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Evolution of Actual Evapotranspiration in the Drying Phase on Sandy Deposits in Burkinabe Sahel

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Abstract This article deals with the spatio-temporal variability of actual evapotranspiration on sandy veneers in the Burkinabe Sahel characterized by a large variability of rainfall and exceptional dry conditions according to the seasons. In order to establish a water balance, a tensio-neutronic device was deployed on seven (07) sites located on three (03) surface states (Unprotected grazed area, Restored fenced area and Protected area). Results showed a difference in the behavior of the actual evapotranspiration during the drying phase on the different surface states. Indeed, the presence of superficial film (site S1) significantly limits water infiltration. On desiccation sites (S3, S5, S6 and S7) characterized by the scattered or abundant presence of vegetation, the absence of indurated superficial film creates more favorable conditions for infiltration which results in a more or less significant accumulation of water in the soil. As for the partially encrusted sites (S2 and S4), we observed an intermediate behavior with respect to the other two sites with more or less water storage in the soil.

Keywords: *dry spells, soil water content, soil physic, evapotranspiration, sahel*

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1. Introduction

The Sahelian part of Burkina Faso is facing to significant environmental tension, because of their great ecological fragility and the scarcity of water resources. The growth and the transformation of the populations needs increase the pressure on the natural resources and can generate phenomena of environmental degradation, often amplified by the climate changes. Indeed, this area is essentially characterized by a low rainfall combined with high evaporation resulting from high temperatures which have resulted in an intense evaporative demand [1] resulting in a rapid decrease in soil water stock. Considered at the regional level and at the multi-year scale, the Sahelian climate appears to be homogeneous. But this is only an appearance because at the local scale, there is a strong heterogeneity that mainly concerns rainfall, which, in addition to its relative rarity, has a high spatial and temporal variability at any time scale and space [2,3,4]. This irregularity has generated significant water constraints for agrosystems. This paper presents the results of the evolution of the spatio-temporal variability of the actual evapotranspiration during two periods of desiccation on several surface states.

2. Materials and Methods

2.1. Study Area

The study area is located in the Sahelian part of Burkina Faso on an experimental field located close to the village of Katchari, 15 km West of Dori. It is a non-cultivated pastoral area overgrazed by livestock. Vegetation is of Sahelian steppe type with thorny species, characterized by discontinuous grassland and woodland areas. Two main vegetal units that can be distinguished [5]:

i) Dune and sandy formations with a dense vegetable cover of up to 90% in the rainy season;

ii) Pediment (glacis) formations where vegetation is virtually absent, with only sparse wooden species at a density of 1 to 2 trees/ha.

On the whole, vegetation is facing to a permanent degradation caused by numerous physical and socio-economic factors. In woodland areas, the mortality rate can be as high as 200 to 300 trees/ha/year [6]. The cumulated annual rainfall presents a strong inter-annual variability with an average of 513 mm and a standard deviation of 123 mm (period 1925 to 2005). The one observation year (2004) are characterized by a rainfall deficit year (369 mm). Rainfalls occur essentially between

August and May (rainy season), the other months (September to April) being characterized by an almost total absence of precipitations. The study was focused mainly on three types of soil crusting (by reference to the crust classification established by [7] frequently observed in the study area, namely:

i) Drying crusts (Dry): Surfaces characterized by a massive single sandy microhorizon, presenting a high porosity and supporting most of the vegetation;

ii) Drying crusts in transition (Dry/Ero) on which the soil proportion occupied by surface features of erosion crust type increases regularly in importance;

iii) Erosion crusts (Ero): Smooth surfaces made of a single seal of fine cemented particles and characterized by a very low porosity; no vegetation grows in these areas.

The soil surface classification used here stems from the morphogenetic typology established by [7,8] from data obtained under simulated rainfall conditions in Sahelian areas. Soil surface features are prone to spatial and time dependent variations [9,10] influenced by the combination of successive or simultaneous climatic, faunal and anthropic processes causing soil superficial reorganizations susceptible to the formation of surface crusts. The experiments were performed on seven sites located in three distinct areas:

i) An unprotected grazed area undergoing a continuous degradation due to natural and anthropic processes. Three measurement sites were installed in this area: one on an erosion crust (S1) ; a second on a drying crust (S3) and a third on a drying crust in transition (S2) ;

ii) A restored fenced area with restoration practices carried out in 1998, consisting in the application of branches to increase the roughness of the ground and to accelerate the processes of trapping the aeolian sands. Two sites of measurements were set up in this area: one (S5) on a drying crust and the other (S4) on a drying crust in transition ;

iii) A protected area, isolated from anthropic activities since 1985, of approximately 20 ha, in which two sites of measurements were installed on a drying crust (S6 and S7).

