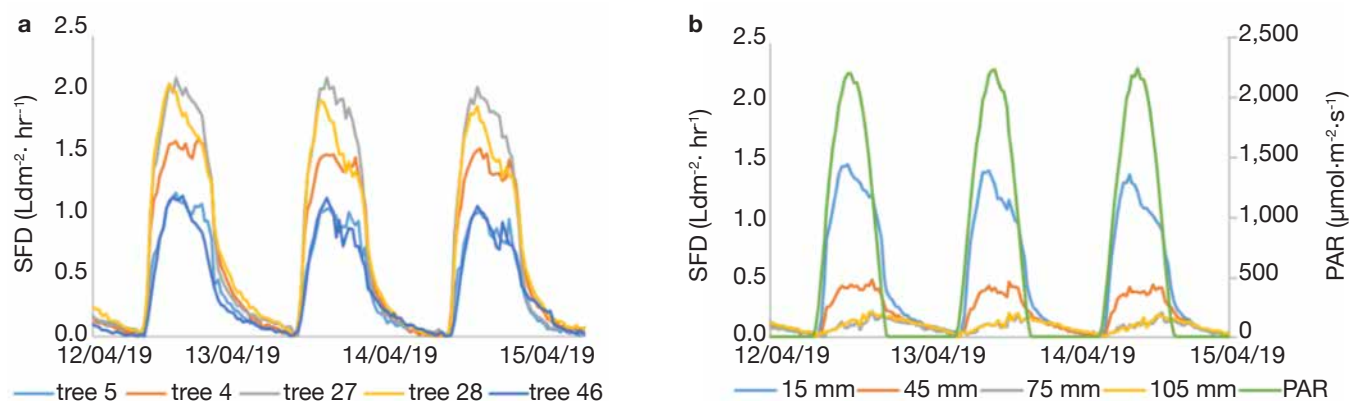

Figure 2. Patterns of sap flux density in the five sampled trees: **a.** averages per tree at the outest xylem location, **b.** total averages according location in the xylem radial profile (*i.e.* **Figure 1**) and Photosynthetic Active Radiation — *Cinétique horaire de la densité du flux de sève chez les arbres échantillonnés : **a.** moyennes par individu dans le xylème externe, **b.** moyenne totale selon la position dans le profil radial dans la profondeur du xylème (cf. **Figure 1**) et rayonnement photosynthétique actif.*

3.2. Seasonal variation of sap flux density, leaf phenology and meteorological conditions

All measurements started on April 2019 till December 2020, but leaf foliage assessment ended on June 2020. Rainfall in 2019 was late as for the two previous years, and scarce in the beginning before being more regular in late August. The total annual rainfall was 513 mm in 2019 and 599 mm in 2020. The soil water stock in the 2 m profile increased during the rainy seasons and reached higher values during September within the highest value in 2020 which lasted longer than in 2019. In contrast, the VPD, sap flux density, and leaf foliage increased during dry seasons and reached the lowest values in rainy seasons (**Figure 3**).

3.3. Correlation between tree water use and canopy leafing

Tree water use (Q) variation significantly ($p < 0.05$) depends on the stage of leaf foliation (**Figure 4**). The correlation coefficient is 81%.

3.4. Seasonal variation of tree water use between trees

The tree water use (Q) showed a clear seasonality and variation between trees (**Figure 5**). Tree water use follows the same trend for all trees as the mean average (Qd_mean). For all trees, higher Qd values are noticed at early dry season mid-November (100-300 l·day⁻¹) with a quick increase then a slow decrease during the dry season. *Faidherbia albida* Fa5 and Fa46 maintained water use lower than the mean average (Qd_mean) particularly during dry season both in 2019 and 2020. In contrast, Q was higher than the mean average for trees Fa4, Fa27 and Fa28. During the wet season, August to October 2019 and July-August 2020, Q was very low, close to zero.

4. DISCUSSION

We observed in this study large seasonal *F. albida* water use which strongly changes according to season, leaf phenology and VPD as previously revealed by Roupsard et al. (1999). Thanks to the monitoring of water use throughout the year, we measured that values rose from 7 l in September to 212 l in December and January. When trees completely dropped leaves, from July to September 2019, corresponding to the growing season for crops, the sap flow density was at the lowest value, but was not nil. This residual sap flow was likely due to bark transpiration as recently revealed in other deciduous tree species (*Anogeissus acuminata*, *Dipterocarpus tuberculatus* and *Tectona grandis*)

(Zafar & Kun-Fang, 2022). However, this has to be confirmed in the future in *F. albida*.

