P1.26 AN ECOPHYSIOLOGICAL PROCESS MODEL FOR SEMI-ARID GRASSLANDS

Y. Nouvellon *,[1] S. Rambal,[2] A. Begue,[1] J. P. Lhomme,[3] M.S.Moran,[4] J.Qi,[4] A. Chehbouni,[5] D. Loseen[1]
[1]CIRAD, Montpellier, France
[2]CEFE, CNRS, Montpellier, France
[3]ORSTOM/CICTUS, Hermosillo, Mexico
[4]USDA-ARS, Tucson, Arizona
[5]ORSTOM/IMADES, Hermosillo, Mexico

1. INTRODUCTION

The ultimate objective of this study is to develop a model that describe water and carbon budget of semi-arid grasslands at the regional scale. At this scale, satellite remote sensing can provide valuable information to improve simulation results. One approach consists in assimilating radiometric data into the plant growth model by re-calibration of the plant growth model parameters (Bouman, 1991). This approach supposes the mediation of a radiative transfert model that uses the canopy structural parameters (LAI, percent cover, plant height,…) given by the plant-growth model to simulate temporal variations of surface reflectances.

In this paper, we describe in a first section an ecophysiological process model developed for this purpose. In a second section, we present its validation on a grassland site in San Pedro Basin.

2. MODEL DESCRIPTION

2.1. General model structure

The model aims at simulating, on a daily time step, the biomass dynamics of three main compartments : green shoots, dead shoots and living roots. The main processes simulated in a vegetation growth submodel are photosynthesis, allocation of photosynthetates to shoots and roots, translocation of carbohydrates from roots to shoots at the early regrowth, respiration and mortality. Many physiological processes such as photosynthesis and mortality are dependent of water availability in the root zone, which is calculated in a water budget submodel.

2.2. Model equations

2.2.1 Vegetation growth model

The biomass dynamics in the three main compartments is described by the three differential equations :

$$d\,B_{ag} / dt = a_a\ .\ Pg + T_{ra} - R_{at} - S_a \qquad (1)$$

$$d\,B_r / dt = a_r\ .\ Pg - T_{ra} - R_{rt} - S_r \qquad (2)$$

$$d\,B_{ad} / dt = S_a - L \qquad (3)$$

where B_{ag}, B_r, and B_{ad} are green aerial biomass, root living biomass and standing dead aerial biomass respectively. Pg is the daily gross photosynthesis, a_a and a_r are the photosynthetates allocation coefficients to the shoot and root compartments respectively ($a_a + a_r = 1$), and T_{ra} represents the translocation of biomass from the roots to the green aerial compartment. R_{at} and R_{rt} are the total daily respiration of aerial and root compartments, S_a and S_r represent the biomass losses of the living shoots and living roots due to senescence. L represents the litter production.

Photosynthesis sub-model

The daily carbon increment for the whole system comes from photosynthesis. The maximum gross daily canopy photosynthesis can be expressed as

$$Pg = S.\ ec\ .\ el\ .\ eb\ .\ f1\ (Yl).\ f2(T) \qquad (4)$$

where *S* is the daily incoming solar radiation, e_c is the climatic efficiency (=*PAR/S*), e_l the interception by green leaves efficiency (=PAR_i /*PAR*), and e_b the energy conversion efficiency (=g(CH_2O) produced/*PARi*). f_1 and f_2 are empirical stress functions representing the effects of water and temperature stresses respectively. To calculate f2, we assume a linear relationship between daily photosynthesis and daily mean air temperature. Water stress reduces photosynthesis by reducing the CO2 diffusion from air to leaf tissues as an effect of stomatal closure. It is expressed as a function of leaf water potential as in Mougin et al. (1995) :

$$f1\ (Yl) = (1.64\ rsmin + rm + 1.39\ ra) / (1.64\ rs + rm + 1.39\ ra) \qquad (5)$$

where rs and rs_{min} are actual and minimum canopy stomatal resistance to water vapor, rm and ra are mesophyll resistance and canopy layer boundary resistance to water vapor. 1.64 is the ratio of diffusivities of C02 and water vapor in the air at 20°C, and 1.39 is the ratio of the rate of transfer of CO2 and water vapor in the canopy boundary layer. rs is calculated as a function of leaf water potential Ψ_l (see below).