Some characteristics of the various measurement sites are summarized in Table 1**.**

Pedological studies and grain size distribution analysis reveal a clear prevalence of leached ferruginous soils. They present a loamy-sandy to sandy-loam texture (according to the USDA Soil Textural Triangle) close to the soil surface, evolving towards a sandy clay loam below 30 to 40 cm. These tropical ferruginous soils are characterized by a poor structural stability of the surface horizons attributable to their high silt and fine sand contents and low organic matter content. They are subject to a very active dynamics, largely determined by water and wind erosion. The perpetual shaping leads to the formation of new surface features as pointed out by [8]. Such an evolution is accompanied by the emergence of more recent sandy aeolian deposits and by sand losses from the surface horizon which may reveal a drying crust in transition. When all the sand has disappeared, the soil evolves towards an erosion crust. Some other basic physical characteristics (soil density, organic matter content and porosity) have been determined on undisturbed soil samples collected before the beginning of the rain season 2003. The values of bulk density range between 1.49 and 1.74 g/cm^3. The organic matter content is always lower than 2% with most values ranging between 1.3 and 1.8%.

2.2. Experimental Design and Measured Parameters

Each experimental site was equipped with devices making it possible to estimate the main components of the soil water balance, namely run-off, spatio-temporal variations of the soil water content and water pressure head, as well as the drainage at the depth of 50 cm. The run-off was estimated using 1m^2 microplots delimited by a metallic frame from which the surface water was transferred to a barrel located downstream [11,12]. The soil water content was measured up to a depth of 80 cm using a neutron probe and helped us determine the change in water stock. The values of the soil water pressure head were given by tensiometers installed at various depths (10, 20, 30, 40 and 60 cm) and connected to a mercury pressure gauge. The measurements of water content and pressure head were taken daily during the rainy season and monthly during the dry season. The drainage was estimated at the depth of 50 cm from tensiometric values measured at 40 and 60 cm after determination of the unsaturated hydraulic conductivity function from internal drainage experiments. The rain was measured with 3 hand rain gauges and an automatic recording rain-gauge installed in the study area. Subtraction of the run-off volume from the rainfall volume gives the volume of infiltrated water.

The actual evapotranspiration (ETR) was estimated from the different measured / calculated parameters (rainfall P, water stock change ΔS, runoff R and drainage D) of the water balance equation which states that any difference between water inlets and outlets, during the considered period, results in a variation of the water stock (ΔS) in the soil profile.

$$\Delta S = \text{water inlets} - \text{water outlets} \quad (1)$$

Water inlets were constituted mainly of rainfall (P) and possible capillary rise (G), and water losses included the actual evapotranspiration (ETR), runoff (R) and drainage (D) beyond the lower limit of 50 cm considered. So, we have:

$$\Delta S = (P + G) - (ETR + R + D) \quad (2)$$

In the present study, capillary rise (G) lifts have been neglected. So, equation (2) can be written:

$$\Delta S = P - (ETR + R + D) \quad (3)$$

Table 1. Important features of the measurement sites

Location	Numbering of sites	Surface crust	Slope (%)	Vegetation
Unprotected grazed area	S1	Erosion crust (ERO)	2.5	Absence of vegetation
	S2	Drying crust in transition (DES/ERO)	2.8	Sparse vegetation
	S3	Drying crust (DRY)		Abundant vegetation
Restored fenced area	S4	Drying crust in transition (DES/ERO)	1.0	Sparse vegetation
	S5	Drying crust (DRY)	1.8	Abundant vegetation
Protected area	S6	Drying crust (DRY)		Abundant vegetation
	S7	Drying crust (DRY)	2.5	Abundant vegetation

