SVERIGES
LANTBRUKSUNIVERSITET

Simulation model for transpiration, evaporation and growth of plant communities

Simuleringsmodell för transpiration, avdunstning och tillväxt i växtbestånd

Henrik Eckersten

SPAC-GROWTH
Model description

Institutionen för markvetenskap
Avdelningen för lantbrukets hydroteknik

Swedish University of Agricultural Sciences
Department of Soil Sciences
Division of Agricultural Hydrotechnics

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1 INTRODUCTION

This paper aims to describe the theory of the SPAC-GROWTH model. The description serves as a tool when using the model and then should be used together with a manual (Eckersten, 1991). The link to the manual is through the symbols given in the List of symbols. The text always refers to the model and not directly to reality, unless otherwise stated. As regards the validity of the model, the reader is referred to other publications (see list of references) in which tests of different parts of the model have been made. The software of the model is available from the author on request.

The model is a combined transpiration-growth model based on the Soil-Plant-Atmosphere-Continuum (SPAC) concept (which simulates the flow of water from soil through the plant to the atmosphere). In short, the model works like this: The plant has a reservoir of water that regulates the transpiration rate which affects the total growth rate. The total growth is allocated to root, leaf+stem and grain, respectively. In turn, the size of the plant affects the evaporation of intercepted water and the transpiration through the leaf area and root development (Fig. 200). Although developed for crops, the model can be applied on species with only vegetative growth by cancelling the grain development. For woody plants like willow the maximum size of the plant water reservoir can be regulated with parameters. For plants older than one year, the biomass compartments of the model represent only the accumulated growth of the current year.

Some of the input variables to the model need to be given at a time scale of minutes. However, in many cases only daily values are available. Then the model can be applied by estimating minute values of input variables from synoptic weather data using a special subroutine of the model (see the special section on analytical input data).

The basic version of the transpiration calculations, which simulates the transpiration of a fixed plant that does not change in size, was described by Turner & Kowalik (1983) and Kowalik & Eckersten (1984). The transpiration-growth relations have to some extent been described by Eckersten (1986 a,b) and allocation functions for assimilates within the plant are taken from Eckersten & Jansson (1991).

Since the model aims to be a research tool, although hopefully suitable for many practical purposes, it includes possibilities to choose among different hypotheses (see the section on special functions) and will be modified as research makes progress. This model description hence includes some processes that do not originate from other publications. New or modified equations including these processes are denoted with an asterisk (*). Most new equations are related to the relations between water flows and the canopy size.

A section of the model description usually starts with a short general summary of its contents (written in italics) followed by a more detailed verbal (and graphic) description of the calculation procedure. The section ends with the mathematical expressions. This enables understanding of the model regardless of whether or not the reader is familiar with mathematical expressions. Also, for the reader who is familiar with equations, this gives a good overview of the model. The numbers given to equations, figures and tables are related to the number of the subsection concerned.

2 MODEL

The model is conceptually divided into the water submodel and the biomass submodel. The water submodel consists of two compartments, one for easily available water located in the leaves and one for intercepted water on the canopy surface. The biomass submodel consists of three compartments, the leaf plus stem biomass, the grain biomass and the root biomass.

The factors linking the two submodels are the transpiration rate calculated by the water submodel and the leaf area and root growth calculated by the biomass submodel (see Fig. 200). The root growth is of use for the water submodel only as a special function (see the section on special functions). The combined model is valid for horizontally uniform stands and the growth is assumed not to be limited by a shortage of nutrients other than nitrogen. The time step of the water submodel is 1-4 minutes, whereas for the biomass submodel it is one day. Input data are minute values on global radiation, net radiation, air temperature, air relative humidity, wind speed and precipitation, registered above the canopy, and daily values on soil water potential and leaf nitrogen concentration.

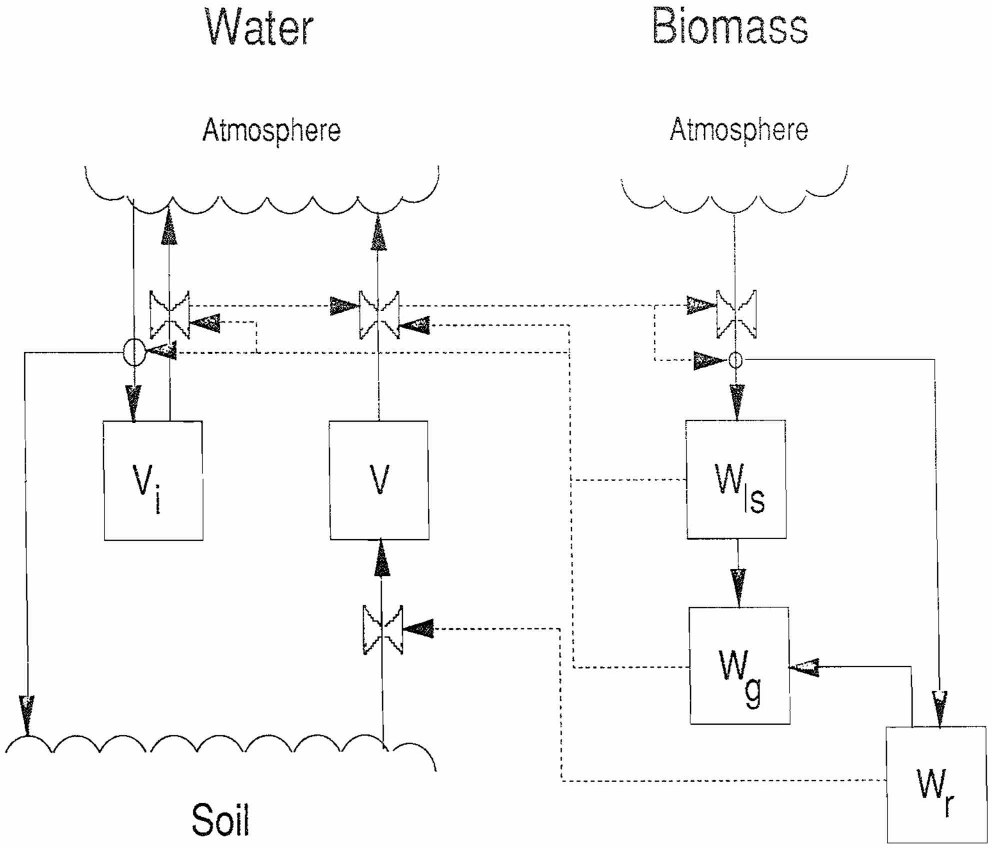


Figure 200. Schematic description of the SPAC-GROWTH model consisting of two "submodels": the water submodel (V) and the biomass submodel (W). Indices are as follows: g=grain, i=intercepted, ls=leaf+stem and r=root. Solid lines are flows of water or assimilates whereas dotted lines represent flows of information. *Schematisk beskrivning av SPAC-GROWTH modellen. Modellen består av två "delmodeller"; en för vatten (V) och en för biomassa (W). g=kärna, i=intercepterat, ls=blad+stam och r=rot. Heldragna linjer är flöden av vatten eller assimilat. Streckade linjer är informationsflöden.*

3 WATER SUBMODEL (SPAC)

The leaves contain water which is easily available for transpiration. The transpiration occurs during day-time when stomata are open and the rate is determined by the radiation energy available, the drying "power" of the air and several factors regulating the flow of water from the plant to the atmosphere. The loss of plant water is compensated by the uptake of water from the soil which, however, for several reasons can be delayed or is too small to meet the transpiration demand. If, for instance, the root development is poor or soil water availability is small, the plant water reservoir decreases. The plant then closes its stomata and the transpiration decreases and the plant can stabilize its water status on a new lower level. During the night the stomata are closed and the plant loses water only very slowly through the cuticle. Then the plant can recover to a plant water status close to that of the soil. The flow of water is described in terms of water potentials and resistances.

3.1 Plant water

The amount of easily available water is proportional to the leaf area. It is decreased by transpiration but increased through the root uptake created by the differences in water potentials of the plant and the soil. A closed canopy typically contains much less water than is lost and gained daily through transpiration and uptake. Hence the water reservoir is replaced several times a day.

Once leaves are present (see the biomass submodel) there is a reservoir of easily available water in the plant (V) from which water can be transpired (F_T). The driving force for transpiration is the vapour pressure difference (e_a - e_s) between the ambient air and the air inside the stomata cavities. The flow is retarded by the resistances of stomata (r_c) and the air outside the leaf (r_a). As the plant loses water from its maximum value (V_{Max}) the canopy water potential (ψ_c) drops below that of the soil (ψ_s). This difference is the force for uptake of water (F_U) against the resistances of the soil (r_r) and the plant (r_p). Each unit of leaf area can maximally contain V_o amount of easily exchangeable water (see also section on special functions) corresponding to a maximum water potential (ψ_{cMax}). When the reservoir is emptied the canopy water potential is ψ_{cMin} (Eqs. 311-313).

The difference in plant water content (δV) during a time-step (δt) equals the integration of the difference between F_T and F_U during the period concerned. This integral is solved numerically using an iterating method that is described in the section on plant water change (Eq. 310).

$$\delta V = \int (F_U - F_T)dt \qquad F_T \geq 0 \qquad (310)$$

where:

$$F_U = (\psi_s - \psi_c)/(r_r + r_p) \qquad (311)$$

$$\psi_c = \psi_{cMax} - (\psi_{cMax} - \psi_{cMin})(1 - V/V_{Max}) \qquad V_{Max} = V_o A_{li} \qquad (^*312)$$

$$F_T = \frac{\rho c_p}{\gamma \lambda} \; \frac{e_s - e_a}{r_c + r_a} \qquad (313)$$

3.2 Canopy energy balance

The radiation energy absorbed by the canopy is used for the evaporation of water from the plant. The evaporation rate (latent heat flux) is also determined by other factors and often, during day-time, more radiation is absorbed than is needed to meet the energy demand by evaporation. Then the canopy surface becomes warmer than the ambient air. The excess heat is leaving the plant through the sensible heat flux. During night or at rainfall, normally the opposite occurs. We assume that the energy storage rate in leaf tissues is negligible in comparison with the other flows. This assumption is not so good when the other flows are small, as at sunrise or sunset. The variables determining the partitioning of solar energy between the latent and sensible heat fluxes are for instance wind speed, air humidity and stomata resistance.

The surface temperature (T_s) is adjusted so that the canopy energy balance is fulfilled. The radiation energy exchange between canopy and the surroundings is the net radiation intercepted by the canopy (R_n) which is the net radiation above canopy (R_{no}) minus the corresponding value below canopy. The latter value is calculated according to Beers' law using a radiation extinction coefficient (k) and the leaf area index (A_{li}). The energy balance is, in addition to R_n, also affected by the fluxes of sensible heat (H) and latent heat (λF_T) whereas storage of heat in plant tissues is neglected (Eqs. 320-322).

The sensible heat flux is proportional to the difference between the surface temperature and the air temperature (T_a) divided by the resistance for flow of heat in the air which is assumed to be the same as for vapour (r_a) (see section on special functions). The latent heat flux (which is proportional to transpiration) is created by the vapour pressure difference between the surface of the stomata cavities (e_s) and that of the surrounding air (e_a) having a relative humidity equal to h_a. The air in the stomata cavities is assumed to be at saturation. T_s is determined by changing iteratively its value until the sum of all three fluxes is below a certain limit (Δ_{Max}) (Eqs. 320, 322-324).

$R_n - H - \lambda F_T \leq \Delta_{Max}$	T_s is changed until this statement is fulfilled	(320)
$R_n = R_{no}(1-\exp(-kA_{li}))$		(321)
$H = \rho c_p (T_s - T_a)/r_a$		(322)
$F_T = \text{Eq. } 313$		
$e_s = a_e \exp((b_e T_s' - c_e)/(d_e T_s' - e_e))$	$T_s' = T_s + 273.15$	(323)
$e_a = h_a a_e \exp((b_e T_a' - c_e)/(d_e T_a' - e_e))$	$T_a' = T_a + 273.15$	(324)

3.3 Resistances

The pathway for water flow from bulk soil to the atmosphere is represented by four resistances: the soil-root resistance (r_r) from the soil where the water potential is ψ_s to the root surface, the plant resistance (r_p) from the root surface to the mesophyll of leaves, the stomata resistance (r_c) from the leaf-mesophyll to the air just outside the leaf surface and finally, the aerodynamic resistance (r_a) from close to the leaf surface to the ambient air above canopy. The resistances vary with environmental conditions of the air and the soil as well as with the plant conditions. If, for instance, the wind speed or the radiation or the soil water potential increases then the resistance against water flow decreases (Fig. 330).

