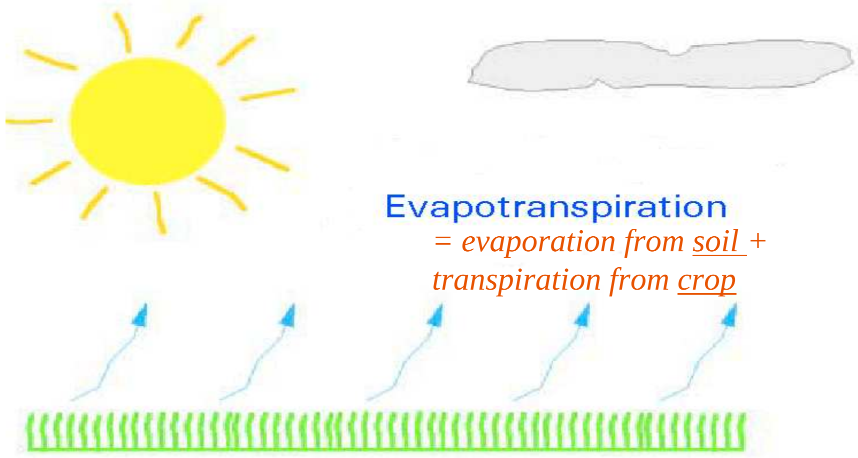
Evapotranspiration
&
Lintul2: Water limited crop growth

Chapter 10B, <u>the math-model p.1-16</u> & the program p.17-25, p.30-32, p.36-40;
Chapter 10C, p.472 & 475-477.

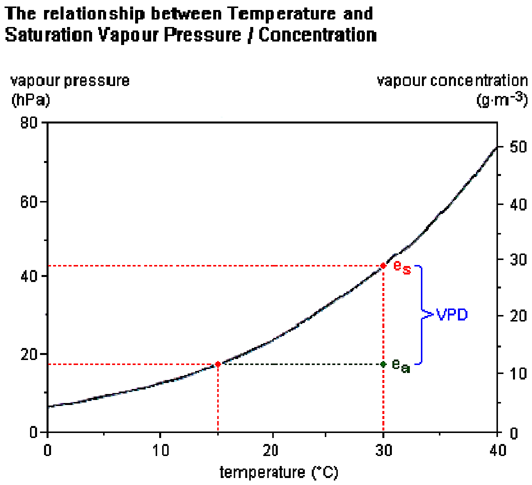
Peter Leffelaar
Eelco Meuter

Crop Ecology (HPC-21306)

Evapotranspiration



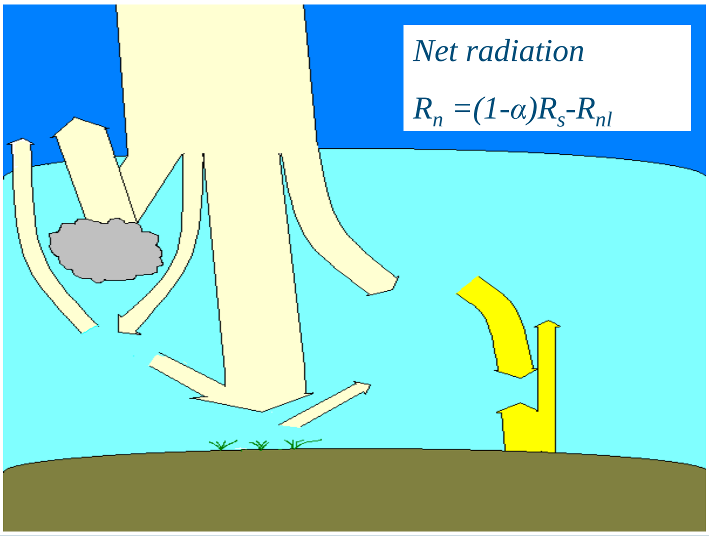
Temperature and saturation vapour pressure



$$e_s = 6.11\, e^{\{(17.47\, T_s)/(239+T_s)\}}$$

$$\Delta = \frac{4175.3\left(6.11\, e^{\{(17.47\, T_s)/(239+T_s)\}}\right)}{(239+T_s)^2}$$

Energy balance



How much heat is needed for evaporation of water?