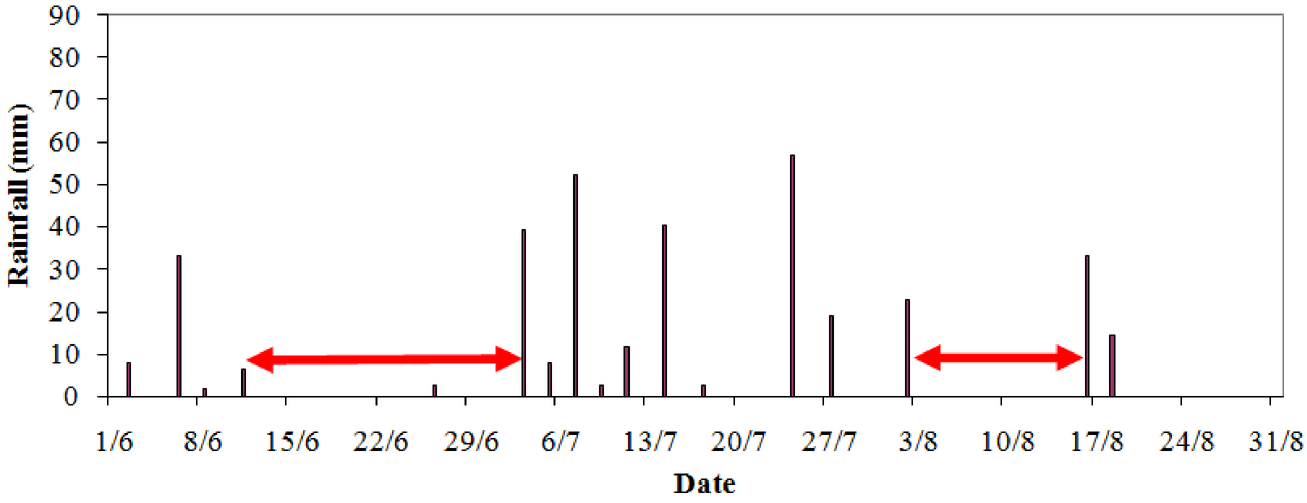

Figure 1. Daily rainfall at Katchari for the 2004 rainy season

3. Results and Discussion

3.1. Evolution of Rainfall

Figure 1 represents the evolution of the daily rainfall during the year 2004. This is a rainfall year marked by a significant deficit characterized by the appearance of 2 dry periods, one located between June 12 and July 2nd, the other between August 3rd and 15th.

3.2. Evolution of the Daily ETR during These Two Dry Phases

The daily values of the actual evapotranspiration (ETR) calculated on the basis of daily water balances and the reference evapotranspiration (ETo) show on the dry phases a rapid decrease of the water content which leads to very low humidities on all the sites. At sites S1, S2 and S4, devoid of any vegetation, only evaporation is involved in soil water loss, while at other sites transpiration adds to evaporation, even if vegetation is not very abundant. The representation of the time evolution of the cumulative daily actual evapotranspiration (ETRcum) during the two considered periods (Figure 2 and Figure 3) reveals that this variable (ETRcum) follows a power function of the type: $ETR_{cum}=\alpha t^{\beta}$ with very high coefficients of determination (R^2), always greater than 0.99. It is often considered that from the moment when the capacity of the soil to feed the surface is lower than the evaporative demand (stage with decreasing regime), which is obviously the case here, the cumulative evaporation ERcum is proportional to the square root of time and can be estimated by the expression : $ETR_{cum}=\alpha t^{0.5}$ in which α is a coefficient and t is the time elapsed since the beginning of the decreasing phase. We note that on all sites the coefficient β is systematically higher than 0.5 (between 0.55 and 0.75) as shown in Table 2.

Examination of Table 2 reveals that, in general, the values of the α and β coefficients were substantially lower at the S1, S2 and S4 sites, which indicates a reduced cumulative evapotranspiration at these sites (17 to 23 mm, compared to 28 to 35 mm at sites S3, S4, S5, S6 and S7 for the period from June 12 to July 2 and 8 to 14 mm against 23 to 36 mm, respectively, for the period from August 3 to 15). It also appears that the values of the exponent β are significantly lower on the sites S1, S2 and S4 for the period from August 3 to 15, whereas they are very close on the other sites for the two periods considered. The relationship between the values of the daily actual evapotranspiration (ETR) and the corresponding water content measured at 10 cm depth is shown in Figure 4 and Figure 5, whereas the evolution of the ETR/ETo ratio as a function of this same variable (water content at 10 cm depth is shown in Figure 6). These different figures indicate a dependence between the soil water content at 10 cm depth and the ETR. This dependence appears relatively linear for low water content values (<10%) and increases more rapidly thereafter. The overall behavior once again confirms that the sites can be grouped according to the categories already mentioned above, namely at sites S2 and S4 (drying crust in transition) and, moreover, on the site S1 (erosion crust), the evapotranspiration is smaller than on the sites on the drying crust (S3, S5, S6 and S7). [13] demonstrated that evapotranspiration can be controlled by two fundamental factors, either by soil or climate, hence the introduction of the concepts of "climate controlled" and "soil controlled". When soil water content is very high, evapotranspiration occurs at a potential rate (ETo), and it is the atmospheric conditions in the region that primarily control the ETR ("climate controlled"). On the other hand, if soil moisture is low, the rate of ETR is limited by the availability of water (it is lower than the potential rate), it is called the exfiltration capacity of the water vapor towards the soil surface [14]. In our study area the rate of ETR is more governed by the moisture and physical properties of the soil as well as the thermal energy stored in the soil layer immediately below the surface. Plant cover is another factor that influences ETR by its differences in surface albedo and its ability to draw water from the soil by transpiration. The results obtained show that the erosion crust is the medium that generates the highest levels of ETR. This phenomenon is explained by the presence of a higher water content, related to the existence of more or less important vegetation [15]. This reflects the importance of vegetation on the spatial variability of ETR. The main reason is probably related to a lower initial water content and the absence of vegetation on S1, S2 and S4 sites exposed to evaporation alone, while on the other sites the extraction of water from soil is due to the combined effects of evaporation and plant transpiration. It is confirmed that evapotranspiration depends on both surface type, soil moisture and vegetation.

