Biomass Production Chain and Growth Simulation Model for Kenaf

QLK5-CT-2002-01729

WP3. Development of the Kenaf growth simulation model

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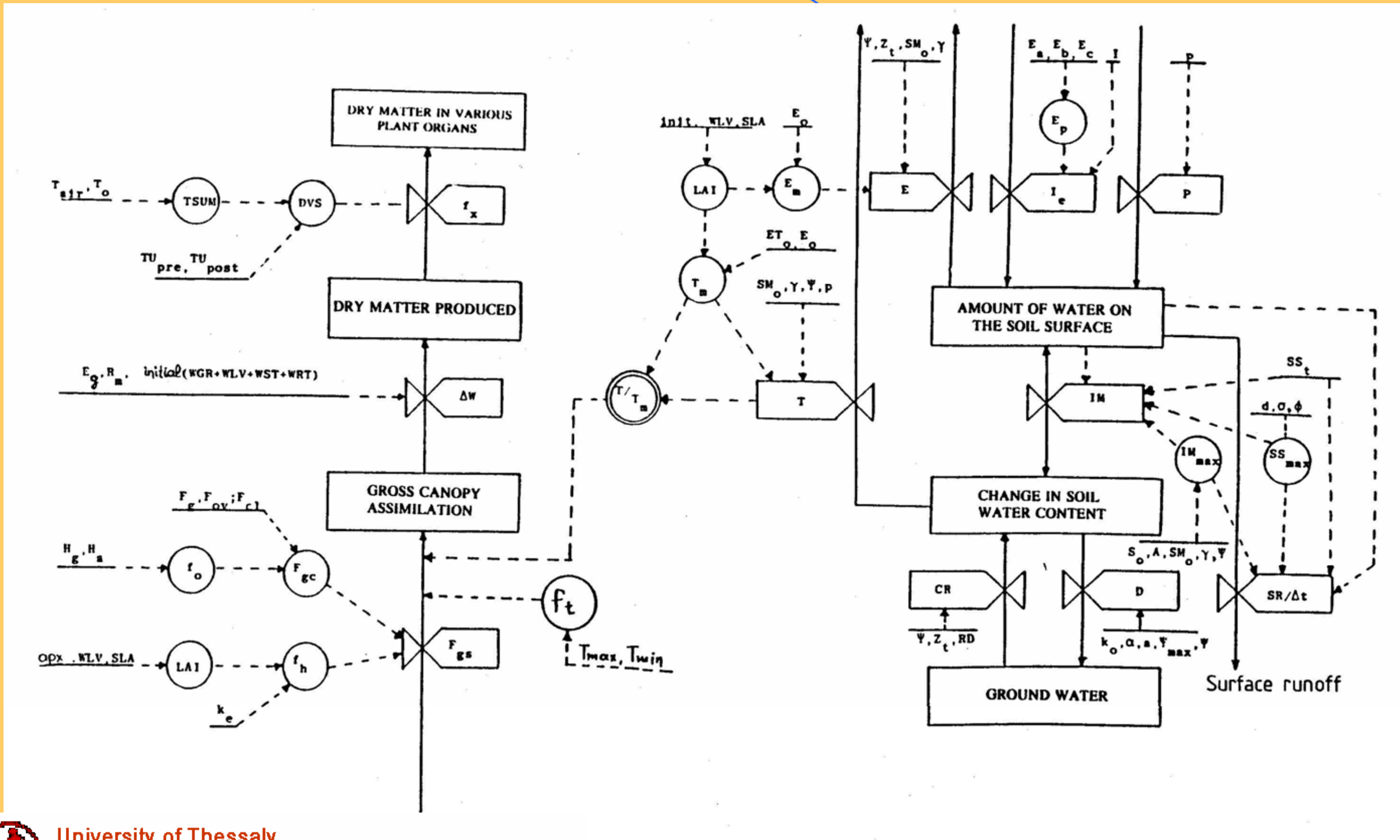
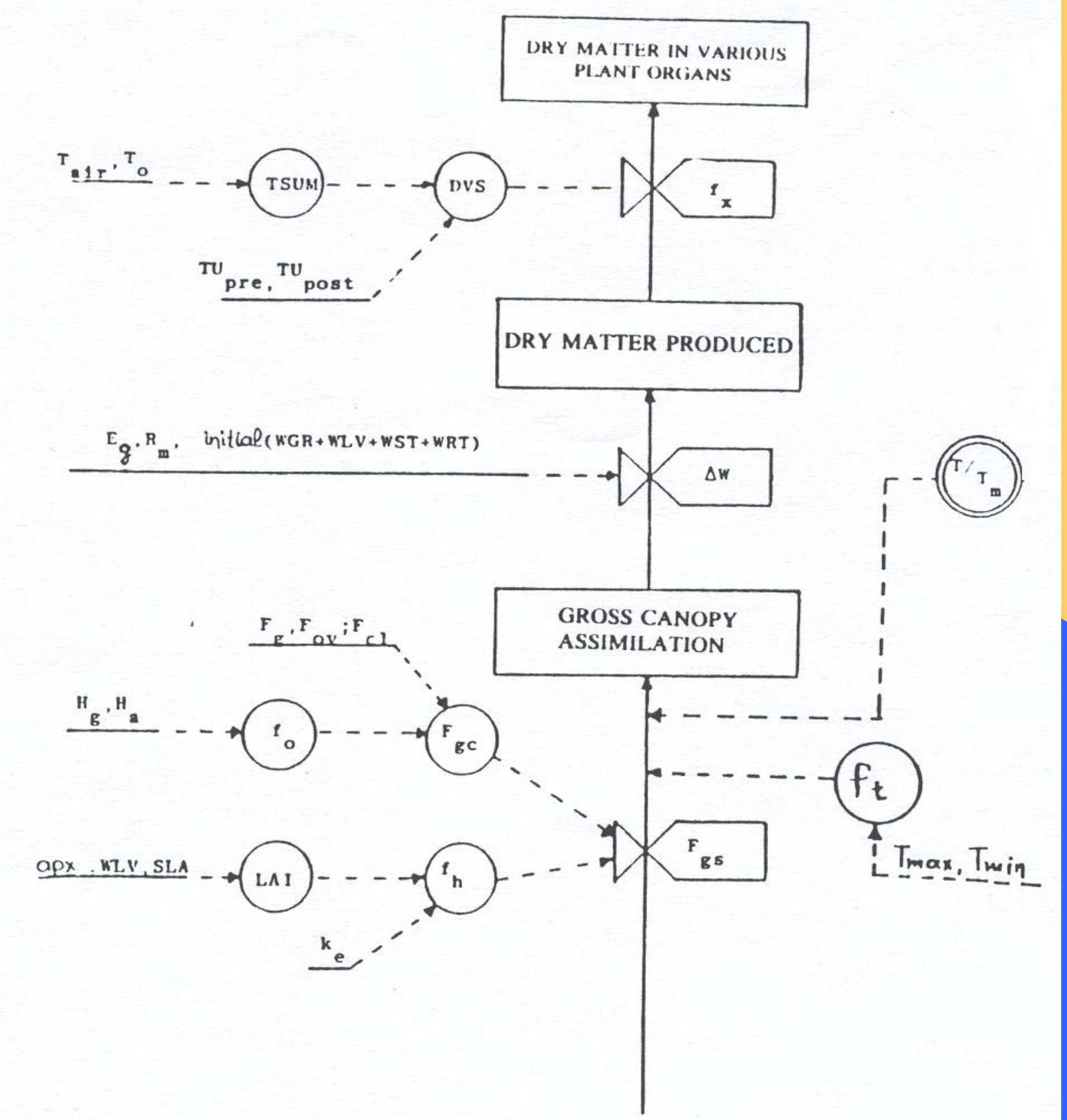
Simplified flow chart of kenaf production during one interval of calculations



