



Dynamics Simulation of Radial Flow Water in Aerial Roots of Corn by Deposit of Dew in Atmosphere

Aerial Roots Continuum

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Authors' contributions

This work was carried out in collaboration among all authors. Author ORY designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors AEM and GKN managed the analyses of the study. Author BBK managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Maize plants have different aerial roots from those that serve as an anchor and develop on the stem and live in the atmosphere. Much literature has reported that aerial roots are able to absorb moisture from the air, and even reduce water loss. But very little is known about the exchange of condensed atmospheric water between the aerial roots and the surrounding air. The main purpose of this article is to simulate the absorption of condensed atmospheric moisture by the aerial roots of corn plants. The evaluation of the amount of dew deposited on the roots and the radial water flow through the root is made using the Penman-Monteith equation and the Fick's law correlated with the Ohm's law respectively. The various simulations prove that the aerial roots condense atmospheric humidity and that the latter have expressed the transpiration function for certain angles of inclination

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with a particularity for the inclination of 30° which, from a certain amount of dew expressed the function of dew absorption. On the other hand, for other inclinations, the roots expressed the function of the absorption of humidity with an optimization for the inclination of 60°. The absorption and transpiration mechanism needs further studies in the future about the characteristics of the radial conductivity through the parameters which influence the coefficient of radial conductivity in the terminal parts of the root than in the lateral parts. In addition, the comparative study of the Priestley-Taylor and Penman-Monteith models is necessary to better understanding of the specific parameters.

Keywords: Dew; absorption; transpiration; aerial root.

1. INTRODUCTION

The beginning of the 21st century is marked by the effects of climate change, which results in extreme events that sometimes lead to the worldwide scarcity of water resources. One of the manifestations of climate change is the delay or failure of precipitation, which has a negative impact on crop periods. Recent studies have reported that the rainy seasons and the growing season are shorter [1, 2]. In the Sahelian regions of Africa, for example, the increasingly dry conditions eventually led to the reduction of the rainy season, with a direct negative effect on crop yields and the frequency of hunger periods [3]. We are also confronted with the management of the environment and the substantial sustainability of the ecosystem made up of various plants with very varied root systems. Hence the need to understand how these different species through their roots can adapt to climatic conditions linked to their living environment [4]. Some authors made a comparative study of the different types of Adventist roots of certain types of plants in relation to their living environment. They found that these roots have several functions [4]. They develop on plants in response to stressful conditions, such as soil degradation, nutrient deficit, and play an important role in the development of areas such as economy, ecology and human existence [5]. There is also probably a benefit component under moist conditions for the collection of water from clouds and uptake of water and nutrients via the flow of stems requiring physiologically active (not desiccated) roots. The average African population is approximately 1.2 billion inhabitants in 2015 [6]. Most of this population lives in rural areas. For this part of the population, agriculture is the main source of livelihood [7]. In West Africa in particular, the agricultural sector plays a decisive role in terms of national economies, employment, income of rural households, the balance of the trade balance and the food security of the

population [8]. This agriculture contributes about 35% of gross domestic product (GDP) in West Africa [7]. In the current context of climate change, without appropriate adaptation measures, this agriculture, already threatened by rapid population growth and reduced access to technological change [8] is likely to increase in fragility. [9], in their work, also concluded that in the face of the pronounced climatic variations experienced by West Africa since the 1970s, adaptation methods are appeared to be the only alternatives for reducing the vulnerability of rural populations [9]. Today, for example, the practice of early sowing and the use of short-cycle varieties make it possible to match the crop cycle with the rainy season and thus reduce the period of water stress at the end of the cycle in the plants [10]. The atmosphere abounds with a very large amount of moisture in vapor form, especially in the intertropical zone [11]. In the current context where agricultural yield is threatened because of water stress in plants, the valuation of this atmospheric humidity becomes imperative. According to [12], the formation of dew (condensed atmospheric humidity) and the direct adsorption of water vapor are the two mechanisms by which atmospheric water can reach the ground in arid environments where rainfall is almost nonexistent. In this environment, the amount of condensed atmospheric humidity may exceed that of rainfall, or even be the only source of liquid water for plants [12]. Studies have shown that condensed atmospheric humidity can be mobilized by plants [13, 14] and reduce water stress in plants [15]. Some plant families absorb moisture from the air through their aerial roots: this is the case of Orchidaceae, Morigeniaceae, Araceae, Liliaceae, Amaryllidaceae [16, 17]. The mobilization of atmospheric moisture by these plants is possible to an adsorbent spongy envelope of water vapor called velamen. Understanding the mechanism of mobilization of atmospheric moisture by the plant through the aerial roots becomes a necessary condition for the development of new