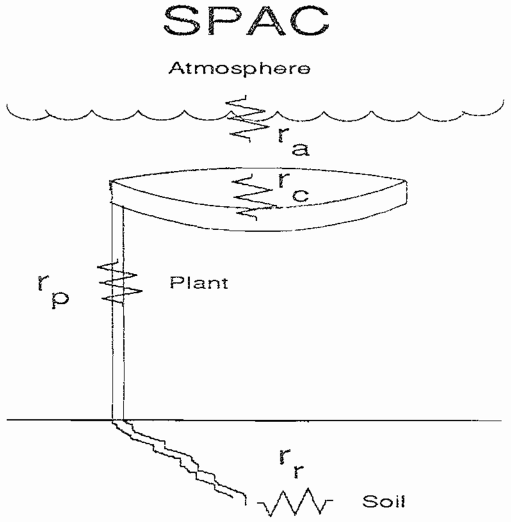


Figure 330. Schematic description of the pathway for water from soil through the plant to the atmosphere. For explanation of symbols, see text. *Schematisk beskrivning av vattnets väg från marken till atmosfären.*

The soil-root resistance (r_r) is proportional to the root density factor (b) which accounts for the geometry of the root system. The resistance increases with decreasing unsaturated hydraulic conductivity ($a|\psi_s|^{-n}$) which in turn decreases faster with decreasing soil water potentials (ψ_s) when the "soil pore size factor" (n) is high. The size and depth of the root-system do not explicitly affect r_r (see section on special functions). Instead, increased availability of water due to root development can be considered by choosing appropriate values for the root density factor and the soil water potential (Eq. 330) (Fig. 331).

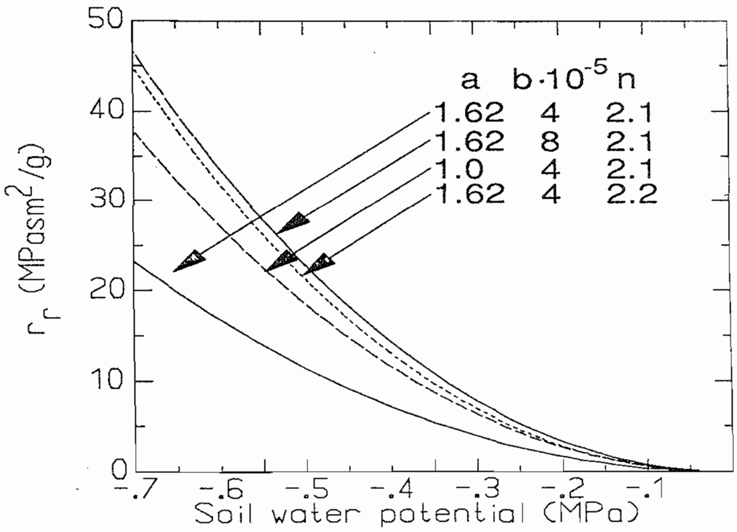


Figure 331. The soil-root resistance as function of the soil water potential. *Mark-rotmotståndet som funktion av markens vattenpotentialen*

The plant resistance (r_p) is assumed to be constant during the vegetative growth but increases rapidly as grain development starts. r_p is assumed to be proportional (a_{rp}) to the grain biomass (W_g). (Eq. 331).

The stomata resistance per unit leaf area (r_s) is affected either by the incoming short-wave radiation (R_s) or by the canopy water potential (ψ_c). Two separate mechanisms are assumed to regulate stomata, one represented by $r_s(R_s)$ and the other by $r_s(\psi_c)$. Since there is only one reservoir of water in the canopy the water potential is the same for all leaves. However, the incoming radiation differs among leaves and for each sublayer (i) in the canopy, $r_s(R_s(i))$ is calculated separately. The radiation incident on the top of this layer ($R_s(A_{li}(i))$, which depends on the leaf area above the layer ($A_{li}(i)$), is intercepted by the leaf area of the layer (δA_{li}) according to Beers' law and the radiation extinction coefficient (k). The actual value of r_s is then the highest value given by $r_s(R_s(i))$ and $r_s(\psi_c)$. The resistances of single stomata are assumed to be coupled in parallel with each other. Then, assuming the number of stomata to be proportional to the leaf area, the resistance of the sublayer is inversely proportional to the leaf area of that layer. The stomata resistance per unit of ground surface (r_c) is the sum of the conductances of sublayers ($\delta A_{li}/r_s$) (Eqs. 332-336) (Figs. 332 and 333).

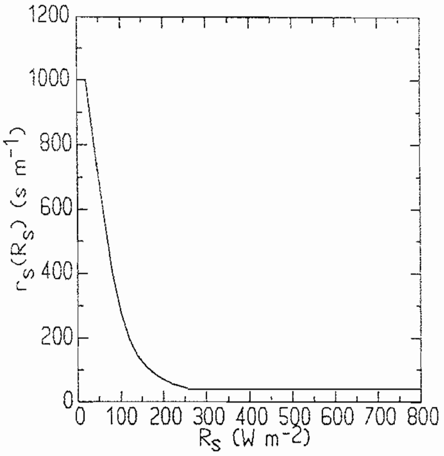


Figure 332. Stomata resistance as a function of radiation. *Stomatamotståndet som funktion av strålning.*

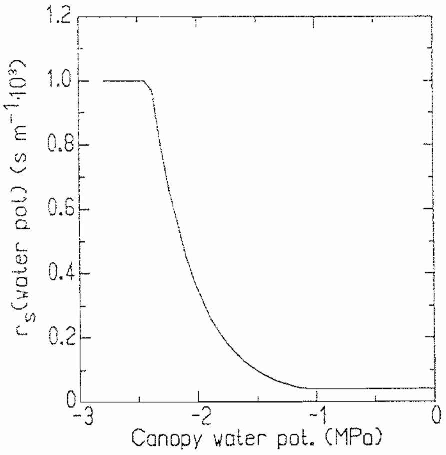


Figure 333. Stomata resistance as a function of the canopy water potential. *Stomatamotståndet som funktion av bladens vattenpotential.*

The aerodynamic resistance (r_a) is inversely proportional to the wind speed (u) measured above the canopy. r_a is an increasing function of the smoothness of the surface which increases during the season as the leaf area index (A_{li}) increases (Lindroth equation; Persson & Lindroth, 1991). The values of the coefficients (a_{Li} and b_{Li}) are related to the level of the input data on wind speed. (Eq. 337).

$$r_r = \frac{b}{a|\psi_s|^{-n}} \qquad (330)$$

$$r_p = r_{po} + a_{rp} W_g \qquad (^*331)$$

$$1/r_c = \sum_{i=1}^{m} \delta A_{li}/r_s(i) \qquad \text{m=number of layers} \qquad (^*332)$$

where:

$$r_s(i) = \min\,(r_s(R_s(i))\,,\, r_s(\psi_c)) \qquad r_{sMin} \leq r_s \leq r_{sMax} \qquad (333)$$

where:

$$r_s(\psi_c) = \frac{1}{(a_c + b_c\psi_c + c_c\psi_c{}^2 + d_c\psi_c{}^3 + e_c\psi_c{}^4)} \qquad (334)$$

$$r_s(R_s(i)) = \frac{1}{(a_r + b_{rr}R_s(i) + c_r R_s(i)^2)} \qquad = r_{sMax} \text{ if } R_s(i) < R_{sMin} \qquad (335)$$

where:

$$R_s(i) = R_s(A_{li}(i))(1 + \exp(-k\delta A_{li}))/2 \qquad (336)$$

$$r_a = (a_{Li} + b_{Li} A_{li})/u \qquad (337)$$

3.4 Rain interception

A fraction of the rain falling on the canopy (F_P) is intercepted on the vegetative surfaces and thereafter evaporated to the air. The rest (F_G) falls onto the ground and is not included in the calculations of the model any longer, although considered through the soil water potential input variable. The rain is assumed to be intercepted by the canopy in a similar way as the radiation. This means that the fractional interception of the rain is the same for all "sublayers" of leaf area in the canopy. Hence Beers' law is used but, instead of the radiation extinction coefficient, we use the rain interception coefficient (k_P). Grain is assumed to intercept rain in a similar way. The coefficient (k_{Pg}) used here is related to the grain biomass (W_g). The upper limit of water interception (V_{IMax}) is determined by the maximum amount of water possible to be retained by the unit leaf area (V_{Io}) and the relative efficiency in interception between leaf and grain (Eqs. 340-342).

The intercepted water evaporates (F_I) in a way similar to that of the transpired water (F_T) after it has passed through the stomata. Hence, F_I is calculated using the same equations as for F_T but with the stomata resistance (r_c) equal to zero. When there is intercepted water on the vegetative surfaces the transpiration is assumed to stop and hence the plant water status can recover to the level determined by the soil conditions. Thereafter no uptake or change in plant water status occur as long as the canopy is wet. Since the evaporation takes place during the same time step as the interception, the reservoir for water on the canopy (V_I) often becomes zero already during the current time step (Eqs. 343-344).

$$\delta V_I = (F_P\text{-}F_G\text{-}F_I)\delta t \qquad \leq V_{IMax}\text{-}V_I(t\text{-}1)+(F_P\text{-}F_G)\delta t \qquad (340)$$

where:

$$V_{IMax} = V_{Io}(A_{li}+W_g k_{Pg}/k_P) \qquad (^*341)$$

$$F_G = F_P \exp(\text{-}k_P A_{li}\text{-}k_{Pg} W_g) \qquad (^*342)$$

$$F_I = F_T \text{ in Eq. 313 but with } r_c=0 \qquad \geq 0 \;\; ; \text{if } V_I>0 \qquad (343)$$

$$F_T = 0 \qquad \text{if } V_I>0 \qquad (344)$$

3.5 Plant water change

The calculation of the plant water change (Eq. 310) is basically according to the Euler method of integration. Numerically, the change in plant water content (δV) is determined by changing the plant water content (V) until a new balance between transpiration (F_T), uptake (F_U) and V is achieved.

The iterating method used for calculating the difference in V from one time (t_1) to the next (t_2) is as follows: First step (j=1): F_T and F_U are calculated for the meteorological variables and the plant water content at time t_1 ($V(t_1)$). If this causes a change in V that corresponds to a change of leaf water potential (ψ_c) higher than a certain limit ($\Delta\psi_{cMax}$), then we move to the second step. Second step (j=j+1): using the new plant water status, F_T and F_U are calculated again and if the change of the resulting plant water status is too high compared to the previous one we go to the third step (j=j+1). This procedure is repeated until the change in plant water status is below the specified limit. The same values of the meteorological variables are used throughout. The last values obtained for V, F_T and F_U are those valid for time t_2.

$$\delta V = V(t_2)-V(t_1) \tag{350}$$

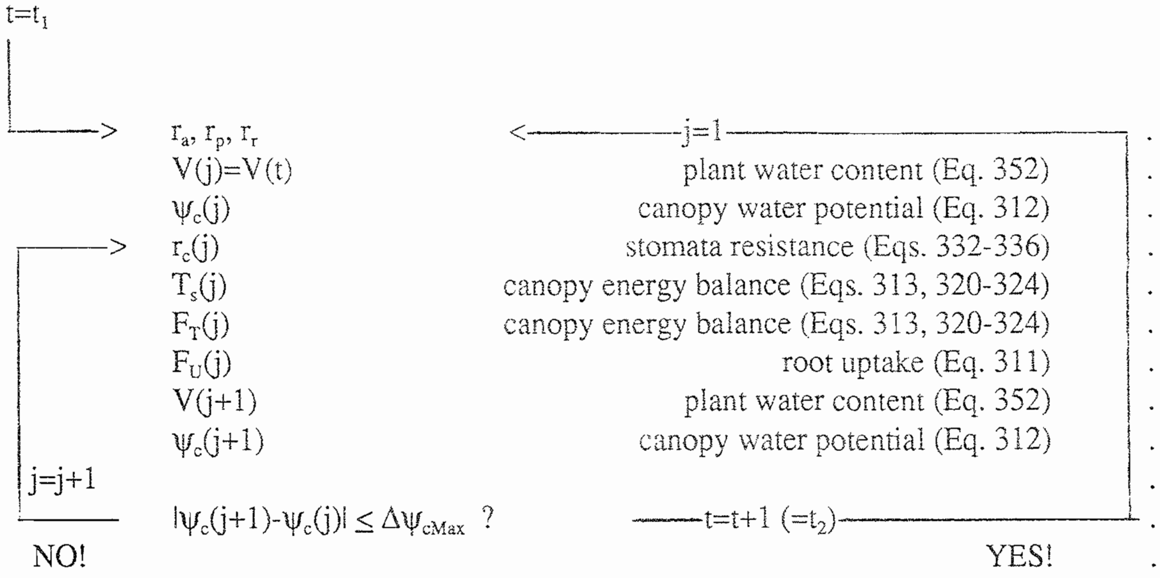
where:

$$V(t_2) = V(j+1) \qquad \text{if } V(j+1)-V(j) \text{ is not too high} \tag{351}$$

where:

$$V(j+1) = V(j)+(F_U(j)-F_T(j))(t_2-t_1) \qquad j=\text{number of iteration} \tag{352}$$

