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A conceptual dynamic vegetation-soil model for arid and semiarid zones

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Abstract

Plant ecosystems in arid and semiarid zones show high complexity from the point of view of water resources, since they depend on water availability to carry out their vital processes. In these climates, water stress is the main factor controlling vegetation development.

The available water in the system results from a water balance where the soil, vegetation and the atmosphere are the key issues; but it is the vegetation which modulates (to a great extent) the total balance of water and the mechanisms of the feedback between soil and atmosphere, being the knowledge about soil moisture quite relevant for assessing available water and, as a consequence, for growth and plants maintenance and the final water balance in the system.

A conceptual dynamic vegetation-soil model (CDVSM) for arid and semiarid zones was developed. This model based in a tank type conceptualization represents in a suitable way, for Mediterranean climate, the vegetation responses to soil moisture fluctuations. Two tanks interconnected were considered using the water balance equation and the appropriate dynamic equation for all considered fluxes. The first one corresponds to the interception process done by the vegetation. The second one models the upper soil moisture determination. In this tank parameters are based on soil and vegetation properties. The transpiration of the vegetation is a function of the soil moisture, the vegetation type and the biomass. Once all water state variables are evaluated at each time step, the modifications in the biomass are made as a function of transpiration rate and water stress.

Simulations for monoculture of *Quercus Coccifera* L. were carried out. Results shows that CDVSM is able to represent the vegetation dynamic, reflecting how the monoculture is stabilized around 0.7 of relative biomass, with adaptation to the soil moisture fluctuations in the long term. The model shows the vegetation adaptation to the variability of the climatic conditions, demonstrating how either in the presence or shortage of water, the vegetation regulates its biomass as well as its rate of transpiration trying

to minimize the total water stress.

1 Introduction

Water-controlled ecosystems are complex, their properties, evolving structures whose characteristics and dynamic properties depend on many interrelated links between climate, soil and vegetation (Rodriguez-Iturbe and Porporato, 2004). On one hand, soil and climate control the vegetation dynamic; on the other hand, the vegetation modulates the total water balance, turning into responsible of feedback mechanisms between atmosphere and soil (Larcher, 2003; Porporato and Rodriguez-Iturbe, 2002). The vegetation needs resources like light, water and nutrients for its development but, in arid and semiarid climates, available light and nutrients plays a second role, being the availability of water the main controlling factor, so, the knowledge about soil moisture is the key variable in the soil-vegetation- atmosphere continuum (Daly et al., 2004; Rötzer et al., 2004; Porporato et al., 2002; Albertson and Kiely, 2001; Laio et al., 2001; Porporato et al., 2001; Rodriguez-Iturbe et al., 2001; D'Odorico et al., 2000).

Because of the non-linearity of climate-soil moisture, the vegetation has developed adaptation strategies to low or null water availability, grouping in functional types, characterized by optimum use of resources (Baldocchi et al., 2004; Cantón et al., 2004; Gitay and Noble, 1997; Shugart, 1997; Eagleson and Segarra, 1985); in this way, the plant maximizes the water use guaranteeing the minimum water stress (Eagleson, 2002, 1978).

Nowadays, there are many ways to answer the vegetation modeling question. Most of the hydrological models are able to represent hydrological processes, at watershed scale, but all of them consider the vegetation like a static parameter. Models of the physiological processes of vegetation like light interception (Kiniry et al., 2005; Dewar et al., 1998; Kiniry et al., 1999); water interception (Eltahir and Bras, 1993; Calder, 1990); transpiration (Guswa et al., 2004; Mackay et al., 2003); and the sensibility to resources availability, (Gracia et al., 2003; Mackay et al., 2003; Rosati and Dejong, 2003; Nouvellon et al., 2000a) were developed at plant or vegetation plot scale, but with high parameter requirements.

Terrestrial ecosystems models (TEM) simulate mainly photosynthesis processes, autotrophic and heterotrophic respiration, allocation, turnover, mortality, fire, land-use change, competition, etc. The TEM involves the plant physiological processes at regional to global scales to be coupled to Global Circulation Models to measure climate changes (Arora and Boer, 2005; White et al., 2000).

Models designed to simulate agriculture management (SWAP Kroes and van Dam 2003; SWAT Neitsch et al., 2002) are limited to simulate crops growing, irrigation practices, pesticides use, nutrients requirements, nevertheless it needs a large amount of data.

More recently proposals such as Soil-Vegetation-Atmosphere Transfer scheme (SVAT) (Arora, 2002; Dawes et al., 1997; Federer, 1979), or Land-Surface Models (LSM) coupled to TEM are designed to simulate energy and carbon fluxes, requiring that the processes of photosynthesis, respiration from vegetation and soil carbon components and allocation of net carbon uptake to several vegetation components to be explicit, requiring too many data (Montaldo et al., 2005; Arora, 2003; Nouvellon et al., 2000b; Cao and Woodward, 1998; Noilhan and Mahfouf, 1996; Famiglietti and Wood, 1994;Wigmosta et al., 1994; Dawes and Hatton, 1993; Mackay and Band, 1997; Spittlehouse and Black, 1981). SVAT or LSM-TEM are done to solve the static character of the vegetation in hydrological processes simulation, to study vegetation response to disturbances like fire, or simply to manage land and water resources.

Soil moisture dynamic and bare-soil evaporation are highly important processes in semiarid and arid ecosystems dynamic. These processes are modelled together due to closest interaction between both, neglecting or simplifying the other hydrological processes. These models are based on energy fluxes and soil properties (Aydin et al., 2005; Snyder et al., 2000; Langridge, 1996; Lee and Pielke, 1992); on surface soil moisture forecast proposed by Deardorff in 1977 and Philip in 1957 (Kondo et al., 1992, 1990; Alvenäs and Jansson, 1997) and complementary relationship proposed by Bouchet in 1963 (Parlange and Katul, 1992).