$\lambda = 2.45$ MJ/kg (around 20 ºC) = 2.45 kJ/g

Drivers of evapo(transpi)ration

- *Radiation*
- *Evaporative demand*

These are combined in the Penman and Penman-Monteith equations for estimating Potential Evapotranspiration

(from an amply watered, 12 cm tall grass crop with an albedo of 0.23)= Reference evapotranspiration

Penman (1948) equation used in Lintul2:

$$ET_0 = \frac{0.408\Delta R_n}{\Delta + \gamma} + \frac{\gamma(e_s - e_a) * 2.63(1.0 + 0.54u_2)}{\Delta + \gamma}$$

Penman modified

1956: Monteith and Rijtema independently modified the Penman equation to include surface & aerodynamic resistances of crops

The full Penman-Monteith equation:

$$ET = \frac{\Delta R_n + \rho_a c_p \frac{e_s - e_a}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}$$

where:

r_a is aerodynamic resistance

r_s is stomatal resistance

For a 12cm tall grass surface:

$$ET_0 = \frac{0.408\Delta(R_n) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}$$

See e.g.: Allen, Pereira, Raes & Smith, 1998

Data needed by Penman & Penman-Monteith equations

- *Solar radiation*
- *Temperature*
- *Humidity / Vapour pressure*
- *Wind speed*

Other equations with less data needs, e.g.:

- *Makkink*
- *Priestley-Taylor*
- *Blaney-Criddle*
- *Turc*

(Even more methods exist: Hargreaves, McNaughton & Black, Linacre, Thorntwaite, Shuttleworth-Wallace, Jensen-Haise, etc.)

Turc Method (1961)

$$ET_0 = 0.013\frac{T}{T+15}(Rs+50)$$

(For Relative Humidity > 50%)

$$ET_0 = 0.013\frac{T}{T+15}(Rs+50)\left(1+\frac{50-RH}{70}\right)$$

(For Relative Humidity < 50%)

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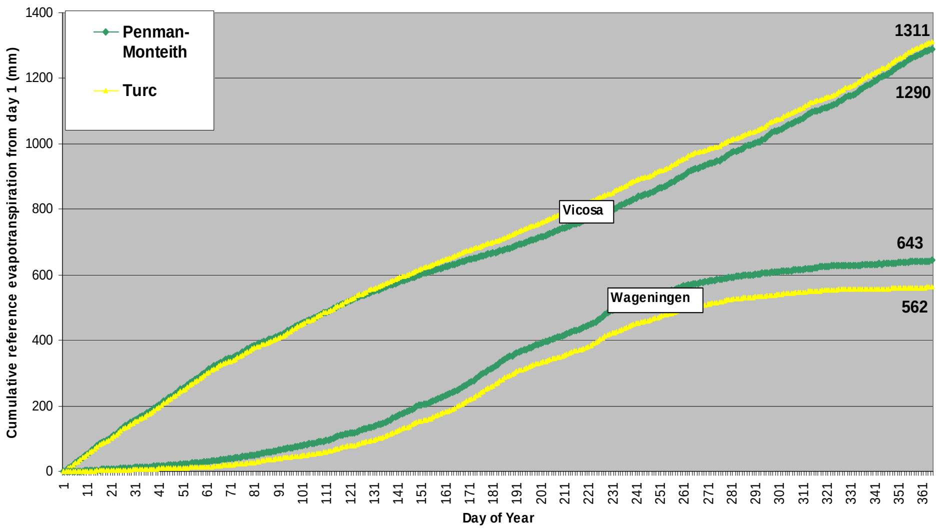
Cumulative annual reference evapotranspiration in *Vicosa, Brazil* and *Wageningen, The Netherlands*, 1973 estimated according to Turc and Penman-Monteith