CALCULATION PROCEDURE



4 BIOMASS SUBMODEL (GROWTH)

The plant is separated into three compartments of biomass: the root, the stem plus leaf and the grain. Through the open stomata of the leaves the plant receives carbon dioxide from the atmosphere, whereas when the stomata are closed (i.e. when the stomata resistance is at maximum) no growth occurs. The assimilation rate is proportional to the transpiration rate. However, this proportion (water use efficiency) decreases for dry conditions because water is then more readily lost than carbon dioxide is gained. Similarly, the water use efficiency changes with leaf nitrogen status. The assimilates are partitioned between roots and above-ground tissues. The root development is stimulated by low plant nitrogen and water status. The feedback on water and nitrogen uptake of increased root growth is, however, not calculated by the model, but considered through the input variables on leaf nitrogen concentration and soil water potential. The rate of leaf area expansion increases with shoot growth but decreases with above-ground biomass and at a certain high level of above-ground biomass no further expansion *occurs. The grain development starts when a function of air temperature and day-length rises above a certain limit. The vegetative growth goes on also after this time, although considerably affected by the grain development. Litter-fall of all kinds is neglected. However, since in reality no litter usually appears before the grain growth has started, we assume that the grain development is overestimated by the litter amount (i.e. the grain compartment could be regarded as the grain plus litter compartment)*

The day for start of growth (t_o), together with the initial amount of total biomass ($W_t(t_o)$) at this time, are input to the model. The initial assimilates are partitioned between leaf plus stem growth (W_{ls}') and root growth (W_r') and developing leaf area following the ordinary equations for allocation (Eqs. 402-411). Once this flushing has occurred the transpiration through leaves starts and thereby the growth of the plant. The daily total growth per unit of soil surface (W_t') is proportional to the transpiration (F_T) according to the "water use efficiency" factor (τ) which decreases with increasing vapour pressure deficit of the ambient air ($\Delta e=e_d-e_a$) and leaf nitrogen concentration (n_l) (Eqs. 400-401, Figs. 400 and 401).

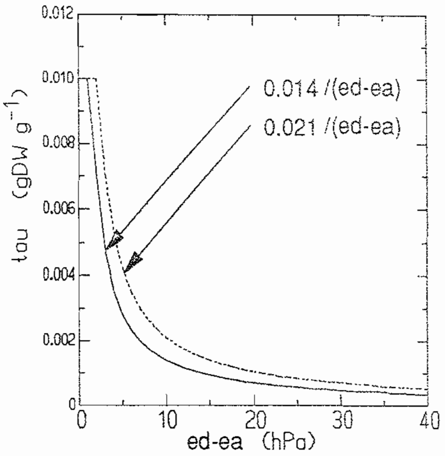


Figure 400. Water use efficiency as function of vapour pressure deficit. *Vattenutnyttjande som funktion av luftens ångtrycksdeficitet*

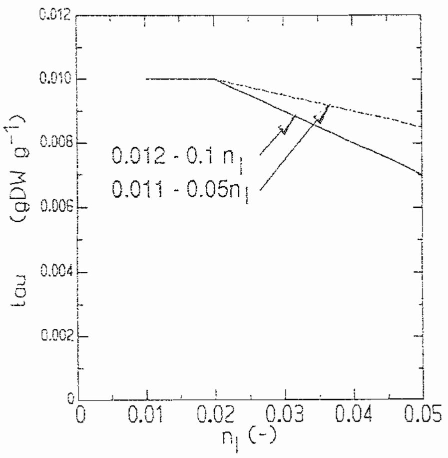


Figure 401. Water use efficiency as function of leaf nitrogen concentration (Tom Ericsson unpublished data for *Salix*). *Vattenutnyttjande som funktion av bladens kvävehalt.*

The amount of assimilates allocated to roots (W_r') is a fraction (b_r) of the total daily growth where b_r is the highest value of two functions. The first function depends on n_l and has a minimum value (b_{rMin}) at or above the maximum (optimum) leaf nitrogen concentration (n_{lMax}) and increases as n_l decreases. The second is a similar function but with the plant water status as independent variable. The plant water status is here represented by the ratio between the actual (F_T) and the potential (F_{Tp}) transpiration, the latter being identically calculated to the actual, however assuming the plant water status to be at maximum (i.e. $V=V_{Max}$, see Eq. 312) (Eqs. 412-414, Fig. 402).

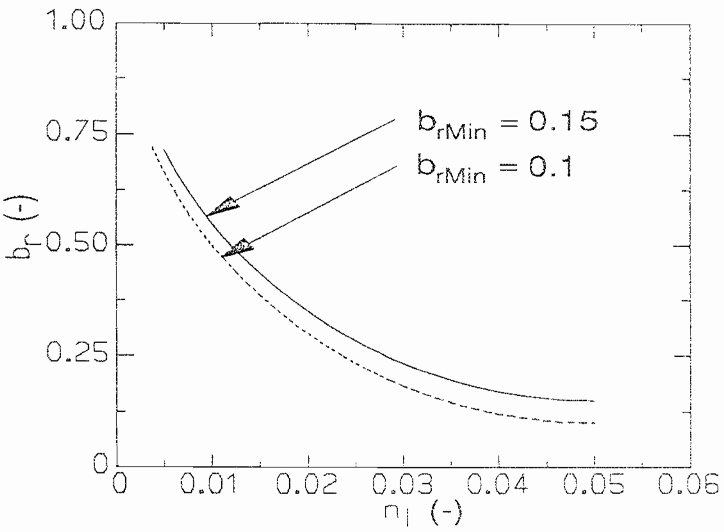


Figure 402. Fraction of assimilates allocated to roots as function of leaf nitrogen concentration. *Andelen rottillväxt som funktion av bladens kvävehalt.*

The remaining part of the daily total growth ($(1-b_r)W_t'$) is allocated to the leaf plus stem biomass (W_{ls}). At a certain day (t_g) the vegetative growth is accompanied by the development of grains (W_g). This day appears earlier if the accumulated values of air temperature (T_a) and day length (Y) are high and is estimated to be the day when the grain switch (i_g) becomes equal to one (Eqs. 405-408, Figs. 403 and 404).

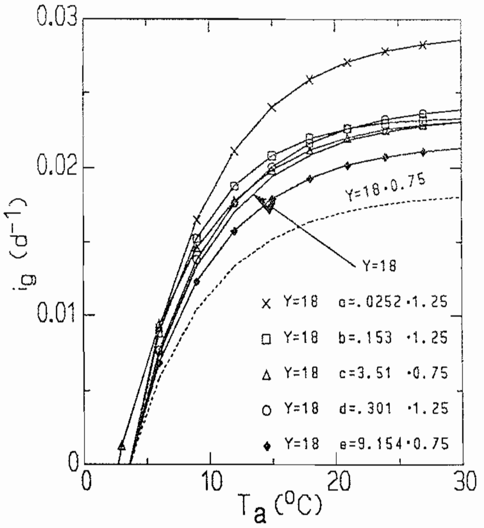


Figure 403. Daily value of index related to start of grain development as function of air temperature. *Index för start av kärnans tillväxt som funktion av lufttemperaturen.*

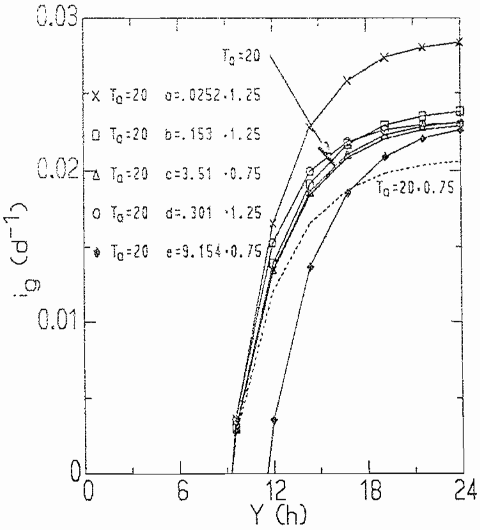


Figure 404. Daily value of index related to start of grain development as function of daylength. *Index för start av kärnans tillväxt som funktion av daglängden.*

The leaf area expansion ($A_{li}'(in)$) is such that a certain balance between the leaf area index (A_{li}) and the total above-ground biomass ($W_{ls} + W_g$) is maintained. This balance is expressed as the ratio (b_l) between the two variables and is an input function that decreases with plant size ($b_l = b_{lo} - b_{l1}\ln(W_{ls}+W_g)$) (Fig. 405). From this function an expression for $A_{li}'(in)$ is derived. A_{li} decreases ($A_{li}'(ut)$) when the leaf assimilates are allocated to grains (Eqs. 409-411).

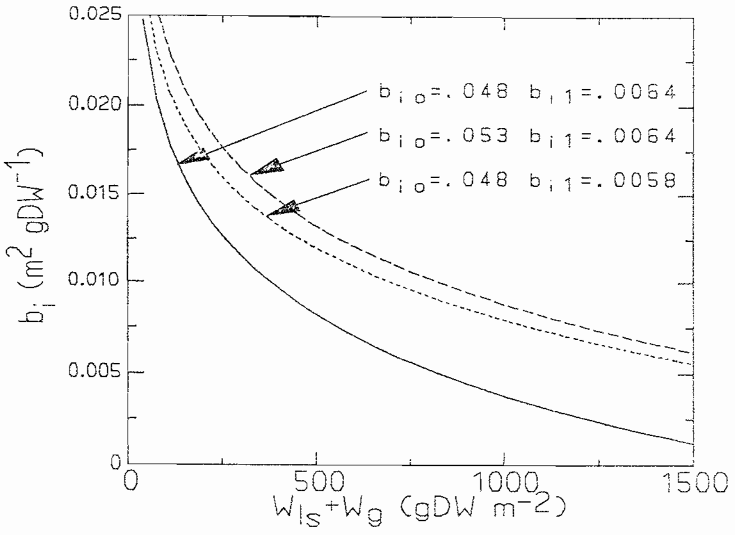


Figure 405. Leaf area to above-ground biomass ratio as function of above-ground biomass. *Kvoten mellan bladyta och ovanjordisk biomass som funktion av ovanjordisk biomassa.*

$$W_t' = \sum_{t=1}^{1440} \tau(t) F_T(t) \tag{400}$$

where:

$$\tau(t) = \min\left(a_\tau/\Delta e\ ,\ b_\tau - c_\tau n_l/n_{lMax}\right) \qquad \leq \tau_{Max} \tag{*401}$$

$$W_r' = b_r W_t' - b_g W_r \qquad b_g=0 \text{ if } i_g<1 \tag{402}$$

where:

$$b_r = 1 + b_{rMin} - (1-x^2)^{0.5} \qquad \leq 1 \tag{403}$$

where:

$$x = \max\left((n_{lMax}-n_l)/n_{lMax}\ ,\ (1-F_T/F_{Tp})\right) \qquad 0 \leq x \leq 0.99 \tag{*404}$$

$$W_{ls}' = W_{ls}'(in) - b_g W_{ls} \qquad b_g=0 \text{ if } i_g<1 \tag{405}$$

where:

$$W_{ls}'(in) = (1-b_r) W_t' \tag{406}$$

$$W_g' = b_g (W_r + W_{ls}) \qquad b_g=0 \text{ if } i_g<1 \tag{407}$$

$$i_g = \sum_{t=t_o}^{t_g} a_g (1-\exp(-b_{gg}(T_a(t)-c_g))(1-\exp(-d_g(Y(t)-e_g)) \qquad T_a \geq c_g\ ,\ Y \geq e_g \tag{408}$$

$$A_{li}' = A_{li}'(in) - A_{li}'(ut) \tag{409}$$

where:

$$A_{li}'(in) = (W_{ls}' + W_g')(b_{io} - b_{i1}(1+\ln(W_{ls}+W_g))) \qquad \geq 0 \tag{410}$$

$$A_{li}'(ut) = b_g A_{li} \qquad b_g=0 \text{ if } i_g<1 \tag{411}$$

5 SPECIAL FUNCTIONS

5.1 Resistances

In this section alternative or complementary calculations are presented. These are available in the model and normally activated using the switch named Special.

The soil-root resistance (r_r) that is a function of the soil water potential (Eq. 330) can be given a value that is inversely proportional (a_{rr}) to the root biomass (W_r). This modified resistance ($r_r(W_r)$) then reflects an increased efficiency in water uptake per unit of soil volume when the root biomass increases (Eq. 510).