The main objectives of this paper include:

- Developing a conceptual vegetation-model for arid and semiarid ecosystems that represent the vegetation response to the soil moisture fluctuations.
- Formulating biomass model based on its water demand and water-soil availability.
- Using water stress concept indicating survival plant conditions as function of the plant water demand versus soil offer.

2 Model description

A conceptual dynamic vegetation-soil model for arid and semi-arid zones was developed to model soil-vegetation-atmosphere relations. The vegetation-soil model was based in a tank type conceptualization, considering two tanks interconnected, using the water balance equation at each tank and the appropriate dynamic equation for all considered fluxes.

The vegetation model is mainly a monoculture, functional vegetation type or dominant species. This means that we only considered parameters for the species that represent the group of vegetation to simulate the vegetation-soil processes.

In Fig. 1, the rainfall X_0 enters to the system; a quantity of water D_1 is derived to first tank; this quantity of water intercepted (H_1) is function of biomass, precipitation and previous water intercepted, and is available to direct evaporation (Y_1). The quantity of rainfall that can not enter to first tank is considered the throughfall (X_1), and is an amount of water able to enter the second tank. The quantity of derived water to second tank depends on soil and vegetation properties, and is available to transpiration (T) and bare-soil evaporation (BSE). Finally, the amount of water that not participate in initial abstractions and capillary water storage in upper soil represents the water excedeence (X_2) and it is considered available to infiltration and direct runoff.

The CDVSM only models the initial abstractions and upper soil storage, because there occurs the main processes related with the vegetation; but for its structure CDVSM is easily coupled with hydrological models, given that, this evaluates the first processes in the hydrologic cycle and returns the water available to infiltration and direct runoff.

2.1 Interception and direct evaporation

The first tank represents the water retained by leaves and only is able to outflow by direct evaporation. The maximum capacity of the first tank is I_{mx} [mm], depending on shape, quantity and intensity of rainfall, leaf biomass and vegetation type. According to the model scheme, the rainfall X_0 [mm] is stored in the first tank until the maximum capacity is reached. Then the throughfall X_1 is defined by,

$$X_1 = \max\left[0; X_0 - I_{mx} \cdot R + H_1\right] \tag{1}$$

where R [–] is the relative biomass. The water intercepted can outflow mainly by evaporation or by leaf and stem absorption in low percentages so, this last way is rejected. The water evaporated from interception Y_1 [mm day^{-1}] is evaluated by,

$$Y_1 = \min\left[H_1; PET\right] \tag{2}$$

where H_1 [mm] is the water intercepted and PET [mm day $^{-1}$] is potential evapotranspiration rate.

2.2 Upper soil storage and evapotranspiration

The second tank represents the water retained by capillary-soil forces in upper part of the soil or rooting zone. This storage has a maximum capacity (H_u) function of field capacity and effective root depth (z_e). The throughfall X_1 is stored in the second tank up to H_u then, the water exceedence X_2 is determined by,

$$X_2 = \max\left[0; X_1 - H_U + H_2\right] \tag{3}$$

where H_2 [mm] is the available water in the second tank.

The water inside the second tank can outflow by bare-soil evaporation (*BSE*) or by transpiration (*T*). The actual evapotranspiration Y_2 represents the sum of losses of water by *T* [mm day^{-1}] and by *BSE* [mm day^{-1}]. The model gives priority to *T* instead to *BSE*, that is, in the sequence of water extraction from the second tank, *T* has the first chance to do it following the expression,

$$T = \min\left[PET \cdot R \cdot f(\theta)\,;\, PET - Y_1\,;\, H_2\right] \tag{4}$$

where θ is the upper soil moisture content and is related with available water H_2 computed by

$$\mathrm{H}_2 = (\theta - \theta_w) \cdot z_e \tag{5}$$

The variable *T* is limited on one hand, by atmospheric conditions represented by *PET* and the residual potential evapotranspiration (PET–Y_1); on the other hand, is restricted by soil moisture conditions represented by extraction curve f(θ) and H_2. When θ is between optimum soil moisture (θ^*) and field capacity (θ_{fc}) contents, *T* depends on type of plant (biomass and soil moisture threshold of normal physiological processes) and climatic conditions (temperature, relative humidity, etc.). As long as θ decreases, *T* is reduced by stomatal closure to prevent water losses, and H_2 determines *T*, which continues until the θ reaches the wilting point (θ_w), where suction to extract water from soil produce damage in the plant tissues. This relationship was studied widely at the level of both individual plant and plantation scale (Federer, 1979; Spittlehouse and Black, 1981; Daly et al., 2004) and has been demonstrated that can be approached to a linear piecewise function, when θ^* determines if the plant is unstressed or stressed.

$$f(\theta) = \begin{cases} 1 & \text{for} \quad \theta^* < \theta \le \theta_{fc} \\ \frac{\theta - \theta_w}{\theta^* - \theta_w} & \text{for} \quad \theta_w < \theta \le \theta^* \\ 0 & \text{for} \quad \theta \le \theta_w \end{cases} \tag{6}$$

The *BSE* process is limited to the area not covered by vegetation (1–*R*) and is considered to take place into the soil surface layer with the same soil texture than rooting zone and soil surface depth z_{ss} [mm], much smaller than z_e. The *BSE* process is limited by the actual residual potential evapotranspiration ($PET - Y_1 - T$), bare-soil surface and θ, assuming the same distribution along the z_e,

$$BSE = \min\left[\mathrm{H}_2 \cdot \left(\frac{z_{ss}}{z_e}\right) \cdot (1 - R); PET - Y_1 - T\right] \tag{7}$$