crop varieties that can adapt to current climate trends. When conditions are favorable, dew can occur in almost all climates and ecosystems of the world for example: the arid Negev desert in Israel, the flooded rice paddies of China, the semi-arid coastal steppes of Spain, American wheat fields, lush Northern European lawns, and Tropical Forests [18]. It is the natural deposition of water on a surface due to the condensation of water vapor. Although dew is a vital source of moisture for arid climate ecosystems [19], knowledge of its spatial and temporal variations can enable farmers to manage their crops and make decisions which could benefit them. Dew water can directly affect the water balance of plants through the absorption leaves [20,18] and can be a major source of water for vegetation where fresh water is scarce [12, 21]. Some species that do not have access to soil water including bromeliad epiphytes [22, 23] and lichens [24] physical allowing them to collect dew water. However, most plant species that accumulate dew droplets on the leaf surface directly affect

the foliar energy balance by evaporative cooling by altering the albedo, and emissivity. These factors and their interactions lead to reduced transpiration at the leaf level [18, 25]. There is growing interest in the suppression of transpiration for leaf-dew interactions [26, 27]. Therefore, a key objective of this article is to study the mechanism of dew mobilization by the plant through its aerial roots in order to highlight the potential of aerial roots for crop improvement.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Site description

The study site (Guéné) is located between latitude 11.20° and 12° North and longitude 2.5° and 3.05° East, a locality in northern Benin, Guéné is extends over an area about 1560km² or about 1% of the total surface area of Benin as shown in (Fig. 1).