Production Situation 1



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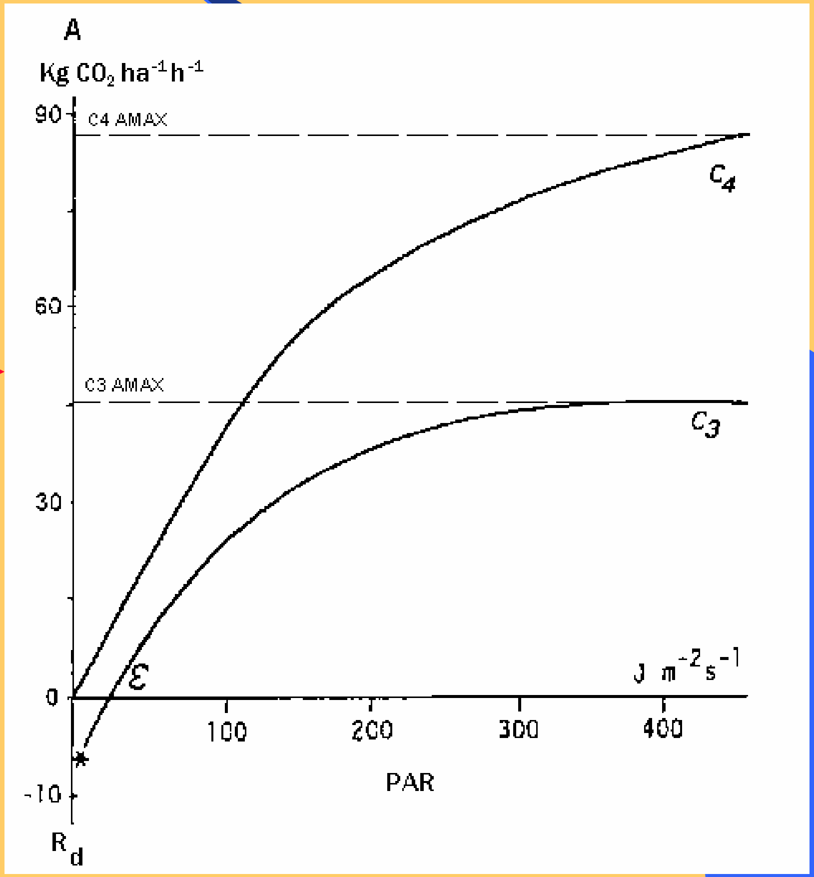
Single leaf assimilation

$A = Amax\ (1 - e^{\varepsilon * PAR/Amax})$



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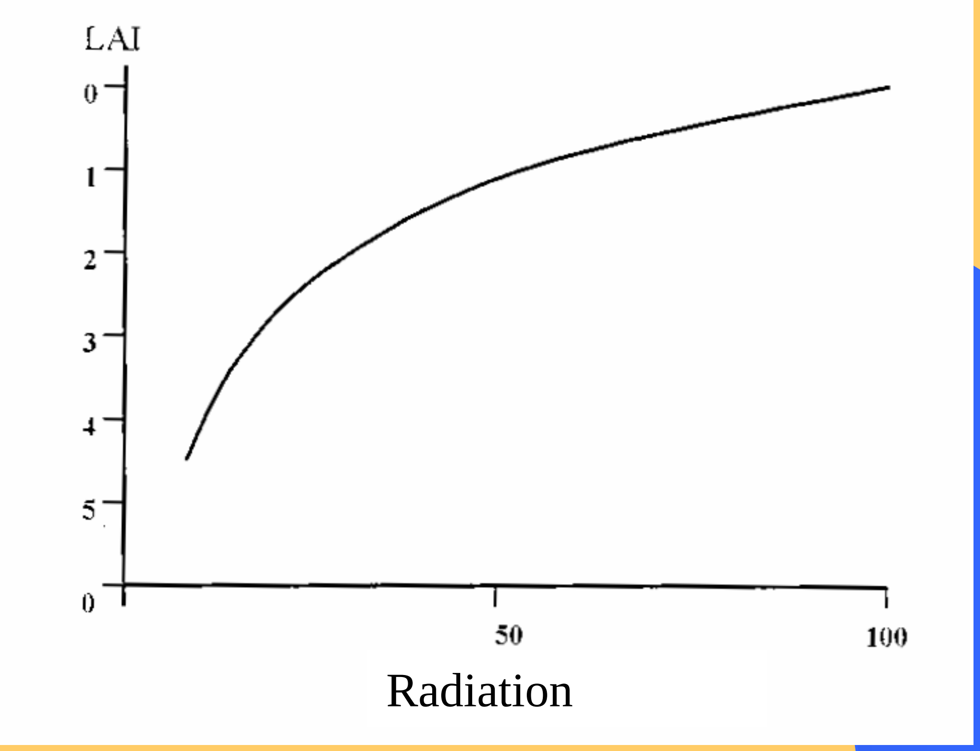
Canopy Assimilation

$$PAR_{ef} = 1 - e^{-kc \times LAI}$$



Canopy Assimilation

- ✓Angle of radiation interception
- ✓Light distribution within the crop canopy
- ✓ Effect of direct and diffuse radiation
- ✓Leaf area (index)
- ✓Leaf angle (extinction coefficient)

Model operations

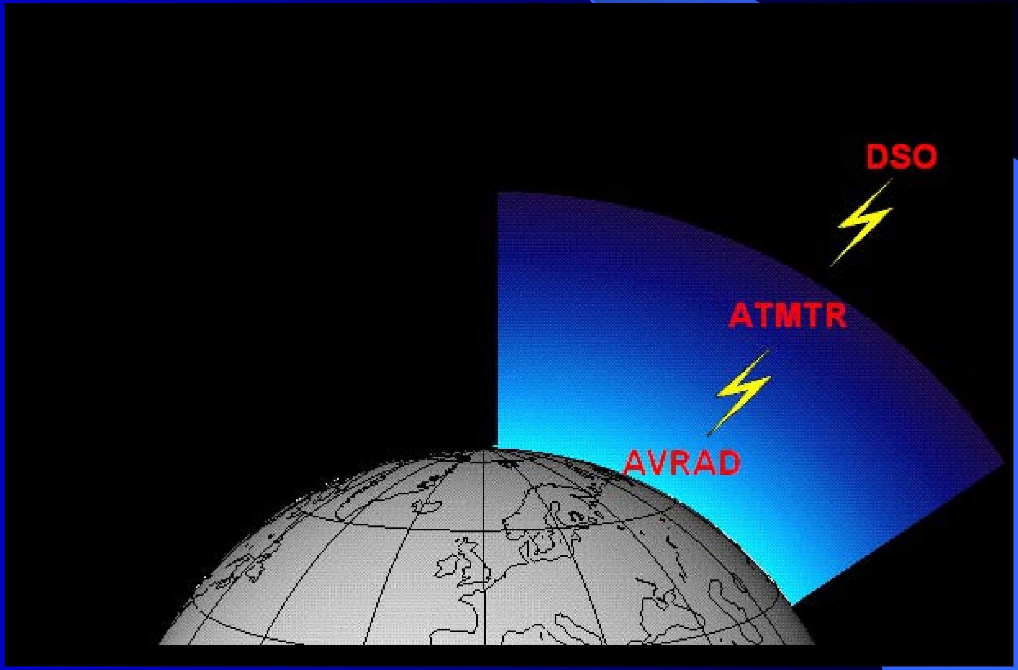
- ✓ Calculation of global radiation
- ✓ Differentiation of direct from diffuse radiation
- ✓ Calculation of PAR
- ✓ Calculation of radiation within the canopy
- ✓ Calculation of gross canopy assimilation rate
- ✓ Calculation of dry mass productivity
- ✓ Dry mass separation to plant organs

Total radiation.
AVRAD ($J\ m^{-2}\ d^{-1}$)

From the total radiation reaching the atmosphere (DSO = 1370 W/m^2), only a part reaches the earth’s surface (AVRAD) according to the value of the atmospheric transmission (ATMTR).

AVRAD = DSO x ATMTR

(300-3000nm)



Direct and diffuse radiation
Coefficient FRDIF

Important improvement of the model comprises the differentiation between of the direct and diffuse parts of the global radiation.

$$\frac{FRDIF}{AVRAD} = 1 \qquad \gamma\iota\alpha \qquad ATMTR < 0.07$$

$$\frac{FRDIF}{AVRAD} = 1 - 2.3(ATMTR - 0.07)^2 \qquad for \qquad 0.07 \le ATMTR < 0.35$$

$$\frac{FRDIF}{AVRAD} = 1.33 - 1.46 \times ATMTR \qquad for \qquad 0.35 \le ATMTR < 0.75$$

$$\frac{FRDIF}{AVRAD} = 0.23 \qquad for \qquad 0.75 \le ATMTR$$

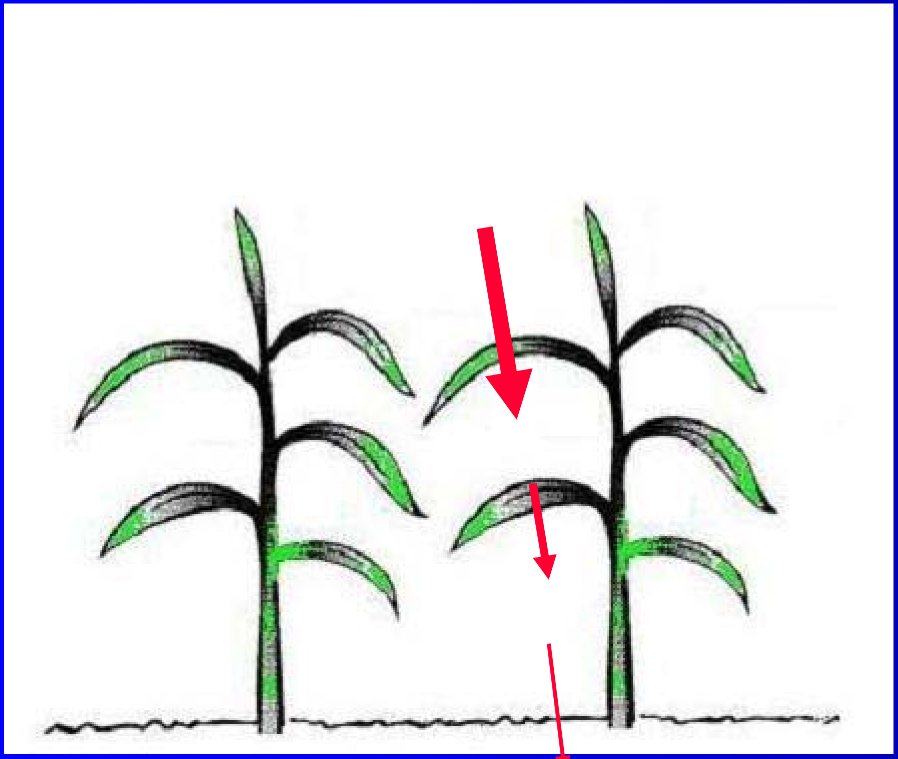
PAR (J m^{-2} s^{-1})

