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Water Balance and Sustainability of Eucalyptus Plantations in the Kouilou Basin (Congo-Brazzaville)

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Abstract—To appreciate the sustainabilty of these plantations of Eucalyptus, it is necessary to make a comparative study of energy, carbon, mineral and water balances of two ecosystems, i.e. the original savannah ecosystem, and the man-made ecosystem the Eucalyptus plantations that have succeeded it. The aim of this work is to study the water balance of the two ecosystems and more particularly their actual evapotranspiration. Throughfall, net interception during the rainy seasons (1996–99) were 867 mm and 112 mm for the Eucalyptus plantation and 878 mm and 101 mm for the savannah, respectively. The mean total annual actual evapotranspiration respectively 1127 mm for a plantation and 821 mm for a savannah. During the year transpiration/potential evapotranspiration ratio (T/E_p) is related to the soil-water depletion: The T/E_p ratio of 0.79 was not reduced from field capacity until 65% of R_{FC}, and then it decreased quickly to near zero at wilting point. The drainage out of rooting depths of savannah during the rainy season was of 827 mm, a total over 3 years; while the drainage out of rooting depths of Eucalyptus plantation was of 470 mm, a difference in drainage between two ecosystems of 357 mm a total over these three years. The Eucalyptus plantation is man-made ecosystem which takes up and transpires every day throughout the year and uses all available water. The succession of several rain-deficient years will reduce the wood production of the plantation but, knowing that between 1949 and 1998 four successive rain-deficient years have only occured once while the length of rotation is seven years; this dry episode does not compromise the survival of the plantation, although it reduces its wood production. The savannah has a cycle of vegetation such that at the end of the dry season the water remaining in the rooting depths of savannah is sufficient for three successive rain-deficient years to have no impact on its production.

Keywords: Sustainability; Plantation; Eucalyptus; Savannah; Soil-water balance; Evapotranspiration.

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1. INTRODUCTION

Since approximately 1950, the savannah of the Congolese littoral (Fig. 1) has gradually been planted with Eucalyptus in dense populations harvested on rotations of seven years (Laclau et al., 2000).

Plantations are sustainable if they meet multiple sociological, economic and ecological criteria that have been redefined by the report of Brundtland (World Commission on Environment and Development, 1987). These Eucalyptus plantations would meet these criteria of sustainability if an ecosystem similar to the original the savannah would follow if the planting of eucalyptus were stopped; this would prove that climatic and pedologic local conditions have not been radically modified by the existence of these plantations. To find out whether or not this is the case, it is necessary to make comparative studies of energy, carbon, mineral and water balances of the two ecosystems namely, the original savannah ecosystem, and the man-made Eucalyptus ecosystem that has succeeded it.

The aim of the work described in this paper is to study the water balance of the two ecosystems and more particularly their actual evapotranspiration (transpiration and evaporation). The transpiration is the "engine" of the water-flux through the plant. Transpiration from the plant canopy is determined by:

- climatic demand (potential evapotranspiration), dependent on solar radiation, air temperature, humidity deficit and wind speed,
- physiological response mechanisms to environmental conditions, dependent on genotype,
- plant canopy structure, particularly leaf area index,
- availability of soil water to the vegetation roots, soil water content.

Eucalyptus has been chosen for its rapid growth. Sustainable Eucalyptus plantations would be plantations whose water-use would not be excessive relative to the original savannah. This study provides necessary

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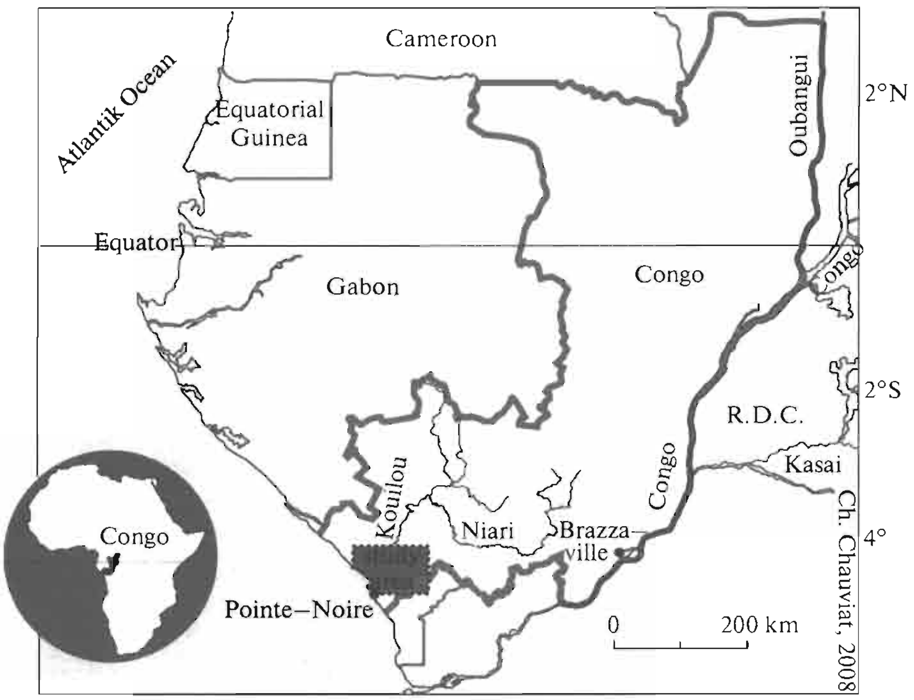

Fig. 1. Location of the study area—the Kouilou region (covered 13315 km^2) is situated on the Atlantic Ocean front of the Congo between Cabinda in the South and Gabon in the North.

data for a soil-water balance model allowing researchers of Unite de Recherche sur la Productivite des Plantations Industrielles (Pointe Noire, Congo), of CIRAD (Montpellier, France) and of INRA (Nancy, France) to lead field work on the same plots on the essential mineral elements cycle (N, P, K, Ca, Mg) which constitute another aspect of sustainability of these Eucalyptus plantations (Bouillet et al., 1999).

