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Mapping maximal canopy transpiration over a Mediterranean watershed

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ABSTRACT

In Mediterranean-type climate, evapotranspiration of woodland canopy reach about 600 mm/year. Evapotranspiration, the main component of the water budget, is largely due to canopy transpiration, which participates with more than 2/3 to total evaporation. It is thus important to consider canopy ecophysiological response for the estimation of water fluxes and for modelling vegetation canopy functioning at ecosystem scale. For the extrapolation of functioning from local to watershed scale, it is necessary to consider spatial and temporal variations of the canopy, most particularly, of its leaf area index (LAI). LAI mapping allows the spatialization of the photosynthetically active tissues quantity and also, of the transpirating surface. Many methods have been developed for LAI estimation from remote sensing data. We have chosen an empirical approach using multitemporal Landsat TM images. For modelling the canopy maximal transpiration, we have chosen the Penman-Monteith model, which consider climatic demand and canopy characteristics. This model has been applied to the upper part of the Peyne watershed (Southern France), with a drainage area of about 31 km^2. This watershed is covered by a dense oak forest dominated by *Quercus ilex*. Radiation flux density components (direct and diffuse) of Penman-Monteith model were corrected in relation to slope and aspect derived from a digital terrain model. The outputs of this distributed model are the maps of seasonal variations of maximal canopy transpiration on a monthly basis. From this study, we have observed a strong influence of watershed topography on the estimation of maximal transpiration. Simulated transpiration is less sensible to LAI; above 2.5, there is no sensible increase in the maximal transpiration.

1 INTRODUCTION

The water cycle in Mediterranean-type climate is characterized by rainfall events of high intensity (above 100 mm/h) and non-perennial streamflows. The hydrological role of vegetation may be evaluated through latent heat fluxes or actual evapotranspiration, the main component of the water cycle. In Southern France, the annual amount of evapotranspired water in woodland areas is about 600 mm, more than 2/3 of this amount being due to canopy transpiration (Rambal, 1991). Piñol *et al.* (1991) estimated annual transpiration of holm oak (*Quercus ilex* L.) woodlands to be 81% of rainfall in a watershed located in Northeastern Spain. Consequently, an assessment of ecophysiological responses of plant canopies and of environmental variables is needed when estimating and modelling water fluxes at ecosystem level (Stewart, 1984). Key parameters appear to be foliage amount, climatic conditions and physiography (aspect and slope angle, length and shape). Häsler (1982) demonstrated the influence of terrain aspect (North-facing vs. East-facing slopes) on canopy photosynthesis and transpiration. Several other studies have shown the influence of terrain morphology on vegetation structure and ecosystem functioning, from local to watershed scale (Segal *et al.*, 1985; Running *et al.*, 1987; Nemani and Running, 1989; Band *et al.*, 1991; Noguchi, 1992; Band *et al.*, 1993; Wigmosta *et al.*, 1994).

When scaling up from site to region, it is necessary to take into account spatial and temporal variation of vegetation abundance, which may be expressed through the area of leaves per unit ground area or leaf area index (LAI). Mapping LAI at watershed level allows the implementation of a distributed water balance model incorporating as input variable the area of photosynthetically active canopy elements, which represents also an estimate of the evaporating