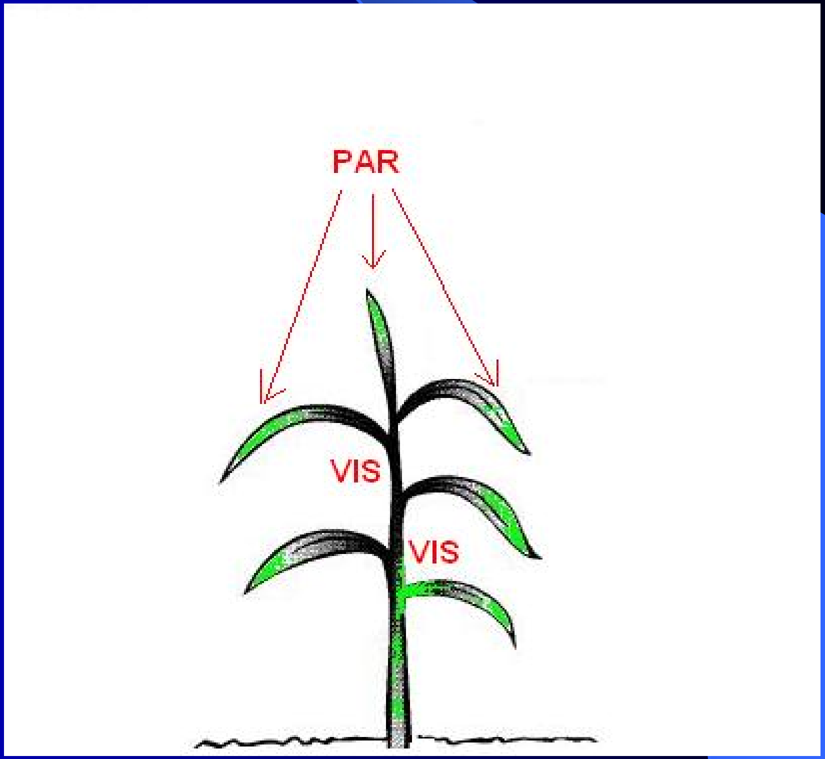
The part of AVRAD (300-3000 nm) that is photosynthetically active (400-700 nm).

$$
\begin{array}{ccc}
 & \boxed{\text{AVRAD}} & \\
 & \downarrow & \\
 & \boxed{\text{PAR}} & \\
\swarrow & & \searrow \\
\boxed{\text{PARDIR}} & & \boxed{\text{PARDIF}}
\end{array}
$$

Radiation within the canopy
VIS ($J\ m^{-2}\ s^{-1}$)

PAR is not constant within the canopy but it degreases exponentially with increasing leaf area index. VIS is the value of PAR in every canopy level.





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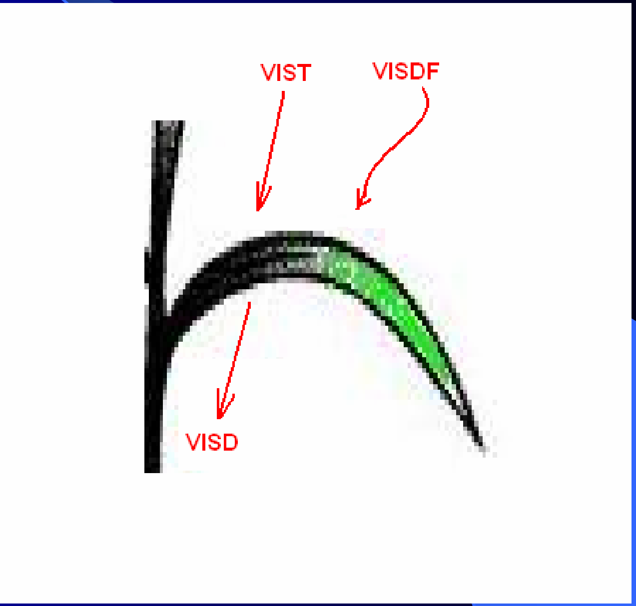
Radiation within the canopy
VIS ($J\ m^{-2}\ s^{-1}$)

VIS

VIST
(PARDIR)

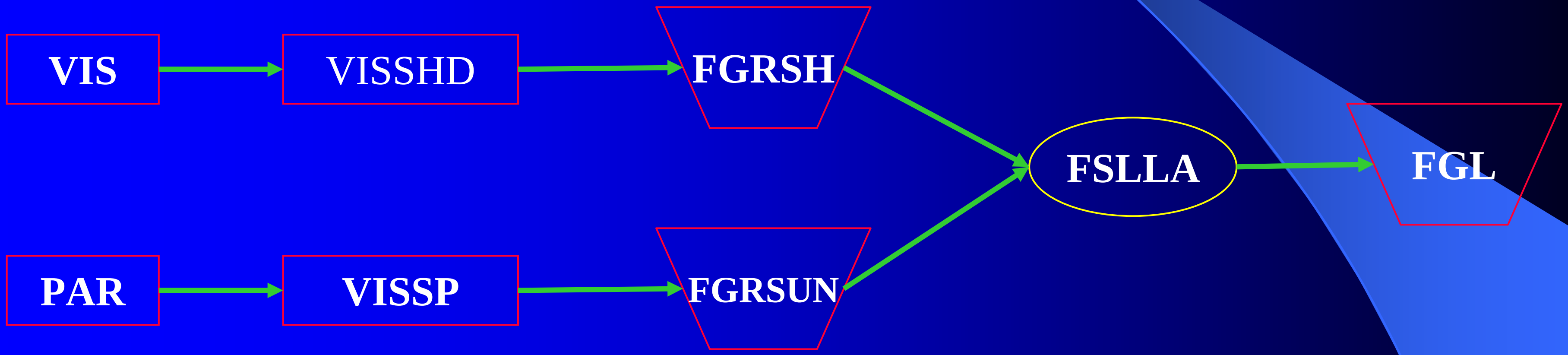
VISDF
(PARDIF)

VISD
(PARDIR)



Instant assimilation rate at any canopy level

FGL (kg (CO_2) ha^{-1} h^{-1})



Dry weight increase

DWI (kg ha^{-1} d^{-1})

$$\textbf{FGL} \xrightarrow{\textbf{Integrated for day length}} \text{FGC} \longrightarrow \textbf{FGASS} \longrightarrow \text{DWI}$$

What follows next

$$DWI = FGC * (30/44) * CFT * CFW * 0.6 \quad kg\ ha^{-1}\ d^{-1}$$

Growth respiration

Maintenance respiration

Influence of (leaf canopy) temperature

Influence of water availability (TRa/TRm)

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Functional relations

$$DSO = 1370 \times \left[1 + 0.033 \times \cos\left(2 \times \pi \times \frac{DAY}{365}\right)\right] \times \int_0^{DAYL} \sin(B)dt \quad Jm^{-2}d^{-1}$$

$$AVRAD = DSO \times ATMTR \quad Jm^{-2}d^{-1}$$

$$ATMTR = \left(a + b \times \frac{n}{DAYL}\right)$$

$$DEC = -\arcsin(\sin(23.45 \times RAD) \times \cos(2 \times \pi \times \frac{DAY + 10}{365})$$

$$SSIN = \sin(RAD \times LAT) \times \sin(DEC)$$

$$CCOS = \cos(RAD \times LAT) \times \cos(DEC)$$

$$DAYL = 12 \times \left[1 + \frac{2 \times \arcsin\left(\frac{SSIN}{CCOS}\right)}{\pi}\right] \quad hours$$

$$\sin(B) = SSIN + CCOS \times \cos(\frac{2 \times \pi \times (HOUR + 12)}{24})$$