2. MATERIALS, METHODS AND STUDY SITES

2.1. Water Balance Equation Method

The water balance of an element of the soil (direct or surface run off and water table may be ignored in the present context) can be expressed as (photo):

$$Pi = E_a + D \pm \Delta R/t, \quad (1)$$

$$\text{where} \quad E_a = T + In + Es, \quad (2)$$

$$\text{and} \quad In = Pi - (Ps + Ec), \quad (3)$$

with Pi is gross precipitation (mm day^{-1}); E_a is actual evapotranspiration (mm day^{-1}); D is drainage (mm day^{-1}); R is change in soil water content (mm); t is time resolution (day); T is transpiration (mm day^{-1}); In is net interception (mm day^{-1}); Es is evaporation from soil (mm day^{-1}); Ps is throughfall (mm day^{-1}); Ec is stemflow (mm day^{-1}).

Since direct evaporation from soil or litter (Es) may be ignored in the present context (Eq. (2)) provides a reasonable approximation for drying period. The soil water content (R), rainfall (Pi), throughfall (Ps) and stemflow (Ec) were measured; drainage (D), actual evapotranspiration (E_a), net interception (In) and transpiration (T) were derived. Moreover, transpiration was measured using the radial flow meter. A soil depth of 5 m (Eucalyptus) and of 3 m (savannah) was taken into account in the water balance equation. The field capacity (R_{FC}) and permanent wilting point (R_{WP}) were measured *in situ*. When the actual soil water content exceeds its field capacity ($R > R_{FC}$), drainage occurs and the actual evapotranspiration equals the potential evapotranspiration ($E_a = E_p$). When the soil water contents lower than field capacity it is assumed that no drainage occurs; thus, drainage and actual evapotranspiration can be quantitatively expressed as follows:

$$\text{if} \quad R \geq R_{FC} \quad \text{then} \quad E_a = E_p,$$

$$\text{and} \quad D = Pi - Ep \pm R/t; \quad (4)$$

$$\text{if} \quad R < R_{FC} \quad \text{then} \quad D = 0,$$

$$\text{and} \quad E_a = Pi \pm R/t, \quad (5)$$

with E_p being potential evapotranspiration (mm day^{-1}). To estimate potential evapotranspiration, we used the Penman (1948) formula; values of the E_p were calculated for the two study plots, for each day and also for longer periods corresponding to the intervals between the measurements of the soil-water balance.

$$E_p = (\Delta Rn/\lambda + \gamma E_0)/(\mathrm{D} + \gamma), \quad (6)$$

Net radiation (*Rn*), gross precipitations (*Pi*), throughfall (*Ps*), net interception (*In*), transpiration (*T*), drainage (*D*), actual (E_a) and potential evapotranspiration (E_p). Cumulative values during the rainy seasons and the dry seasons from 17 February 1997 to 26 July 1999: (a) Eucalyptus plantation (*Eucalyptus PF1* and *Eucalyptus 12ABL* saligna*); (b) savannah with *Loudetia arundinacea*

	RAINY SEASONS—1st November to 30 April (181 days)								DRY SEASONS—1st June to 30 September (122 days)					
	1996–1997		1997–1998		1998–1999		mean 1996–1999		1997		1998		mean 1997–1998	
	Eucalyptus	*Savannah*	*Eucalyptus*	*Savannah*	*Eucalyptus*	*Savannah*	*Eucalyptus*	*Savannah*	*Eucalyptus*	*Savannah*	*Eucalyptus*	*Savannah*	*Eucalyptus*	*Savannah*
Net radiation (*Rn*), W m^{-2}	416.9	345.3	441.9	366.6	435.5	359.8	431.4	357.3	272.4	223.2	290.3	238.1	281.4	230.7
Potential evapotranspiration (E_p),														
mm,	780.5	717.2	851.5	779.2	856.7	785.0	829.6	760.5	373.9	347.8	402.4		388.2	361.2
mm day^{-1}	4.3	4.0	4.7	4.3	4.7	4.3	4.6	4.2	3.1	2.9	3.3	3.1	3.2	3.0
Gross precipitations (*Pi*),														
mm,	459.3	459.3	1338.5	1338.5	1139.9	1139.9	979.2	979.2	15.5	15.5	63.5	63.5	39.5	39.5
mm day^{-1}	2.5	2.5	7.4	7.4	6.3	6.3	5.4	5.4	0.1	0.1	0.5	0.5	0.3	0.3
Throughfall (*Ps*),														
mm,	412.3	422.5	1198.0	1206.3	991.0	1005.5	867.1	878.1	9.8	13.4	39.9	47.1	24.8	30.3
mm day^{-1},	2.3	2.3	6.6	6.7	5.5	5.6	4.8	4.9	0.1	0.1	0.3	0.4	0.2	0.2
% of *Pi*	89.8	92.0	89.5	90.1	86.9	88.2	88.7	90.1	63.1	86.6	62.9	74.2	63.0	80.4
Stemflow (*Ec*),														
mm,	9.2		26.8		22.8		19.6		0.3		1.3		0.8	
mm day^{-1},	0.1		0.1		0.1		0.1		0.0		0.0		0.0	
% of *Pi*	2.0		2.0		2.0		2.0		2.0		2.0		2.0	
Net Interception (*In*),														
mm,	47.0	36.8	140.5	132.2	148.9	134.4	112.1	101.1	5.7	2.1	23.6	16.4	14.7	9.2
mm day^{-1},	0.3	0.2	0.8	0.7	0.8	0.7	0.6	0.6	0.0	0.0	0.2	0.1	0.1	0.1
% of *Pi*	10.2	8.0	10.5	9.9	13.1	11.8	11.3	9.9	36.9	13.4	37.1	25.8	37.0	19.6
Transpiration (*T*),														
mm,	693.2	436.2	707.8	584.6	564.7	412.7	655.2	477.8	93.9	112.2	242.8	112.2	168.4	112.2
mm day^{-1}	3.8	2.4	3.9	3.2	3.1	2.3	3.6	2.6	0.8	0.9	2.0	0.9	1.4	0.9
Actual evapotranspiration (E_a),														
mm,	740.2	473.0	848.3	716.9	713.6	547.1	767.4	579.0	99.7	114.3	266.4	128.6	183.0	121.5
mm day^{-1}	4.1	2.6	4.7	4.0	3.9	3.0	4.2	3.2	0.8	0.9	2.2	1.1	1.5	1.0
Drainage (*D*),														
$D = Ps + Ec - E_a$ mm,	0.0	0.0	376.4	489.4	300.1	458.4	225.6	315.9	0.0	0.0	0.0	0.0	0.0	0.0
$R_{30.04}$ mm,	377.6	360.9	508.1	337.8	462.8	347.0			345.3	298.6	484.8	297.8		
$R_{1.11}$ mm,	361.1	222.3	338.7	238.1	425.8	326.2			311.8	230.2	380.3	344.1		
$R = R_{30.04} - R_{1.11}$ mm,	16.5	138.5	169.4	99.7	37.0	20.8			33.5	68.5	104.5	–46.3		
$D = Ps + Ec - E_a - R$ mm,	0.0	0.0	207.1	389.7	263.2	437.6	156.8	275.8	0.0	0.0	0.0	0.0	0.0	0.0
mm day^{-1}	0.0	0.0	1.1	2.2	1.5	2.4	0.9	1.5						