2.3 Dynamic vegetation modelling

As mentioned before, in spite of the fact that vegetation growth requirements are depending on light, water and nutrients, in semiarid and arid environments the vegetation is highly conditioned to the availability of the water to carry out vital processes. To represent this dependency, the model considers the relation among vegetation growing, *T* and vegetation water stress (*VWS*) to estimate the relative biomass production *R* [–] (Daly et al., 2004; Kramer and Boyer, 1995; Kramer, 1969; Rosenzweig, 1968; Dachnowski, 1914)

$$\frac{dR}{dt} = \left(\frac{A_{n,mx}}{B_{pot}}\right) \cdot \left(\frac{T}{T_{mx}R}\right)^c - k \cdot VWS \cdot (1 - R) \tag{8}$$

where $A_{n;mx}$ [t ha^{-1} year^{-1}] is maximum net assimilation, B_{pot} [t ha^{-1}] is leaf potential biomass, T_{mx} [mm day^{-1}] is maximum transpiration rate, c [–] shape exponent, *k* [day^{-1}] is leaf shedding rate and *VWS* [–] is vegetation water stress calculated by the expression proposed by Rodriguez-Iturbe and Porporato (2004) as a function of the soil moisture θ

$$VWS = \begin{cases} \left[\frac{\theta^* - \theta}{\theta^* - \theta_w}\right]^q & \text{for} \quad \theta_w \le \theta \le \theta^* \\ 0 & \text{for} \quad \theta > \theta^* \end{cases} \tag{9}$$

where θ^* [–] is the optimum soil moisture for vegetation transpiration, associated to an optimal water potential ψ^* [MPa]; below it, the transpiration starts being reduced; θ_w

[–] is the wilting soil moisture, related to the water potential value ψ_w [MPa], below it, the vegetation can not extract more water and can suffer damage on its tissues; and exponent q [–] is a measure of the nonlinearity of the effects of soil-moisture deficit on plant conditions (see Fig. 2).

3 Model application

Our Conceptual Dynamic Vegetation-Soil Model (CDVSM) was applied to a Mediterranean semiarid slope covered by kermes oak species. The kermes oak, *Quercus coccifera* L., is an evergreen sclerophyllous shrub which covers extensive areas of Mediterranean garrigue in Mediterranean watershed (Le-Houérou, 1981). *Quercus coccifera* L., inhabits in regions when the edaphic conditions lead to a great aridity, and is considered pyrostable since shows a high regeneration after fire, due to the continuity of belowground biomass after fire plays an important role in determining the optimum tactics to be adopted during succeeding cycles (Delitti et al., 2005; Cañellas and San-Miguel, 2000; Abril and Gracia, 1989). The kermes oak is found commonly in Spain in continental vegetation structure, in meso-Mediterranean belt and varied ombrotype climates (dry-humid, semiarid-dry, dry-subhumid and dry) reaching up to 2 m of height; or in coastal formation, in thermo-Mediterranean belt and several ombrotype climates (semiarid-humid, dry, dry-subhumid and semiarid) the kermes covers 75% of terrain impeding development of herb substrate, reaching no more to 1 m of height. Sanchis et al. (2003), point out the kermes oak species is able to live in soils with any kind of chemical characteristics, but it is very frequently found in soils with low depth, over Chromic Luvisols ("terras rossas").

Model time discretization is daily, with the aim of modelling as well as the dynamic vegetation, vegetation water stress response and fluctuations of the soil moisture content along the year. Spatial scale is at 10 m order, because done possible to model the physiological process that occurs at level both of individual and set of plant, taking into account the hydrological processes scale.

3.1 Data series

The climatic conditions correspond to upper thermo-Mediterranean belt and dry ombrotype, according to Rivas-Martinez (1983) bioclimatic classification, and were taken from two stations belonging to the National Meteorological Institute of Spain. The first station, Manises, is located in Southwest of Valencia (latitude 39°25′30″ N, longitude 0°26′17 W, altitude 30 m a.s.l.) and monitors precipitation (P). The second station, Forn d'Alcedo is located in Southwest of Valencia too (latitude 39°29′22″ N, longitude 0°28′16″ W, altitude 57 m a.s.l.) and monitors mean, maximum and minimum daily temperature.

The observed period for both stations, is from 1 January 1966 at 31 December 2001. During the complete recorded period, the mean annual precipitation is about 511.45 mm; along the first 25 years, annual precipitation oscillates between humid to dry years, with three years specially humid 1969 (794 mm), 1971 (1133 mm) and 1989 (1158 mm); and three years specially dry 1978 (273 mm), 1981 (270 mm) and 1983 (271 mm), but from 1992 to 2000 driest period has been recorded. Along the mean year, total precipitation is near to 137.31 mm in winter, decreasing to 116.10 mm in spring until 56.49 mm in summer and increasing 204.65 mm in autumn (see Fig. 3).

For the recorded period, the mean temperature was 17°C. The whole recorded period is characterized by a summer season with temperature around 30°C and 18 mm precipitation; the winter season is characterized by reach –1°C of minimum temperature and 45 mm of mean precipitation. Spring and autumn seasons have 16°C of mean temperature but with mean precipitation of 38 mm and 70 mm respectively, being both the optimal seasons for vegetation growing. The mean annual potential evapotranspiration (PET) computed with Hargreaves equation (Allen et al., 1998) is approximately 1250 mm, which is much larger than the precipitation. Along the mean year PET is around 55 mm day^{-1} in winter, increasing to 122 mm day^{-1} in spring and then up to 150 mm day^{-1} in summer and decreasing 90 mm day^{-1} in autumn, as it is shown in Fig. 3.