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$$\frac{FRDIF}{AVRAD} = 1 \qquad \gamma\iota\alpha \qquad ATMTR < 0.07 \qquad (3.11a)$$

$$\frac{FRDIF}{AVRAD} = 1 - 2.3(ATMTR - 0.07)^2 \qquad \gamma\iota\alpha \qquad 0.07 \le ATMTR < 0.35 \qquad (3.11b)$$

$$\frac{FRDIF}{AVRAD} = 1.33 - 1.46 \times ATMTR \qquad \gamma\iota\alpha \qquad 0.35 \le ATMTR < 0.75 \qquad (3.11c)$$

$$\frac{FRDIF}{AVRAD} = 0.23 \qquad \gamma\iota\alpha \qquad 0.75 \le ATMTR \qquad (3.11d)$$

$$PAR = \frac{0.5 \times AVRAD \times \sin'(B)}{\int_0^{DAYL} \sin'(B)\,dt} \qquad Jm^{-2}s^{-1}$$

$$PARDIF = 0.5 \times AVRAD \times FRDFIR \times \sin(B) \qquad Jm^{-2}s^{-1}$$

$$PARDIR = PAR = PARDIF \qquad Jm^{-2}s^{-1}$$

$$VIS = (1 - REFS) \times PAR \times e^{-k \times LAI} \qquad Jm^{-2}(leaf)s^{-1}$$

$$VISDF = (1 - REFS) \times PARDIF \times KDIF \times e^{-KDIF \times LAI} \qquad Jm^{-2}(leaf)s^{-1}$$

$$VIST = (1 - REFS) \times PARDIR \times KDIRT \times e^{-KDIRT \times LAI} \qquad Jm^{-2}(leaf)s^{-1}$$

$$VISD = (1 - SCV) \times PARDIR \times KDIRBL \times e^{-KDIRBL \times LAI} \qquad Jm^{-2}(leaf)s^{-1}$$

$$KDIF = 0.8 \times \sqrt{1 - SCV} \qquad SCV = 0.2$$

$$KDIRBL = \frac{0.5}{\sin(B)}$$

$$KDIRT = KDIRBL \times \sqrt{1 - SCV}$$

$$REFH = \frac{1 - \sqrt{1 - SCV}}{1 + \sqrt{1 - SCV}}$$

$$REFS = REFH \times \frac{1}{0.5 + \sin(B)}$$

$$VISSHD = VISDF + VIST - VISD \qquad Jm^{-2}(leaf)s^{-1}$$

$$FGRSH = AMAX \times \left(1 - e^{\frac{-VISSHD \times EFF}{AMAX}}\right) \qquad kg(CO_2)ha^{-1}h^{-1}$$

$$VISSP = (1 - SCV) \times \frac{PARDIR}{\sin(B)} \qquad Jm^{-2}(leaf)s^{-1}$$

$$FGRSUN = AMAX \times \left[1 - (AMAX - FGRSH) \times \frac{\left(1 - e^{\frac{-VISPP \times EFF}{AMAX}}\right)}{EFF - VISPP}\right] \qquad kg(CO_2)ha^{-1}h^{-1}$$

$$FGL = FSLLA \times FGRSUN + (1 - FSLLA) \times FGRSH \quad kg(CO_2)ha^{-1}h^{-1}$$

$$FSLLA = e^{-KDIRBL \times LAI}$$

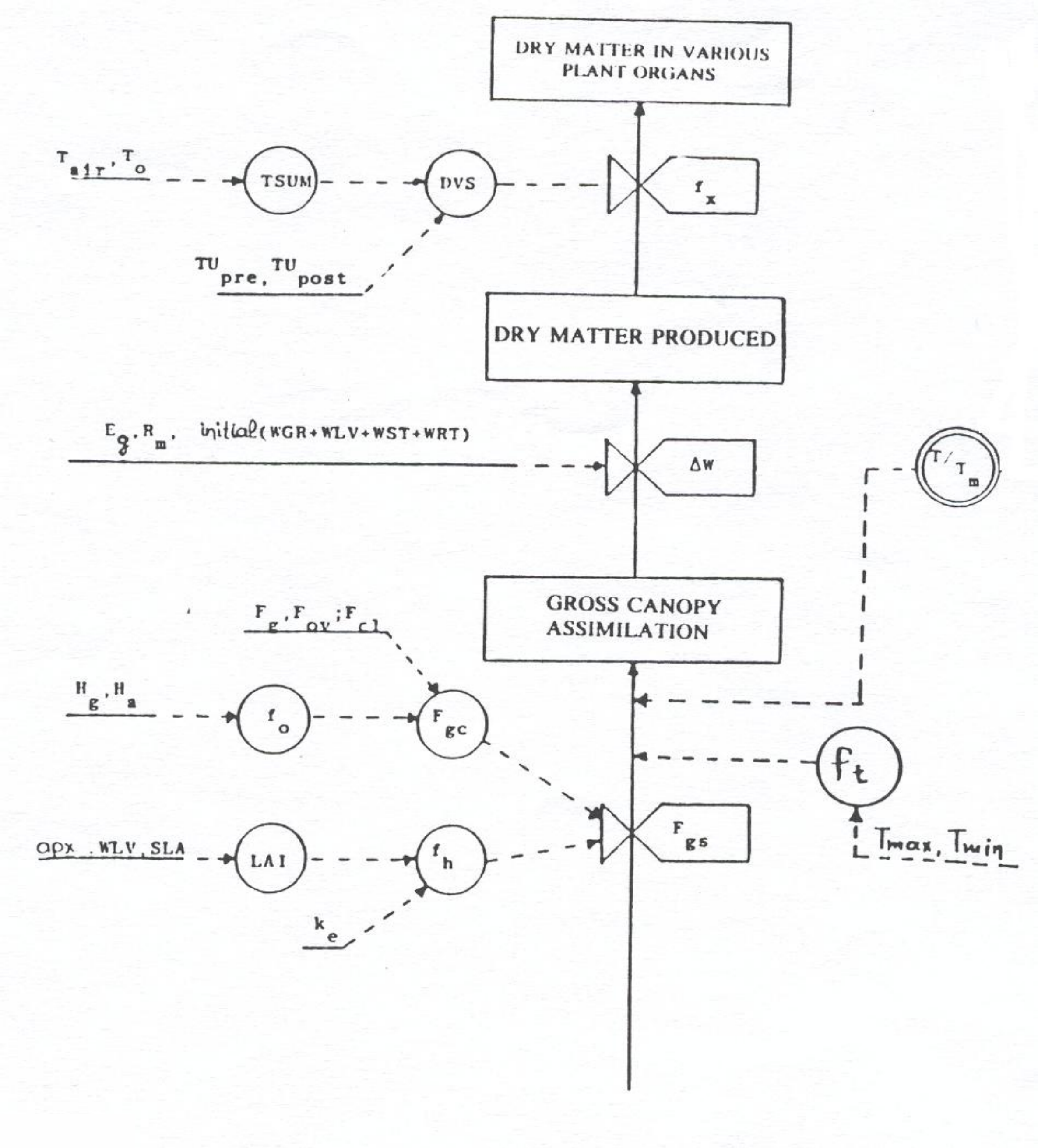
$$LAIC(I) = 0.5 \times LAI + I \times LAI \times \sqrt{0.15}$$

$$HOUR(I) = 12 + DAYL \times 0.5 \times \left(0.5 + I \times \sqrt{0.15}\right) \qquad I = -1,0,1$$