Furthermore, *F. albida* water use on average (7 l·day⁻¹) appears to be very small when compared to other dryland agroforestry trees such as *Vitellaria paradoxa* (26.8 l·day⁻¹) and *Acacia tortilis* subsp. *raddiana* (50 l·day⁻¹). Our results confirm Roupsard et al. (1999) ones. Thanks to its reverse phenology (leafing in dry season) compared to most of other agroforestry species, *F. albida* minimizes competition for water with associated crops. This contrast in terms of water use confirms *F. albida* advantage in dryland ecosystems.

The maximum sap flow density reaches on average ca 3.6 l·dm⁻²·h⁻¹, higher than in Sudanian (wetter) climate conditions (ca 2.5 l·dm⁻²·h⁻¹) for the same species (Roupsard et al., 1999) and much higher than other agroforestry trees species *V. paradoxa* (1.68 l·dm⁻²·h⁻¹) and *Acacia tortilis* (1.17 l·dm⁻²·h⁻¹) (Do et al., 2008; Awessou et al., 2017). The highest daily water use, 212 l on average, despite drier upper-soil conditions, is explained by higher atmospheric demand (VPD) in dry season combined with access to groundwater by *F. albida* (Roupsard et al., 1999).

However, despite strong relationship between water use and tree, observed by Awessou et al. (2017) on *V. paradoxa* and recently in a forest species *Populus tomentosa* by Zafar & Kun-Fang (2022) on fully irrigated tree species, the relationship between sap flow density and tree size in our study was not significant. But, as the sampling size was low (5), increasing tree sampling in future studies may give insight on whether or not tree size affects *F. albida* water use. Finally, the monitoring throughout the year allowed us to measure that *F. albida* annual water consumption reached on average 40,000 l·tree⁻¹ in 2019/2020, *i.e.* 27 mm according to the density of 6.8 trees·ha⁻¹. This value represented 5.3% of 2019 annual rainfall (513 mm) in our study site. It is close to the one reported by Roupsard et al. (1999) of about 4% (39 mm) of total rainfall amount, but with a tree density (23.9 tree·ha⁻¹) and annual rainfall (992 mm) which is higher than in our current study (6.8 tree·ha⁻¹). Hence, it seems important to take into account a possible trade-off between tree density, climate conditions, and *F. albida* water use. Therefore, more ecophysiological research is needed to depict the determinant factors in *F. albida* water use. The low tree water consumption during the associated crop growing season, the species significant nitrogen fertilizing effect that increases associated crop yield that was observed by previous authors (Louppe, 1990; Rhoades, 1995; Mai Moussa et al., 1999; Yengwe et al., 2018; Roupsard, 2020; Faye, 2022; Clermont-Dauphin et al., 2023) suggest that *F. albida* density can be increased and that an increase in crop yield can be expected as a consequence until a threshold to be determined. Moreover, tree density variation
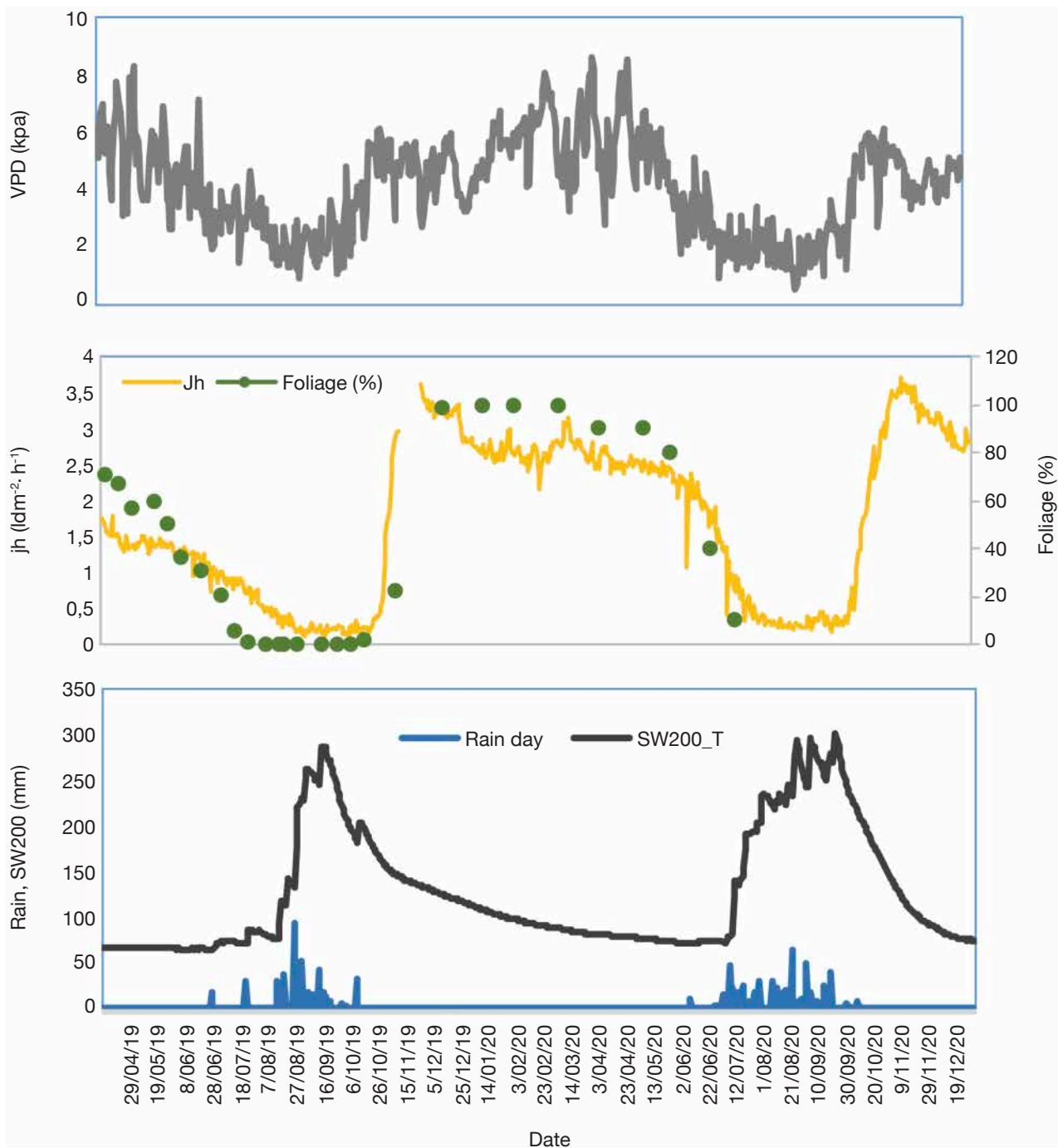
Figure 3. Seasonal variation of meteorological conditions (rainfall, vapor pressure deficit [VPD], soil water content at 200 cm depth [SW200]) and *Faidherbia albida* leaf foliage (%) and daily max sap flux density (Jh) in an agroforestry parkland in Senegal. Leaf phenology is average of leafing stage across the five trees — *Variabilité saisonnière des conditions météorologiques (pluie, déficit de pression de vapeur [VPD] de la teneur en eau du sol à une profondeur de 200 cm [SW200]), du stade de feuillaison de* Faidherbia albida *(%) et de la densité maximale de flux de sève (Jh) dans un parc agroforestier au Sénégal. Le stade phénologique est la moyenne entre les cinq arbres.*