with Rn being net radiation (W m^{-2}); λ is latent heat of vaporisation (2451.8 J g^{-1}); γ is psychometer constant (kPa °C^{-1}); E_0 is free water evaporation (mm day^{-1}); Δ is the slope of the curve relating saturation vapour pressure to temperature (kPa °C^{-1}), where:

$$Rn = (1 - a)Rg - (Ra - Rt), \qquad (7)$$

where Rg is global radiation (W m^{-2}); Ra is longwave downward flux of radiation from the sky (W m^{-2}); Rt is longwave upward flux radiation from the surface (W m^{-2}); a is albedo of the surface, fraction of incident short-wave radiation that is reflected from the surface (albedo for the Eucalyptus plantation is $a_{E_{\mathrm{UCALPTUS}}} = 0.13$; albedo for the savanah is $a_{S_{\mathrm{AVANNAH}}} = 0.25$).

The assumption that no drainage occurs when the soil water content is lower than field capacity ($R < R_{FC}$) is valid for sandy soils; the sandy texture promotes a rapid decline of the hydraulic conductivity with decreasing soil water content. In the two cases (Eqs. (4) and (5)), the transpiration was derived from actual evapotranspiration (E_a) as follows:

$$T = Ea - In. \qquad (8)$$

2.2. Study Sites

The Kouilou region (covered 13315 km^2) is situated on the Atlantic Ocean front of the Congo between Cabinda in the South and Gabon in the North; the climate of the region is sub-equatorial tropical with mean annual rainfall $Pi_{49-98} = 1188$ mm, potential evapotranspiration $E_{p92-98} = 1390$ mm year^{-1} ($E_{p92-98} = 3.8$ mm day^{-1}; $E_{p\mathrm{RAINY\ SEASON}} = 4.2$ mm day^{-1}, $E_{p\mathrm{DRY\ SEASON}} = 3.2$ mm day^{-1}), mean air temperature 24.9°C ($t_{\max} = 28.2$°C, $t_{\min} = 21.9$°C), relative air humidity 81.1% ($H_{\max} = 95.5\%$, $H_{\min} = 66.4\%$) (the long-term values estimated over the period of 1949–98, meteorological station, Pointe Noire, Congo). The rainy season, which lasts about 180 days, starts in November and ends in April, the dry season from June to September; May and October are the months of transition. The study area is situated on thick detritic formations of continental origin, dating from the pliopleistocene. The soils are ferrallitic and highly desaturated, on sandy to sandy-clay material (grayish-ochre colour, more than 90% of sand content and particular structure (Vennetier, 1968). Field work was carried out on two plots located near Kondi (latitude 4°34′S, longitude 11°54′E, altitude 80–120 m above sea level), about 40 km north from Pointe Noire.

Study site n°1—a 90% *Loudetia arundinacea* dominated savannah (associeted with *Bulbostylis laniceps, Cassia mimosoides, Ctenium newtonii, Cyperus amabilis, Cyperus tenax, Cyanotis lanata Elionurus argenteus, Eriosema glomeratum, Eriosema erici-rosenii, Loudetia simplex, Rhynchelytrum nerviglume, Scleria boivinii*) (mean height 1.5 m; maximum biomass 3.5 tonnes ha^{-1}; standing dead material 4.6 tonnes ha^{-1}; mean annual leaf area index 2.6; rooting depth is 3 m; field capacity, $R_{FC} = 363$ mm; permanent wilting point, $R_{WP} = 182$ mm; available water content, $R_{AW} = 181$ mm.

Study site n°2—a six years-old Eucalyptus plantation: *Eucalyptus PF1* and *Eucalyptus 12ABL* saligna* were planted in January 1992 with transplants (0.3 m high) in pits dug at a spacing of 4.0 m × 4.7 m (rows facing south-west); mean height 24.2 m, mean stem diameter at soil level 0.17 m, stand density 502 trees ha^{-1}, total basal area 11.0 m^2 ha^{-1}, mean annual leaf area index 3.2, total wood production 118.5 m^3 ha^{-1}; rooting depths 5 m; field capacity, $R_{FC} = 618$ mm; permanent wilting point, $R_{WP} = 309$ mm; available water content, $R_{AW} = 308$ mm.