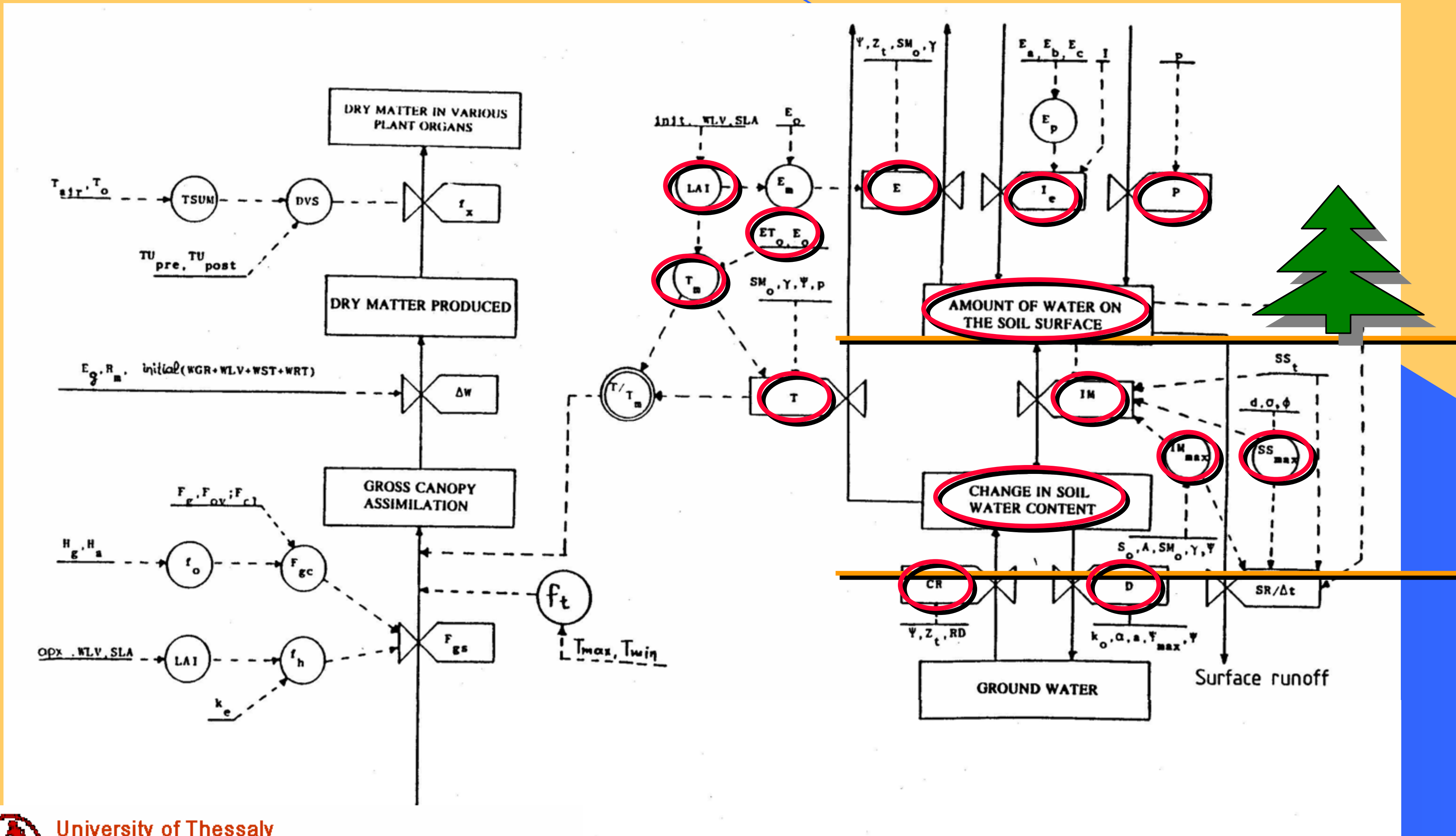
$$FGROS(I) = \left(FGL(-1) + 1.6 \times FGL(0) + FGL(1)\right) \times \frac{LAI}{3.6} \qquad kg(CO_2)ha^{-1}d^{-1}$$

$$FGC = \left(FGROS(-1) + 1.6 \times FGROSS(0) + FGROS(1)\right) \times \frac{DAYL}{3.6} \; kg(CO_2)ha^{-1}d^{-1}$$

Production Situation 1



Simplified flow chart of kenaf production during one interval of calculations



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THEORETICAL BACKGROUND AND FUNCTIONAL RELATIONS

The water balance

$$RSMs = IM - (D + CRISE) - TR(RD)$$

RSMs	is the change in moisture content of the system
IM	is the rate of net influx through the upper system boundary
(D+CRISE)	is the rate of net outflux through the lower system boundary, composed of capillary rise (CRISE) and drainage to the subsoil (D)
TR(RD)	is the rate of water loss from the interior of the rooted profile.

All variables are expressed in cm d^{-1}.

$$IM = (PREC + IRR + DS - ROFF) - EA$$

PREC and IRR are the effective precipitation and irrigation rates

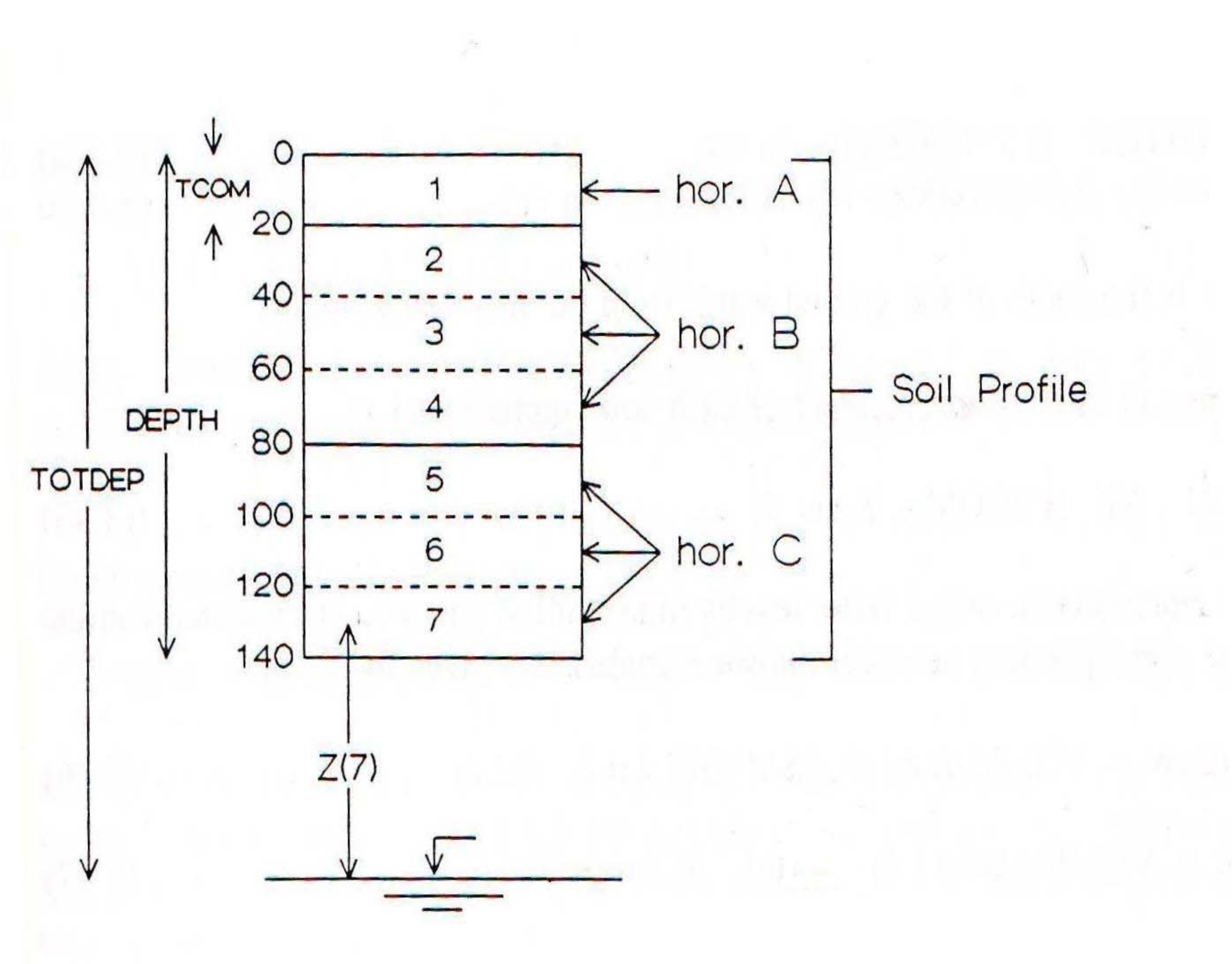
DS is the rate at which water stored on the surface declines ($DS \geq 0$)