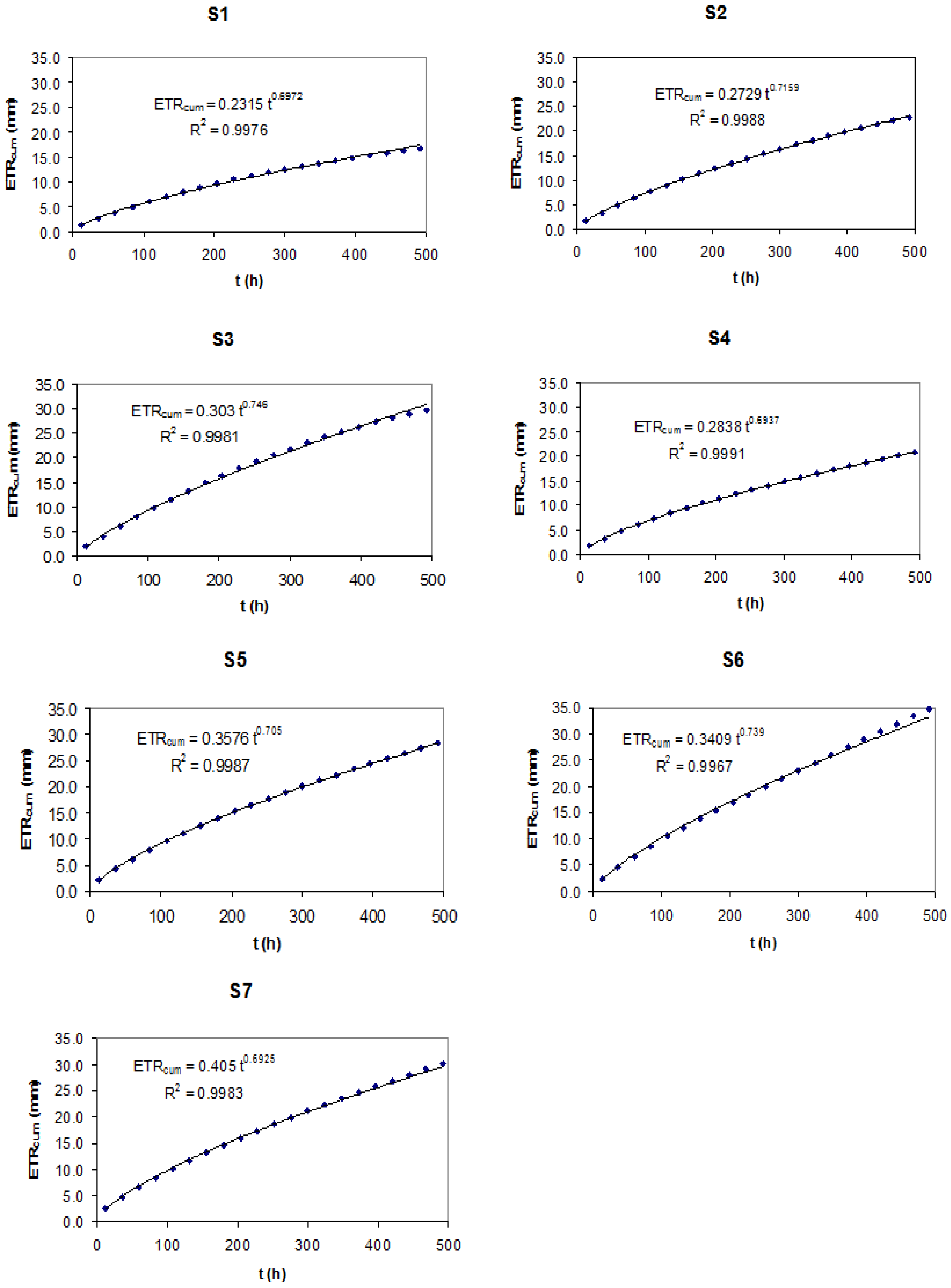

Figure 2. Evolution of daily actual evapotranspiration for the period from June 12 to July 2, 2004