2.3. Sampling and Measurement Technique

Water balance, plant water status and environmental measurements

- weekly measurements (savannah and plantation): gross precipitation, throughfall (22 rain gauges "Association"; collecting area 8800 cm^2), stemflow (10 stemflow collars), soil water content (neutron probe "Solo25", Centre d'Etudes Nucléaires, Cadarache, France; 8 permanent acess tubes).
- hourly measurements (plantation): sap flow measurement (4 trees; thermocouples), leaf water potential (pressure chamber PMS, Inst. Co., Corvallis, Oregon, USA), leaf transpiration, stomatal resistance (porometer AP4, Delta-T-Devices, U.K.), soil-water potential (tensiometers, Soil Moisture Equipment Corporation, Oh, USA).
- twenty-minutes interval measurements (savannah): air humidity, mean air temperature (R.H. probe HMP35AC, Vaisala, Helsinki, Finland), wind speed (anemometer A100R, Vector Instruments, Rhyl, UK) at 5 m and 2 m below the savannnah's soil surface; global radiation (pyranometer sensor, L1-200SZ, Li-cor, NE, USA) and net radiation (net radiometer REBS/Q-7, Campbell Scientific, Logan, USA) at 6 m below the savannnah's soil surface; soil temperatures (at 0.05 m and 0.15 m depth, 107 probes, Campbell) were recorded on a 21XL Datalogger (Campbell Scientific Inc., Logan, USA).
- Daily meteorological data: mean air temperature, dew point temperature, air humidity, total air pressure, insolation, and wind speed. These data come from the aerport meteorological station of Pointe Noire (Direction de l'Exploitation Meteorologique de l'ASECNA, Pointe Noire, Congo; 4°49′S, 11°54′E), located about 40 km south of the study plots.

3. RESULTS AND DISCUSSION

3.1. Local Climate and Vegetation

Our results relate to the period from 17 February 1997 to 26 July 1999. According to Vennetier (1968), there are three main seasons in the annual cycle of the local climate in the Congolese littoral: rainy seasons from November to April (in this study: 1996–97, 1997–98 and 1998–99), dry seasons from June to September (in this study: 1997 and 1998); May and October are the months of transition. The annual rainfall (Pi) and annual potential evapotranspiration (E_p), were, respectively: in 1996, 1150 mm year^{-1} and 1353 mm year^{-1}; in 1997, 1231 mm year^{-1} and 1357 mm year^{-1}; in 1998 1274 mm year^{-1} and 1389 mm year^{-1}; the values for these three years values are very close to long-term annual means of $Pi_{49-98} = 1188$ mm year^{-1} (from 1949 to 1998) and of $E_{p92-98} = 1390$ mm year^{-1} (from 1992 to 1998), respectively (table). The seasonal annual rainfall during the rainy seasons in recart years differed from the average for the period 1949–98 as follows:

- $Pi_{49-98} = 1034$ mm = 100%
- $Pi_{96-97} = 459$ mm = 44%
- $Pi_{97-98} = 1338$ mm = 129%
- $Pi_{98-99} = 1140$ mm = 110%.

E_p were approximately equal to the long-term mean of 1992–98 (E_{p92-98} = 1390 mm year^{-1}) throughout the study: in 1996 E_p was 1353 mm year^{-1} (97% of E_{p92-98}); in 1997, 1357 mm year^{-1} (98% of E_{p92-98}); in 1998, 1389 mm year^{-1} (100% of E_{p92-98}).

The Eucalyptus plantation (*Eucalyptus PF1* and *Eucalyptus 12ABL* saligna*) is a man-made ecosystem which maintained live leaves and transpires throughout the year (mean annual leaf area index 3.2). The herbaceous vegetation of savannah (*Loudetia arundinacea* dominated savannah, associeted with *Bulbostylis laniceps, Cassia mimosoides, Ctenium newtonii, Cyperus amabilis, Cyperus tenax, Cyanotis lanata Elionurus argenteus, Eriosema glomeratum, Eriosema erici-rosenii, Loudetia simplex, Rhynchelytrum nerviglume, Scleria boivinii*) are the annuals which take up/transpire during the rainy season and during the "transition period" (May and October), with the mean annual leaf area index of 2.6 (in February, the leaf area index is maximal at 4.1; Nizinski et al., 2002).

3.2. Impact of Afforestation on Soil Water Balance

The soil water balance is dependent on the parameters of vegetation canopy structure. Field work was carried out at the plant community level, with a daily one-dimentional heat and mass transfer model approach, assuming a pure closed, horizontally homogeneous stand, and the canopy with the horizontal dimension much larger than the vertical one. Values of the albedo used in the calculation of E_p (Eq. (7)) for the years 1996 and 1997 are derived from the bibliography according to Pinker et al. (1980): albedo $a_{E_{\text{UCALPTUS}}} = 0.13$ and $a_{S_{\text{AVANNAH}}} = 0.25$; these values have been verified by measurements in September 1998: $a_{E_{\text{UCALPTUS}}} = 0.12$ and $a_{S_{\text{AVANNAH}}} = 0.23$.

3.2.1. Net radiation. For the period 1992–98 (duration of Eucalyptus plantation rotation) the long-term mean annual daily net radiation were for Eucalyptus plantation and savannah, respectively 387 W m^{-2} and 320 W m^{-2}, with 426 and 353 W m^{-2} for rainy season (from November to April) and 307 and 253 W m^{-2} for dry season (from June to September). Thus, the quantity of available energy for the Eucalyptus plantation exceeds that for the savannah by 74 W m^{-2} during the rainy season and by 51 W m^{-2} during the dry season. The mean daily net radiation in 1996, 1997 and 1998 (table) was less than the long-term mean of 1992–98 period, for Eucalyptus plantation and savannah. The figures were, respectively: in 1996, 385 and 319 W m^{-2}; in 1997, 367 and 303 W m^{-2}; and in 1998, 377 and 311 W m^{-2}. If one details the Rn of two seasons, we thus have for the Eucalyptus plantation and the savannah, respectively, during the rainy season in 1996, 417 and 345 W m^{-2}; in 1997, 442 and 367 W m^{-2}; in 1998, 435 and 360 W m^{-2}; and during the dry season in 1997, 272 and 223 W m^{-2} and in 1998, 290 and 238 W m^{-2}. We will compare values of Rn of the savannah (mean seasonal three-year values) with those obtained by Riou (1975) for grass well supplied with water for the period of 1968–71: during the rainy season 240 W m^{-2} and during the dry season 166 W m^{-2}. These values are inferior, respectively by 117 W m^{-2} and of 65 W m^{-2} to ours, the difference being attributed to the type of vegetation and to the insolation between Pointe Noire and Brazzaville (Congo).