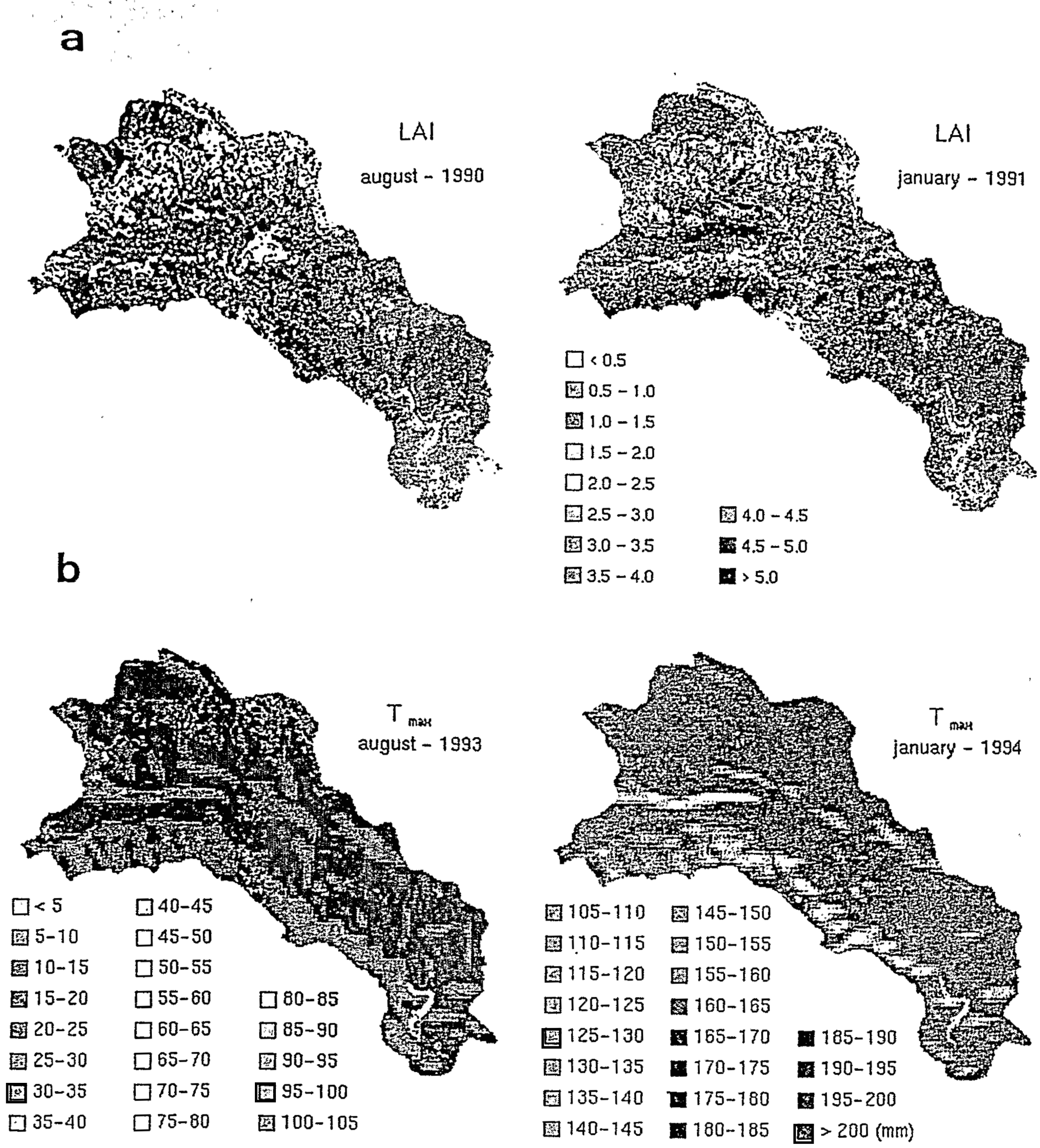

Figure 1. (a) Maps of LAI derived from Landsat-TM data (8 August 1990 and 31 January 1991). (b) Maps of simulated monthly maximal transpiration, August 1993 and January 1994. (colour plate, see page 483)

surfaces. Several methods have been proposed for mapping LAI from remote sensing data (Lacaze, 1995). In this study, we have used an empirically-based method, which has been applied to a multitemporal set of satellite data to derive seasonal maps of LAI.

2 MATERIAL AND METHODS

2.1 *Study area*

The selected area is the watershed of *La Peyne*, a river located in Hérault region (Southern France), with a drainage area of about 100 km^2. This watershed can be divided into two broad physiographic and land-use units: upper watershed (hilly landscape covered with woodlands), and lower watershed (alluvial plain cultivated with vineyards). We have chosen the upper watershed (about 31 km^2) as a test area for evaluating maximal transpiration. Dominant vegetation communities in this area are coppices of evergreen species (*Quercus ilex* L. and *Arbutus unedo* L.), with scattered patches of deciduous species like downy oak (*Quercus pubescens* Willd.). Most soils have a sandy clay loam texture and a high stones content.

2.2 *Microclimatic measurements*

An automatic weather station has been installed at one site (*Ru de Fer*) on a tower, at 10m height above ground (i.e. about 1.5m above canopy top). Global solar radiation, air temperature and relative humidity, wind speed and rainfall have been recorded on a half-hourly basis with a Campbell CR21X data logger, from June 1993 to May 1994.