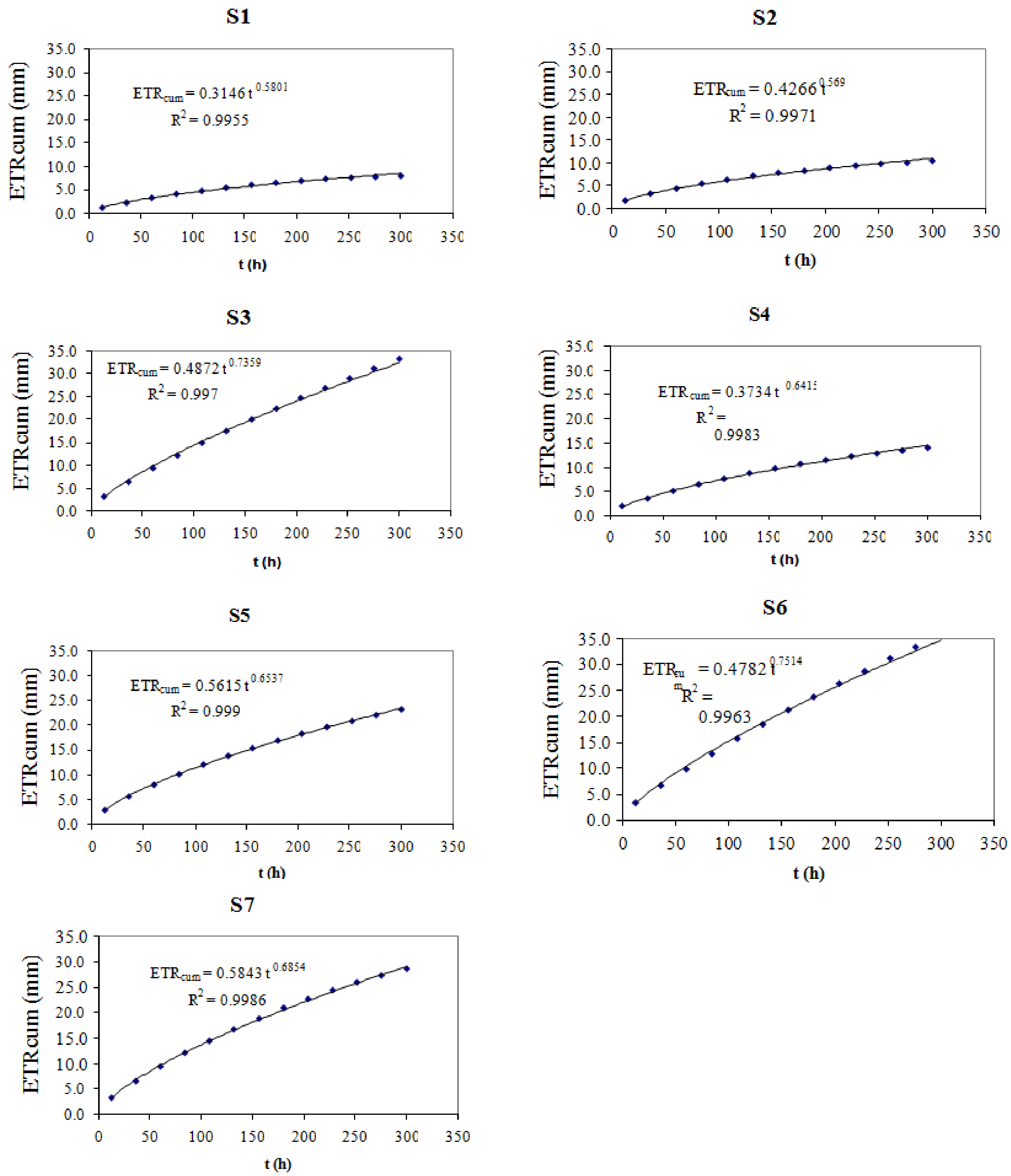

Figure 3. Evolution of daily actual evapotranspiration for the period from August 3 to 15, 2004

Table 2. Values of the coefficients α and β of the relation ETRcum = αt^β on the various sites during the 2 periods of drying studied

		June 12– July 2, 2004		August 3 to 15, 2004	
		α	β	α	β
S1	(Ero)	0.2315	0.6972	0.3146	0.5801
S2	(Des/Ero)	0.2729	0.7159	0.4266	0.569
S3	(Des)	0.303	0.746	0.4872	0.7359
S4	(Des/Ero)	0.2838	0.6937	0.3734	0.6415
S5	(Des)	0.3576	0.705	0.5615	0.6537
S6	(Des)	0.3417	0.739	0.4782	0.7514
S7	(Des)	0.405	0.6925	0.5842	0.6854

