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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 :

$$\begin{aligned} d B_{ag} / dt &= a_a \cdot P_g + T_{ra} - R_{at} - S_a & (1) \\ d B_r / dt &= a_r \cdot P_g - T_{ra} - R_{rt} - S_r & (2) \\ d B_{ad} / dt &= S_a - L & (3) \end{aligned}$$

where  $B_{ag}$ ,  $B_r$ , and  $B_{ad}$  are green aerial biomass, root living biomass and standing dead aerial biomass respectively.  $P_g$  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

$$P_g = S \cdot \epsilon_c \cdot \epsilon_l \cdot \epsilon_b \cdot f_1(\Psi_l) \cdot f_2(T) \quad (4)$$

where  $S$  is the daily incoming solar radiation,  $\epsilon_c$  is the climatic efficiency ( $=PAR/S$ ),  $\epsilon_l$  the interception by green leaves efficiency ( $=PAR_l / PAR$ ), and  $\epsilon_b$  the energy conversion efficiency ( $=g(CH_2O) \text{ produced} / PAR_l$ ).  $f_1$  and  $f_2$  are empirical stress functions representing the effects of water and temperature stresses respectively. To calculate  $f_2$ , 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) :

$$f_1(\Psi_l) = (1.64 r_{smin} + r_m + 1.39 r_a) / (1.64 r_s + r_m + 1.39 r_a) \quad (5)$$

where  $r_s$  and  $r_{smin}$  are actual and minimum canopy stomatal resistance to water vapor,  $r_m$  and  $r_a$  are mesophyll resistance and canopy layer boundary resistance to water vapor. 1.64 is the ratio of diffusivities of CO2 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.  $r_s$  is calculated as a function of leaf water potential  $\Psi_l$  (see below).

The climatic efficiency  $\epsilon_c$  is approximately 0.45, and the interception efficiency  $\epsilon_l$  is calculated as a function of green LAI ( $LAI_g$ ) and total LAI ( $LAI_t$ ) :

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$$d = [1 - e(-k1 \cdot LAIt)] (LAIg / LAIt) \quad (6)$$

$$LAIg = SLAg \cdot Bag \quad (7)$$

$$LAId = SLAd \cdot Bad \quad (8)$$

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

where  $LAId$  is the dead biomass LAI,  $SLAg$  and  $SLAd$  are the specific leaf areas of the aerial green biomass and the standing dead biomass respectively.

The energy conversion efficiency  $\epsilon_b$  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  $\epsilon_b$  is considered :

$$\epsilon_b = \epsilon_{bmax} \cdot f3(\text{age}) \quad (10)$$

where  $\epsilon_{bmax}$  is the energy conversion efficiency for young mature tissues, and  $f3$  is an empirical function representing the effect of the aging on  $\epsilon_b$ . The physiological leaf age and  $f3$  were 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 ( $CH_2O$ ) 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

$$B_{ax} = r_x \cdot Bag - Br \quad (11)$$

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.

$$r_x = (Br + Ta) / (Bag - Ta) \quad (12)$$

which means that

$$Ta = B_{ax} / (1 + r_x) \quad (13)$$

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  $P_g$ .

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

and the allocation coefficient for aerial parts is calculated as

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

#### 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)  $Br > r_x B_{ag}$ .

If these conditions are met :

$$Tra = tr \cdot Br \quad (16)$$

$t_r$  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 :

$$R_{at} = m_a \cdot Bag + (1 - Y_{ga}) \cdot (aa \cdot Pg + Tra) \quad (17)$$

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

$$R_{rt} = m_r \cdot Br + (1 - Y_{gr}) \cdot (ar \cdot Pg) \quad (18)$$

$m_a$  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

$$S_a = d_a \cdot Bag \quad (19)$$

$$S_r = d_r \cdot Br \quad (20)$$

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 superficial 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 sparse 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 continuous canopy, and evaporation of a bare soil, taking into account the relative surface which is covered by vegetation and bare soil. If  $f_{vg}$ ,  $f_{vd}$  and  $f_s$  are respectively the fractional cover of green vegetation, dead vegetation and bare soil ( $f_{vg} + f_{vd} + f_s = 1$ ),  $E_c$  and  $E_s$  are calculated as