ROFF is surface run-off

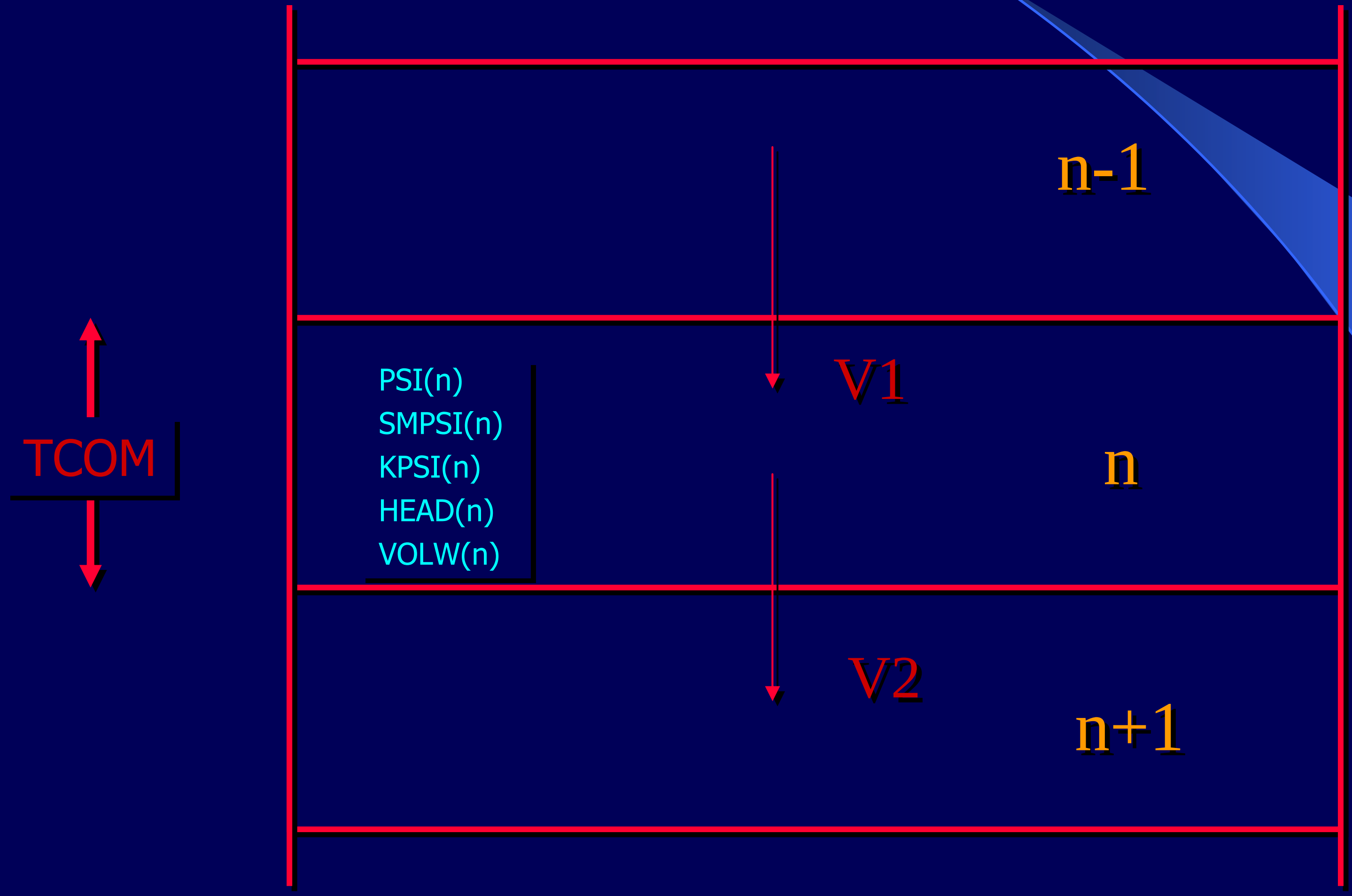
EA is the actual evaporation rate (all in cm d^{-1}).

Soil moisture dynamics

Soil profile



Soil compartments



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Functional relations (Darcy's Law)

V1=KAV1*(HEAD(n-1)-HEAD(n))/(0.5*(TCOM(n-1)+TCOM(n))

V2=KAV2*(HEAD(n)-HEAD(n+1))/(0.5*(TCOM(n)+TCOM(n+1))

(in cm d^{-1})

HEAD(n) is the hydraulic head in the centre of compartment (n)

TCOM(n) is the size of compartment (n)

KAV1 and KAV2 are the arithmetic averages of the hydraulic conductivities

$$KAV1 = 0.5*(KPSI(n)+KPSI(n-1)), \text{ in cm d}^{-1}$$

$$KAV2 = 0.5*(KPSI(n)+KPSI(n+1)), \text{ in cm d}^{-1}$$

KPSI(n) is the hydraulic conductivity in the compartment (n) (cm d^{-1})

$$HEAD(n) = Z(n) - PSI(n), \text{ in cm}$$

PSI represents the matrix suction, i.e. the absolute value of the matrix potential (cm)

Z(n) the distance from the centre of compartment (n) to ground-water table

At ground-water level, Z=PSI=HEAD=0.

A positive value for water moving in downward direction (HEAD>0).

At the middle of each soil compartment, Z is calculated according to the following formulations:

Z(1) = TOTDEP - 0.5*TCOM(1), in cm
Z(n) = Z(n-1) - 0.5*(TCOM(n-1)+TCOM(n)), in cm

where TOTDEP is the depth of the ground water from the soil surface (cm).

The rate of change in the moisture content of each soil compartment is:

$$RSM = V1 - V2 - TRCOM, \ \text{in cm d}^{-1}$$

where TRCOM represents the actual water loss by transpiration (cm d^{-1}).

The updated volume of water and the corresponding new soil moisture content are given by:

VOLW(n)new = VOLW(n)old + RSM*DELTAT, in cm

SMPSI(n) = VOLW(n)new / TCOM(n), in $cm^3 cm^{-3}$

where VOLW is the water volume, and DELTAT is the time interval of calculations.

Water uptake

Maximum transpiration rate

$$LET = \frac{1}{PENX + g} * (PENX * NETRA + hu * (EASAT - EAC)), \text{ in J } m^{-2}d^{-1}$$

where

LET	is the evaporative heat loss above the canopy (J $m^{-2}d^{-1}$)
PENX	is the slope of the saturation vapour pressure curve at mean temperature,
g	is the psychrometer constant (=0.66 mbar $^{o}C^{-1}$),
NETRA	is net absorbed radiation (J $m^{-2}d^{-1}$),
hu	is the sensible heat transfer coefficient (J $m^{-2}d^{-1}K^{-1}$),
EASAT	is the saturated vapour pressure at mean air temperature,
EAC	is the actual vapour pressure (both in mbar).

NETRAdiation

$NETRA = SHRA - INRA$, in $J\ m^{-2}d^{-1}$

$SHRA = (1\text{-}r)*AVRAD$, in $J\ m^{-2}d^{-1}$

$INRA = 4900*(TA+273)^4*(0.56-0.079*EAC^{1/2})*(0.1+0.9*SD)$

where

AVRAD	is the total global radiation $J\ m^{-2}d^{-1}$
r	is the albedo (reflection coefficient) for kenaf (=0.25).
SD	is the sunshine duration ratio
TA	is the average air temperature (^oC).
4900	is the value of the Stefan-Bolzman constant ($J\ m^{-2}d^{-1}K^{-4}$)
EAC	is the actual vapour pressure (bar)

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hu (heat transfer coefficient)

The value of the sensible heat transfer coefficient, hu, depends on atmospheric turbulence and is expressed as an empirically determined function of mean wind velocity at a defined height (Penman, 1948):

$$hu = au*(1+WVAL*WIND) \quad \text{in J } m^{-2}d^{-1}{}^{o}C^{-1}$$

where
WIND is the mean wind velocity ($m\ s^{-1}$)
au and WVAL are empirical constants

Frère & Popov (1979) suggest a value for au of $6.4*10^5$ J $m^{-2}d^{-1}{}^{o}C^{-1}$. Indicative WVAL values are reported by Frère (1979) in the range 0.54-0.89 s m^{-1}, depending on the value of TMAX-TMIN (oC).

Saturated and actual vapour pressures

EASAT=6.11*exp(17.4*TA/(TA+239) (Goudriaan, 1977)

EAC = EASAT * RH

where
RH is the average air humidity (%)
EAC and EASAT are both expressed in mbar.

Tabulated values for PENX are taken for various combinations of air temperature (TA) and altitude (ALT) in meters above or below sea level (in meters).

Max. Transpiration

$$TRM = 0.1 * LET / L, \text{ in cm d}^{-1}$$

where L is the latent heat of vaporization ($2.45*10^6$ J kg^{-1})

Root growth and distribution

IF FRROOT>0 THEN RRG=RRG ELSE RRG=0, in cm d^{-1}

IF RD<RDM THEN RD=RD+RRG ELSE RD=RDM, in cm

where RD is the momentary rooting depth (cm).

Actual transpiration rate

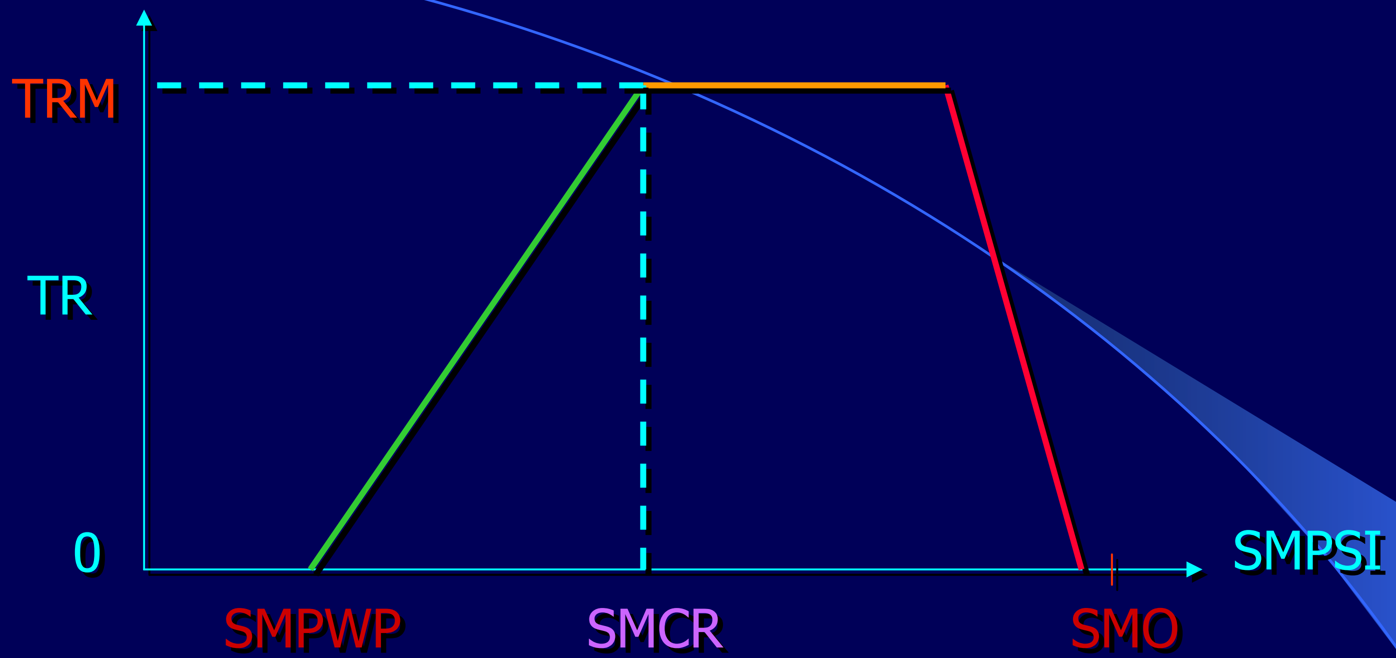
Table 1. Soil water depletion fraction (DEPLF) for crop groups and maximum (evapo) transpiration (TRM).