3.2.2. Potential evapotranspiration. The long-term mean (1992–98) annual and daily potential evapotranspiration (E_{p92-98}) were 1395 mm year^{-1} and 3.8 mm day^{-1}, respectively (for rainy season 4.2 mm day^{-1} and for dry season 3.1 mm day^{-1}, Penman (1948) (we treat the savannah as a low vegetation type well supplied with water). Annual potential evapotranspiration is close to E_{p68-71} = 1420 mm estimated by Riou (1975), using the Penman equation for Brazzaville (Congo). The mean annual and mean daily potential evapotranspiration for 1996, 1997 and 1998 (table) were for the Eucalyptus plantation and the savannah, respectively during the rainy season: 830 and 760 mm (4.6 and 4.2 mm day^{-1}) and during the dry season: 388 and 361 (3.2 and 3.0 mm day^{-1}). If one details the E_p of two seasons, we have then for the Eucalyptus plantation and the savannah, respectively during the rainy season: in 1996, 780 and 717 mm (4.3 and 4.0 mm day^{-1}); in 1997, 851 and 779 mm (4.7 and 4.3 mm day^{-1}); in 1998, 857 and 785 mm (4.7 and 4.3 mm day^{-1}); and during the dry season: in 1997, 281 and 230 (2.3 and 1.9 mm day^{-1}); in 1998, 299 and 246 mm (2.5 and 2.0 mm day^{-1}).

3.2.3. Throughfall and net interception. The mean three-year seasonal value of throughfall (Ps) and net intereption (In) were for Eucalyptus plantation and for savannah, respectively 867 mm, 112 mm (89 and 11% of rainfall) and 878 mm, 101 mm (90% and 10% of rainfall). For the Eucalyptus plantation, the values of throughfall and net interception were close to In = 12% of rainfall obtained by George (1978) for the six years-old *Eucalyptus tereticornis* plantation (India, $Pi = 1670$ mm year^{-1}) as well as $In = 12\%$ of rainfall by Calder (1986) concerning a six years-old *Eucalyptus saligna* plantation (Brazil, $Pi = 1280$ mm year^{-1}) and $In = 11\%$ of rainfall by Smith (1974) concerning a *Eucalyptus regnans* plantation (Australia, $Pi = 810$ mm year^{-1}). Throughfall in the savannah was larger (11 mm year^{-1}, the three-year average) than in the Eucalyptus plantation. The differing interception losses occur beacause savannah canopy storage capacity (0.6 mm) is lower than that of Eucalyptus plantation (0.9 mm), the canopy storage capacities being establised by the use of a linear regression between cumulative throughfall and cumulative rainfall. The values of Eucalyptus canopy storage capacities were close to the 0.8–1.4 mm obtained by Calder (1986) for the *Eucalyptus* plantations, situated to Fidji. But if one adds stemflow which occurs in Eucalyptus plantation exclusivelly (19.6 mm year^{-1}, the three-years mean), entries of water in the soil of the Eucalyptus plantation were in turn 8.6 mm year^{-1} greater than those in soil of the savannah.

3.2.4. Transpiration. The seasonal and daily three-years mean of transpiration (1996, 1997 and 1998), for the Eucalyptus plantation and the savannah were respectively: 655 and 478 mm (3.6 and 2.6 mm day^{-1}) during the rain season and 168 and 112 mm (1.4 and 0.9 mm day^{-1}) during the dry season. According to Roberts and Rosier (1993), the daily mean transpiration of the Eucalyptus plantations which are well supplied with water varies from 3 to 5 mm day^{-1}, with daily maxima up to 6-8 mm day^{-1} (Dye, 1987) and daily minima from 1 to 3 mm day^{-1} according to Roberts and Rosier (1993).

3.2.5. Leaf area index, stomatal resistance and T/E_p ratio. The maximal leaf area index obtained for our Eucalyptus plantation was 3.2; this value is close to those of comparable plantations: according to Roberts et al. (1992) the leaf area index was 2.2 in a six years-old *Eucalyptus tereticornis* plantation (India) and of 2.3 in a six years-old *Eucalyptus camaldulensis* plantation (India). The leaf area index cited by Gazarini et al. (1990) was 3.8 in six years-old *Eucalyptus grandis* plantation (Portugal), and that cited by Beadle et al. (1995) was 3–4.5 in four years-old *Eucalyptus globulus* plantation (Australia).

The three-years mean leaf stomatal resistance of the Eucalyptus plantation (r_s) was establised using the Jarvis model (Stewart, 1988) where the actual daily stomatal resistance depends on: (a) minimal stomatal resistance (r_{smin}), measured *in situ* during the rainy season when the Eucalyptus plantation was well supplied with water; (b) leaf area index; (c) net radiation; (d) air vapour pressure deficit; (e) difference between the soil-water content at the field capacity and the actual soil-water content (R_{FC}-R). For the leaf area index of 3.2 the mean minimal leaf stomatal resistance of the Eucalyptus plantation was 16.7 s m^{-1} in the dry season and 6.1 s m^{-1} in the rainy season; this value, according to Beadle et al. (1995), being close to $r_{\mathrm{smin}} =$ 5.9 s m^{-1} of comparable plantations, with the leaf area index of 3.5, well supplied with water (the mean minimal seasonal stomatal resistance).

The mean minimal leaf stomatal resistance of savannah, establised from Bowen ratio measurements, was 3.5 s m^{-1} in the rainy season and 5.4 s m^{-1} in the dry season while the leaf area index ranged between 1.3 (August) and 4.1 (February).