2.3 *Digital terrain model*

We have used a digital elevation model provided by French National Geographical Institute; original raster data with 75m spatial resolution have been resampled to be registered with Landsat-TM satellite data (30 m resolution). Slope and aspect values have been computed using LAMONT software (Depraetere, 1990).
Dominant aspect facets in the watershed are those facing South-West, South and South-East. Slopes are predominantly lower than 12%, with a mean value of 10%.

2.4 *Evaluation of leaf area index*

The evaluation of LAI has been done from Landsat-TM data on a pixel by pixel basis by using an empirically-derived relationship (Lacaze, 1995) :

$$LAI = 6.NDVI - 0.39 \qquad [1]$$

This relationship has been derived from ground measurements of LAI of selected sites, obtained from gap fraction measurements along 120m transects at selected sites, using a LI-COR Plant Canopy Analyzer (Pinault, 1992), and related with NDVI values computed from Landsat-data at the same sites. NDVI is the Normalized Difference Vegetation Index computed from reflectance values in the visible (TM3) and near infrared (TM4) channels :

$$NDVI = \frac{\rho_{tm4} - \rho_{tm3}}{\rho_{tm4} + \rho_{tm3}} \qquad [2]$$

The derivation of reflectance values from raw data has been done using a radiometric correction software package elaborated by Gu (1988): Operational Ground Reflectance Estimation Software (OGRES).

2.5 *Maximal transpiration modelling*

The Penman-Monteith equation has been used. According to this equation, evaporation can be computed as a function of microclimatic parameters and of canopy characteristics: LAI, height and roughness (Stewart, 1988). The model has been formulated for homogeneous canopies; 2 parameters are used to model water exchanges between soil, vegetation, and atmosphere (aerodynamic conductance and canopy conductance). Maximal transpiration T_{max} in mm/s is estimated by the following equation:

$$\lambda T = \frac{\Delta . R_n + \rho . c_p . D_{sat} . g_a . LAI^*}{\Delta + \gamma .(1 + \frac{g_a}{g_c})} \qquad [3]$$

With λ = latent heat of vaporization of water (J/kg); Δ = slope of the saturation vapour pressure curve at ambient air temperature (Pa/°C); R_n = net radiation (W/m^2); D_{sat} = vapour pressure deficit from canopy to air (Pa); ρ = density of air (Kg/m^3); c_p = calorific capacity (J/Kg/K); γ= psychrometric constant (Pa); g_{cmax} = maximal canopy conductance (m/s); LAI* = sun-exposed leaf area index of foliage. The aerodynamic conductance expressed in m/s (g_a) has been derived from wind speed measurements recorded each 30mn at 1.5m above the canopy, using the formulation proposed by Thom (1975):

$$g_a = \frac{k^2 . v}{(\frac{\ln(h-d)}{z_0})^2} \qquad [4]$$

With k = von Karman constant; v = wind speed above the canopy (m/s); h = height above soil for wind speed measurement (m); d = displacement height of the reference level (m); z_0 = roughness length (m).
The roughness parameters have been deduced from an empirical function of the mean height H of the canopy proposed by Thom (1971) for forest canopies: d = 0.75H and z_0 = 0.1H. LAI* was derived from total LAI following the Norman model parametrized for Mediterranean evergreen oak canopies (Hollinger, 1992) :

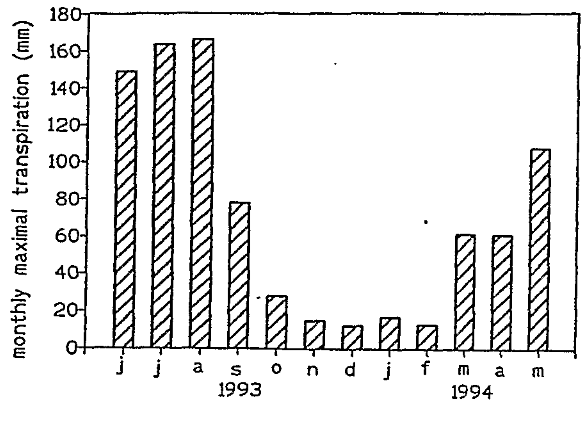

Figure 2. Monthly course of simulated maximal transpiration, from June 1993 to May 1994.