The stomata resistance (r_s) can, in addition to the radiation (R_s) and the canopy water potential (ψ_c), also be a function ($r_s(R_s,\Delta e)$) that decreases with the vapour pressure difference of the air (Δe). This function can either be the Lohammar equation (Eq. 512) or a polynomial function of R_s and Δe (Eq. 513). The actual stomata resistance is taken to be the highest value given by all the "sub-functions" chosen to be included (Eqs. 511-513).

The aerodynamic resistance (r_a) is modified by a factor named the Richardson number (Ri) which accounts for the effect of thermal convection on the transport of heat and vapour in the air. This factor is proportional to the gravitation force (g), the distance from the canopy top to the roughness height (z_h-z_o) and the temperature difference between the surface and the air ($T_s(t_1)$-T_a; t_1 means that the input value of the time step is used). Normally it is very small (Eqs. 514-515, Fig. 510).

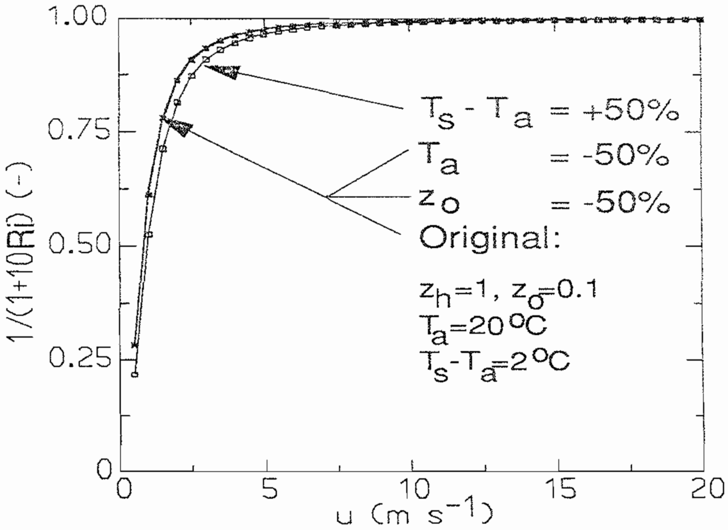


Figure 510. The relative modification of r_a as function of wind speed for different values on the Richardson number. *Relativa ändringen i aerodynamiskamotståndet som funktion av vindhastigheten för olika värden på Richardsontalet.*

The aerodynamic resistance (r_a) is inversely proportional to the wind speed (u) measured at height (z_h). Then, in the original version of the model, r_a is also a function of the leaf area (Eq. 337). An alternative method is to let r_a be a function of characteristic heights of the stand. r_a decreases with the roughness height (z_o) and the height at which the logarithmic wind profile (derived for the conditions above the canopy) yields a wind speed equal to zero (z_d) (Eq. 516) (Fig. 511).

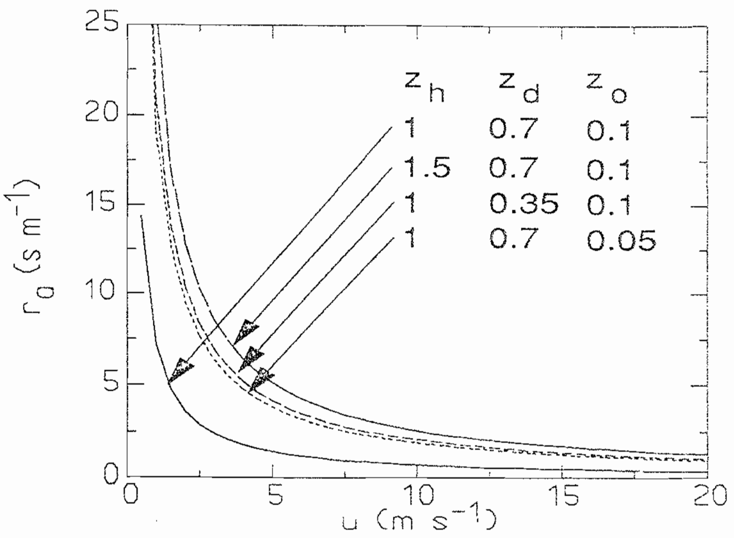


Figure 511. Aerodynamic resistance as function of wind speed. *Aerodynamiskamotståndet som funktion av vindhastigheten.*

The height above ground for the wind speed measurements (z_h) can be placed in proportion (a_h) to the above-ground biomass ($W_{ls}+W_g$). The displacement height (z_d) and the roughness height (z_o) used for calculating the aerodynamic resistance can, in their turn, be proportional to z_h (a_d and a_o, respectively). Using these last relationships, however, implies that the aerodynamic resistance is affected by z_h only through the Richardson number (Eqs. 517-519).

In the original version of the model the aerodynamic resistances for heat and vapour are given equal values. The resistance for heat (r_{aH}) could, however, be divided by a factor (a_{ra}) as compared to that for vapour (r_a) (Eq. 519a).

$$r_r(W_r) = r_r/(a_{rr}W_r) \qquad (^*510)$$

$$r_s = \min\,(r_s(R_s)\,,\, r_s(\psi_c)\,,\, r_s(R_s,\Delta e)) \qquad r_{sMin} \leq r_s \leq r_{sMax} \qquad (^*511)$$

where:

$$r_s(R_s,\Delta e) = r_{sMin}(b_L\Delta e+1)(R_s+a_L)/(R_s) \qquad \text{if switch=1} \qquad (512)$$

$$= (a_v+b_v\Delta e+c_v(R_s/100)^2) \qquad \text{if switch=-1} \qquad (^*513)$$

$$r_a = r_a/(1+10Ri) \qquad (514)$$

where:

$$Ri = g(z_h-z_o)(T_s(t_1)-T_a)/((T_a+273.15)u^2) \qquad (515)$$

$$r_a = \frac{\ln^2((z_h-z_d)/z_o)}{a_k^2 u} \qquad (516)$$

where:

$$z_h = a_h(W_{ls}+W_g) \qquad (^*517)$$

$$z_d = a_d z_h \qquad (518)$$

$$z_o = a_o z_h \qquad (519)$$

$$r_{aH} = r_a/a_{ra} \qquad (519a)$$

5.2 Other functions

The net radiation above canopy (R_{no}) should be an input variable. However, this variable is often lacking and then it can be estimated from the global radiation above canopy (R_s) (Eq. 520).

The maximum amount of easily available plant water (V_{Max}) is proportional to the leaf area index (A_{li}). However, with three coefficients (a_V, b_V and c_V) this dependency can be altered. For instance, for a large tree a high fraction of the water reservoir can be located in the stems and then it is possible to put V_{Max} in proportion to the leaf+stem biomass (W_{ls}) or to give it a high offset value (c_V) (Eq. 521).

$$R_{no} = a_R R_s - b_R \tag{520}$$

$$V_{Max} = a_V(V_o A_{li} + b_V W_{ls}) + c_V \tag{*521}$$

6 ANALYTICAL INPUT VARIABLES

Most of the input weather variables to the SPAC-GROWTH model need to be given at a time scale of minutes. However, in many cases only synoptic or daily values are available. Then the model can be applied by estimating minute values of the input variables from the daily values. The daily values needed are: (i) the daily maximum and minimum air temperature (for air temperature), (ii) relative air humidity at three time points a day and minute values of air temperature (for relative air humidity), (iii) daily sum of global radiation or the ratio between this variable and the daily sum of global radiation below the clear sky (for global radiation), (iv) daily mean value of the wind-speed (for wind-speed) and (v) daily sums of precipitation (for precipitation).

The methods used for estimating the analytical variables of temperature and humidity have been described by Eckersten (1986b) and for parts of the radiation routines by Eckersten (1985), whereas the other methods are presented for the first time here. Using the routines of this section means that errors will be introduced in the plant water and growth simulations as a consequence of errors in the estimates of the analytical input variables. This effect has been examined by Eckersten (1985 and 1986b) for temperature, humidity and radiation, showing that the analytical input variables works fairly well for daily outputs. The estimates of temperature and humidity also work well for within-day simulations.

6.1 Temperature

Air temperature (T_a) is estimated from daily values of maximum (T_x) and minimum (T_n) air temperatures. Temperature is a sinusoidal function of time during the day, while it decreases exponentially during the night. In order to prevent an unrealistic increase of temperature during night, the sinusoidal function of the day is divided into two parts. In the first part of the day, the minimum temperature of the last night is used, while for the second part we use the value of the following night.

The "day", from sunrise (t_r) to the sunrise on the following day (t_{r+}), is divided into three parts: (i) from t_r to the time for maximum temperature (t_x), (ii) from t_x to the time for sunset (t_s) and (iii) from t_s to t_{r+}. During the first period T_a shows a sinusoidal increase over time (t) normalized with respect to the daylength (Y), from its minimum to its maximum value. Then, T_a starts to decrease in much the same way as it increased, however, with the amplitude determined by the difference between the maximum temperature of this day and the minimum temperature of the following day (T_{n+}). For the third period, T_a decreases exponentially over the time normalized with respect to the night length (Z), from the temperature at sunset (T_{as}) to T_{n+}. b_T is the parameter that regulates the rate of decrease (Eqs. 610-616, Fig. 610).

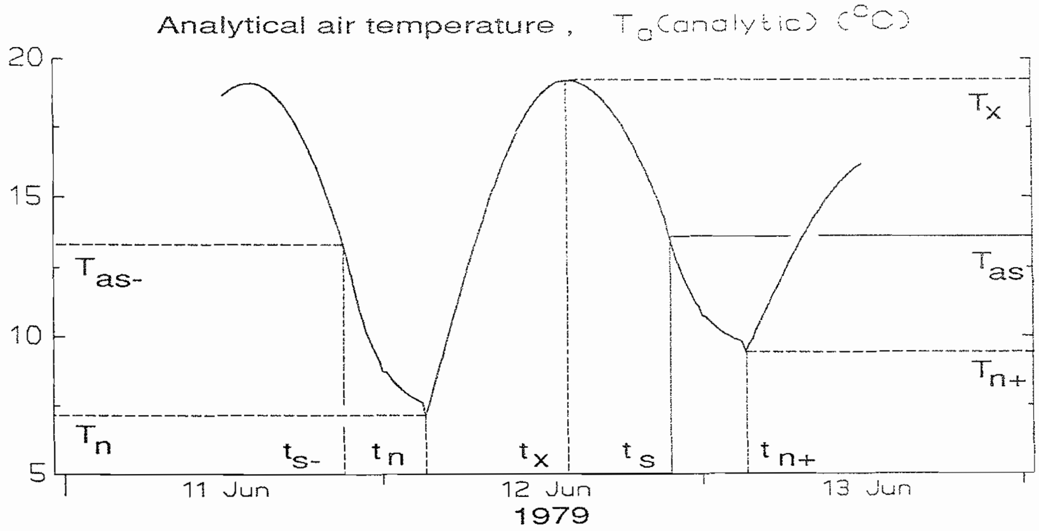


Figure 610. Analytical air temperature during three days. *Analytisk lufttemperatur för tre dagar.*

$$T_a = T_n+(T_x-T_n)\sin(\pi t'/(Y(1+2a_T))) \qquad t_r \le t < t_x \tag{610}$$
$$T_a = T_{n+}+(T_x-T_{n+})\sin(\pi t'/(Y(1+2a_T))) \qquad t_x \le t < t_s \tag{611}$$
$$T_a = T_{n+}+(T_{as}-T_{n+})\exp(-b_T(t'-Y)/Z) \qquad t_s \le t < t_{r+} \tag{612}$$

where:

$$t' = t-t_r \tag{613}$$
$$Y = t_s-t_r \tag{614}$$
$$Z = t_{r+}-t_s \tag{615}$$
$$a_T = (t_x-12)/Y \tag{616}$$

6.2 Humidity

Minute values are estimated from synoptic values of the relative air humidity by first determining the absolute air humidity (weight per volume) which is much better suited for linear interpolation over time than relative air humidity. Then, together with minute values on air temperature, the relative air humidity can be calculated from the interpolated values on absolute air humidity.

Using the values of relative air humidity ($h_a(i)$) for three fixed time points during the day (t_1, t_2, t_3) and the corresponding air temperature values ($T_a'(i)$, Kelvins) from equations 610-616, the absolute humidity ($w(i)$) can be calculated for each time point and also the last time point on the previous day (t_{3-}) and the first of the following day (t_{1+}). It is also necessary to estimate the saturated vapour pressure of the air (e_d) (Eqs. 620 and 621).

The absolute humidity of each minute (w) can be estimated by linear interpolation over time between the different values of $w(i)$. Knowing also the minute values of the temperature (T_a'), the relative air humidity for every minute (h_a) is determined. The ratio (a_w) between the molecular weight for vapour (m_v) and the universal gas constant (R_u) is taken as constant (Eqs. 622 and 624) (Fig. 620).