During the year, transpiration (T) and potential evapotranspiration (E_p) ratio, T/E_p (relative transpiration), is related to the soil-water content, being expressed as the ratio of actual soil-water content and soil-water content at the field capacity (R/R_{FC}), depends on the species and accounts for its stomatal regulation. In the Eucalyptus plantation's soil (Fig. 2), the T/E_p ratio was 0.79 (the three-years mean for the rainy season) and not reduced from field capacity ($R_{FC} = 618$ mm) until 65% of R_{FC} ($R = 402$ mm), and then decreased quickly to near zero, $T/E_p \approx 0$–0.2, at permanent wilting point or 53% of R_{FC} ($R_{WP} = 328$ mm). The T/E_p ratio of 0.79 (for $R \approx R_{FC}$) is close to $T/E_p = 0.81$ as cited by George (1978) for a six years old *Eucalyptus tereticornis* plantation (India, $Pi = 1670$ mm year^{-1}); or $T/E_p = 0.84$ cited by Calder (1985) for a six years old *Eucalyptus saligna* plantation (Brazil, $Pi = 1280$ mm year^{-1}); according to Myers et al. (1996) and Honeysett et al. (1996), T/E_p varied between 0.76 and 0.86 for the *Eucalyptus grandis* plantations while the leaf area index ranged from 2.8 to 3.1 (New South Wales, Australia and Tasmania).

The variation of the savannah's T/E_p ratio versus soil-water content (Fig. 2) is different from that of the plantation: there is a linear regression between the T/E_p ratio and soil-water content deplation R/R_{FC} (Fig. 2); the three-years rainy season mean of the T/E_p ratio was 0.61 (R close to $R_{FC} = 363$ mm) and 0.34 during the dry season (R close to 51% of R_{FC}; $R = 185$ mm). While for the plantation, one observes the values of T/E_p ratio being close to zero (for R values close to R_{WP}), the weakest values observed for the savannah go from 0.19 to 0.25. And, whatever the soil-water content of the Eucalyptus plantation's soil, for a given value of this soil-water content the T/E_p ratio is always superior to that of the savannah. The stomatal regulation of the Eucalyptus plantation must thus be regarded as "little significant".

3.2.6. Actual evapotranspiration. During the rainy seasons of 1996, 1997 and 1998, the seasonal actual evapotranspiration of Eucalyptus plantation was 767 mm (740; 848 and 714 mm), giving a daily seasonal mean of 4.2 mm day^{-1}. According to Dye (1987) the daily seasonal mean estimated on 57 days for a six years old *Eucalyptus grandis* plantation (Eastern Transvaal, South Africa, $Pi = 1250$ mm year^{-1}, mean height 21.9 m, 725 trees ha^{-1}, $LAI = 4.23$) was 4.7 mm day^{-1}. During the same periods, the seasonal actual evapotranspiration of savannah was 579 mm (473; 717 and 547 mm during the three rainy seasons), giving a daily seasonal mean of 3.2 mm day^{-1}. During the dry sea-

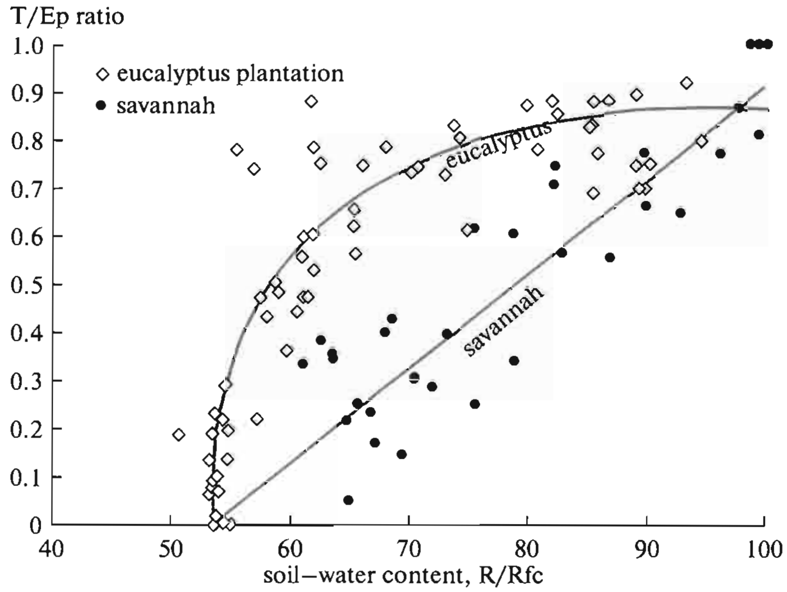

Fig. 2. Relationship of transpiration (transpiration/potential evapotranspiration, T/E_p) and soil water content (mean weekly values from 17 February 1997 to 26 July 1999: (a) Eucalyptus plantation (*Eucalyptus PF1* and *Eucalyptus 12ABL* saligna*); (b) savannah with *Loudetia arundinacea*.

sons the mean seasonal actual evapotranspiration of the Eucalyptus plantation and savannah were, respectively 183 and 121 mm (1.5 and 1.0 mm day^{-1}). The annual mean of the E_a for the three years (total annual value, including May and October) of the Eucalyptus plantation was larger by 306 mm than in the savannah; they were respectively: 1127 mm (95% of Pi_{49-98} and 75% of E_{p92-98} with E_{p92-98} equal to 1510 mm year^{-1}) and of 821 mm (69% of Pi_{49-98}, 59% of E_{p92-98} with E_{p92-98} equal to 1395 mm year^{-1}). In the analysis of the sustainability of Eucalyptus plantations, this actual evapotranspiration value will be used for the comparison with the rainfall of the 1949–98 period.