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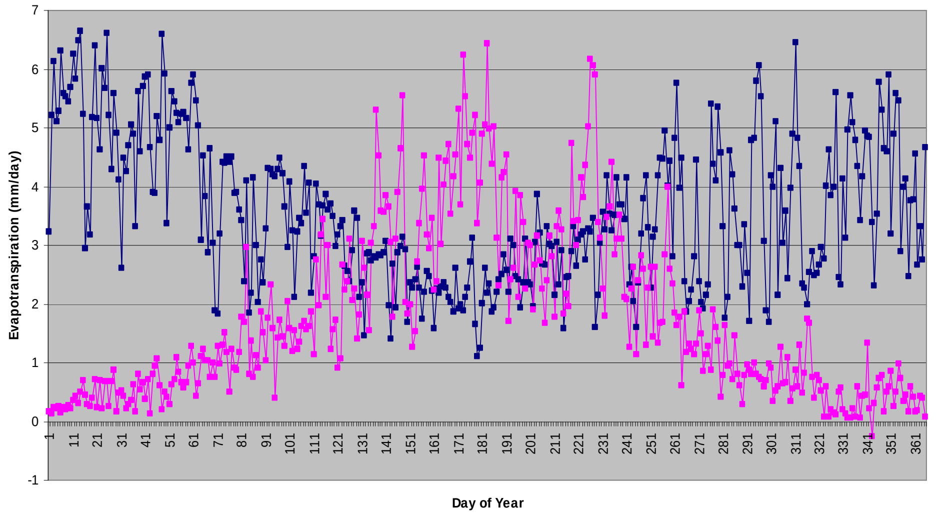
Daily reference evapotranspiration in Vicosa, Brazil and Wageningen, The Netherlands, 1973
estimated according to Penman-Monteith method



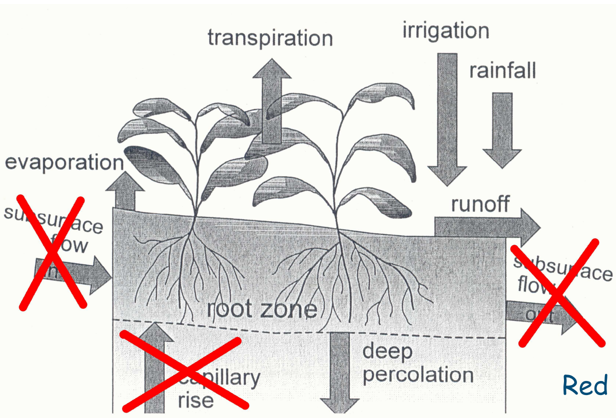
Coupling environmental conditions with crop growth

- General model ideas
- The water balance
- Effects of water on:
  - Roots
  - Emergence
  - Overall growth rate
  - Partitioning
- Transpiration reduction factor
- Relational diagram
- Practical

General modelling ideas

- Crop - LINTUL1
  LUE based
  Development based on TSUM
  Exponential light extinction
  Fixed partitioning of assimilates
- Soil - One layer
  Increasing in depth with growing roots
  Exploring new soil means new water, assuming pF = 2
  Immediate homogeneous incoming water distribution
  Water held at pF = 2 (field capacity)
- Crop <-> Soil
  Overall crop growth affected by water shortage
  Root - shoot partitioning affected
  Emergence affected
  Root growth rate affected

Soil water balance terms of the root zone



Red crosses: not in LINTUL2

From: Allen, Pereira, Raes & Smith, 1998

Water dynamics in LINTUL: (1) placement of calculations

```
DEFINE_CALL GLA          (...)
DEFINE_CALL PENMAN       (...)
DEFINE_CALL EVAPTR       (...)
DEFINE_CALL DRUNIR       (...)
TITLE LINTUL2
***  1. Initial conditions and run control
***  2. Environmental data and temperature sum
***  3. Leaf growth and senescence
***  4. Light interception and total crop growth rate
***  5. Growth rates and dry matter production of plant organs
***  6. Soil moisture balance
***  7. Functions and parameters for spring wheat
END
STOP
     SUBROUTINE  GLA      (...)
     SUBROUTINE  PENMAN   (...)
     SUBROUTINE  EVAPTR   (...)
     SUBROUTINE  DRUNIR   (...)
```

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Water dynamics in LINTUL: (2) their parameters

```
***  6. Soil moisture balance
    EXPLOR  = 1000. * RROOTD * WCFC
    RNINTC = MIN( RAIN , 0.25*LAI )
    CALL PENMAN( DAVTMP , VP , DTR , LAI , WN , RNINTC ,        PEVAP , PTRAN)
    CALL EVAPTR( PEVAP , PTRAN , ROOTD , WA , WCAD , WCWP , WCFC , WCWET , WCST , . . .
                 TRANCO , DELT ,                                 EVAP,TRAN)
        TRANRF = TRAN / NOTNUL(PTRAN)
    CALL DRUNIR( RAIN , RNINTC , EVAP , TRAN , IRRIGF , DRATE , DELT , WA , ROOTD, . . .
                 WCFC , WCST ,                                   DRAIN , RUNOFF , IRRIG)

    RWA  = ( RAIN + EXPLOR + IRRIG ) - ( RNINTC + RUNOFF + TRAN + EVAP + DRAIN )
    WA   = INTGRL( WAI , RWA )
    WC   = 0.001 * WA/ROOTD

***  7. Functions and parameters for spring wheat
PARAM  WCI      = 0.36
PARAM  ROOTDM = 1.2    ; RRDMAX = 0.012
PARAM  WCAD     = 0.08 ; WCWP    = 0.23 ; WCFC = 0.36 ; WCWET = 0.48 ; WCST = 0.55
PARAM  TRANCO  = 8.     ; DRATE    = 50.   ; IRRIGF = 0.
```