The climatic efficiency ε_c is approximately 0.45, and the interception efficiency ε_l is calculated as a function of green LAI (LAI_g) and total LAI (LAI_t) :

Corresponding author address : Yann Nouvellon, CIRAD-CA, Maison de la télédétection, 34093 MONTPELLIER, FRANCE;
e-mail : nouvello@cirad.teledetection.fr

$$\varepsilon l = [1 - e(-k1 . LAIt)] (LAIg / LAIt) \qquad (6)$$

$$LAIg = SLAg . Bag \qquad (7)$$

$$LAId = SLAd . Bad \qquad (8)$$

$$LAIt = LAIg + LAId \qquad (9)$$

where LAI_d is the dead biomass LAI, SLA_g and SLA_d are the specific leaf areas of the aerial green biomass and the standing dead biomass respectively.

The energy conversion efficiency ε_b is dependent of many factors as the nutrient availability, the plant genotype, and physiological age of the plants. It is therefore site specific and varies during the growing season. The depressing effect of the aging on ε_b is considered :

$$\varepsilon b = \varepsilon bmax . f3 (age \qquad (10)$$

where ε_{bmax} is the energy conversion efficiency for young mature tissues, and f3 is an empirical function representing the effect of the aging on ε_b. The physiological leaf age and f3 where calculated as in the BLUEGRAMA model (Delting et al., 1979).

Allocation sub-model

Carbon pool resulting from photosynthesis is allocated into shoots and roots according to allocation coefficients, a_a and a_r respectively. The daily amount of (CH2O) which should be translocated from shoot to root T_a is calculated according to the model of Hanson et al. (1988). An excess amount of biomass in the shoots is determined as

$$Bax = rx . Bag - Br \qquad (11)$$

where r_x is the maximum root to shoot ratio. If $B_{ax}>0$, biomass flows from the shoots to the roots. If not, there is no allocation. T_a is calculated so that the root to shoot ratio r_x is maintained constant from one day to the next.

$$rx = (Br + Ta) / (Bag - Ta \qquad (12)$$

which means that

$$Ta = Bax /(1 + rx) \qquad (13)$$

This function assures there is no more aerial phytomass than the present root biomass can support (HANSON et al., 1988). From T_a, allocations coefficients are calculated assuming than T_a should not overpass the gross photosynthesis Pg.

$$\begin{aligned} ar &= Ta / Pg \quad \text{if } Ta < Pg \\ ar &= 1 \qquad\quad \text{if } Ta > Pg \qquad (14) \end{aligned}$$

and the allocation coefficient for aerial parts is calculated as

$$aa=1-ar \qquad (15)$$

Root to shoot translocation submodel

Translocations of carbohydrates from roots to shoots, T_{ra} can occur in the early season regrowth, or after if some process has removed a critical amount of green biomass. The model used to calculate T_{ra} is the model proposed by Hanson et al. (1988). In order for this process to occur, three conditions must be met : (1) The average 10-day soil temperature must be greater than 12.5 °C, (2) The average 5-day soil water potential must be greater than -1.2 MPa, (3) $B_r > r_x B_{ag}$.

If these conditions are met :

$$Tra = tr. Br \qquad (16)$$

t_r is the proportion of root biomass daily translocated to shoots.

Respiration sub-model

Total respiration R_t is the sum of total aerial respiration R_{at} and total root respiration R_{rt}. For C4 grasses photorespiration is negligible. Thus the total aerial respiration R_{at} can be expressed as the sum of aerial maintenance respiration and aerial growth respiration :

$$Rat = ma . Bag + (1- Yga) . (aa . Pg + Tra) \qquad (17)$$

and the total root respiration is R_{rt} is expressed as

$$Rrt = mr . Br + (1- YGr) . (ar . Pg) \qquad (18)$$

m_a and m_r are the maintenance respiration coefficients for aerial and root biomass, Y_{ga} and Y_{gr} are the growth conversion efficiency for aerial and root biomass. The expressions $(1- Y_{ga})$ and $(1- Y_{gr})$ are equivalent to the growth respiration coefficients for the aerial parts and roots, which represent the cost for producing new biomass.

Senescence sub-model

The amounts of green aerial biomass and root biomass which die each day, S_a and S_r are calculated as

$$Sa = da . Bag \qquad (19)$$

$$Sr = dr . Br \qquad (20)$$

where d_a and d_r are the death rate for aerial parts and roots respectively. d_r is assumed to be constant during the year, and d_a is calculated as a function of physiological leaf age and soil water potential following the BLUE GRAMA model of Delting et al. (1979).

Litter production sub-model

The model used to calculate litter production (L_a) is the model developed by Hanson et al. (1988), where the total transfer of standing dead to litter is made as a function of the daily wind run, the total daily precipitation and the livestock stocking rate.