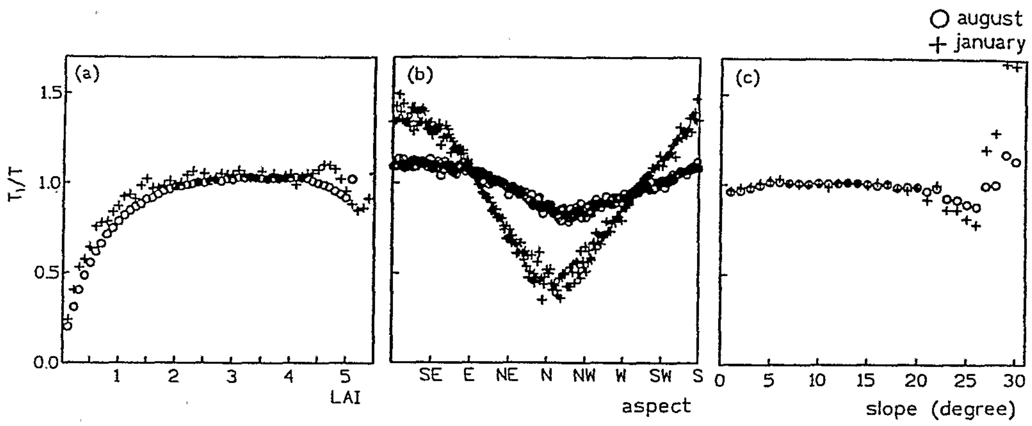

Figure 3. Distribution of simulated transpiration mean normalized values relatively to LAI, slope and aspect classes.

$$LAI^* = 2.\sin\Theta.(1-\exp(\frac{-0.7LAI}{\sin\Theta}) \quad [5]$$

where Θ is the solar elevation angle. The canopy conductance was assumed to be driven by solar radiation. The maximal conductance is assumed to be equal to 10^{-2} m/s (see Acherar & Rambal, 1992). It reached this maximal value when global radiation is higher than 200 $W.m^{-2}$; below this level the conductance is supposed to vary according to a sinusoidal function. Global solar radiation has been measured at the experimental meteorological station of the "Ru de Fer". The model of Spitters *et al.* (1985) has been used to decompose global radiation into direct and diffuse components. The direct radiation component has been spatialized by using the slope/aspect facets derived from the Digital Terrain Model and the relative position of the sun.

3 RESULTS AND CONCLUSION

Equation [1] has been applied to multitemporal Landsat-TM data: 30 May 1990, 08 August 1990, 10 October 1990 and 31 January 1991. LAI maps obtained for 8 august 1990 and 31 January 1991 are displayed at Figure 1a. One can notice relatively high LAI values in January; this may be explained by phenological characteristics of the dominant evergreen species *Quercus ilex*: leaf fall reaches a seasonal pick in May-June (Civeyrel, 1992) and leaf growth is occurring continuously from Spring to Summer. However, some overestimation may also result in January values, because of possible shadowing effects on NDVI. We have assumed that the derived LAI values were also representative of seasonal variations in the year 1993-1994, and could be interpolated on a monthly basis.

The transpiration simulation model has been applied to each pixel (30m x 30m) of the upper part of the watershed using a semi-hourly time step for the period June 1993 to May 1994, and cumulated on a monthly basis. Figure 1b shows the results for August 1993 and January 1994.

The monthly course of simulated values is displayed at Figure 2. The seasonal course of transpiration is clearly depicted and confirms the high evapotranspirative demand: during the studied period, the amount of rainfall has been 974mm and the simulated maximal transpiration 872mm. High values are observed from June to August (mean value of 150mm per month), then a marked decrease occurs in September and low values are persisting until February. Such contrasted seasonal transpiration patterns have also been observed by Wigmosta *et al.* (1994) in a mountain watershed.

Figure 3 illustrates the relationships between maximal transpiration and LAI, slope and aspect classes through the computation of mean transpiration observed for each class, normalized to mean transpiration value over the whole watershed. The dominant effects are mainly related with topographic facets: the influence of LAI amount is less important: if LAI is higher than 2.5, there is no significant increase in LAI*. The influence of aspect classes on simulated transpiration is clearly shown while influence of slope is noticeable only for steeper classes (higher than 25%).

This approach may be considered as a first step for developing a capability to simulate water, energy and carbon fluxes at the watershed scale using a distributed model. Further developments in Mediterranean areas should include the adaptation of the model to sparse canopies.