$$E_c = f_{vg} \cdot [sA + \rho c_p D / r_{ac}] / [(s+g)(1 + r_{sc} / r_{ac})] \quad (21)$$

$$E_s = f_s \cdot [sA + \rho c_p D / r_{as}] / [(s+g)(1 + r_{ss} / r_{as})] \quad (22)$$

$A$  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,  $\lambda$  is the latent heat of vaporization,  $\rho$  is air density,  $c_p$  is the specific heat of air at constant pressure,  $\gamma$  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.  $f_{vg}$  and  $f_{vd}$  are calculated as a function of  $LAI_g$  and  $LAI_d$

$$f_{vg} = 1 - e^{-K2 \cdot LAI_g} \quad (23)$$

$$f_{vd} = 1 - e^{-K3 \cdot LAI_d} \quad (24)$$

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  $\Psi_l$  as

$$r_{sc} = r_{smin} [1 + (\Psi_l / \Psi_{1/2})^n] \quad (25)$$

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

$$r_{ss} = 4140 (W_{sat1} - W_1) - 805 \quad (sm^{-1}) \quad (26)$$

where  $w_1$  represents the volumetric soil moisture content of ground surface layer (dimensionless). The aerodynamic resistances are calculated as

$$r_a = \ln 2 [(z_r - d) / z_0] / (k^2 U) \quad (27)$$

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

$$\Delta W_1 = P - E_{s1} - D_1 \quad (28)$$

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

$$\Delta W_i = D_{(i-1)} - E_{si} - E_{ci} - D_i \quad (29)$$

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  $w_i > w_{fc_i}$   $w_{fc_i}$  being the volumetric water content at field capacity.

### Calculation of leaf water potential

The leaf water potential  $\Psi_l$  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

$$E_{ci} = (\Psi_{si} - \Psi_l) / r_{spi} \quad (30)$$

where  $r_{spi}$  and  $\Psi_{si}$  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,  $\Psi_{si}$  are inferred from  $w_i$  by a water retention curve of the type  $\Psi_s = A w^B$ , where  $A$  and  $B$  are functions of the textural

composition.  $\Psi_i$  of day  $n$  is calculated from  $\Psi_{Si}$  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  $\epsilon_{bmax}$  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.

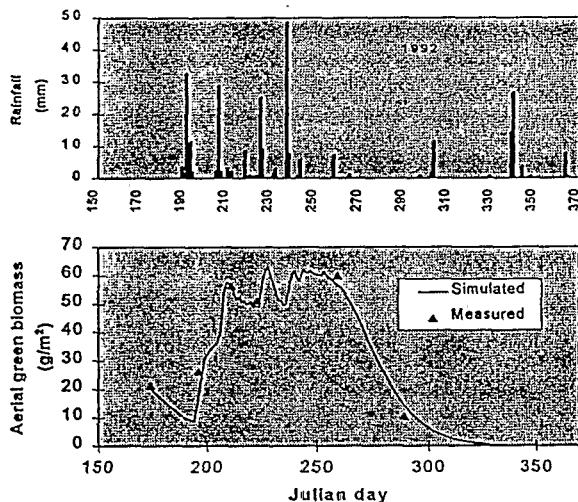


Figure 1 : Comparison of simulated and measured aerial green biomass for year 1992. Daily precipitations for this year are represented on the top.