The validity of actual evapotranspiration measures depends on the choice of study stations that have to conform to the one-dimensional heat and mass transfert model; this approach assumes a pure, closed, horizontally homogeneous stand with a canopy whose horizontal dimention is much larger than the vertical one, without "fetch effect". The difficulty resides in the horizontal energy inputs which Sharma (1984) observed in *Eucalyptus marginata* and *Eucalyptus calophylla* plantations (West Australia, Pi = 1100 mm year^{-1}), where actual evapotranspiration was larger than the potential evapotranspiration because of horizontal energy transfer. In our case, we have not had this type of phenomenon and there has been a good agreement between the potential and actual evapotranspiration estimated by the Penman–Monteith equation, using the soil-water balance method, sap flow measurements and the Bowen ratio method.

The soil-water profiles (soil-water content plotted over soil depth) which were determined for the Eucalyptus plantation and savannah over the period of three years reveal preferential water uptake zones and rooting depths: the exploration of soil by absorptive roots reaches 5 m and 3 m depths, respectively for the Eucalyptus plantation and savannah; a similar value of rooting depth for the Eucalyptus plantation have been given by sap flow measurements during the dry season of 1997: with for example T = 0.8 mm day^{-1}, E_p = 3.1 mm day^{-1} and T/E_p = 0.26, trees of the plantation undergoing a large soil-water stress, but water uptake by roots of the Eucalyptus plantation does not occur from deeper than 5 m depth. These rooting depths of the Eucalyptus plantation and savannah are the foremost element in the precision of the soil-water balance equation method.

3.2.8. Drainage. The drainage out of rooting depths of savannah (table) that occurred during the rainy seasons of 1997–98 and 1998–99, totalled 827 mm, for the three years (0, 390 and 438 mm); while out of rooting depths of Eucalyptus plantation (table) it was of 470 mm (0, 207 and 263 mm), a difference in drainage between the two ecosystems of 357 mm for these three years (0, 183 and 174 mm). During the rainy season of 1996–97, there was no drainage either from the Eucalyptus plantation or from the savannah; during the rainy seasons of 1997–98 and 1998–99, the drainage from savannah was greater than that from the plantation; the respective figures were 183 mm and 174 mm. These values are close to results reported by Van Lill et al., (1980) of a catchment experiment on the Eastern Transvaal, South Africa; these catchments had originally been under natural grass cover and were then planted with *Eucalyptus grandis* (annual rainfall in this

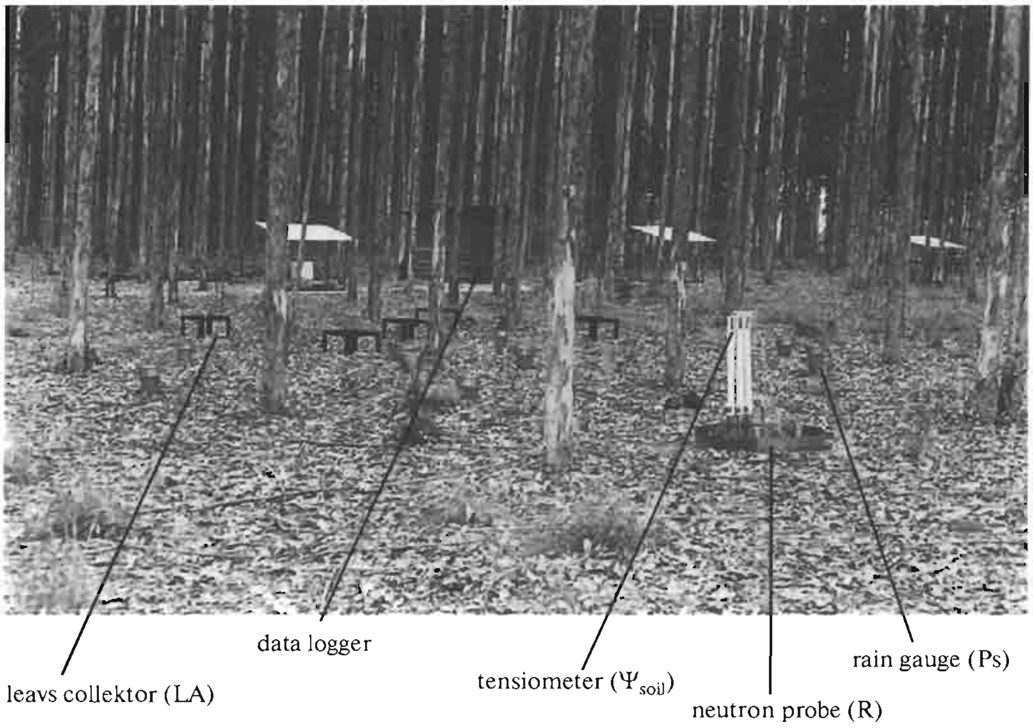

Fig. 3. Study site—a six years-old Eucalyptus plantation. *Eucalyptus PF1* and *Eucalyptus 12ABL* saligna*.

area of 1140-1340 mm year^{-1}); the afforestation with *Eucalyptus grandis* resulted in streamflow reductions of a total of 340 mm, over three years.

3.3. Sustainability of Eucalyptus Plantations

If one compares the actual evapotranspiration and drainage of the Eucalyptus plantations and savannah for the three studied years, the actual evapotranspiration of the plantation exceeds that of the savannah by 688 mm while the drainage of the plantations is 306 mm lower than that of the savannah. The afforestation of savannah thus increases actual evapotranspiration and reduces drainge. The term "theoretical rain-deficient year" refers to a year in which the annual rainfall is inferior to the mean annual actual evapotranspiration of the plantation and savannah during the three years of the study i.e. $E_{a96-99} = 1127$ mm year^{-1} for the Eucalyptus plantation and $E_{a96-99} = 821$ mm year^{-1} for the savannah. From 1949 to 1998, the number of "theoretically rain-deficient years" is 17 years for the plantation and 3 for the savannah (1958, 1978 and 1989). But if one considers the phenomenon "number of theoretical successive rain-deficient years" we find that this phenomenon has taken place once for the plantation during four successive years (1971, 1972, 1973 and 1974) but not at all for the savannah.