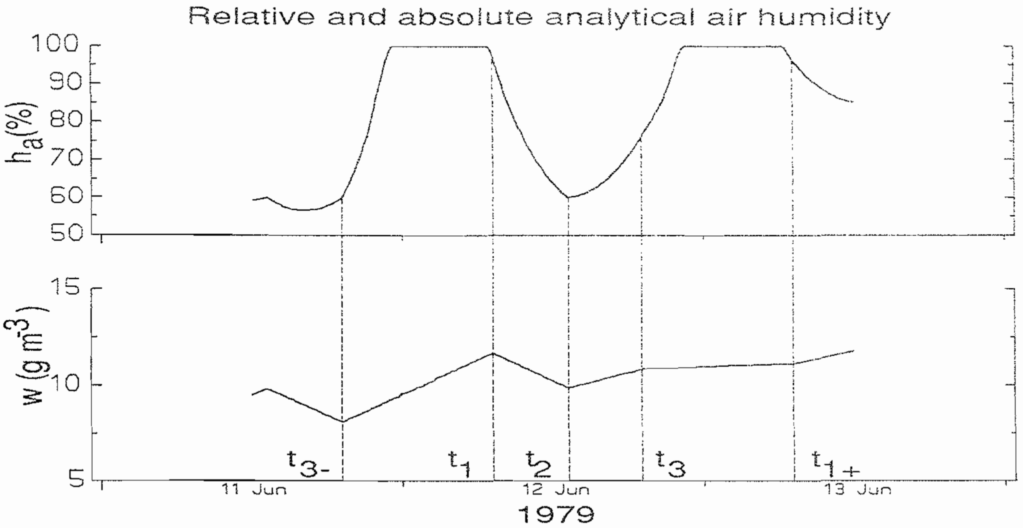


Figure 620. Analytical air humidity during three days. *Analytisk luftfuktighet för tre dagar.*

$$w(i) = a_w h_a(i) e_d(i) / T_a'(i) \qquad i = t_{3-}, t_1, t_2, t_3, t_{1+} \qquad (620)$$

where:

$$e_d = a_e \exp((b_e T_a' - c_e)/(d_e T_a' - e_e)) \qquad (621)$$

$$h_a = w T_a' / (a_w e_d) \qquad (622)$$

where:

$$T_a' = T_a + 273.15 \qquad (623)$$

$$a_w = 100 m_v / R_u \qquad (624)$$

6.3 Radiation

Daily sums of global radiation (300-3000 nm) above canopy ($\Sigma_{Day}R_s$) are converted into minute values (R_s) by firstly determining the radiation for a typical clear and overcast day, respectively. The radiation below the clear sky (R_{sCl}) is calculated from the solar constant (S_o, which is a function of day-number (t)), the solar elevation (β) and a parameter related to the air turbidity (g_s). The radiation for the overcast condition (R_{sOv}) is a fraction (g_o) of R_{sCl} (Eqs. 633-634 and 637).

Assuming the cloudiness to be uniformly distributed over the day, the "mean radiation" at each minute (R_{sM}) equals the ratio (D) between the daily sums of R_s and R_{sCl}. Cloudiness variations for periods within the day are simulated allowing the estimated actual radiation to vary (ΔR_s) around the "mean radiation", using a very simple model that preserves the daily total of R_s. ΔR_s has a sinusoidal variation over time (t, hours) with a certain frequency (g_f). The amplitude of ΔR_s equals a factor (g_d) times the difference between the "mean radiation" and R_{sCl} or R_{sOv}, depending on which one is the closest (Eqs. 630-632 and 635-636) (Fig. 630).

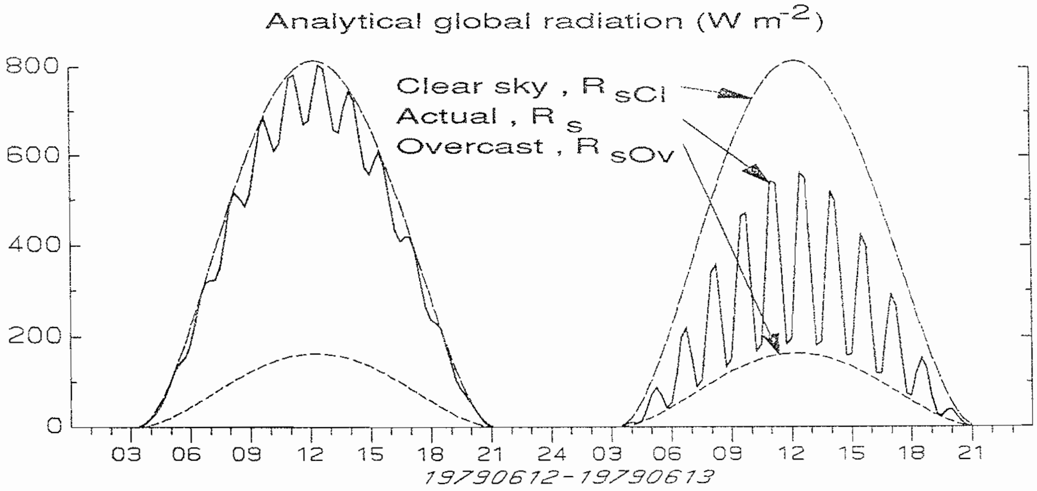


Figure 630. Analytical solar radiation during two days. *Analytisk solstrålning för två dagar.*

$$R_s = R_{sM}+\Delta R_s \qquad (^*630)$$

$$R_{sM} = D\Sigma_{Day}(R_{sCl}) \qquad (631)$$

$$D = \Sigma_{Day}(R_s)/\Sigma_{Day}(R_{sCl}) \qquad (632)$$

$$R_{sCl} = S_o \sin^2\beta/(\sin\beta+g_s) \qquad (633)$$

$$\begin{aligned} S_o = {} & 1353+45.326\cos(xt)+0.88018\cos(xt) \\ & -0.00461\cos(xt)+1.8037\sin(xt) \\ & +0.09746\sin(2xt)+0.18412\sin(3xt) \end{aligned} \qquad x=2\pi/366 \qquad (634)$$

$$\Delta R_s = A_R\sin(g_f 2\pi t) \qquad (^*635)$$

$$A_R = g_d \min(R_{sCl}-R_{sM}\ ,\ R_{sM}-R_{sOv}) \qquad (^*636)$$

$$R_{sOv} = g_o R_{sCl} \qquad (637)$$

6.4 Other variables

Two very simple approaches for calculating wind speed and precipitation are presented here. Wind speed is assumed to be low during the night and high during the day. This variation is more pronounced when the wind is mainly influenced by local conditions. When larger weather systems determine wind speed then smaller diurnal variations appear. Here I have assumed the latter situation to be positively correlated with the average wind speed. Records on daily precipitation are converted to a constant precipitation rate assuming a certain duration of the rainfall.

Input data on wind speed are given as a short time (about 10-minutes) average at time t_u. Minute values of the wind speed (u) are a simple sinusoidal function of time (t, minutes) around the daily mean (u_m). Maximum wind speed occurs at midday and minimum at midnight. The amplitude is a fraction (A_u) of u_m that decreases linearly from unity for low daily wind speeds to zero for u_m higher than parameter u_{Amp}. u_m is calculated from the information on $u(t_u)$ and the diurnal variation of u (Eqs. 640-644).

To prevent a discontinuity occurring in u at midnight, because of different mean wind speeds of adjacent days, a correction term u_{Corr} is introduced. This term affects u from midnight to the time for input variable (t_u). The non-corrected value for the wind speed at midnight ($u_{Nocorr}(0)$) is then corrected so as to yield the corresponding value calculated for the previous day ($u_{Yest}(1440)$). The correction term thereafter decreases linearly over time and is zero at time t_u (Eq. 645, see Fig. 721d in the section on Input & Output variables).

Precipitation is given as a daily sum ($\Sigma_{Day}F_P$). By defining times for start and stop of rainfall (t_P and t_D) the daily sum of precipitation is converted into a rainfall of constant rate (F_P). Note that minute values are used here (Eqs. 646-647).

$$u = u_m(1+A_u\sin(2\pi t/1440-\pi/2))+u_{Corr} \qquad (^*640)$$

where:

$$A_u = 1-u_m/u_{Amp} \qquad \geq 0 \qquad (^*641)$$

$$u_m = x\pm(x^2-u(t_u)u_{Amp}/y)^{0.5} \qquad (^*642)$$

$$x = u_{Amp}(1+1/y)/2 \qquad (^*643)$$

$$y = \sin(2\pi t_u/1440-\pi/2) \qquad (^*644)$$

$$u_{Corr} = (u_{Yest}(1440)-u_{Nocorr}(0))(t_u-t)/t_u \qquad (^*645)$$

$$F_P = (\Sigma_{Day}F_P)/t_D \qquad \text{if } t\geq t_P \text{ and } \Sigma_{Acc}F_P\leq\Sigma_{Day}F_P \qquad (^*646)$$

$$F_P = 0 \qquad \text{otherwise} \qquad (^*647)$$

7 SIMULATION EXAMPLES

Here the input and output variables of two simulation examples are presented. All input variables are shown, except two: the soil water potential and the leaf nitrogen concentration. However, we have assumed a very high soil water potential (i.e. no soil water limitations) and maximum leaf nitrogen concentration (i.e. no nitrogen stress). Where a variable is denoted as artificial this means that the values are not measured but instead are chosen arbitrarily. Hence, the examples do not fully represent a special observed case. Instead they aim at presenting the variables needed by the model and which the model can calculate. For explanation of symbols, reference should be made to the List of symbols.

7.1 Example 1: Minute input variables

The first example represents the most common type of simulation with the model and simulates the water flows in a *Salix viminalis* stand during a three-day period in August 1989 at Uppsala. The leaf area index was about 2.5.

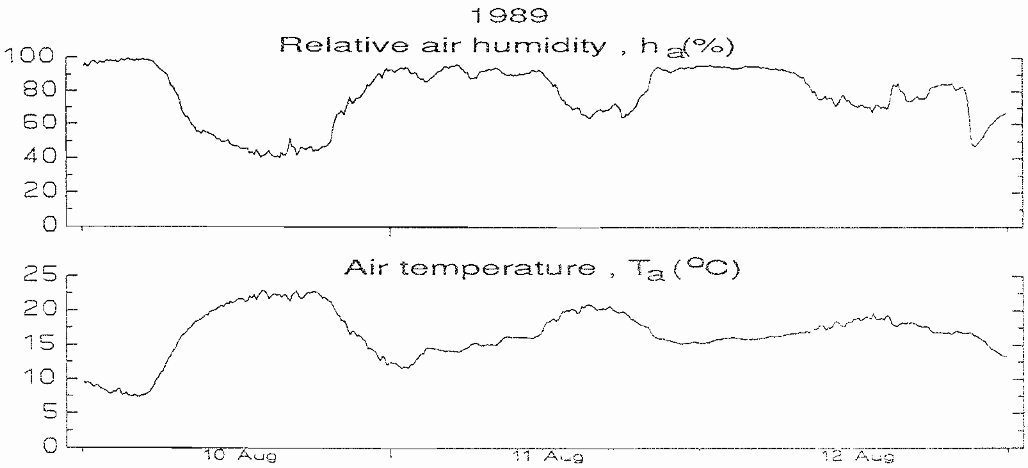
Parameters are presented in the same way as they appear in the program of the model. The units are given in the list of symbols (Table 710).