Crop Group	TRM (cm/day)								
	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1	0.500	0.425	0.350	0.300	0.250	0.225	0.200	0.200	0.175
2	0.675	0.575	0.475	0.400	0.350	0.325	0.275	0.250	0.225
3	0.800	0.700	0.600	0.500	0.450	0.425	0.375	0.350	0.300
4	**0.875**	**0.800**	**0.700**	**0.600**	**0.550**	**0.500**	**0.450**	**0.425**	**0.400**

Table 2. Crop groups according to soil depletion

Group	Crops
1	onion, pepper, potato
2	banana, cabbage, grape, pea, tomato
3	alfalfa, bean, citrus, groundnut, pineapple sunflower, water melon, wheat
4	cotton, maize, olive, safflower, sorghum, soybean, sugar beet, sugar cane, tobacco, **kenaf**

(Source: Doorenbos & Kassam, 1979).



SMCR = (1-DEPLF)*(SMO-0.02-SMPWP) + SMPWP, in $cm^3 cm^{-3}$

IF SMPSI >= (SMO-0.02) THEN TR=0

IF (SMO-0.02) >= SMPSI >= (SMO-0.06) THEN

TR = TRM*(SMO-0.02-SMPSI)/0.04

IF (SMO-0.06) >= SMPSI >= SMCR THEN TR=TRM

IF SMCR >= SMPSI >= SMPWP THEN

TR = TRM*(SMPSI-SMPWP)/(SMCR-SMPWP)

IF SMPWP >= SMPSI THEN TR=0, in cm d^{-1}

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Evaluating the soil moisture content of a particular soil compartment, the above equations are used to approximate the fraction of the water actually taken up from this particular compartment (TRCOM).

For that, the maximum uptake rate (TRMCOM, in cm d^{-1}) is calculated assuming root activity evenly distributed over the entire rooting zone.

If, for example, the rooting depth on a particular day is 85 cm, this will be distributed by 100% (full rooting) in the first 4 and by 25% in the 5th soil compartments (of 20 cm). A maximum transpiration rate of, say, TRM=6 cm d^{-1} would thus be divided over 5 rooted compartments: TRMCOM would be 1.41 cm d-1 for the first 4 compartments and 0.35 cm d^{-1} for the last one; these values are dictated by the equivalent root density of each of these compartments.

Actual Transpiration

$$TR = \int_{0}^{day} \int_{0}^{DEPTH} TRCOM(RD), \text{ in cm d}^{-1}$$

where

DEPTH is the depth of the soil profile

RD in parentheses denotes the dependence of the value of TRCOM on actual rooting depth.

Canopy Temperature

$TCAN = TA + (NETRA-10*TR*L)/hu$, in ^{o}C

where the coefficient 10 (mm cm^{-1}) is used to satisfy the units.

Boundary conditions

*A*ctual evaporation

$$EA = EM*(SMPSI-SMAD)/(SMO-SMAD) \quad \text{in cm d}^{-1}$$

where

SMPSI, SMO and SMAD represent the actual, saturation, and air-dry soil moisture contents of the topsoil respectively ($cm^3 cm^{-3}$).

It applies only for the first soil compartment.

Precise determination of the SMAD is difficult. Here, it is assumed that the moisture content of air-dry soil is approximately one third of SMPWP ($cm^3 cm^{-3}$).

Rainfall-Irrigation

In the case of rain or irrigation, the rain intensity (VO, in cm d^{-1}) and the total amount of water (INP-REC or INPIRR, both in cm) are introduced as forcing variables. The duration of the irrigation or rain (DUR, in d) is also known or calculated as the ratio of INPIRR (or INPREC) over VO. In this case, the rate of water influx in the uppermost soil com-partment, V1, is found as follows:

IF INPIRR > 0 THEN DUR=INPIRR/VO ELSE DUR=0 (d)

IF S (DELTAT) < DUR THEN V1=(VO-EA) ELSE V1= -EA (cm d-1)

Capillary rise

Capillary rise takes place if the matrix suction (PSI) is greater than the gravitational head (Z), according to:

IF PSI(n)>Z(n) THEN V2(n)=CRISE

where

PSI(n) (in cm) is the matrix suction at the centre of the lowermost soil compartment

Z(n) (in cm) is the distance from this point to the ground-water table CRISE is the rate of capillary rise (cm d^{-1})

V2(n) is the flux through the lowermost soil boundary (cm d^{-1}).

Assuming that Z=PSI=0 at ground-water depth and that Z increases upwards, capillary rise (CRISE) over the distance between the lower soil boundary and the ground-water table amounts to:

CRISE = KPSI * [1-(d(PSI)/d Z)], in cm d^{-1}

where KPSI is the hydraulic conductivity (cm d^{-1}).

Working out this Eqn. in the low suction range (below the texture-specific suction limit, PSIMAX) results in:

$$CRISE = \frac{KOn * (\exp(-ALF*Zn) - \exp(-ALF*PSIn))}{1 - \exp(-ALF*Zn)}$$

$$\text{FOR } Z \leq PSI \leq PSIMAX$$

where

KO is the rate of hydraulic conductivity at saturation (cm d^{-1})

ALF (cm^{-1}) and PSIMAX (cm) are texture specific constants.

The suffix (n) denotes the lowermost soil compartment.

Note also that CRISE in the above equations has a negative value.

For the high suction range (PSI>PSIMAX), numerical integration is applied but only if the ground-water table is within the boundaries of the soil profile. Alternatively, tables pre-pared by Rijtema (Danalatos, 1993) are used, relating CRISE over the distance Z to any combination of PSI and Z.

Deep percolation and adjustment of ground-water depth

Downward percolation takes place through the lowest soil boundary if the matrix suction at this boundary is less than the distance to the ground-water depth (PSI<Z):

IF PSI(n)<Z(n) THEN V2(n)=D

where D is the percolation rate (cm d^{-1}).

If it occurs, the percolation rate is approximated with:

$$D = KPSI(n) * (1-d(PSIn)/dZn), \text{ in cm } d^{-1}$$

where KPSIn is the hydraulic conductivity of the lowermost compartment (in cm d^{-1}).

Any flow through the lowest soil boundary affects the moisture content of the subsoil and the depth to ground-water table, which increases (CRISE>0) or decreases (D>0) by a distance DZ.

DZ is approximated with the following relation:

DZ = -2*(D+CRISE)*DELTAT*/(SMO-SMPSI), in cm

and the ground-water depth is then adjusted by:

TOTDEP = TOTDEP + DZ, in cm

The time interval

The permissible length of DELTAT depends on the dynamics of ongoing processes and is therefore influenced by the choice of compartment sizes.

It appears that DELTAT is proportional to the thickness of the compartments squared and depends furthermore on the diffusivity.

In the detailed simulations 20 compartments were considered viz. 10 compartments of 2 cm, 5 compartments of 4 cm and 5 compartments of 6 cm; the DELTAT was set at one second ($11.6*10^{-6}$d).

The simplified model uses considerably larger time intervals, in line with the needs of the connected kenaf-production model. DELTAT was finally set at 15 min or $10.4*10^{-3}$ d; Diffusivity equations and our trials confirm that a compartment size of 20 cm can be safely used.

θ-ψ and θ-k relations

For the calculation of SMPSI, a semi-empirical relation is used which contains a texture-specific geometry constant gama (in cm^{-2}, Danalatos *et al*, 1994)

SMPSI = SMO * exp(-gama*ln(PSI)*ln(PSI))

For the KPSI-PSI relations, Rijtema (1969) have suggested:

KPSI = KO * exp(-ALF*PSI) FOR PSI =< PSIMAX
KPSI = AK * PSI-1.4 FOR PSI > PSIMAX

where ALF (cm^{-1}) and AK (cm^{-2}) are texture-specific geometry constants, and PSIMAX (cm) is a texture-specific suction limit.