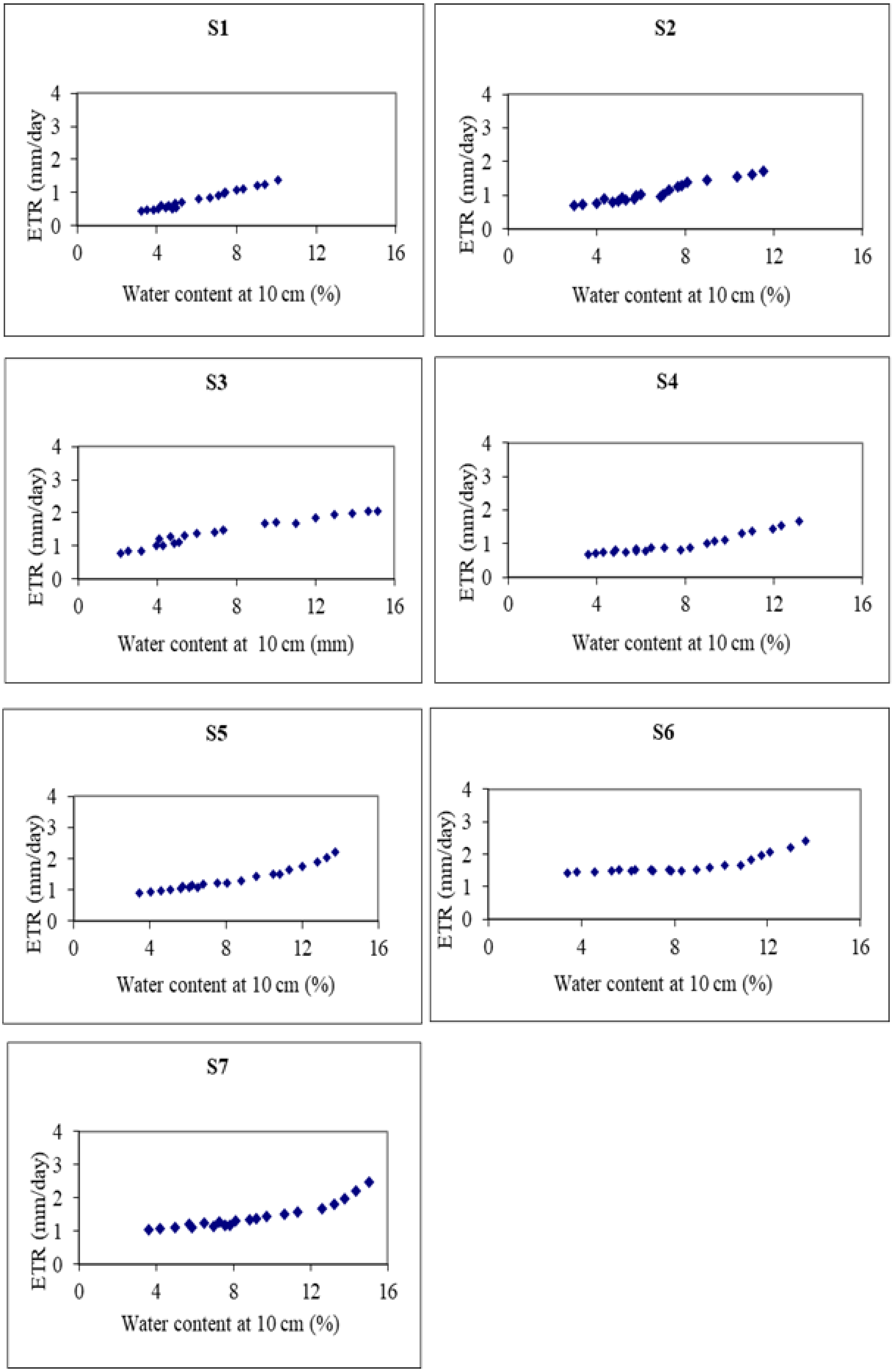

Figure 4. Evolution of the daily actual evapotranspiration as a function of the water content at 10 cm for the period from June 12 to July 2, 2004