Table 710. Parameter values used in simulation example 1. Explanation of symbols and their units are given in the List of symbols. *Parametervärden använda i simuleringsexempel 1.*

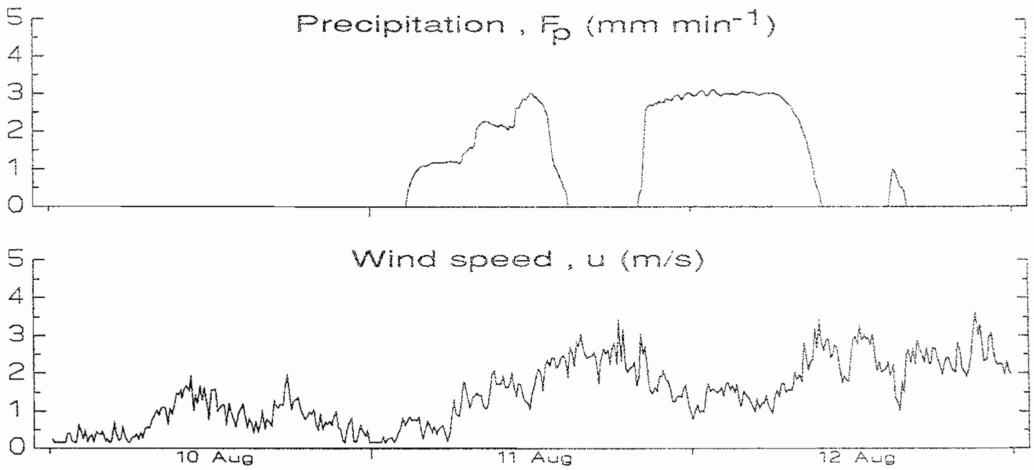
Parameter	Value	Parameter	Value	Parameter	Value
START					
Δ_{Max}	0.1				
$\Delta\psi_{cMax}$	0.08				
δt	3				
δT_{so}	25	T_{so}	-10		
δA_{li}	0.5				
Latitude	59.8				
$A_{li}(t_o)$	2.5				
PLANT WATER					
ψ_{cMin}	-2.7	ψ_{cMax}	0.0		
V_o	100				
RESISTANCE; STOMATA					
r_{sMin}	40	r_{sMax}	1000		
a_c	0.157	b_c	0.02144		
c_c	0.001118	d_c	2.617e-005	e_c	2.301e-007
a_r	0.001384	b_{rr}	-2.012e-005	c_r	4.216e-007
R_{sMin}	30				
RESISTANCE; OTHER					
r_{po}	16				
a	1.62	b	4e-005	n	2.1
a_{Li}	40	b_{Li}	4		
INTERCEPTION					
k_p	0.2				
V_{Io}	1000				
GROWTH					
b_{io}	0.048	b_{i1}	0.0064		
b_{rMin}	0.15				
k	0.5				
n_{lMax}	0.05				
$a_\tau(\Delta e)$	0.014	$b_\tau(\Delta e)$	0.01		

The input variables were 10-minute values of relative air humidity, air temperature, precipitation, wind speed, global radiation and net radiation above the canopy (Figs. 710a-f).

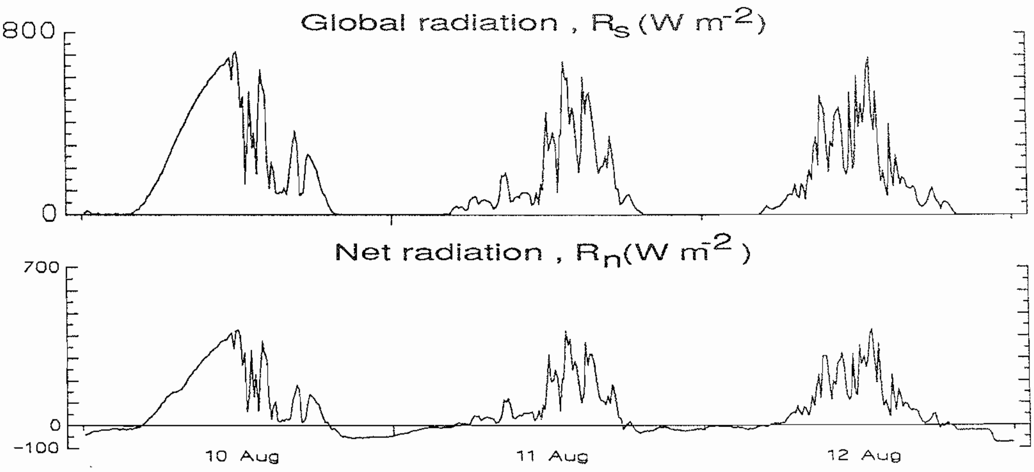
a, b



c, d

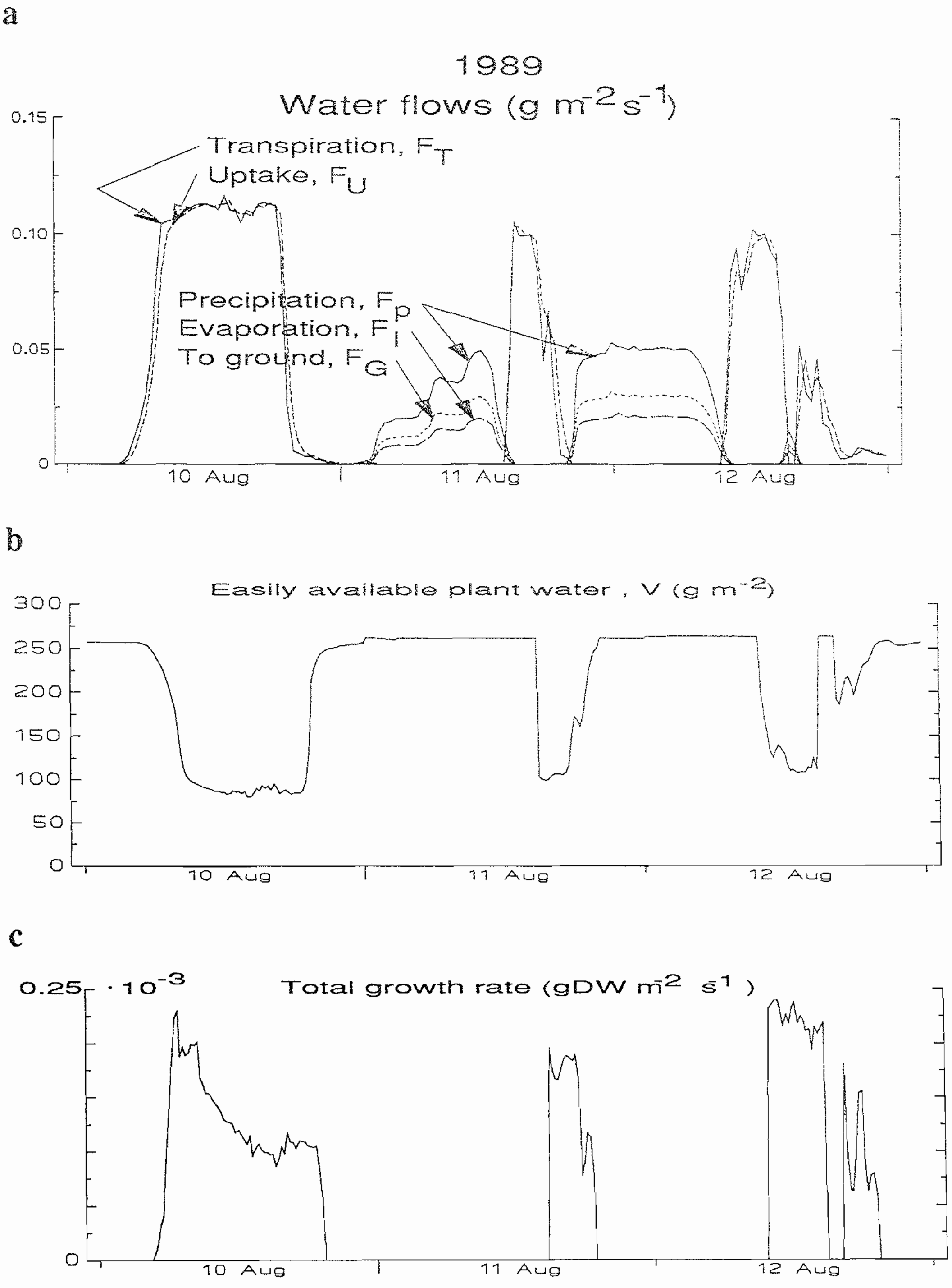


e,f



Figures 710a-f. Input variables to water flow and growth simulation of example 1. Precipitation data is artificial.
Indata till vattenflödes och tillväxtsimuleringarna i exempel 1. Nederbördsdata är inte verkliga.

The output variables selected are those represented in the schematic description of the water submodel (Fig. 200). The transpiration created a shortage of water in the plant which then creates a root uptake. When precipitation starts to fall the transpiration stops. Only a smaller fraction of the rain is intercepted on the canopy and evaporated. The rest falls to the ground (Fig. 711a). The plant water decreases during day-time but increases to its maximum value during the night or during rainfall (Fig. 711b). The total growth rate increases with transpiration rate but decreases with dry air (Fig. 711c).



Figures 711a-c. Output variables from water flow and growth simulation of example 1. *Utdata från vattenflödes och tillväxtsimuleringarna i exempel 1.*

7.2 Example 2: Daily input variables

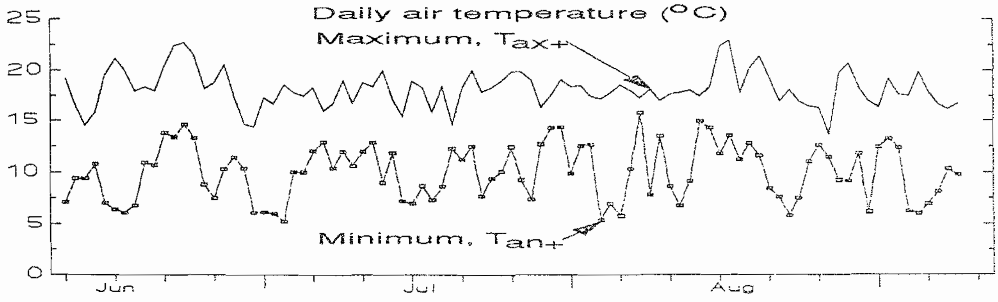
The second example is similar to the first one except that the simulation is made over a three-month period instead of three days. For this rather long period, synoptic values were the only input weather variables available. The synoptic variables were used to create minute values for the weather variables which then could be used for the water and growth simulations similar to those of the first example (see above). Since no synoptic data were available for net radiation it was calculated as a linear function of the global radiation (Eq. 520). Compare to the previous example plant growth was now simulated over a longer period comprising the grain development.

Several parameter values in addition to those of example 1 were needed for the simulation. Most parameters, however, are related to the situation at the day for the start of simulation (t_o). The reason why they are not included among the input variables is purely technical (Table 720).

Table 720. Parameter values used in simulation example 2 in addition to those of Table 710. Explanations of symbols and their units are given in the List of symbols. *Parametervärden använda i simuleringsexempel 2 som ej finns medtagna i Tabell 710.*

Parameter	Value	Parameter	Value	Parameter	Value
START					
δt	15				
$i_g(t_o)$	0.25				
$W_t(t_o)$	100				
a_R	-23.0	b_R	0.649		
PLANT WATER					
V_o	50				
RESISTANCE; OTHER					
a_{rp}	0.1				
INTERCEPTION					
k_{Pg}	0.0002				
GROWTH					
b_g	0.2				
a_g	0.0252	b_{gg}	0.153	c_g	3.51
d_g	0.301	e_g	9.154		
ANALYTIC; START					
$h_a(t_1, t_o)$	94	$h_a(t_2, t_o)$	60	$h_a(t_3, t_o)$	60
$h_a(t_3, t_o\text{-}1)$	41				
t_1	7	t_2	13	t_3	19
$F_P(t_o)$	0				
$R_s(t_o)$	26.5	$\Sigma_{Day}R_{sCl}(t_o)$	26.5		
$T_n(t_o)$	9	$T_{as}(t_o\text{-}1)$	19.9	$T_x(t_o)$	19.1
$t_s(t_o)$	20.5				
t_u	720	$u(t_u, t_o)$	1		
ANALYTIC					
t_D	60	t_p	600		
g_d	1				
g_f	12	g_o	0.2	g_s	0.25
a_T	0.1	b_T	2.6		
u_{Amp}	10				