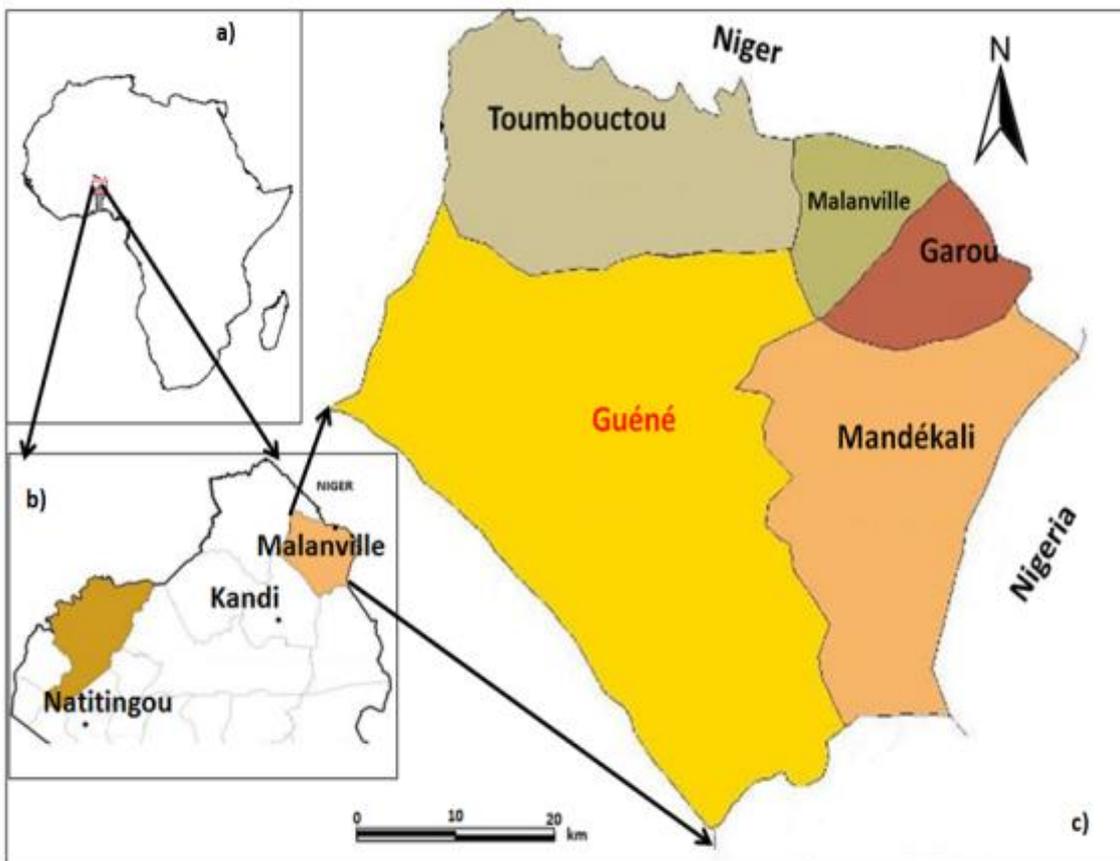


Fig. 1. Study sites location: (a) location of Benin in Africa, (b) location of Malanville in northern Benin, (c) location of Guéné in Malanville

The region is characterized by a humid tropical climate with the existence of two seasons the year, one dry for 8 months (September to May) and the other rainy which extends for 4 to 5 months (May to October). Irregular rainfall is low and around 700 mm / year [28]. The average daily air temperatures over the study period are between 15°C and 38°C. March to April is the hottest period (maximum of 42°C) on the other hand November to December is the coldest period (minimum of 12°C) [28]. The average daily relative humidity during the same period is between 70% and 90% and the wind regime is characterized by a seasonal variation. The study is done on the aerial roots of corn. In addition to the roots which serve as an anchor for the corn stalk and part of which is in direct contact with the atmosphere, there are others which have no contact with the ground (Fig. 2). Maize (*Zea mays* L.) is one of the most important crops in the world. Despite several studies on corn roots, information on the function of different types of roots in extracting atmospheric water is limited. Aerial roots provide a preferential route for absorbing nutrients from the stem. These are supplied to the plant by the underground roots [5] which are often subject to climatic hazards. Aerial roots improve water absorption by the spongy tissue of the lateral part like tips which increase the absorption of plants [5].

2.2 Data Records

Data were provided by the Agency for the Aerial Navigation's Security in Africa and in Madagascar (ASECNA). Air temperature, relative humidity and wind data from Kandi synoptic stations are used during the study period. Air temperature, relative humidity and wind variation from August 5, 2008 at 19:00 to August 6, 2008 at 7:00 is presented in Fig. 3, 4 and 5.

Species like *Ficus microcarpa*(L.) (Fig. 6) have aerial roots used by [17] to design and carry out two experiments in China.

The first relating the absorption characteristics and the second relating the exchange of water vapor between the aerial root and the atmosphere. Authors used the aerial roots of the *Ficus microcarpa*(L.) as experimental material. The rate of water exchange as a function of temperature or relative humidity is used to express transpiration or absorption of the aerial roots. The temperature range of the measurement system is that of the environment with a deviation of $\pm 60^\circ\text{C}$ for a relative humidity between 0 ~ 90%. They kept the air temperature constant under different relative humidity values

and vice versa. To study characteristics of absorption, they inserted the young and ripe parts of aerial roots in a vertical bottle containing water at the bottom, and the roots suspended above the water. The bottle opening was sealed and electronic scales were used to assess the mass difference representing the amount of water absorbed by the roots. Certain species of corn develop these types of roots in order to adapt to the consequences of climate change. The roots of these species in arid environments can directly capture moisture from the air or condense moisture across the exterior surface. We used for this work the aerial roots of the corn plants. The data used in the dew quantity calculation models are climatic data and parameter data related to the corn root that condense atmospheric humidity. The first such as air temperature, relative humidity and wind are collected by the synoptic station of kandi (11.08°N 2.52°E) in 15 min steps and the seconds, namely the emissivity of the root is taken equal to 0.95 and the emissivity of the sky is a function of the cloud cover.