changes water infiltration rate (Koala et al., 2021). It is possible that *F. albida* impacts the water cycle as tree transpiration and the water table recharge are in the same order of magnitude. Actually, tree water use only represents 5% of rainfall amount, but the direct water table recharge is also estimated at around 5% (data not shown). Therefore, tree water use may have an important impact on the recharge pathway. However, the main water table recharge pathway is supposed to be *via* the temporary watershed ponds because they alone could, through lateral transfer, be responsible of rapid water table recharge after the rainy season. These

give insights to fostering the desired balance between tree density and productivity in *F. albida* parklands in the future.

5. CONCLUSIONS

Unlike other agroforestry trees, *F. albida* uses less water during cropping season. This study revealed
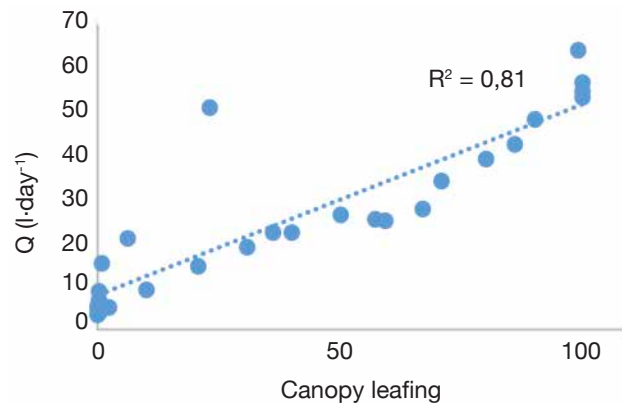