3.2 Parameters estimation

The parameters of CDVSM can be separated into soil and vegetation parameters. Soil parameters, as was explained before, are related with the estimation of available water by transpiration and evaporation processes at different soil moisture contents (θ). According to the soil-water retention curve of Campbell (1974) soil moisture content can be computing by

$$\psi = \psi_{ae} \cdot \left(\frac{\phi}{\theta}\right)^{b} \tag{10}$$

where aeration pressure ψ_{ae} [MPa], porosity distribution index b dimensionless and porosity ϕ [–] are required to determine the typical curves for main kind of soils; ψ_{ae} and b were experimentally determined by Clapp and Hornberger (1978).

Table 1 includes parameters required for Eq. (10) for loam sand soil texture, which will be used in basic scenario by analysis purposes. To compute soil moisture content at field capacity (θ_{fc}) and wilting point (θ_{w}), Larcher (2003) proposes 0.015 MPa for field capacity and Laio et al. (2001) uses 3 MPa for wilting point, both values for vegetation in semiarid and arid environments.

Vegetation parameters are related to interception, vegetation water stress response and relative biomass calculation. Parameters as $A_{n,mx}$, B_{pot}, T_{mx}, k and I_{mx} depend on the species selected to be modelled; whereas, θ^{*} depends on both, soil and vegetation properties. Respect to leaf shedding parameter k, Castro-Diez and Montserrat-Martí (1998) point out that *Quercus coccifera* L. leaves falls in spring and continues through summer season and occasionally in autumn, so, the leaf shedding used correspond to 0.0018 in winter and autumn 0.002 in spring and 0.0019 in summer. For the maximum interception (I_{mx}) parameter estimation, Federer (2002) proposes a simplified version of Gash model

$$I_{mx} = C_{LAI} \cdot LAI + C_{SAI} \cdot SAI \tag{11}$$

where C_{LAI} and C_{SAI} are the interception capacity by unit of leaf area index and stem area index respectively; and, LAI and SAI are maximum leaf area index and maximum stem area index respectively. Fundamental physical characteristics and resulting model parameters are defined in Table 1.

3.3 Calibration of vegetation equation

Although the time resolution model is daily, the CDVSM calibration was made minimizing the root mean square error (RMSE) of annual relative biomass simulated with CDVSM compared with biomass field observations obtained from Cañellas and San-Miguel (2000).

The parameters include in Table 1 are considered the basic scenario, and were used in calibration processes of c parameter, which is considered the key factor in Eq. (8), since it determines the relationship between vegetation growing and transpiration rate, according to relative biomass conceptualization.

Daily biomass simulated with CDVSM and Cañellas and San Miguel (2000) field observations are showed in Fig. 4. After the first year of simulation the leaf biomass is 2.6 $\mathrm{t\,ha^{-1}}$, continues arising until reaches a mean of 4.6 $\mathrm{t\,ha^{-1}}$ over 4–10 years of simulation, and then it is stabilized around 4.1 $\mathrm{t\,ha^{-1}}$ along the simulation period. In Fig. 4 the dots, represent Cañellas and San Miguel (2000) field observations, these correspond to 20 communities in Valencia, with similar soil and climatic conditions that our basic scenario, but there are plots previously devastated by fire; the year represent the age of community after fire. Younger communities show maximal development until 6–8 year, reaching 4.9 $\mathrm{t\,ha^{-1}}$ on average; the oldest communities show a biomass stabilization around 4.0 $\mathrm{t\,ha^{-1}}$. Our CDVSM has been developed considering mature communities and neglecting successional processes. So, in spite of these technical differences, the CDVSM model and Cañellas and San Miguel (2000) observations show similar results for a c calibrated parameter equal to 0.05096.

4 Soil-vegetation system response

Sensitive analysis of CDVSM considers a basic scenario fixed by loam sand texture soil parameters, rooting soil depth (z_e) of 500 mm, maximum available water storage (H_u) of 52 mm, mean annual potential evapotranspiration (PET) of 1250 mm and annual precipitation (P) of 514 mm. Details for all parameters are presented in Table 1. For this basic scenario, Table 2 includes the annual evapotranspiration (Y_2), annual transpiration T, annual bare-soil evaporation BSE, mean available water H_2, mean vegetation water stress VWS and mean relative biomass R; all variables computed by 36 years of CDVSM simulation, starting with H_u equal to 51.99 mm and recirculating for R until an stable R mean value is reached. Values from Table 2 are assumed 100% in the following figures.

The Fig. 5 shows the general behaviour (means) of the main state variables of CDVSM (transpiration T, bare-soil evaporation BSE, available water H_2, vegetation water stress VWS and relative biomass R) due to changes in climate and soil conditions.

4.1 Soil types

The Fig. 5a shows the variation respect to H_u as a function of soil texture. Thus, H_u for loam sand is 51.99 mm (100%), silty loam soil texture is 126.95 mm (245 % of H_u for loam sand); sandy loam soil texture is 76.93 mm (148 %); and clay loam soil texture is 92.98 mm (178%). The most sensible state variables to changes in soil type were H_2 and BSE. Changes in H_2 from 17 (10% of H_u) to 180 % (190% of H_u) showed positive correlation with H_u, which was in agreement to the expected, given that any increment of H_2 is favoured by chemical and physical characteristics of the silt and clay and, as soon as z_e increases, H_2 also increases. Positive correlation between BSE and H_u was found, changing from 11% (10% of H_u) to 185% (250% of H_u), clearly reflecting soil characteristics. I.e., silty loam soil evaporates more water quantity (173.72 mm; 185% of BSE) than sand loam (125.01 mm; 133% of BSE) and clay loam (146.18 mm; 156% of BSE) since fine grained soils hold more water than coarse soils and, consequently, evaporation losses are greater than in coarse soils (Wythers et al., 1999).