2.3 Methods

2.3.1 Amount of dew deposited on the root

The amount of dew is determined from the equation of the energy balance at the root surface [29]. It is written as follows:

$$R_N + H + G + \lambda E + M = 0 \quad (1)$$

Where R_N is the net radiation in (W.m^{-2}); H (W.m^{-2}) the sensible heat flow between the surface and the air; G (W.m^{-2}) the heat flux on the ground; λE (W.m^{-2}) the latent heat flow and M (W.m^{-2}) the heat flow required due to metabolism at the condenser level (the root). The energy due to metabolic processes will not be taken into account because of its very negligible share compared to other forms of energy on the balance sheet [30], as shown in equation (2).

$$R_N + H + G + \lambda E = 0 \quad (2)$$

In which the net radiation at night is expressed by [30]:

$$R_N = Lwin - Lwout \quad (3)$$



Fig. 2. Corn aerial roots: (b) adventitious roots of corn, (a) free aerial root of corn

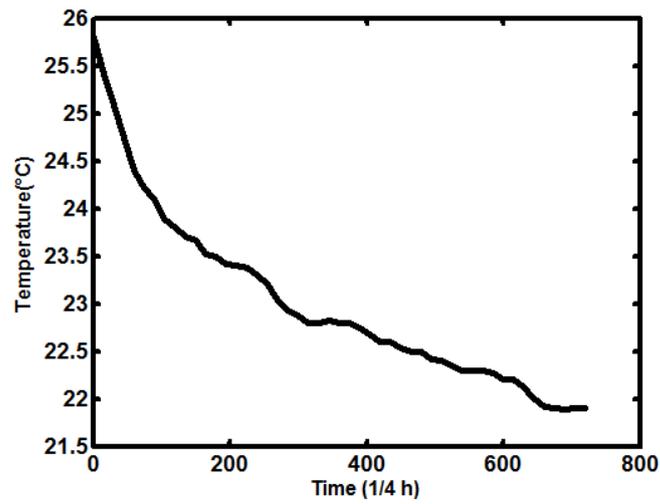


Fig. 3. Air temperature variation during the study period

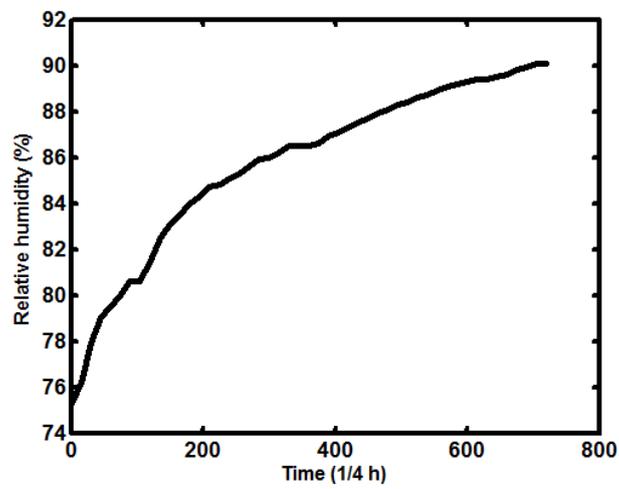


Fig. 4. Relative humidity variation during the study period

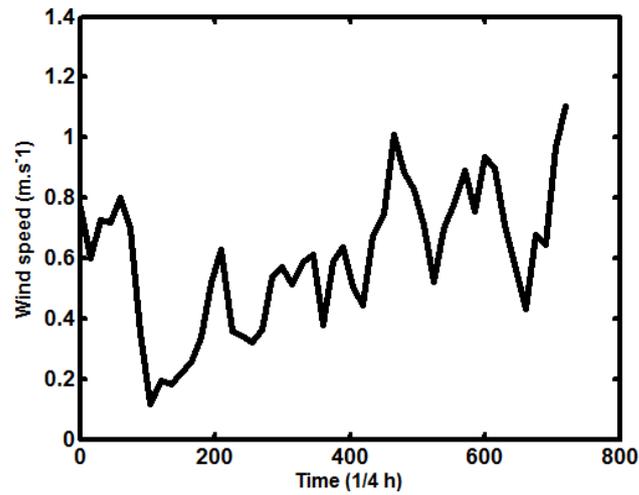


Fig. 5. Wind speed variation during the study period



Fig. 6. *Ficus microcarpa* (L.) aerial roots [17]

Where $L_{win} = \varepsilon_{sky} \cdot \sigma \cdot T_a^4$ et $L_{wout} = \varepsilon_s \cdot \sigma \cdot T_s^4$ respectively; T_a and T_s the temperatures in (K) of the air and the surface respectively. The emissivity of the sky is given by the empirical formula proposed by [31]:
 With σ Boltzman constant ($5.67 \times 10^{-8} \text{ Wm}^{-2} \text{ K}^{-4}$) ; ε_{sky} and ε_s the emissivity of the sky and the surface

$$\varepsilon_{sky} = f_1 \times T_a^2 + (f_2 \times N) / (\sigma \times T_a^4)$$
 with

$f_1 = 9.35 \times 10^{-6} \text{ K}^{-2}$, $f_2 = 60 \text{ W.m}^{-2}$, and N the cloud cover.