Figure 4. Tree water use (Q) *versus* canopy leafing (%) on average values between April 2019 and June 2020 2019 — *Utilisation de l'eau par arbre (Q)* versus *feuillaison (%) sur les valeurs moyennes d'avril 2019 à juin 2020*.

that *F. albida* annual water consumption was about 40,000 l·tree[-1] in 2019/2020 and only represented 5.3% of annual rainfall in the study site. This finding could lead to recommendations in terms of optimal tree density in agroforestry parklands. A strong relationship between total flow and phenology was found which implies leaf phenology as an important factor for this species transpiration in an agroforestry parkland. However, to accurately predict *F. albida* water use, it is crucial to further explore relationships between water use and tree size while considering a larger sampling size.

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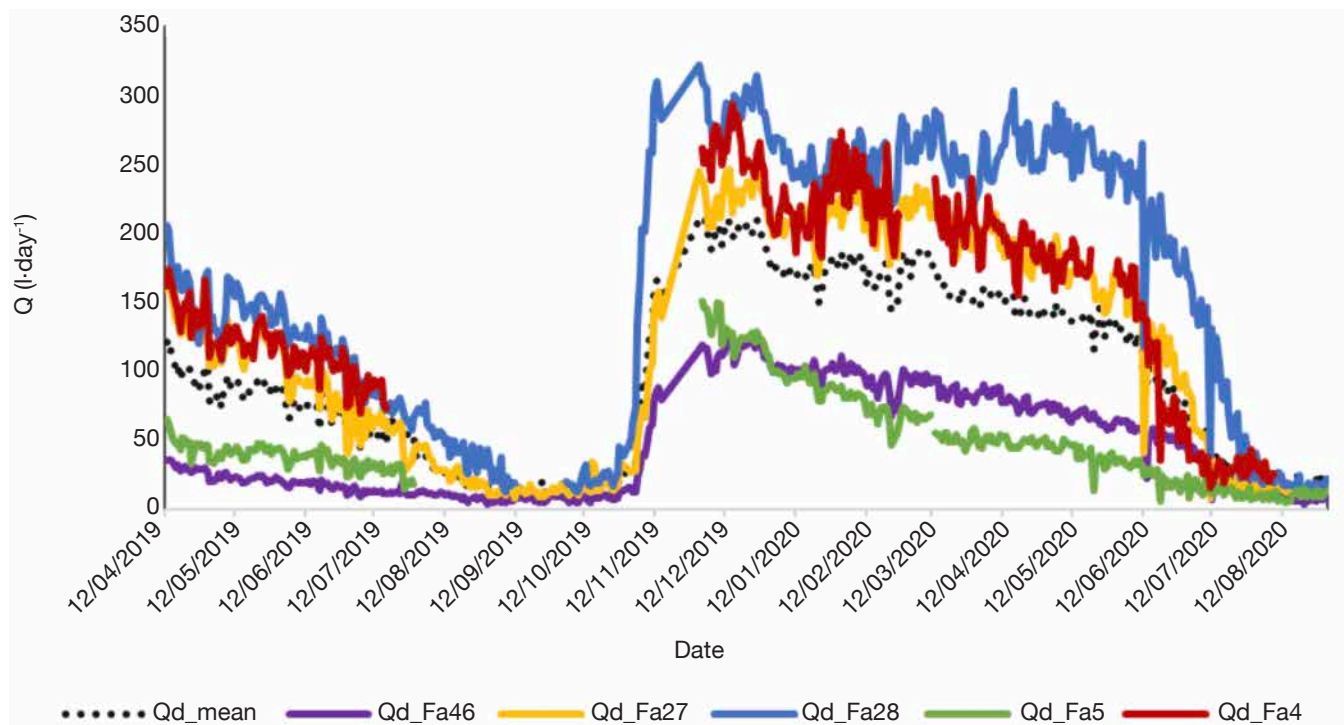

Figure 5. Tree water use (Q) variability by tree. Qd: daily tree water use, Qd_mean: daily mean average tree water use, Fa: *Faidherbia albida*. Between August and December 2019 no sap flow was measured for Fa4 and Fa5 — *Variabilité du flux total de l'eau (Q) par arbre. Qd : utilisation journalière de l'eau par arbre, Qd_mean : utilisation moyenne journalière de l'eau par arbre, Fa : Faidherbia albida. Entre aout et décembre 2019, pas de mesure effectuée pour les arbres Fa4 et Fa5.*

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