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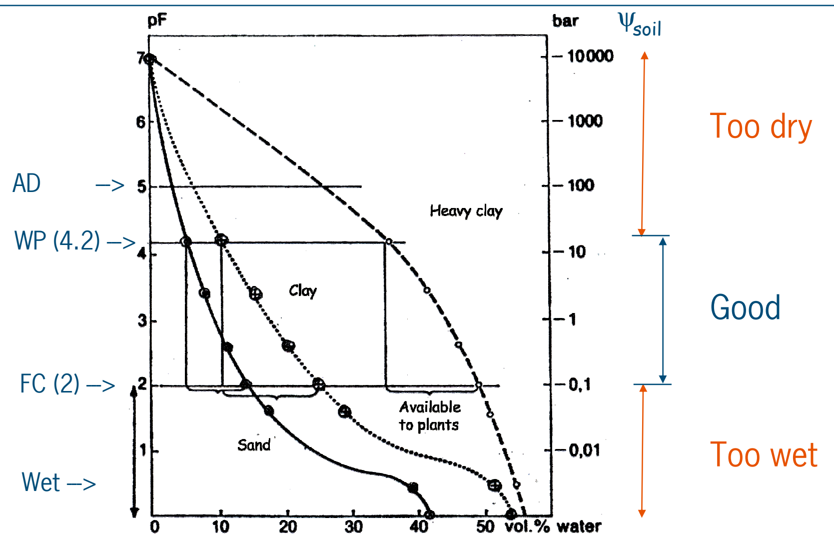
Soil water retention curve

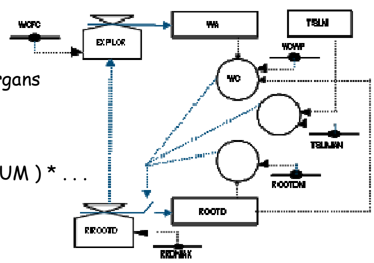


From: Koorevaar et al., 1983 (adapted)

Root growth and exploration of water

```
TITLE LINTUL2
***   1. Initial conditions and run control
INCON ROOTDI = 0.1
WAI    = 1000. * ROOTDI * WCI
***   2. Environmental data and temperature sum
WEATHER WTRDIR='D:\SYS\WEATHERBRAZIL\'; CNTR='BRAZIL'; ISTN=3; IYEAR=1975
*     VP      Vapour pressure          kPa
*     WN      Wind speed               m/s
*     RAIN    Precipitation            mm

***   5. Growth rates and dry matter production of plant organs
      RROOTD = RRDMAX * . . .
                INSW( WC-WCWP, 0., 1. ) * . . .
                REAAND( ROOTDM-ROOTD, TSUMAN-TSUM ) * . . .
                EMERG
      ROOTD  = INTGRL( ROOTDI, RROOTD)
```



How water affects emergence and crop growth

```
TITLE LINTUL2
***   2. Environmental data and temperature sum
      EMERG  = MAX ( REAAND(TIME-DOYEM+1.,WC-WCWP), . . .
                                   INSW(-LAI,1.,0.) )

***   3. Leaf growth and senescence
      CALL GLA( TIME    , DOYEM , DTEFF , TSUM , LAII , . . .
                RGRL    , DELT   , SLA    , LAI    , GLV  , . . .
                TRANRF, WC     ,WCWP   ,                GLAI )

***   4. Light interception and total crop growth rate
      PARINT = 0.5 * DTR    * (1. - EXP(-K*LAI))
      GTOTAL = LUE * PARINT * TRANRF
```

TRANRF ($T_{red\text{-}tran}$, Fig.4 or FR in Subroutine EVAPTR)