The sensible heat flux is obtained from the equation (4):

$$H = C_p . gH . (T_a - T_s) \quad (4)$$

where C_p , specific heat of the air at constant pressure ($\text{J.kg}^{-1}\text{K}^{-1}$) , T_s , radiometric surface temperature (K), T_a , air temperature at the reference height (K) and $gH = \frac{\rho}{r_a}$ with ρ ,

molar density of air (mol.m^{-3}); r_a , resistance to heat transfer (s.m^{-1}) of expression $r_a = \frac{1}{k^2 u} \times (\ln(\frac{z-d_0}{z_{om}}))^2$; u , wind speed (m.s^{-1})

; k , Von Karman constant ($k = 0.41$); z , the height at which the wind speed was measured; d_0 , displacement height; z_{om} , roughness length for the moving flow.

The heat flux in soil G depends on the texture of the soil, its structure and the humidity it contains according to [32]. It is proportional to the net radiation and the ratio of G and R_N is a function of the leaf area index (LAI) and the psychometric constant. Its expression is:

$$G = R_N . \omega . \exp(-\gamma \times LAI) \quad (5)$$

Where γ ($\text{kPa } ^\circ\text{C}^{-1}$) is the psychometric constant and ω , the proportionality factor.

The latent heat flux λE represents the rate of night condensation which derives from the mass transfer equation:

$$\lambda E = h_v \times (e_a - e_s) \quad (6)$$

Where e_a (kPa) is the vapor pressure of the air; e_s (kPa), the saturated vapor pressure at the surface temperature and h_v ($\text{w.m}^{-2}.\text{kPa}^{-1}$) the vapor transfer coefficient between the surface and the air which is expressed by: $h_v = \frac{\lambda g v}{P}$ and $\lambda = 2.501 - 2.361 \times 10^{-3} T_a$ (J.mol^{-1}), the latent heat of vaporization; $g v$ ($\text{mol.m}^{-2}.\text{s}^{-1}$) ,

the conductance of air vapor which is equivalent to gH and p (hpa) the air pressure.

$$\lambda E = \lambda . g v \times \frac{e_a - e_s(T_s)}{p} \quad (7)$$

Using, $s = \frac{e_s(T_a) - e_s(T_s)}{T_a - T_s}$ the slope of the saturated vapor pressure curve; $H = C_p . gH . (T_a - T_s)$ and $H = -(R_N + G + \lambda E)$ we arrive at the Penman-Monteith model [29]:

$$\lambda E = \frac{-s[R_N + G] + C_p \times g v \times [e_a - e_s(T_a)]}{s + P \times \frac{C_p}{\lambda}} \quad (8)$$

If λE is negative, it corresponds to the vaporization of atmospheric humidity. On the other hand, it represents atmospheric condensation (night dew).

2.3.2 Radial transfer of water through the root

The radial transfer of water through the root comes from Fick's first law whose variable responsible for the transfer is the water potential. It is often correlated with Ohm's law [33]. The radial water flow is therefore defined by:

$$j_r = k_r \times (\psi_s - \psi_x) \quad (9)$$

k_r ($\text{m.Pa}^{-1}.\text{s}^{-1}$); the coefficient of radial conductivity, ψ_s (Pa); the water potential of the surrounding external environment of the root and ψ_x (Pa); the water potential at each point of the root given by expression:

$$\psi_s = \psi_\pi + \psi_p + \psi_g + \psi_m \quad (10)$$

ψ_π ; Osmotic potential, ψ_p ; hydrostatic potential, ψ_g ; gravitational potential, ψ_m ; matrix potential. According to [34]; the radial flow of water through the root is given by:

$$j_r = k_r \times (\Delta P - \sigma \Delta \pi) \tag{11}$$

Where ΔP ; the hydrostatic pressure difference (Pa) and $\Delta \pi$ the osmotic pressure difference (Pa). The membrane reflection coefficient σ takes values between 0 and 1 and is an indication of the efficiency of the complex membrane. For a well developed endoderm, therefore a perfect semi-permeable membrane, $\sigma = 1$ [34]. We find:

$$j_r = k_r \times [(P_s + \pi_s) - (P_x + \pi_x)] \tag{12}$$

With: $\psi_x = P_x + \pi_x$ and $\psi_s = P_s + \pi_s$; the water potential of xylem and the water potential of the surrounding external environment of the root respectively. These different water potentials are the result of different pressure forces depending on whether one is at the level of the xylem or on the surface of the root. Equation (12) becomes:

$$j_r = k_r \times s \times [\pi_s - \pi_x] \tag{13}$$

It is assumed that the water potential is reduced to the hydrostatic potential and that the amount of water (λE) deposited on the root by condensation is evaluated in height of water per m². Therefore,

the expression of π_s becomes: $\pi_s = \frac{\rho \times \lambda E \times g}{s}$ and ψ_x is the axial water flow in the xylem deduced from the equation (14)

$$j_z = \int_R^0 2\pi r \frac{r^2}{4\mu} \left[\frac{\partial \psi_x}{\partial z} - \rho g \right] dr = -\frac{\pi R^4}{8\mu} \left[\frac{\partial \psi_x}{\partial z} - \rho g \cos \theta \right] \tag{14}$$

Using the boundary condition $\frac{d\psi_x}{dz} - \rho g \cos \theta = 0$ We get to:

$$j_r = k_r (\rho \lambda E g - 2\pi \sigma \rho g e z^2 \times \cos \theta) \tag{15}$$

3. RESULTS AND DISCUSSION

The condensation process is complex and involves several meteorological parameters with high variability. The dew applications developed are still incomplete. Like all surfaces, those of the aerial roots of corn collect atmospheric water in the form of dew for its water needs especially for the roots which are not directly in contact with the soil. Apart from precipitation in semi-arid environments, non-rain water sources such as dew and fog can play an important role in the search for adaptation strategies of plants in environments where water is scarce. We studied the contribution of dew in the water absorbed by the aerial root in corn. The profile of the radial water flow in the corn root is evaluated function to the time in connection with the accumulated dew deposit. The evolution of the radial flow of water in the root as a function of time with respect to the cumulative quantity of dew (Fig. 7) has an

increasing speed whatever the inclination of the root.

The amount of water absorbed increases with increasing dew on the root surface. On the other hand sweating decreases when the amount of dew increases on the root surface. For the angles 0°, 45° and 70° the radial water flow increases while remaining negative. The root loses water. The amount of water lost decreases with the increasing surface water [17]. With the inclination of 30°, the radial flow becomes positive when the cumulative dew has reached at least 0.187mm indicating the entry of water into the root at this time. For slopes of 60°, 80° and 90°, the root absorbs water regardless of the amount of dew deposited. The water inlet is more important with the inclination of 60°. The movement of the radial flow depends on the water potentials of the two environments delimited by the aerial roots (inside and outside) [34].

The orientation of the root influences the radial water flow. It appears that the radial water flow depends not only the time that the water remains on the aerial root surface but also on the slope. The roots at 60° promote the flow of water on the surface of the roots and the lifting of water from the xylem to over part of the plant. Taking into account the angles of inclination of the roots is important in mobilizing water from the root-atmosphere interface for the root xylem. Considering the cylindrical geometry of the roots, some angles of inclination are favorable to the length of time that the dew will spend on the root

and others do not allow the dew to stay long on the root. Our data show that dew water is frequently deposited on plant organs (leaf, stem and root) and physiologically advantageous [12, 35, 36]. The water absorption capacity of the root system depends on the one hand on the intensity of water colonization by the roots in the area considered and on the other hand the capacity of water penetration into the root cortex and its conduction towards the xylem. The first is measured by root densities and completed by the calculation of the average distances between roots and water available [37, 38].