In spite of that H_2 increases with changes in soil texture, T does not it at the same rate, exhibiting fast increment from 48% (10% of H_u) to 100% (100% of H_u); but, after this only increments until 103% (250% of H_u); this behaviour may be because the main T restriction is the evaporative demand of the atmosphere and the total leaf biomass. Also as it was expected, VWS decreases from 120% (10% of H_u) to 98% (250% of H_u). Contrary behaviour shows R, while H_u increases from 10% to 250 %, R increases slowly from 75% to 102%.

In general, the model exhibits a consistent behaviour to the expected one. Changes in soil texture reports great changes in BSE and H_2, but not thus in R, VWS and T.

4.2 Effective root depth

In Fig. 5b effective root depth (z_e) was the variable parameter, and the texture soil was fixed to loam sand (the basic scenario). The most sensible state variable was H_2 which is positive correlated with z_e, changing from 3% (10% of z_e) to 230% (190% of z_e). Slow changes in BSE were exhibited, changing from 71.5% (10% of z_e) to 101% (190% of z_e); it would be explained given that BSE depends on one hand by available water, so, to at lower values of H_2 low values for BSE has been recorded; on the other hand, at highest values of H_2, the evaporative demand of the atmosphere controls BSE, reaching no more than 101%, being neglected the relation $z_{ss}/z_{e.}$ These results are in agreement with Ritchie (1972) bare-soil conceptualization, which suggests that BSE processes occur in two stages: stage 1, is determined by the evaporative demand of the atmosphere; and stage 2, evaporation rates are limited by the lack of water in the upper soil layer and soil hydraulic (Snyder et al., 2000).

Variables like T and R had similar behaviour, for lower values of z_e, they decrease below to 30% and 60% respectively, but at higher values of z_e, they not increase more than 120%. These values reflect that vegetation-soil system is more sensible to shortage of water (shallow soils) than abundance of it.

4.3 Precipitation

In Fig. 5c changes of the model to variations on precipitation were analyzed. Variables T and H_2 showed positive correlation with precipitation, reaching 155% and 140% respectively. Changes in BSE between 22% (10% of P) to 95% (70% of P) were found, but after 70% of P until 190%, BSE reached a steady state around 99%. This behaviour may be because z_{ss} and z_e continue fixed to 50 and 500 mm respectively and, according to model conceptualization, the soil can not evaporate more water that can storage. Although R showed increasing values, it does it slowly, starting from 72% (10% of P) and only increasing to 110% (190% of P). I.e., the sensitivity of the vegetation biomass is higher for reductions in precipitation than for increases.

4.4 Potential evapotranspiration

Finally, Fig. 5d shows model sensibility to changes in PET. The variables VWS, T and BSE had the same behaviour. At 10% of PET, T and BSE presented percentages near to 30%, and VWS near to 10%, increasing slowly to 115% (190% of PET). These values would mean that at higher evaporative demand of the atmosphere, T and VWS will be regulated by vegetation.

Negative correlation between H_2 and PET was found, at lower values of PET (10%) higher values of H_2 has been recorded (382% of H_2); but, as soon as PET increases more than 100%, slow changes in H_2 are recorded (64% of H_2 for 190% of PET). About R, changes between 90% (10% PET) to 115% (190% PET) were recorded. Changes in PET affect gradually the relative biomass changes, exhibiting adaptation strategies to this kind of climate change.

5 Model dynamics

The Fig. 6 shows the long term behaviour of the main model state variables (relative biomass R, vegetation water stress VWS, transpiration T, bare-soil evapotranspiration

BSE and available water H_2) through the year. By graphical convenience T and *BSE* has been scaled by mean daily evapotranspiration (*DET*) equal to 3.45 mm day^{-1} and H_2 has been scaled by H_u equal to 51.99 mm (maximum available water for loam sand soil texture). The set of parameters used were the same for previous analysis, but the initial condition for relative biomass R was equal to 0.73.

In winter (Fig. 6a) the model recorded the maximum *VWS* variability, with a standard deviation of 0.35. Most of the time, *VWS* was below than 0.85, with a mean value of 0.54. Mean value of T was less than 17% of *DET*, in spite of mean value of H_2 was around 40% of H_u; this result may be because the vegetation is dormant due the lower temperatures in winter season and the transpiration processes is minimized. Lower variations on R were recorded, remaining around 0.72 with a standard deviation of 0.04. In respect of *BSE*, a low mean value was recorded (9% of *DET*).

In spring (Fig. 6b), temperature and precipitation increase and vegetation is activated. Mean values of T and R, 24% of *DET* and 0.73 respectively, were recorded; these increments in T and R with respect to winter values produce that *VWS* increases and H_2 decreases, registering 0.74 and 23% of H_u respectively. In respect of *BSE*, a low mean value of 7% of *DET* was recorded, due to low value of H_2 after water extraction for T. Spring dynamic could be explained, because despite P increment, the vegetation reactivates its growth (R) and consume more water (T), so, H_2 in soil decreases, and the system records a moderated *VWS*.

In summer (Fig. 6c), due to shortage of precipitation and higher temperatures, H_2 remained at lower values (9% of H_u) and *VWS* was maximum reaching most of the time a mean value of 0.9. The reductions in H_2 implied a reduction in R (mean value of 0.69), lower mean values of T and *BSE*, 11% and 4% of *DET* respectively, in spite of higher values of *PET* in this season.

In autumn (Fig. 6d), precipitation increases and temperature decreases slowly, so the system was recovered. Despite of the fact that H_2 increases to 34% of H_u and mean *VWS* decreases from 0.9 to 0.6, the vegetation reactivate its growth with mean value of R equal to 0.71 and consume more water in transpiration process reaching

T a mean value of 20% of *DET*. This dynamic does that system records a moderated *VWS* in this season. In respect to *BSE*, since that H_2 increases, *BSE* increases too, reaching 10% of *DET*.