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How water affects growth of leaf area

```
      SUBROUTINE GLA(TIME , DOYEM , DTEFF , TSUM , LAII , RGRL , DELT , SLA , LAI , GLV,
     $               TRANRF ,  WC , WCWP ,                                  GLAI)
      IMPLICIT REAL (A-Z)

      GLAI = SLA * GLV

      IF ( (TSUM .LT. 330. ) .AND. (LAI .LT. 0.75) )
     $   GLAI = LAI * (EXP(RGRL * DTEFF * DELT) - 1.) / DELT * TRANRF

      IF ( (TIME .GE. DOYEM) .AND. (LAI .EQ. 0.) .AND. (WC .GT. WCWP) )
     $   GLAI = LAII / DELT

      IF (TIME .LT. DOYEM) GLAI = 0.

      RETURN
      END
```

($T_{red\text{-}tran}$, Fig.4 or FR)

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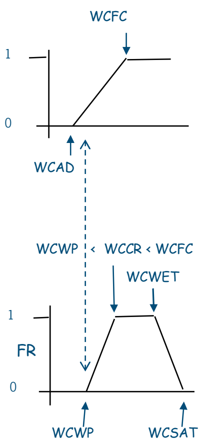
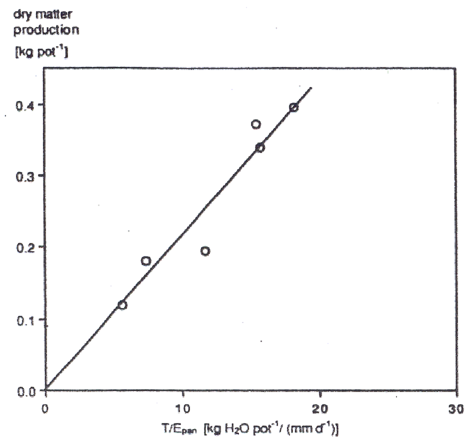
Evapo(transpi)ration reduction and physiologically determined critical point WCCR




```
 SUBROUTINE EVAPTR( PEVAP    , PTRAN , ROOTD   , WA   , WCAD , WCWP , WCFC ,
$                  WCWET , WCST  , TRANCO , DELT ,           EVAP,TRAN )
  IMPLICIT REAL (A-Z)
  WC     = 0.001 * WA   / ROOTD
  WAAD = 1000. * WCAD * ROOTD
  WAFC  = 1000. * WCFC * ROOTD
  EVAP   = PEVAP * LIMIT( 0., 1., (WC-WCAD)/(WCFC-WCAD) )

     WCCR = WCWP + MAX( 0.01, PTRAN/(PTRAN+TRANCO) * (WCFC-WCWP) )
     IF (WC.GT.WCCR) THEN
        FR = LIMIT( 0., 1., (WCST-WC)/(WCST-WCWET) )
     ELSE
        FR = LIMIT( 0., 1., (WC-WCWP)/(WCCR-WCWP)  )
     ENDIF
  TRAN = PTRAN * FR
     AVAILF = MIN( 1., ((WA-WAAD)/DELT)/NOTNUL(EVAP+TRAN) )
  EVAP  =  EVAP * AVAILF
  TRAN =  TRAN * AVAILF
  RETURN
  END
```


Experimental evidence of proportional reduction of growth with transpiration



$\frac{\text{TRAN}}{\text{PTRAN}}$

Maize in pots

From: Briggs & Shantz, 1914

Effect of drought on dry matter partitioning

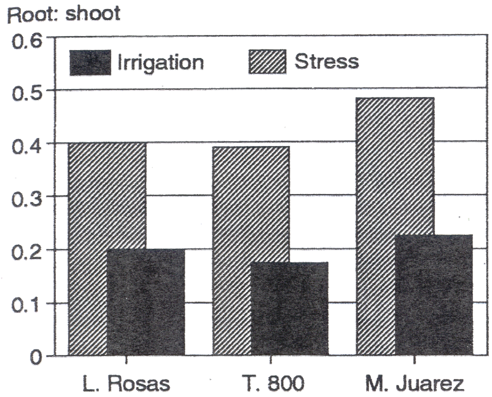
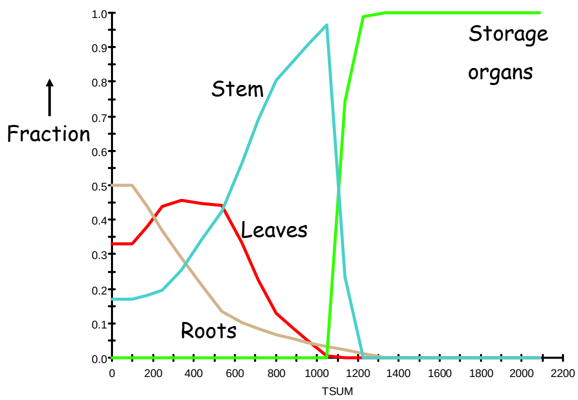


Figure 4. Root:shoot ratios in irrigated and droughted treatments. Values derive from one lysimeter per treatment.