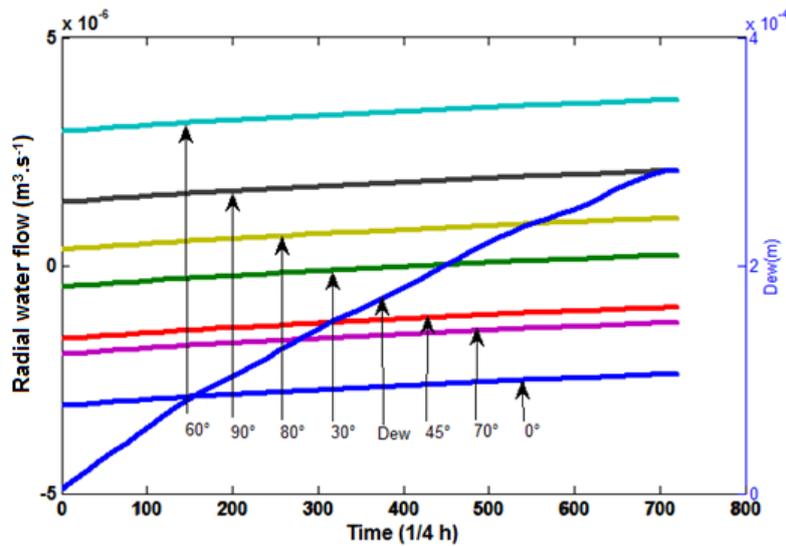


Fig. 7. Radial water flow in the root as a function of the length of the root for some angles of inclination of the root

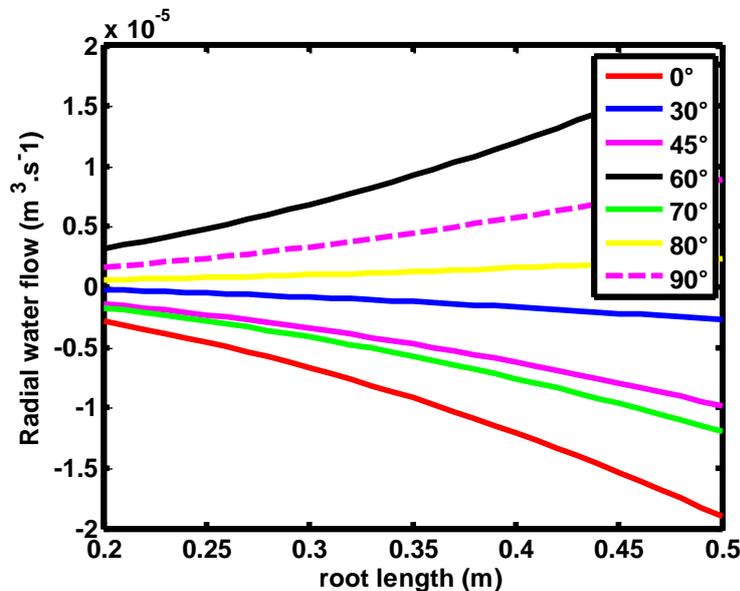


Fig. 8. Radial water flow in the root as a function of the length of the root for some angles of inclination of the root

Fig. 8 shows the evolution of the radial flow water as a function of the root length. For a quantity of dew ≈ 0.1 mm deposited on the roots, the radial flow of water through the root depends on the inclination of the root. For inclinations of 0° , 30° , 45° , 70° ; the root loses water along the root although there is water on the surface of the root. The movement of water takes place from the inside of the root to the outside. The amount of water has lost by the root increases with the length of the root. This phenomenon known as transpiration is observed when the water potential of the external environment surrounding the root is lower than the water potential of xylem. The behavior of the root at this moment could be explained by the fact that the osmotic component (which we did not take into account in this work) of the xylem becomes larger in the face of the gradient of hydrostatic pressures [39, 40]. On the other hand for the inclinations of 60° , 80° and 90° the infiltration of water into the root increases as a function of the length of the root. The water movement is weak for very short lengths (Fig. 8) but more and more important from 0.07 m. The apparent hydraulic conductivity per m^2 of root area is strongly linked to the increase in the length of the roots [41]. Although different species may show a different pattern in radial pathways for water movement [42], all root segments have equal absorption capacity water with a reduction in old roots due to their thickening (lengthening of the distance to covered) and the formation of an aerenchyma [39]. This is controversial by the results of [17] which showed that young aerial roots had the

function of transpiration when the relative humidity of the air was less than 90%. With a rate of transpiration which has a negative relationship with the relative humidity of air. But the aerial roots expressed the function of moisture absorption when the relative humidity of air reached 100%. The older aerial roots had weak and transient moisture absorption and transpiration due to the epidermal cells of the root.