2.2.2 water balance model

The water balance uses a simplified two layers canopy evapotranspiration model where soil profile is divided into three layers : a thin supifercial layer (0 to 4 cm) which is supposed to participate only to the soil evaporation process E_s, and two deeper layers (4 to 15 cm and 15 to 60 cm) corresponding to the root zone, which participate both to evaporation and transpiration.

Estimation of actual evapotranspiration

The total evaporation from the sparce grass canopy is calculated as the sum of bare soil evaporation E_s and of canopy evaporation E_C. E_C and E_s are calculated empirically from the evapotranspiration of a continous canopy, and evaporation of a bare soil, tacking into account the relative surface which is covered by vegetation and bare soil. If fvg, fvd and fs are respectively the fractional cover of green vegetation, dead vegetation and bare soil (fvg + fvd + fs = 1), E_c and E_s are calculated as

$$Ec = fvg \,.\, [sA + r cp\, D / rac\,] / [(s+g\,(1 + rsc / rac)\,)\, l] \qquad (21)$$

$$Es = fs \,.\, [sA + r cp\, D / ras\,] / [(s+g\,(1 + rss / ras)\,)\, l] \qquad (22)$$

A is the available energy which is the sum of net radiation R_n and soil heat flux G, D is the vapor pressure deficit of the air at a reference height above the surface, λ is the latent heat of vaporization, r is air density, c_p is the specific heat of air at constant pressure, γ the psychrometric constant and s is the slope of the saturated vapor pressure curve at the temperature of the air T_a . r_{sc} and r_{ss} are the surface resistances for a completely covering canopy and a bare soil respectively. r_{ac} and r_{as} are the corresponding aerodynamic resistances. fvg and fvd are calculated as a function of LAI_g and LAI_d

$$fvg = 1 - e\ (\,-K2 \,.\, LAIg) \qquad (23)$$

$$fvd = 1 - e\ (\,- K3 \,.\, LAId) \qquad (24)$$

The evaporation E_s is distributed between the different layers of the profile following an extinction coefficient which depends on the soil water content, thickness and depth of each layer:

Resistance models

The bulk stomatal resistance of the canopy r_{sc} is calculated as a function of leaf water potential Y_l as

$$rsc = rsmin\ [1 + (\,Yl\, /\, Y1/2\,)n\,] \qquad (25)$$

where r_{smin} is the minimal stomatal resistance observed in optimal conditions, $Y_{1/2}$ is the leaf water potential corresponding to a 50 % stomatal closure and n is an empirical parameter (Rambal and Cornet 1982).

The soil surface resistance r_{ss} is calculated as a function of the water content of the first soil layer by means of the empirical relationship (Camillo and Gurney 1986)

$$rss = 4140\ (Wsat1\ - W1) - 805 \quad (sm\text{-}1) \qquad (26)$$

where w_1 represents the volumetric soil moisture content of ground surface layer (dimensionless).

The aerodynamic resistances are calculated as

$$ra = ln2\ [\ (zr - d) / zo] / (k2\ U) \qquad (27)$$

where z_r is the reference height where wind speed U and air humidity are measured, k is the von Karman constant (0.41). d is the zero plane displacement and z_0 is the roughness length calculated as a fraction of the mean height h_c of the vegetation canopy: $z_0=0.1\ h_c$ and $d=0.67\ h_c$. For a bare soil: $z_0=0.01\ m$ and $d=0$.

Soil water balance sub-model

The daily variation of the volumetric water content W_1 of the first layer is

$$DW1 = P - Es1 - D1 \qquad (28)$$

where P are the precipitations, D_1 is the drainage from the first layer to the second layer and E_{s1} is the evaporation from the first layer. In the two other layers, the daily variation of the volumetric water content are

$$DWi = D(i\text{-}1) - Esi - Eci - Di \qquad (29)$$

where i is the number of the soil layer, $D_{(i-1)}$ is the water drained from the previous layer, and E_{ci} is the water extracted from the layer i due to transpiration (see below). Drainage from a layer i to the layer (i+1) occurs when $w_i > w_{fci}$ w_{fci} being the volumetric water content at field capacity.