From: Magrin, Hall, Castellano & Meira, 1991

Substrate allocation patterns in Spring Wheat



Allocation pattern of assimilates for spring wheat as used in Lintul (Light interception and utilization)

How to take account of the effect of drought on dry matter partitioning?

- The idea is:

  if it is too dry,
  more roots will be formed to compensate the water shortage,
  and this will cost extra assimilates that go to the roots.

- Thus, less assimilates are left for the shoot, but the distribution of assimilates among the stem, the leaves and the storage organs remains the same.

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Derivation of the modification factor: shmod

Idea: if too dry -> more roots formed to compensate -> extra assimilates to the roots (r)
Thus, less assimilates then go to the shoot, but the distribution among stem (s), leaves (l) and storage organs (so) remains the same:

$$r_{new} = r_{old}\, rMOD, \quad \text{with } 1 \le rMOD \le f_{max}$$

s + l + so then get (r_{new} - r_{old}) less assimilates in the distribution $s_{old} : l_{old} : so_{old}$
For instance, s will get less assimilates of quantity

$$\frac{s_{old}}{s_{old} + l_{old} + so_{old}} (r_{new} - r_{old})$$

of course s_{old} + l_{old} + so_{old} = 1-r_{old}, so s_{new} will be: $s_{new} = s_{old} - \{\frac{s_{old}}{1-r_{old}}(r_{new} - r_{old})\}$

Taking s_{old} outside brackets, the factor ($1-\frac{r_{new} - r_{old}}{1-r_{old}}$) will be the sMOD or, generally, the shoot modification factor shMOD, so:

$$shMOD = 1 - \frac{r_{new} - r_{old}}{1-r_{old}} = \frac{1-r_{new}}{1-r_{old}} = \frac{1-r_{new}}{1-{}^{r_{new}}\!/_{rMOD}}$$

where r_{old} is taken as r_{new} / rMOD according to the above 1st equation

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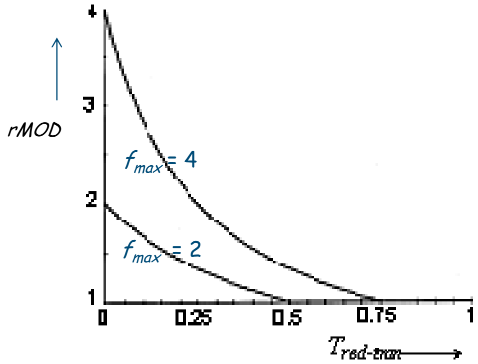
The calculation and use of the modification factor

$$\begin{Bmatrix} rMOD = \dfrac{1}{T_{red-tran} + \frac{1}{f_{max}}} & ,\text{if } T_{red-tran} \leq \frac{1}{f_{max}} \\ rMOD = 1 & ,\text{if } T_{red-tran} > \frac{1}{f_{max}} \end{Bmatrix}$$

$$r_{new} = r_{old} \quad rMOD$$

$$\begin{Bmatrix} s_{new} = s_{old} \quad shMOD \\ l_{new} = l_{old} \quad shMOD \\ so_{new} = so_{old} \quad shMOD \end{Bmatrix}$$



The root modification factor *rMOD* as a function of $T_{red-tran}$ for $f_{max} = 2$ and $f_{max} = 4$. Note that the origin is (0,1), rather than (0,0).