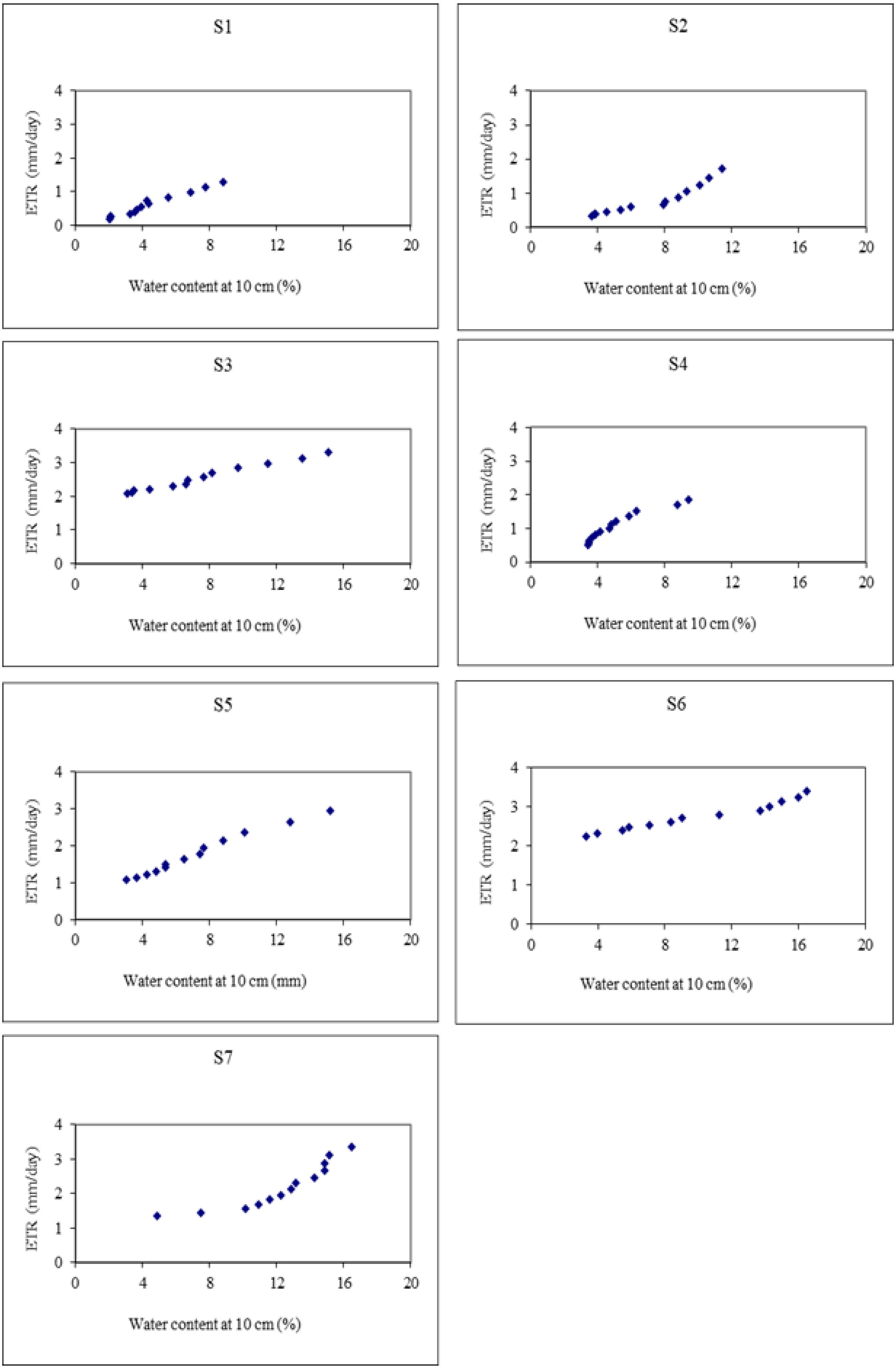

Figure 5. Evolution of the daily actual evapotranspiration as a function of the water content at 10 cm for the period from August 3 to 15, 2004