The input variables during 1979 were daily values of maximum and minimum air temperatures, relative air humidity at 7.00, 13.00 and 19.00 local time, ratio between sums of actual and potential global radiation, mean wind speed and precipitation sum (Figs 720a-g).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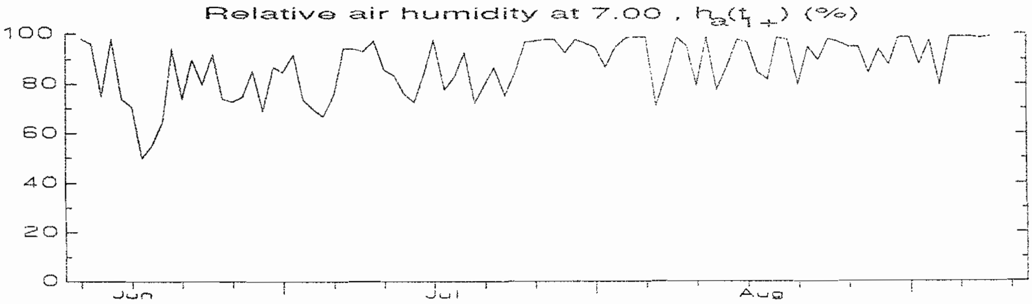
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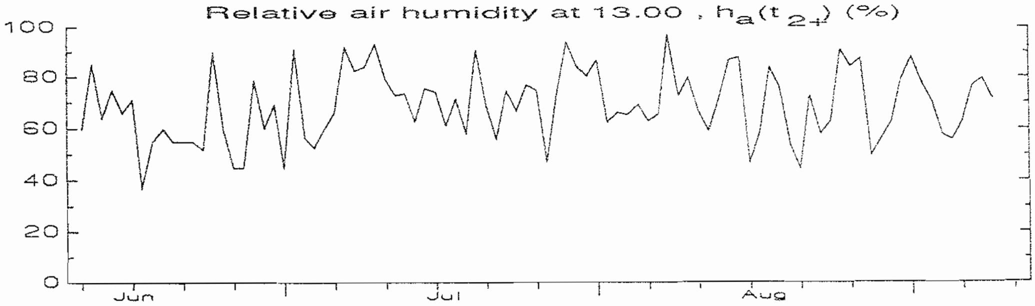
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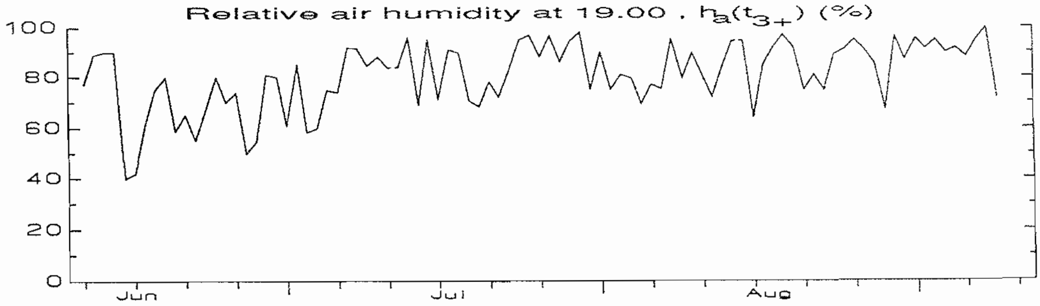
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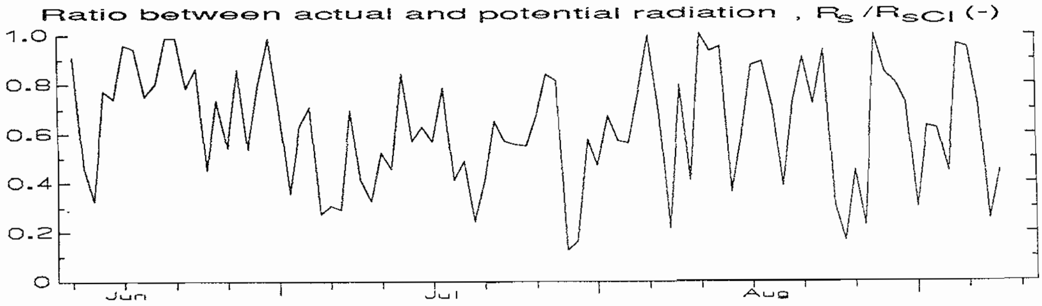
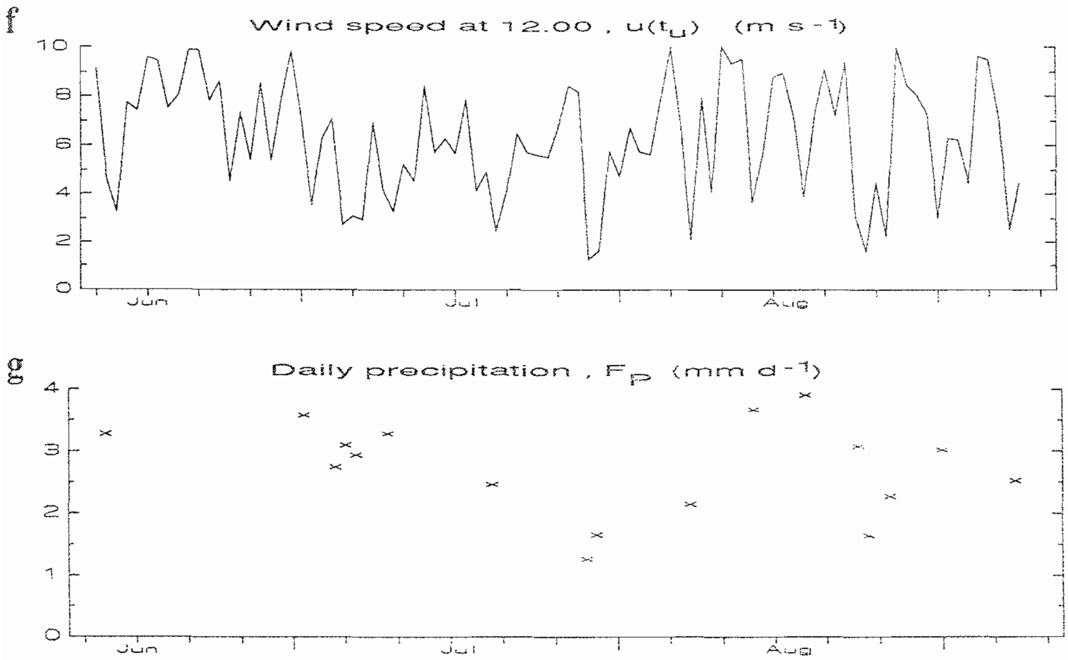
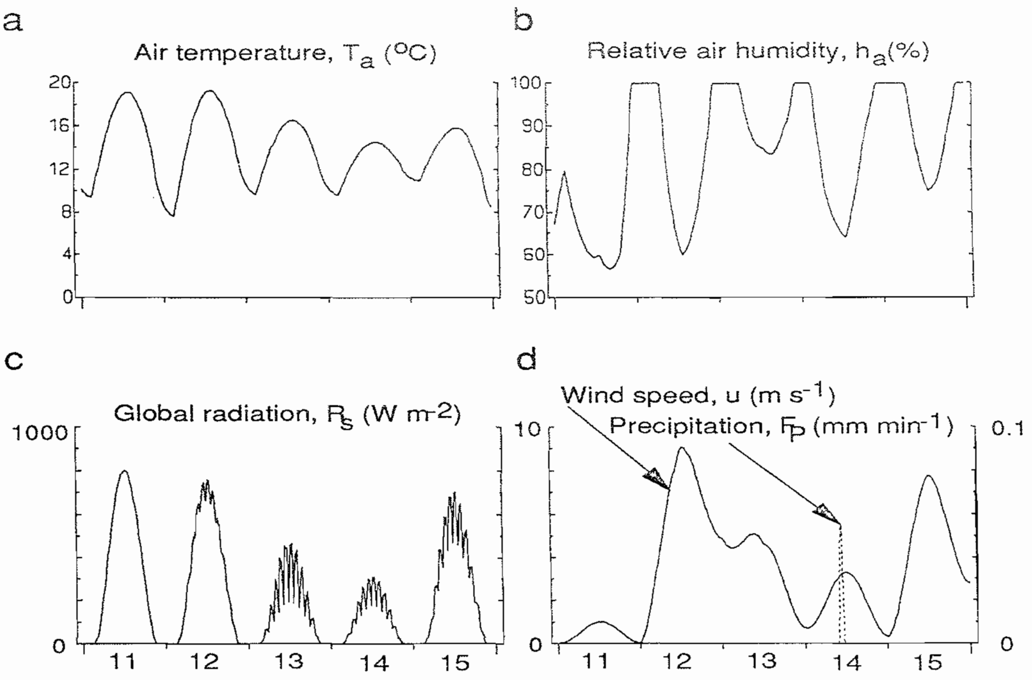

e



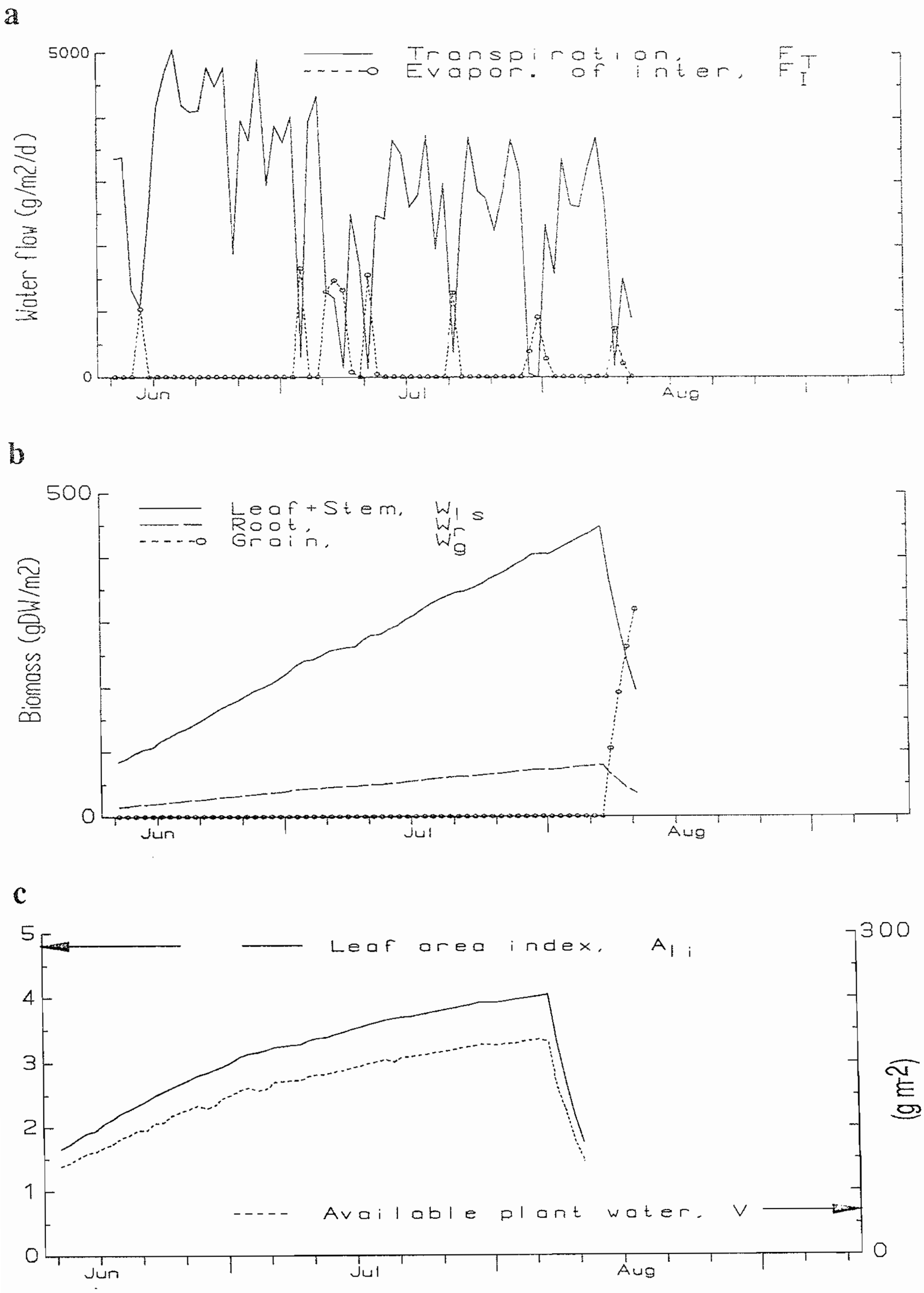
Figures 720a-g. Input variables to calculations of analytical weather variables for simulation example 2. Wind speed and precipitation data are artificial. *Indata till beräkningarna av analytiska väderdata för simuleringsexempel 2. Vindhastighets och nederbördsdata är ej verkliga.*

The analytical weather variables were calculated for every 15-minutes during the whole three-month period in 1979 although only five days (11 to 15 June) are shown in the figures below (Figs 721a-d).



Figures 721a-d. Analytical weather variables calculated by the model and used as input to the water flow and growth simulations of example 2. *Analytiska väderdata beräknade av modellen som sedan används som indata till vattenflödes och tillväxtsimuleringarna i exempel 2.*

Using the analytical weather variables shown in Figs. 721a-d as input, the transpiration and evaporation of intercepted water was simulated for every third minute during the summer of 1979. These flows were summed up to daily values (Fig. 722a). The accumulated growth of leaf plus stem and root biomass increased until the grain development started (Fig. 722b). The leaf area development and the water reservoir at midnight (which was always at maximum at that time; Fig. 722c) were similar since the latter is proportional to the leaf area.



Figures 722a-c. Output variables for the water flow and growth simulations of example 2. *Utdata från vattenflödes och tillväxtssimuleringarna i exempel 2.*

8 LIST OF SYMBOLS

Symbols used only in the subroutine of analytical input variables are followed by the notation (A).