Drainage, runoff and irrigation

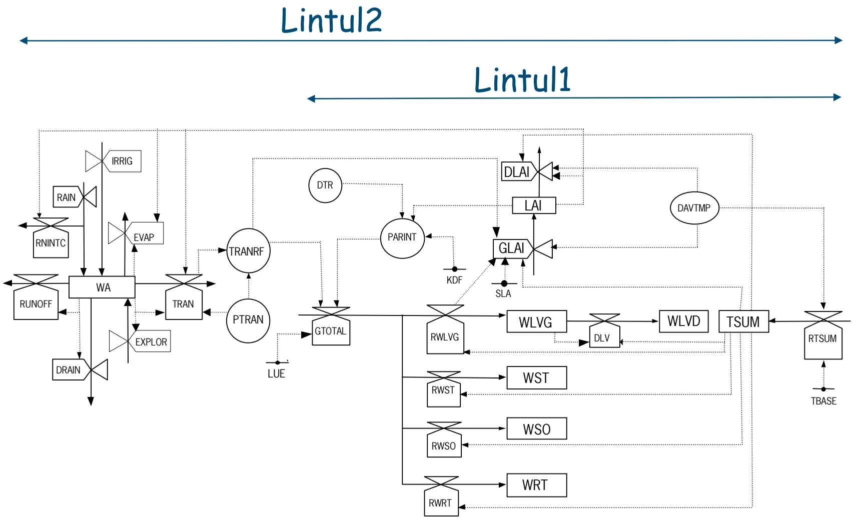
```
SUBROUTINE DRUNIR(RAIN , RNINTC , EVAP , TRAN , IRRIGF , DRATE , DELT ,
$                 WA , ROOTD , WCFC , WCST ,
$                 DRAIN , RUNOFF , IRRIG)
 IMPLICIT REAL (A-Z)
 WC     = 0.001 * WA    / ROOTD
 WAFC  = 1000. * WCFC * ROOTD
 WAST = 1000. * WCST * ROOTD

 DRAIN   = LIMIT( 0., DRATE,   (WA-WAFC)/DELT + (RAIN - RNINTC - EVAP - TRAN)  )

 RUNOFF = MAX( 0., (WA-WAST)/DELT + (RAIN - RNINTC - EVAP - TRAN - DRAIN) )

 IRRIG    = IRRIGF *
             MAX( 0., (WAFC-WA)/DELT - (RAIN - RNINTC - EVAP - TRAN - DRAIN - RUNOFF) )
RETURN
END
```

Relational diagram of LINTUL2 = LINTUL1 + Water



Practical Crop Ecology Thursday February 4, 2010

Exercises (end of Chapter 10B, p. 41-45) concern the following subjects:

- Differences between potential and water limited growth
- Variation of yields between different years
- Sensitivity of results for different soil water-holding capacities
- Effects of different emergence days in rain fed agriculture on yields

Questions are based on information about Lintul1 and Lintul2

Prepare a Word-report of your findings and hand it in <u>no later then</u> Monday February 8, 16.00 hours (Place will be announced in the lecture)

E-mail reports will not be accepted

References used in the slides

Allen, R.G., L.S. Pereira, D. Raes & M. Smith, 1998. Crop evapotranspiration (guidelines for computing crop water requirements). FAO irrigation and drainage paper No. 56.

Briggs L. J. & H. L. Shantz, 1914. Relative water requirements of plants. Journ. of Agr. Res. 3, 1-65.

Koorevaar, P., G. Menelik & C. Dirksen, 1983. Elements of soil physics. Developments in soil science 13. Elsevier, Amsterdam-Oxford. pp.228.

Magrin, G.O., A.J. Hall, S. Castellano & S.G. Meira, 1991. Rooting depth, growth cycle duration, and timing of the jointing stage in wheat: Traits that can contribute to early drought tolerance. In: 'Wheat for the Nontraditional, Warm Areas', by D.A. Saunders (Ed.), Mexico, D.F.: CIMMYT, p.509-515.

Turc, L. (1961). Evaluation des besoins en eau d'irrigation, évapotranspiration potentielle. Ann. Agron. 12 (1): 13-49.
(Estimation of irrigation water requirements, potential evapotranspiration: A simple climatic formula evolved up to date)

Preparation of the Radiation use efficiency Lecture of P.A. Leffelaar

Study time scheduled on Monday February 8

Read from the article
by

Sinclair, T.R. & Muchow, R.C., 1999. Radiation use efficiency. Adv. Agron. 65, 215-265.
(See full article in course information on EDU-web)

- Read pages 215 – 234 including half a page on page 241.
- Have a glace on Table I
- Read half of page 244 about wheat
- Than pages 248- 258 (section V)
- (Total about 30 printed pages out of 44)

Crop Ecology (HPC-21306)