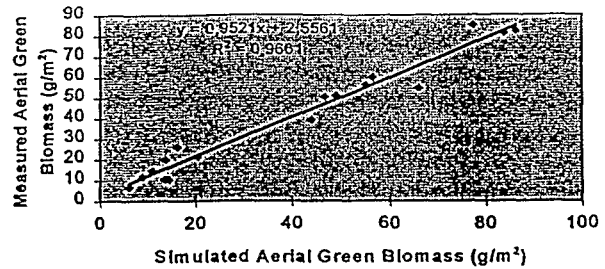


Figure 2 : Comparison of simulated and measured aerial green biomass for years 1990, 1991 and 1992

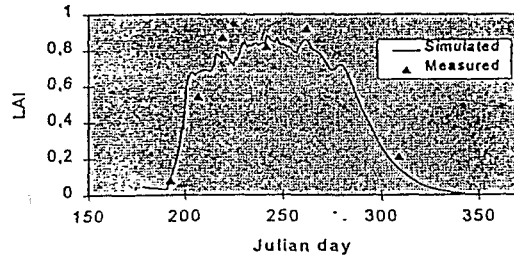


Figure 3 : Comparison of simulated and measured LAI (1990)

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 CO<sub>2</sub> 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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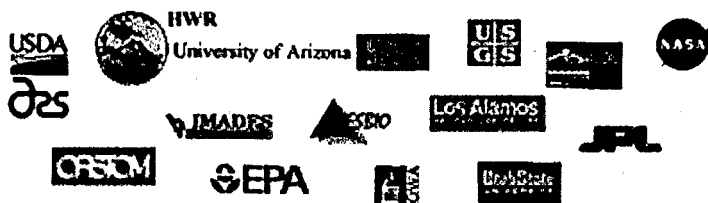
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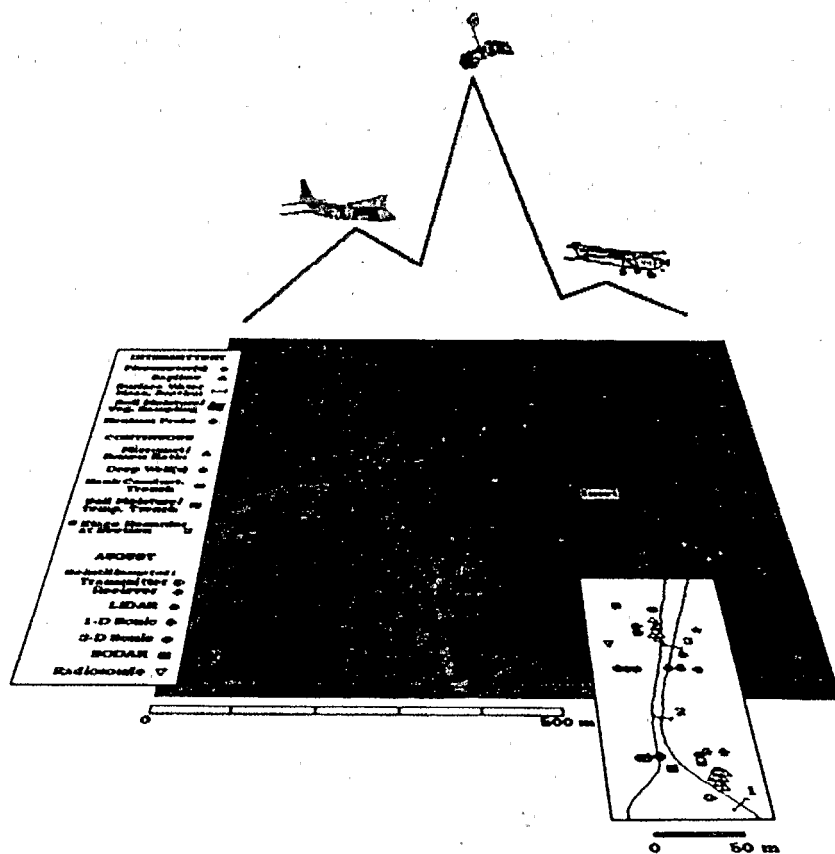


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