6 Conclusions

This paper presents a conceptual vegetation-soil model based in a tank type schematization. Assuming vegetation biomass must be a state variable instead of a fixed parameter, the objective was to develop a simple model to represent the soil-vegetation-atmosphere dynamic in arid and semiarid zones, which means water-limited ecosystems, in order to reproduce the possible interactions in both ways between vegetation and soil moisture. To do this, the biomass dynamic (relative biomass R) was linked to water demand (transpiration T) and water-soil availability (H_2), using the vegetation water stress (*VWS*) as indicator of plant survival conditions to the environmental restrictions and T as an indicator of biomass growing.

The proposed dynamic vegetation-soil conceptualization results in a parsimonious model (CDVSM), with low computational cost and which can be easily linked with others complete hydrological or land surface models. It can be proved CDVSM reproduces well the biomass dynamic based on soil water balance, considering *VWS* as an index of its dynamic in semiarid and arid zones, due to – a great extent – *VWS* determines the growing season, water-uptake dynamic and can help to understand the adaptations strategies of the vegetation to shortage of water. Respect to bare-soil evaporation (*BSE*), the model reproduces this dynamic in agreement with Wythers et al. (1999) but using a lower level of parameterization.

For a Mediterranean semiarid slope with *Quercus coccifera* L. T is more sensible to changes in precipitation (P), effective soil depth (z_e) and maximum available water (H_u). The H_2 variable (or soil moisture) is sensible to changes in all parameters (soil types, P, potential evapotranspiration *PET* and z_e). The *BSE* variable is sensible to changes in precipitation amount and maximum available water H_u. And finally, *VWS* and R do not show high sensitive to these parameters and inputs. I.e., the *Quercus coccifera* L. changes evapotranspiration fluxes and soil moisture content in order to maintain more stable values of VWS and R.

In the long term, R shows variations along the year, recording its maximum values in spring (mean value 0.73) and minimum in autumn (mean value 0.68); these results are agree with the reality, because in spring the vegetation experiments the optimal conditions of temperature and H_2 (23% of H_u) for growing. In summer, the higher temperatures and shortage of water (H_2=8% of H_u) implies regulation in all vital processes like T (11% of DET) and losses of R (from 0.73 to 0.69) to keep itself in optimal conditions. And in autumn, the vegetation exhibits accumulative response of all processes of leaf shedding (k), extreme temperature in summer and shortage of water; in this season R decreases slowly from 0.69 to 0.68, but recording reductions in VWS (from 0.89 in summer to 0.62) and increments in H_2 (from 9% of H_u in summer to 34%).

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Table 1. Soil and vegetation (for *Quercus coccifera* L.) model parameters for case study.

Parameter	Description	Value	Source[a]
C_{LAI}, mm	Interception capacity by unit of *LAI*	0.15	
C_{SAI}, mm	Interception capacity by unit of *SAI*	0.15	1
LAI, dimensionless	Maximum leaf area index	6	1
SAI, dimensionless	Maximum stem area index	0.7	1
k, day^{-1}	Leaf shedding	0.0018–0.0024	2
T_{mx}, mm day^{-1}	Maximum transpiration rate	4.7	3
$A_{n,mx}$, t ha^{-1} year^{-1}	Maximum net assimilation carbon	5.7	3
B_{pot}, t ha^{-1}	Potential leaf biomass	6	4
c, dimensionless	Shape exponent	0.05096	cal
z_e, mm	Rooting soil depth	500	obs
z_{ss}, mm	Soil surface depth	50	obs
ψ_{ae}, MPa Aeration pressure	0.88x10^{-3}	5	
ψ_{ae}(log), MPa	Aeration pressure	1.74×10^{-4}	5
b, dimensionless	Porosity distribution index	4.38	5
ϕm^3 cm^{-3}	Porosity	0.410	5
ψ^*, MPa	Optimum water potential	0.03	6
ψ_{fc}, MPa	Field capacity water potential	0.015	7
ψ_w, MPa	Wilting water potential	3	6
q	Nonlinearity effect exponent	1	obs

[a] Sources are as follow: 1, Federer (2002); 2, Specht (1988); 3, mail communication with C. A. Gracia; 4, Delitti et al. (2005) ; 5, Laio et al. (2001); 6, Clapp and Hornberger (1978); 7, Larcher (2003); cal, value from model calibration; and obs, approximated value from field observations.

Table 2. Reference values from basic scenario obtained by CDVSM simulation from 1 January 1966 to 31 December 2001.

Variable	Description	Value
H_u, mm	Maximum available water	51.99
z_e, mm	Effective root depth	500
P, mm	Annual precipitation	511.45
PET, mm	Annual potential evapotranspiration	1251.75
Y_1, mm	Annual intercepted water evaporation	40.93
T, mm	Annual transpiration	219.67
BSE, mm	Annual bare-soil evaporation	93.94
Y_2, mm	Annual real evapotranspiration	354.53
H_2, mm	Mean daily available water	12.86
R, dimensionless	Mean daily relative biomass	0.7059
VWS, dimensionless	Mean daily vegetation water stress	0.7