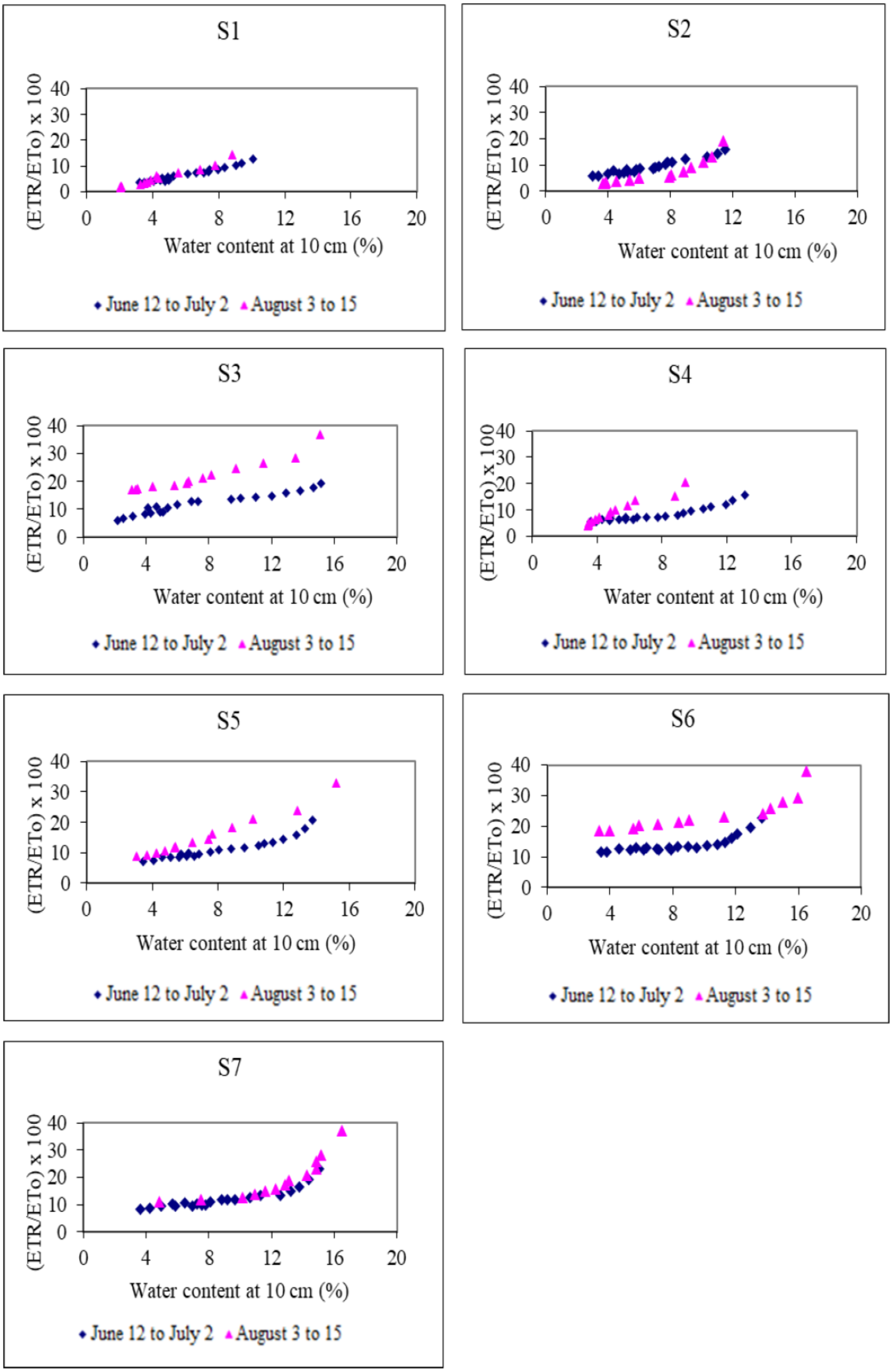

Figure 6. Evolution of the ETR/ETo ratio as a function of water content at 10 cm depth for two dry periods

In the Sahelian zone of Burkina Faso, the rains are generally concentrated in a short period during which the temperatures are high, which cause a strong evaporative demand. This results in very rapid loss of some of the evaporative precipitation water in the days following the rain, even before this water can effectively contribute to the soil water reserve replenishment [16]. In fact, water reserves quickly become insufficient to allow a satisfactory water supply of the plants. Then, the actual evapotranspiration decreases rapidly and the plants dry out. The rainy season is not necessarily synonymous with sufficient water availability because in Sahelian zone this period is marked by an alternation of rainy events and dry episodes of variable duration that can create disastrous situations when they exceed a dozen many days, as the stock of water accumulated during previous showers is rapidly depleted. The rhythm of the rainy events and the dry episodes thus has a decisive influence on the water dynamics of this arid environment. This alternating rainy events-dry episodes is characterized by a strong spatio-temporal variability. The amount of water precipitated and the duration of dry episodes can differ considerably from one year to the next, which imposes on living beings the very changing conditions that they must face and adapt. Moreover, the quantities of water precipitated during a rainy event can be subject to strong spatial variations (observable in the 3 zones selected for this study, yet relatively close to each other). These parameters (interannual variability, irregular rainfall, spatial variability) significantly influence the availability of water for plants ; they must be taken into account in the case of agro-pastoral use of the environment. The water supply of the upper soil layer is thus exclusively through the surface, so that their water functioning is strongly conditioned by the state of the soil surface (encrusting, micro-relief, vegetation) subjected to various phenomena of degradation, and more particularly by the spatio-temporal evolution of the infiltration capacity of the superficial formation. It is likely that the observed differences between the two sets are mainly due to rainfall. Indeed, in the Burkinabe Sahel, this rainfall strongly conditions the water transfer of these environments.

4. Conclusion

The temporal evaluation of the actual evapotranspiration on sandy veneers during a drying phase, showed a systematic difference according to the surface condition. This difference comes essentially from the evolution of the surface states:

- On site S1 (erosion crust), there is the existence of a superficial film characterized by a low infiltration capacity due to a reduced porosity, which appears this film organization to a real hydraulic barrier which strongly limits the entry of water into the soil. These types of surfaces lacking vegetation most often generate significant runoff and lead, correlatively, to a very low accumulation of water in the soil; low infiltration affects only the surface horizon in which most of the moisture fluctuations take place;

- at sites S2 and S4, partial encrustation limits the quantity of water infiltrated resulting in a high rate of runoff (of the order of 50%); variations in water content caused by the water that infiltrates are located mainly in the first 30 centimeters;

- at desiccation sites (S3, S5, S6 and S7), the absence of an indurated surface film creates more favorable conditions for infiltration, which results in more or less accumulation of water in the soil.

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