REFERENCES

Acherar M. & Rambal S., 1992 - Comparative water relations of four Mediterranean oak species. Vegetatio 99-100: 177-184.

Band L. E., Peterson D. L., Running S. W., Coughlan J., Lammers R., Dungan J., Nemani R., 1991 - Forest ecosystem processes at the watershed scale : basis for distributed simulation. *Ecological Modelling*, 56, 171-196.

Band L. E., Patterson P., Nemani R., Running S. W., 1993 - Forested ecosystem processes at the watershed scale : incorporating hillslope hydrology. *Agricultural and Forest Meteorology*, 63, 93-126.

Civeyrel L., 1992 - Etude de la variabilité spatio-temporelle des flux de carbone au sein d'un écosystème à chêne vert. Mémoire DEA, Université de Montpellier (Sciences et Techniques), 48 p.

Depraetere C., 1990 - LAMONT : Logiciel d'Application des Modèles Numériques de Terrain, version 2.0, Laboratoire d'Hydrologie de l'ORSTOM, Montpellier, 146 p.

Gu X. F., 1988 - Mise en relation des luminances mesurées par SPOT avec les réflectances de surfaces agricoles mesurées au sol. Mémoire DEA Méthodes physiques en télédétection, Univ. Paris 7.

Häsler R., 1982 - Net photosynthesis and transpiration of *Pinus montana* on East and North facing slopes at Alpine timberline. *Oecologia*, 54, 14-22.

Hollinger D. Y., 1992 - Leaf and simulated whole-canopy photosynthesis in two co-occurring tree species. *Ecology*, 73, 1-14.

Lacaze B., 1995 - Spectral characterisation of vegetation communities and practical approaches to vegetation cover changes monitoring. Proceedings Workshop "*Remote Sensing for Land Degradation and Desertification Monitoring in the Mediterranean Basin*", Valencia, 13-15 June 1994. (in press).

Nemani R. R. and Running S. W., 1989 - Testing a theoretical climate-soil-leaf area hydrologic equilibrium of forest using satellite data ecosystem simulation. *Agricultural and Forest Meteorology*, 44, 245-260.

Noguchi Y., 1992 - Hydrometeorological differences between opposite valley slopes and vegetation asymmetry in Hawaï. *J. of Vegetation Science*, 3, 213-238.

Pinault N., 1992 - Influence de la végétation sur la ressource en eau du bassin versant de la Peyne (Hérault). Mémoire DAA, Institut National Agronomique de Paris Grignon, 37 p.

Piñol J., Lledo M. J., Escarré A., 1991 - Hydrologic balance of two Mediterranean forested catchments (Prades, NE Spain). *Hydrol. Sci. J.*, 36, 32-43.

Rambal S., 1991 - 2030 : conjecture sur la ressource en eau en Languedoc karstique. *La Météorologie*, 38, 2-7.

Running S. W., Nemani R. R., Hungerford R. D., 1987 - Extrapolation of synoptic meteorological data in mountainous terrain and its use for simulating forest evapotranspiration and photosynthesis. *Can. J. For. Res.*, 17, 472-483.

Segal M., Mahrer Y., Pielke R. A., Ookouchi Y., 1985 - Modeling transpiration patterns of vegetation along South and North facing slopes during the subtropical dry season. *Agricultural and Forest Meteorology*, 36, 19-28.

Spitters C. J. T., Toussaint H. A. J. M., Goudriaan J., 1986 - Separating the diffuse and direct components of global radiation and its implications for modeling canopy photosynthesis. Part I:

Components of incoming radioation. *Agricultural and Forest Meteorology*, 38, 217-229.
Stewart J. B., 1984 - Measurement and prediction of evaporation from forested and agricultural catchments. *Agricult. Water Management*, 8, 1-28.
Stewart J. B., 1988 - Modelling surface conductance of pine forest. *Agricultural and Forest Meteorology*, 38, 217-229.
Thom A. S., 1971 - Momentum absorption by vegetation. *Q. J. R. Meteorol.*, 97, 414-428.
Thom A. S., 1975 - Momentum, mass and heat exchange of plant communities. In: *"Vegetation and the Atmosphere"* (J. L. Monteith ed.), Academic Press.
Wigmosta M. S., Vail L. W., Lettenmaier D. P., 1994 - A distributed hydrology-vegetation model for complex terrain. *Water Resources Research*, 30, 1665-1679.

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