Calculation of leaf water potential

The leaf water potential Y_l is needed to calculate the canopy resistance and hence the canopy transpiration. It is obtained numerically by equaling E_c given by Eq.(21) in which r_{sc} is replaced by its formulation in equation (25) to the sum of the water amounts extracted from the different soil layers and calculated following van den Honert's equation

$$Eci = (\,Ysi\ -\ Yl\,) / rspi \qquad (30)$$

where r_{spi} and Ψ_{si} are the soil-plant resistance and the water potential in the i^{th} soil layer. r_{spi} are calculated as a function of root density in the i^{th} layer, Y_{si} are inferred from w_i by a water retention curve of the type $Y_s=Aw^B$, where A and B are functions of the textural composition. Y_l of day n is calculated from Y_{si} of day $n-1$, and is used to calculate r_{sc} and E_c of day n.

3. SIMULATION RESULTS

The model has been validated with data acquired in 1990, 1991 and 1992 by the USDA-ARS Southwest Watershed Research Center in Kendall site. This site is located on the Walnut Gulch experimental watershed (31°43'N 110°W) within the San Pedro Basin in Southeastern Arizona. The annual precipitation varies from 250 to 500 mm with approximately two thirds falling during the 'monsoon season' (july-september). Elgin-Stronghold complex soil association is found on this site, and the vegetation is dominated by C4 grasses whose dominant species are black grama (*Bouteloua eriopoda*), curly mesquite (*Hilaria belangeri*) hairy grama (*Bouteloua hirsuta)* and three-awn (*Aristida hamulosa*). The parameters needed for the model have been taken from the literature and data obtained on the site. However e_{bmax} and the initial root biomass were unknown and have been optimized for one year. The values obtained by optimization compared well with values given in the literature for similar vegetation types and have been used for the simulations of the other years, assuming little variations of these parameters from one year to the following year.

During the period covered by the simulations (day 150 to 366), total precipitations were 373, 283 and 284 mm for year 1990, 1991 and 1992 respectively. Figure 1 represents precipitations repartition and seasonal aerial green biomass dynamic for year 1992. This figure shows that drought effects are well reproduced by simulations. Figure 2 shows that for the three years, simulated aerial green biomass compared well with observed biomass.

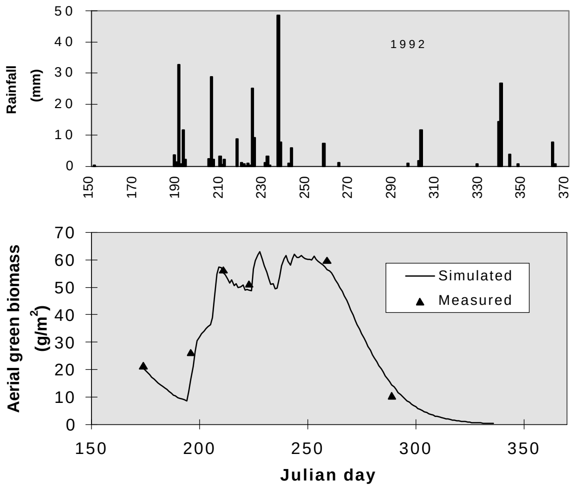

Figure 1 : Comparison of simulated and measured aerial green biomass for year 1992. Daily precipitations for this year are represented on the top.

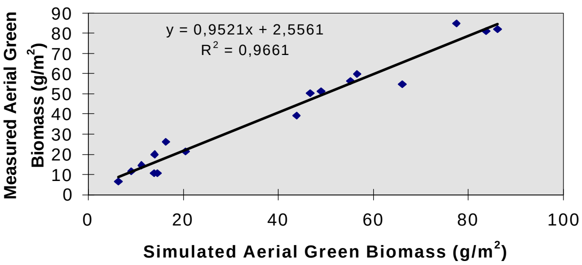

Figure 2 : Comparison of simulated and measured aerial green biomass for years 1990, 1991 and 1992

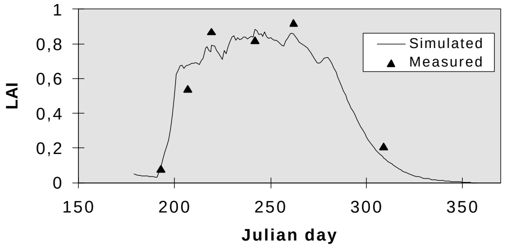

Figure 3 : Comparison of simulated and measured LAI (1990)

As shown in Figure 3, a good agreement was also obtained between observed and simulated LAI, which is essential for the coupling of the plant growth model with reflectivity models.

4. CONCLUSION

In this paper, a plant growth model for semi-arid grasslands is presented. This model is based on CO2 and water exchanges and requires a limited number of input data. Simulated biomass and LAI for the period 1990-1992 compares well with observations at the Kendall site in Southeastern Arizona. The ability to reproduce temporal variations of LAI is encouraging for the coupling with a radiative transfer model.

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