Taking the example of the most rain-deficient rainy season of 1996–97 ($Pi_{96-97} = 459$ mm, or 44% of Pi_{49-98}) we find that the actual evapotranspiration was 740 mm making this a "theoretical rain-deficient year": these 740 mm correspond to the total rainy season rainfall of 1996–97 ($Pi_{96-97} = 459$ mm), to which it is necessary to add 281 mm withdrawn from the rooting zone of 5 m depth; this roofings zone to the end of dry season of 1997 (September) was thus dried to wilting point at 53% of R_{FC} ($R_{FC} = 309$ mm). The soil-water profiles analysis clearly shows this phenomenon. At the same time, the actual evapotranspiration of the savannah was 473 mm, which corresponds to only 14 mm soil-water having been withdrawn from the rooting zone of savannah, as compared with the 281 mm taken up by the Eucalyptus plantation. By the end of the dry season of 1997 (September), the soil of the rooting zone of the Eucalyptus plantation was at wilting point, while in the savannah's soil 27 mm subsist, or 15% of R_{AW} (rooting depth of 3 m).

The Eucalyptus plantation is the man-made evergreen ecosystem, so there is water uptake and transpiration by the trees throughout the year; all available soil-water content is thus used. The succession of several rain-defficient years would lead to the depletion of the available soil-water content; but this depletion is likely to enable the Eucalyptus plantation to continue to produce wood. In the case of the savannah, knowing that 27 mm available water continue to subsist at the end of the dry season 1996–97, one can imagine the two rain-deficient years succeding to a year of the type

1996–97; would still have no impact on savannah's production since, in 1996–97 only 14 mm of soil water was withdrawn and 27 mm is very close to 2 × 13.7 mm.

Knowing that between 1949 and 1998, there has been only a single rain-deficient periodof four years for the Eucalyptus plantation, and that the rotation duration is seven years, one can suppose that this type of "dry" period does not compromise the survival of the plantation, but reduces its wood production. As already mentioned, in the case of the savannah, there has been no loss of production during this type of "dry" period because the savannah is natural grass cover adapted to the ocal Congolease climate, characterized by important annual rainfall variability; these climatic conditions have produced an ecosystem in which E_a is less than the E_a in a Eucalyptus plantation.

The natural distribution of the genus Eucalyptus ranges between latitude 7° North and 43°39′ South: one can classify Eucalyptus species in two large groups, one where the water consumption of trees is low, "low water-use rates trees" and the other where it is high. The studied clones *Eucalyptus PF1* and *Eucalyptus 12ABL* saligna* belong to the high water-user group and, come from a Java hybrid (wet tropical zone with mean annual rainfall of 2030 mm year^{-1}): the trees are fast-growing tree with short life span of leaves (about 6–9 months) and stomatal regulation "little significant" ($r_{\text{smin}} = 3.5$ to 5.9 s m^{-1}, rainy season). The leaf longevity in the studied Eucalyptus plantion was about 6–9 months and minimal stomatal resistances place this Eucalyptus as belonging to the high water-consumers group. The local Congolese climate is characterized by important annual rainfall variability, from $Pi_{58} = 296$ mm year^{-1} to $Pi_{60} = 2045$ mm year^{-1}, then there were again rain-deficient years. The availabity of soil-water is a limiting factor for these two clones, which are nevertheless well adapted to the local Congolese climate. One can illustrate this acclimatization by the hydromass use during the dry season: the foresters have followed the trunk diameter increase in the Eucalyptus plantation to which the studied plots belongs, with steel tapes fastened to the trunk at 1.3 m above ground level, from 1992 to 1998 a period during which there was only one rain-deficient year (1996–97). During the seven years (1992–98), they have not observed any significant reduction of wood increment during dry seasons. If one had used more discriminating sensors, one would perhaps have been able to observe the hydromass use during these dry seasons: the hydromass is about 20–30 mm, in a forest with trees 24 m high (Granier, 1987); if one "spreads" these 30 mm over the dry season, July and August (≈60 days), one obtains a value of 0.5 mm day^{-1} to add to 0.5 mm day^{-1} (mean value from 24 May to 1 August 1997) measuring by heat pulse velocity method (sensors at 1.3 m from the soil surface); one can then estimate daily transpiration to be approximately 1 mm day^{-1}. With the potential evapotranspiration close to 2 mm day^{-1} (dry season 1997), T/E_p ratio would be then close to 0.5, near the optimum value of $T/E_p = 0.79$ ratio and the minimal stomatal resistance. So, the use of the hydromass in the dry season avoids or moderates, according to years, the reduction of wood production during the dry season.

4. CONCLUSIONS

We have shown that a succession of several rain-deficient years would reduce the wood production of the Eucalyptus plantation, but would not compromise its survival because of the short rotation of these plantations; that is the first positive conclusion concerning the sustainability of these plantations.

The afforestation of savannah, planted to Eucalyptus, reduces the drainage; the soil-water content of Eucalyptus plantation's soil was, therefor in general, lower than the soil-water content of savannah's soil. The question there arises whether in the long term; this low soil-water content induces a chemical and biological modification of the soil? The study of soils and the carbon and essential mineral elements cycles will provide the necessary data to determine these sustainability aspects. Another question is whether the afforestation of savannah, planted to Eucalyptus which increases the actual evapotranspiration will in the long term, induce a modification of local and regional climate? The bio-climatological study starting now is intended to provide the necessary data to determine these other sustainability aspects.

At present Eucalyptus plantations cover 43 000 ha, and they are expected to increase to 100 000 ha. The Eucalyptus growth and transpiration studies will have to include the testing and selection of clones in order to ensure the long term sustainability of the plantations. Knowing that the water is a growth limiting factor of wood production from currently used clones of Eualyptus, it will be necessary to study the water-use efficiency of clones, chosen for the future plantations. We shall have to comparing: (a) growth-rate for given water availability; (b) woody biomass produced per milimetre of rainfall, irrespective of growth-rate and then select one or the other of these features. If one supposes that an increase in actual evapotranspiration will in the long term modify the regional climate, clones for sustainable Eucalyptus plantions will not necessarily to be those that produce most wood.

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