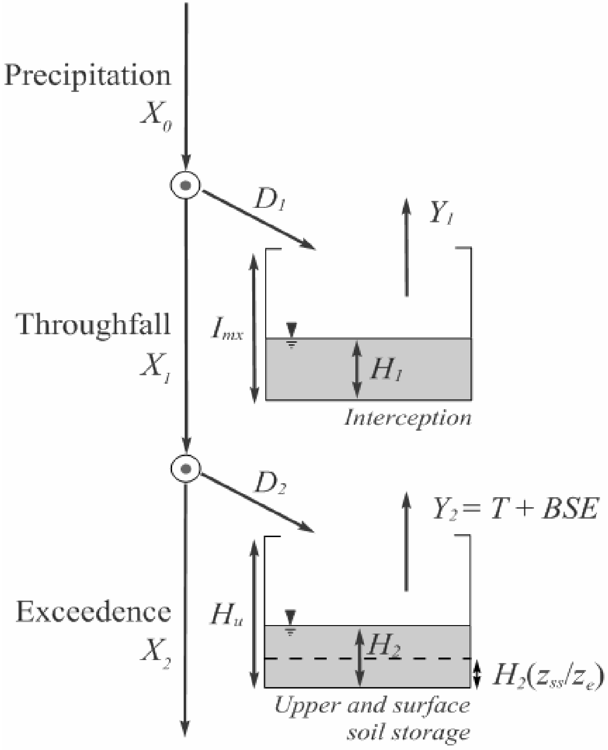

Fig. 1. Conceptual scheme of the Vegetation-Soil Model.

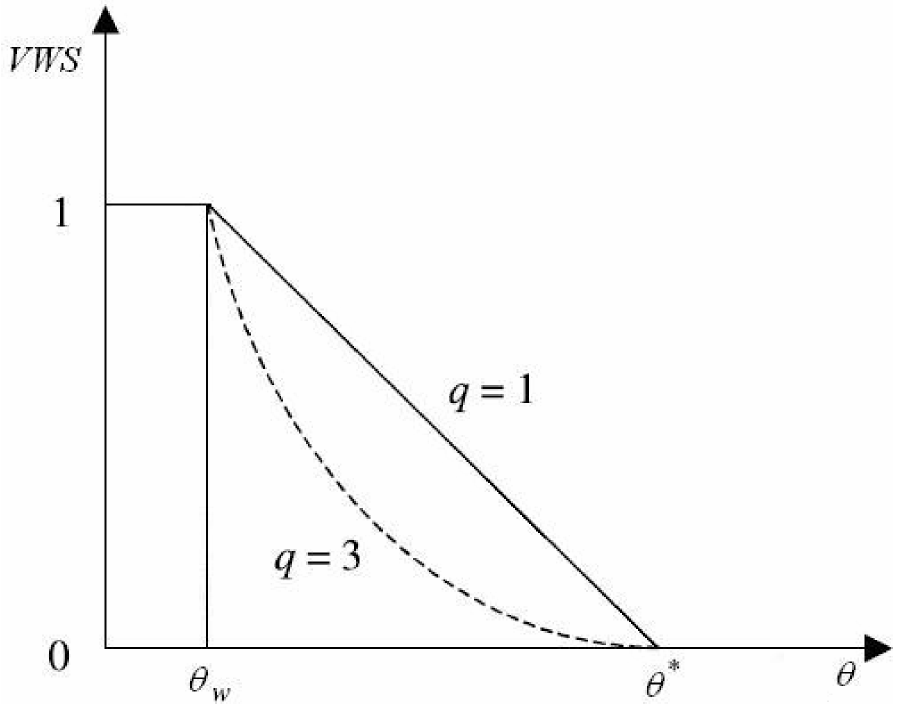

Fig. 2. Relationship between soil moisture and vegetation water stress for two values of non-linearity parameter q, see Eq. (8). After Rodriguez-Iturbe and Porporato (2004).

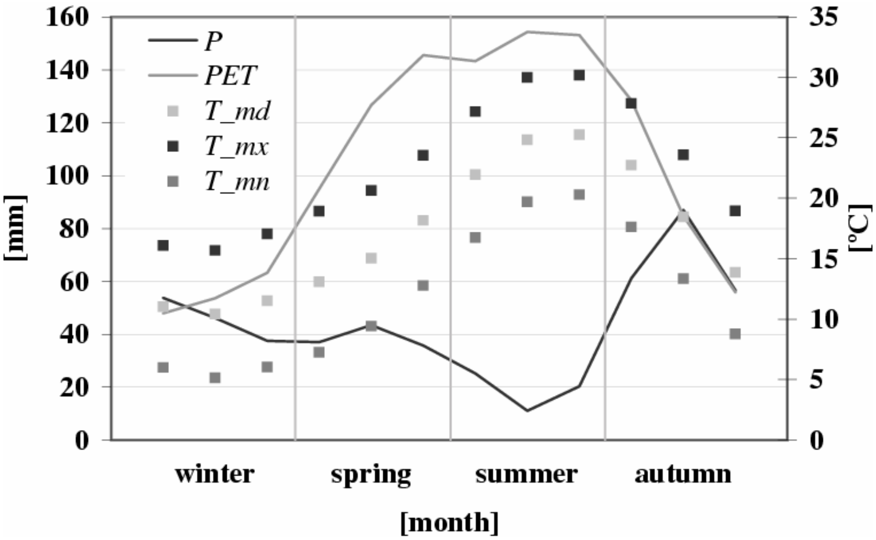

Fig. 3. Climatic mean conditions for model simulation, extracted from Manises (precipitation) and Forn d'Alcedo (temperature) stations, recorded period from 1 January 1966 to 31 December 2001.