Symbol	Description	Unit	Equation
ψ_c	Canopy water potential	MPa	311,312,333, 334
ψ_s	Soil water potential	MPa	311,330
ψ_{cMin}, ψ_{cMax}	Minimum and maximum canopy water potential	MPa	312
$\Delta\psi_{cMax}$	Maximum allowed change of ψ_c from one iteration to another for accepting the water balance.	MPa	-
ρ	Specific density of moist air (=1.2047)	kg m^{-3}	313,321
γ	Psychrometric constant (=67)	Pa K^{-1}	313
λ	Latent heat of water vaporisation (=2.4518 10^6)	J kg^{-1}	313,320
δ	Generally used for a difference during a time step	-	
Δ_{Max}	Maximum allowed deviation in canopy energy balance	W m^{-2}	320
δA_{li}	Leaf area index of canopy internal layers	-	332,336
Δe	Vapour pressure difference between the air inside stomata cavities and the air above canopy	hPa	401,512,513
δT_{so}	Initial increment of temperature for surface heat balance calculations	°C	-
τ	Water use efficiency (Total growth divided by transpiration)	gDW gH_2O^{-1}	400,401
τ_{Max}	Maximum water use efficiency	gDW gH_2O^{-1}	401
ΔR_s	Variations around the analytical "mean radiation"	W m^{-2} (A)	630,635
β	Sun elevation	rad (A)	
'	Denotes the daily change of the symbol concerned	-	
(in)	Denotes a positive change of the symbol concerned	-	
(out)	Denotes a negative change of the symbol concerned	-	
*	Denotes a fully or partly new equation which does not originate from another publication	-	
a	Coefficient of saturated soil hydraulic conductivity	g m^{-2} s^{-1}	330
a_i, b_i, c_i, d_i, e_i	Coefficient names: i= τ(water use eff.), =c($r_s(\psi_c)$), =d(displacement height), =e(saturated vapour pressure), =h(canopy height), =k(von Karman's constant =0.41), =L(Lohammar eq.), =Li(Lindroth eq.), =o(roughness height), =r($r_s(R_s)$), =R(net radiation), =ra(aerodynamic resistance), =rp(plant resistance), =rr(soil-root resistance), =T(analytic temperature), =v($r_s(R_s,\Delta e)$), =V(plant water), =w(analytic humidity)	differs	323,324,331, 334,335,337, 401,408,510, 512,513,516-521,610,611, 616,620-622, 624
A_{li}	Leaf area per unit ground surface (leaf area index)	-	312,321,337, 341,342,409-411,521
$A_{li}(i)$	Leaf area index accumulated from the canopy top to the top of layer number i	-	336
A_R	Amplitude of the variations around the analytical "mean" radiation	W m^{-2} (A)	635,636
A_u	Factor determining the amplitude of the within day variations of the analytical wind speed	- (A)	640,641
b	Root density resistance factor	MPa	330

b_g	Fraction of biomass in plant tissues translocated to grain	d^{-1}	402,405,407, 411
b_i	Leaf area index to shoot biomass ratio	m^2 gDW^{-1}	-
b_{il}	Coefficient relating A_{li} to above-ground biomass	gDW m^{-2}	410
b_{io}	b_i at unity above-ground biomass	m^2 gDW^{-1}	410
b_r	Fraction of daily total growth delivered to roots	-	402,403,406
b_{rMin}	b_r minimum	-	403
c_p	Specific heat per unit mass of air (=1004)	J kg^{-1} K^{-1}	313,322
D	Ratio between the daily sums of actual global radiation and that of a clear day	- (A)	613,632
e_a	Vapour pressure of the air above canopy	hPa	313,324
e_d	Saturated vapour pressure of the air above canopy.	hPa (A)	620-622
e_s	Saturated vapour pressure of the air inside the stomata cavities.	hPa	313,323
F_G	Flow of water to the ground	g m^{-2} s^{-1}	340,342
F_I	Evaporation rate of intercepted water	g m^{-2} s^{-1}	340,343
F_P	Precipitation rate	g m^{-2} s^{-1}	340,342,646, 647
F_T	Transpiration rate	g m^{-2} s^{-1}	310,313,320, 343,344,352, 400,404
F_{Tp}	Potential transpiration rate	g m^{-2} s^{-1}	404
F_U	Water uptake by roots	g m^{-2} s^{-1}	310,311,352
g	Gravitational acceleration	m s^{-2} (A)	515
g_d	Parameter related to the magnitude of the variations around the analytical "mean" radiation	- (A)	636
g_f	Parameter related to the frequency of the variations around the analytical "mean" radiation	h^{-1} (A)	635
g_o	Ratio between global radiation under an overcast sky and that under a clear sky	- (A)	637
g_s	Radiation parameter related to the air turbidity.	- (A)	633
h_a	Relative air humidity above canopy	-	324,620,622
H	Sensible heat flux from canopy to the air	W m^{-2}	320,322
i	Accumulated, from the top, number of canopy sub-layers	number	332,333,335, 336,620
i_g	Index determining the start of grain development	-	402,405,407, 408,411
j	Number of water balance iteration	number	351,352
k	Radiation extinction coefficient related to leaf area	-	321,336
k_P	Rain interception coefficient related to leaf area	-	341,342
k_{Pg}	Rain interception coefficient related to grain biomass	m^2 gDW^{-1}	341,342
m	Total number of canopy layers	number	332
m_v	Molecular weight for vapour (= 18.016)	g mol^{-1} (A)	624
n	Soil pore size distribution factor	-	330
n_l	Leaf nitrogen concentration	-	401,404
n_{lMax}	Optimal leaf nitrogen concentration	-	401,404
r_a	Aerodynamic resistance	s m^{-1}	313,322,337, 514,516,519a
r_{aH}	Aerodynamic resistance specially for heat	s m^{-1}	519a

r_c	Stomata resistance per unit ground surface	s m^{-1}	313,332,343
Ri	Richardson number	-	514,515
R_n	Canopy net radiation	W m^{-2}	320,321
R_{no}	Net radiation above canopy	W m^{-2}	321,520
r_p	Plant resistance	MPa s m^{2} g^{-1}	311,331
r_{po}	Plant resistance, constant value	MPa s m^{2} g^{-1}	331
r_r	Soil-root resistance	MPa s m^{2} g^{-1}	311,330,510
$r_r(W_r)$	Soil-root resistance as a function root biomass	MPa s m^{2} g^{-1}	510
r_s	Stomata resistance per unit leaf area	s m^{-1}	332,333,511
R_s	Incident radiation intensity (300-3000nm) on a horizontal surface	W m^{-2}	333,335,336, 511-513,520, 630,632
$r_s(\psi_c)$	Sub function of the stomata resistance only dependent on the canopy water potential	s m^{-1}	333,334,511
$r_s(R_s,\Delta e)$	Sub function of the stomata resistance dependent on the radiation and vapour pressure deficit	s m^{-1}	511,512
$r_s(R_s)$	Sub function of the stomata resistance only dependent on the radiation	s m^{-1}	333,335,511
R_{sCl}	Global radiation under a clear sky	W m^{-2} (A)	631-633,636, 637
R_{sM}	Analytical "mean" radiation	W m^{-2} (A)	630,631,636
r_{sMax}	Maximum stomata resistance	s m^{-1}	333,335,511
r_{sMin}	Minimum stomata resistance	s m^{-1}	333,511,512
R_{sMin}	Radiation limit below which the stomata resistance achieves its maximum value.	W m^{-2}	335
R_{sOv}	Global radiation for overcast conditions	W m^{-2} (A)	636,637
R_u	The universal gas constant (=8.314)	J mol^{-1} K^{-1} (A)	624
S_o	Solar constant.	W m^{-2} (A)	633,634
t	Time as seconds from midnight, minutes from midnight, hours from midnight or day-number from January 1	differs	310,340,400, 401,408,610, 611-613,634, 635,640,645, 646
t'	Time since sunrise	min	610-613
t_1	Time at the beginning of a time-step	s	350,352,515
t_2	Time at the end of a time-step	s	350,351
$t_{1+}, t_1, t_2, t_3, t_{3-}$	Time for synoptic values of relative air humidity. The first value of the following day, the first, the second and the third of the present day and the last of the previous day, respectively	h (A)	620
T_a	Air temperature	°C	322,324,408, 515,610,612, 620-623
T_{as}	Analytical air temperature at sunset of the present day.	°C (A)	612
T_{as-}	Analytical air temperature at sunset of the previous day.	°C (A)	-
t_D	Duration of rainfall	min (A)	646
t_g	t at start of grain development	day number	408
T_n	Minimum air temperature of the present day	°C (A)	610
T_{n+}	Minimum air temperature of the following day	°C (A)	611,612
t_o	t at start of simulation	day number	408
t_P	Time for start of rain during the day	min (A)	646
t_r	Time for sunrise of the present day	min (A)	610,613,614

t_{r+}	Time for sunrise of the following day	min (A)	612,615
t_s	Time for sunset	min (A)	611,612,614,615
T_s	Canopy surface temperature	°C	320,322,323,515
T_{so}	Initial temperature for surface heat balance calculations	°C	-
t_u	Time for daily records on wind speed	min (A)	642,644,645
t_x	Time for maximum air temperature	min (A)	610,611,616
T_x	Daily maximum of air temperature	°C (A)	610,611
u	Wind speed above canopy	$m\ s^{-1}$	337,515,516,640,642
u_{Amp}	Upper limit of daily mean wind speed for which daily variations occur	$m\ s^{-1}$ (A)	642,643
u_{Corr}	Correction term for analytical wind speed	$m\ s^{-1}$ (A)	640,645
u_m	Daily mean wind speed above canopy	$m\ s^{-1}$ (A)	640-642
u_{Nocorr}	Analytical wind speed not corrected with u_{Corr}	$m\ s^{-1}$ (A)	645
u_{Yest}	Analytical wind speed calculated for the previous day	$m\ s^{-1}$ (A)	645
V	Easily exchangeable water in the plant	$g\ m^{-2}$	310,312,350-352
V_I	Water intercepted on the canopy surface (per unit ground surface)	$g\ m^{-2}$	340,343,344
V_{IMax}	Maximum water intercepted on the canopy surface (per unit ground surface)	$g\ m^{-2}$	340,341
V_{Io}	Maximum water intercepted on the canopy surface per unit leaf area	$g\ m^{-2}$	341
V_{Max}	Maximum easily exchangeable water in the plant (per unit ground surface).	$g\ m^{-2}$	312,521
V_o	Maximum easily exchangeable water in the plant per unit leaf area.	$g\ m^{-2}$	312,521
w	Analytical absolute air humidity	$g\ m^{-3}$ (A)	620,622
W_g	Grain biomass	$gDW\ m^{-2}$	331,341,342,407,410,517
W_{ls}	Leaf+stem biomass	$gDW\ m^{-2}$	405-407,410,517,521
W_r	Root biomass	$gDW\ m^{-2}$	402,407,510
W_t	Total biomass	$gDW\ m^{-2}$	400,402,406
Y	Day length	h	408,610-612,614,616
Z	Night length	h (A)	612,615
z_d	Displacement height	m	516,518
z_h	Height of reference measurements above canopy	m	515-519
z_o	Roughness height	m	515,516,519

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10 SUMMARY

The theory of the simulation model SPAC-GROWTH is presented. The model simulates transpiration, evaporation of intercepted water and growth for horizontally homogeneous cultivations for either non-woody or woody plants. The description aims to serve as a tool when using the model. Transpiration and evaporation simulations are based on the SPAC (Soil Plant Atmosphere Continuum) concept where the soil water potential and vapour pressure deficit of the air are input variables creating the driving force for water flow. The pathway of water through the system is represented by characteristic resistances. The growth is based on the "water use efficiency" concept and is allocated between leaf+stem, root and grain biomass. The plant size affects the water flow mainly through the leaf area development. The presentation also includes functions for converting daily weather input data to minute values required by the water flow simulations. Two simulation examples show all input needed by the model and some output of the model.

SAMMANFATTNING

Här beskrivs teorin för simuleringsmodellen SPAC-GROWTH. Modellen simulerar transpiration, avdunstning av intercepterat vatten och tillväxt för horisontellt homogena odlingar av såväl icke vedartade som vedartade växter. Beskrivningen är direkt avsedd att fungera som ett hjälpmedel vid användningen av modellen. Transpirations- och avdunstningssimuleringarna grundar sig på SPAC-konceptet (Soil Plant Atmosphere Continuum). Markvattenpotentialen och luftens ångtrycksdeficit är indata som skapar drivkraften för vattenflödet. Vattnets väg genom systemet representeras av karaktäristiska motstånd. Tillväxten grundar sig på "vattenutnyttjande-konceptet" och fördelar sig mellan blad+stam, rot och kärna. Växtens storlek påverkar vattenflödet främst genom utvecklingen av bladyta. Presentationen innehåller också funktioner för konverteringen av dagliga värden på indata av olika vädervariabler till de minutvärden som behövs för vattenflödessimuleringarna. Två simuleringsexempel visar alla indata modellen behöver och några utav de utdata modellen ger.

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