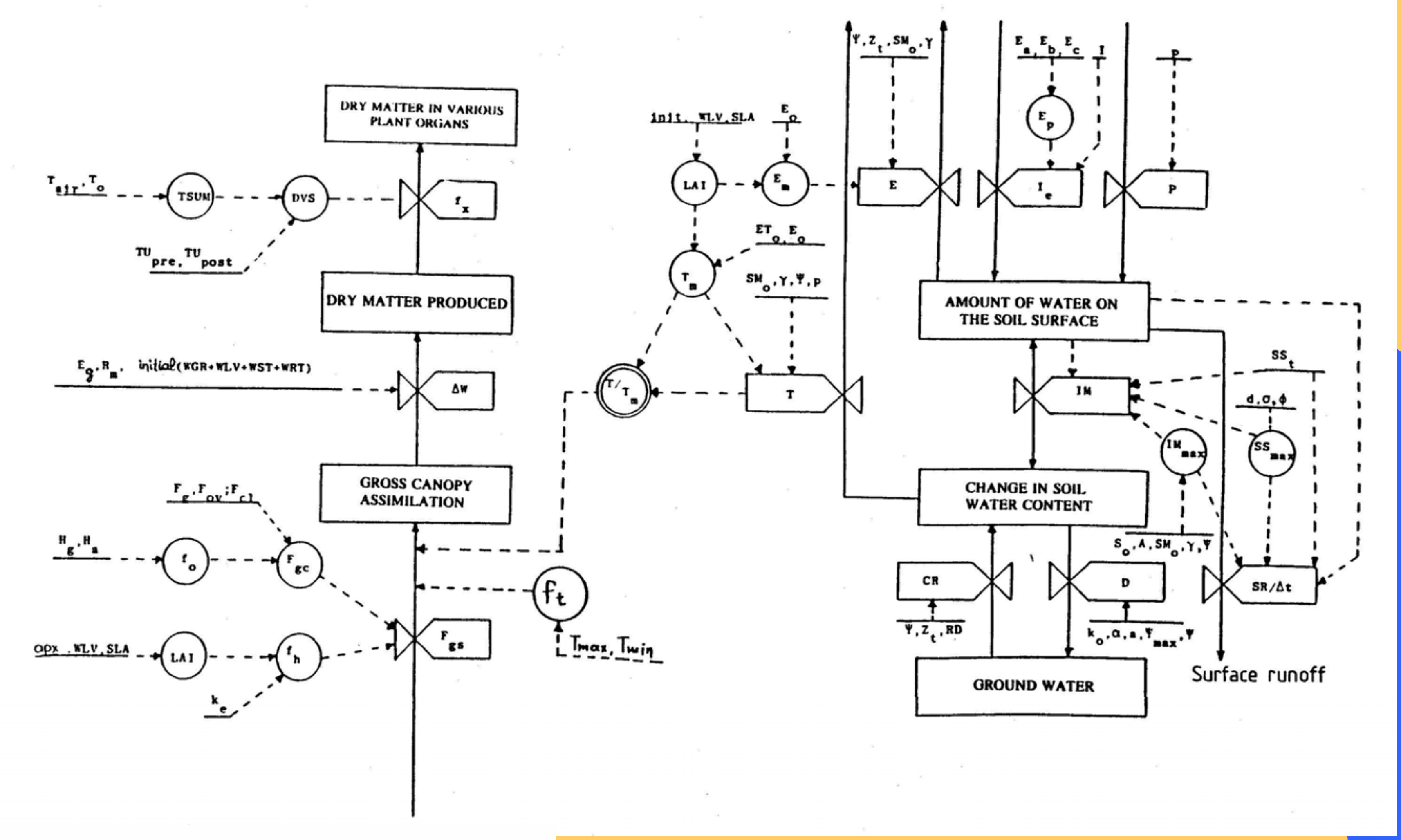
Influx through the upper soil boundary

The maximum surface storage capacity of the soil is determined by the surface properties and the slope angle of the land. SSMAX is mathematically described as:

$$SSMAX = 0.5 * RG * \frac{\sin 2(SIG-PHI)}{\sin SIG} * \frac{\cot(SIG+PHI)+\cot(SIG-PHI)}{2*\cos(SIG)*\cos(-PHI)}$$

where PHI is the slope angle of the land (°), RG is the surface roughness (cm), and SIG is the clod/furrow angle (°).

Simplified flow chart of kenaf production during one interval of calculations



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Dept. of Agriculture, Crop Production & Agric. Environment

Materials

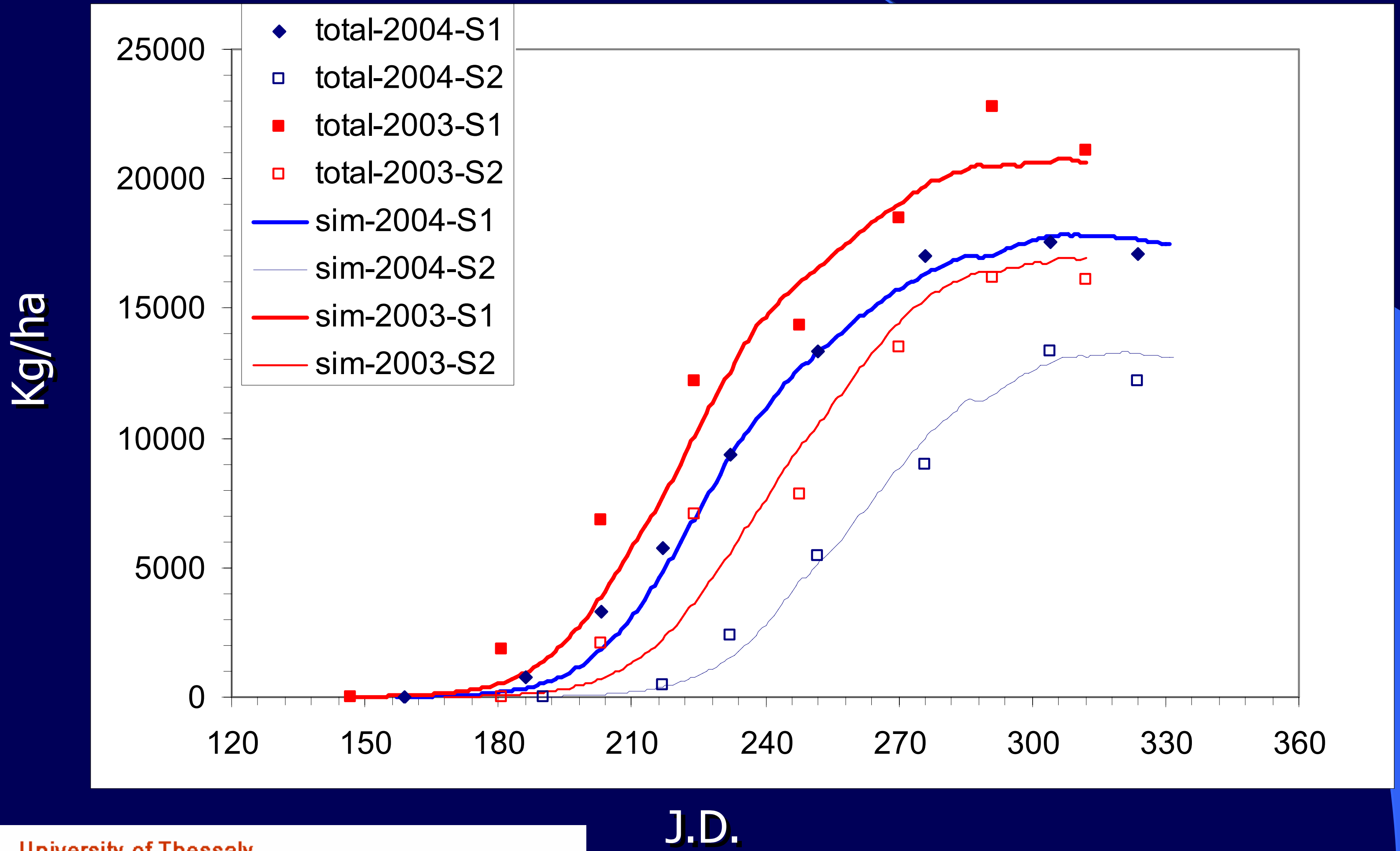
HARDWARE

• Processor:	AMD ATHLON XP 2800+
• Mother board:	Gigabyte 7N400-Pro
• RAM:	512 MB 400 Mhz
• Hard disk:	W.Digital 160 GB
• Graphics:	ATI 9600 pro 128 MB Ram
• Screen:	LG 1710S

SOFTWARE

- Microsoft Visual Basic 6
- Microsoft Excel 2000
- Helexis Icon Catcher v3.0
- Microsoft Paint for windows XP

Measured and simulated total dry weight under optimum conditions in 2003 and 2004



Measured and simulated dry stem weight under optimum conditions in 2003 and 2004