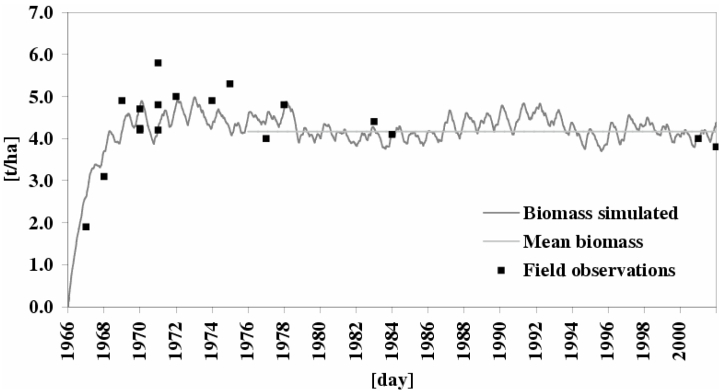

Fig. 4. Leaf biomass simulated (continuous line) and mean relative biomass after stabilisation (horizontal line). Dots are the field observations obtained from Cañellas and San Miguel (2000).

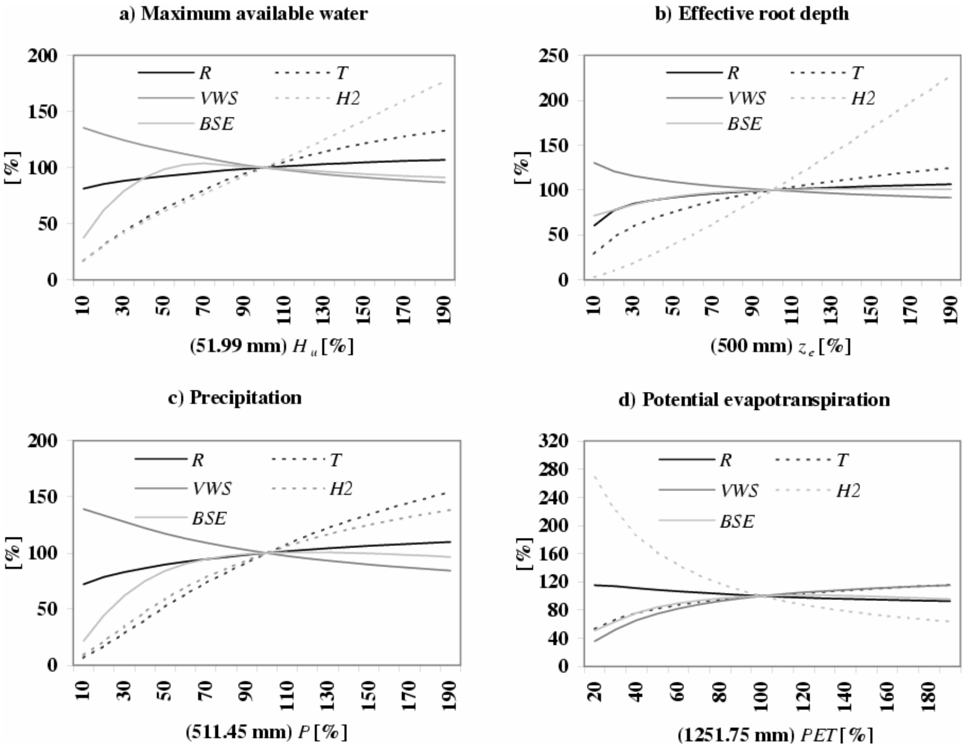

Fig. 5. Analysis of sensitivity to maximum available water (H_u), effective root depth (z_e), annual precipitation (P) and annual potential evapotranspiration (PET). The y-axis is the percentage of transpiration T, bare-soil evaporation BSE, vegetation water stress VWS and relative biomass R; the x-axis is the percentage of parameter reference value showed in parenthesis for H_u, z_e, P and PET.

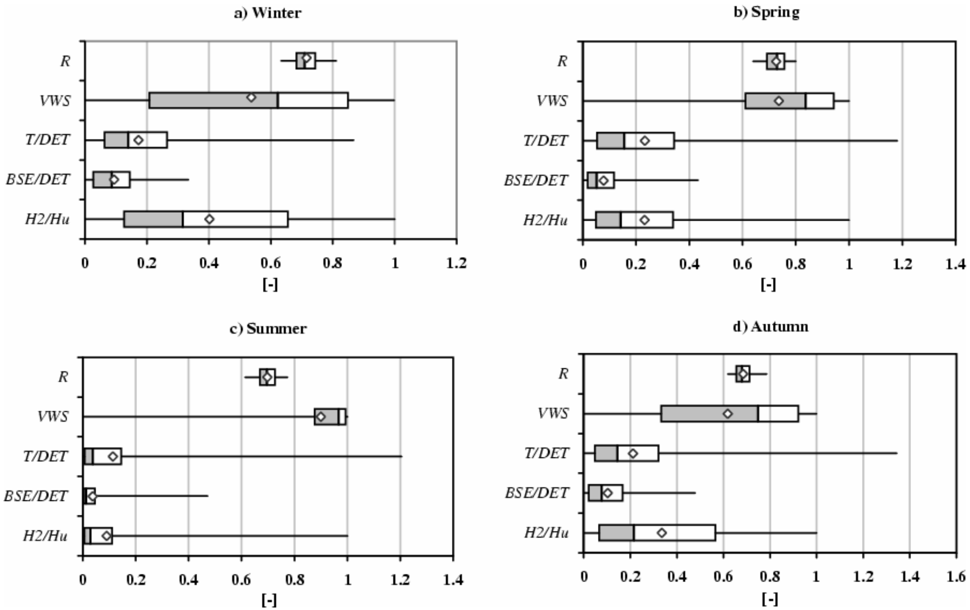

Fig. 6. Box and whisker chart of relative biomass (*R*), vegetation water stress (*VWS*), transpiration (*T*), bare-soil evapotranspiration (*BSE*) and available water (H_2) along the mean year. The variables *T* and *BSE* are scaled with daily mean evapotranspiration (DET=3.43 mm day^{-1}) and H_2 is scaled with maximum available water (H_u=51.99 mm).

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