Figs. 9 and 10 show the profile of the water flow through the root as a function of the thickness and the effective area of the root. The results obtained indicate that the conductivity of the surface is linear and this regardless of the inclination of the root. According to a given angle, the root has the same behavior, that of absorbing or sweating. This behavior has no dependence on the length of the root. As in the case of the profile of the water flow as a function of the length of the roots, certain angles are very favorable for the entry of water into the root but others, on the other hand, are not [20]. The water potential gradient of the roots of young maize plants is constant unlike adult plants whose tissue water potential is very variable although its controversial origin can be explained by the fact that the hydraulic conductance of growing tissue is lower [43]. This is explained by the fact that the growing tissues are very stable whereas the adult tissues have a privileged supply of water as a result of a high hydraulic conductance of the tissues. In hydrostatic experiments, the apparent hydraulic conductivity per m^2 of root area increases sharply with the length of the root.

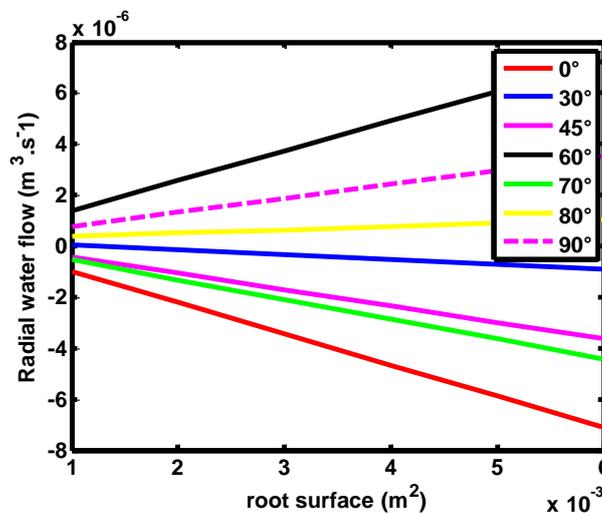


Fig. 9. Radial water flow in the root as a function of the root surface for some angles of inclination of the root

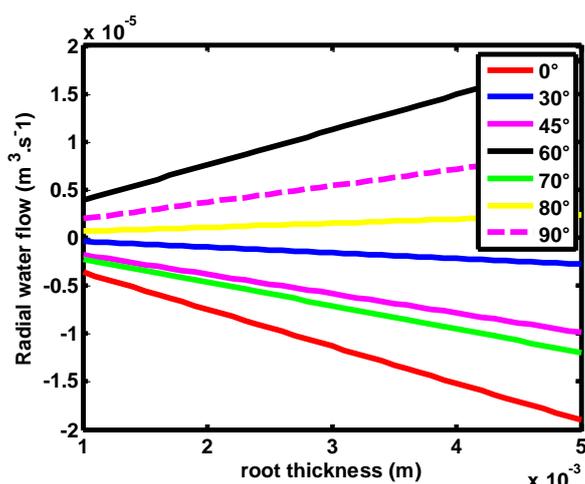


Fig. 10. Radial water flow in the root as a function of the thickness of the root for some angles of inclination of the root

4. CONCLUSION

The aerial roots of maize plants like those of epiphytic orchids and ficus microcarpa(L.) mobilize atmospheric water either directly or by condensation (dew). Condensed humidity is also an available resource; its mobilization by the aerial roots is subject to weather conditions that favor its formation and collection. Once mobilized, this resource enters the plant's water balance and changes the energy balance driving the plant's growth. This mobilization depends on parameters such as the angle of inclination of the roots; temperature; relative humidity of air surrounding the roots. The results of the various simulations show that these parameters strongly influence the entry of water into the root. Therefore, studies to improve the mechanism of mobilization of water by the aerial roots of plants must take into account the influence of these parameters. In order to indicate quantities and limits of water intake of complex systems of aerial roots, it is necessary to have additional information about the characteristics of the radial conductivity through the parameters which influence the coefficient of radial conductivity in of the terminal parts of the root and in the lateral parts by making a comparative study of the two equations (Priestley-Taylor and Penman-Monteith). In addition, modeling the radial water flow rigorously would require knowledge of the changes in osmotic pressure in the root xylem due to the uptake and conduction of water and dissolved bodies in the root.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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