Int. Agrophysics, 2000, 14, 127-134

INFLUENCE OF GROUNDWATER DEPTH AND AVAILABLE SOIL WATER ON EVAPOTRANSPIRATION AND PLANT GROWTH

M. Renger[1], *G. Wessolek*[2]

[1]FG Bodenkunde
[2]FG Standortkunde und Bodenschutz, E-mail: gerd.wessolek@tu-berlin.de
Institut für Ökologie, Technische Universität Berlin, Salzufer 11-12, D-10587 Berlin, Germany

Accepted February 10, 2000

A b s t r a c t. There is a close relationship between available soil water and water consumption as well as plant growth if we assume adequate soil aeration. Transpiration and plant growth increase with an increasing amount of available water, which can be provided either from the soil or from the groundwater, i.e., capillary rise. Interaction between growth and transpiration is based on the stomata regulation of the plant which is involved in both water consumption and photosynthesis. Plants transpire when their stomata are open and at the same time CO_2 diffuses into the plant from the atmosphere. These processes are interrupted when stomatas are closed. Using a calibrated simulation model for cropland, grassland, and pine forest, the actual evapotranspiration E_{act} was determined for various soils and groundwater depth levels. E_{act} increases in the sequence cropland < grassland < coniferous forest. Results show a strong correlation between the ratio of transpiration (E_{act}) and water vapour pressure gradient (Δe) of the air and field measured production of dry matter.

K e y w o r d s: actual evapotranspiration, plant available soil water, dry matter yield, cropland, grassland, coniferous forest

INTRODUCTION

We need to understand relationship between available soil water capacity, water consumption and plant yield before we can use water efficiently in plant production. A number of new contributions to this subject were made in the last few years. They will be described in more detail in the following sections [5-7,9].

THEORY

As far as the relationship between available soil water capacity, evapotranspiration and plant yield is concerned, a general rule applies that, assuming there is adequate soil aeration, the yield is higher the more water is made available to the plant. This is due to the fact that plant stomatas are involved both in transpiration (water consumption) and in photosynthesis (yield development). Plants transpire when their stomatas are open. At the same time CO_2 from the atmosphere can diffuse into the plant and can be used for photosynthesis. Both processes cease when stomatas are closed. One would, therefore, conclude that there is a close relationship within a cultivated species between transpiration and total dry matter as the result of net photosynthesis. Figure 1 shows, however, that this relation exists only for same climatic conditions [8]. Under dry conditions but with the same transpiration level, less dry matter is produced than in moisture areas or years. This shows that both the relationship and dry matter yield are influenced by the climatic features. This can be explained when the processes of transpiration and photosynthesis is shown in the form of diffusion equations [1,3].

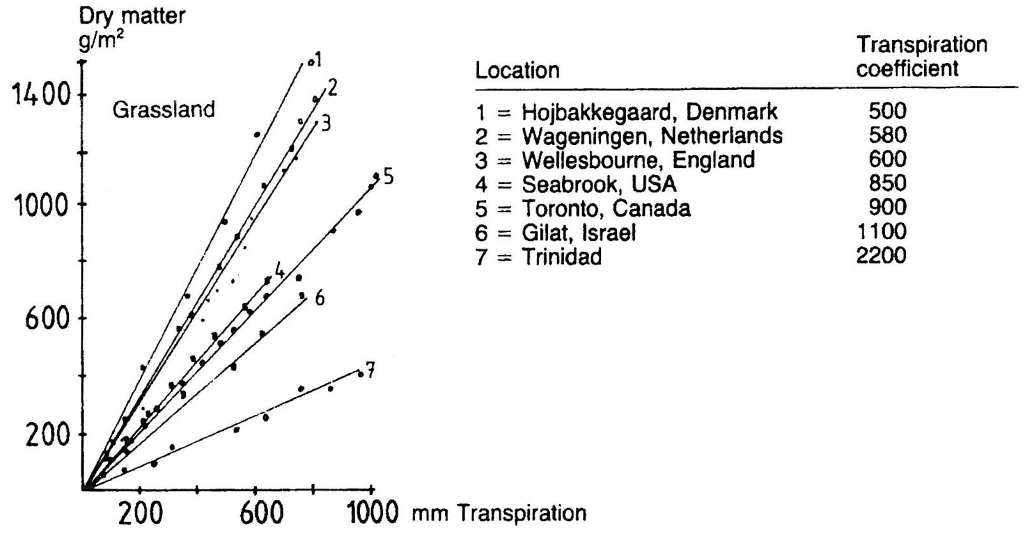

Fig. 1. Relationship between transpiration and dry matter on grassland [8].

Under stationary conditions, photosynthesis can be expressed by the following diffusion equation:

$$\text{Photosynthesis } P = \frac{\Delta CO_2}{r' + r'_s + r'_m}. \quad (1)$$

The following diffusion equation describes transpiration in stationary conditions:

$$\text{Transpiration } E_{act} = \frac{\Delta e}{r_a + r_s}. \quad (2)$$

In the Eqs (1) and (2):

Δe - water vapour saturation deficit between leaf and air,

r_a, r'_a - diffusion resistance to water vapour or CO_2 in the surroundings of the leaf (laminar critical resistance),

r_s, r'_s - stomata resistance to water vapour or CO_2,

r'_m - mesophyll resistance to CO_2,

ΔCO_2 - difference between CO_2 concentration in the air and in leaf.

For Δe we can use the difference between the saturation pressure and the relevant water vapour pressure in the air.

Combining the Eqs (1) and (2), we arrive at:

$$\frac{E_{act}}{P} = \frac{\Delta e (r' + r'_s + r'_m)}{\Delta CO_2 (r_a + r_s)}. \quad (3)$$

However, under field conditions and for the daily time steps, CO_2 and the ratio between various resistance levels can be regarded, to some extent, as constant.

Thus we get the following simple equation for the relation photosynthesis (or dry matter yield) and transpiration:

$$P = A \frac{E_{act}}{\Delta e}. \quad (4)$$

According to the Eq. (4), a close relationship can be expected between the ratio $\frac{E_{act}}{\Delta e}$ and dry matter yield.

The A constant is expressed in kg dry matter $ha^{-1} mm^{-1} hPa$, and can be described as a water efficiency coefficient. The greater the value of A, the more efficiently water is used by the plant. Table 1 shows some A-values for different crops.

Table 1. Water efficiency coefficients (A-values) for different crop

Crop	A-values kg dry matter ha^{-1} mm^{-1} hPa	
Grassland (N-supply = 250 kg ha^{-1})	168	own results
Sugar beets	150	-"-
Summer wheats	135	-"-
Maize	180	-"-
Potatoes	154	[5]
Red cabbage	100	[3]

METHODS

The actual evapotranspiration as a function of soil water available for plants, depth of groundwater and land use were determined for a 30-year period in the region of Hannover and Berlin. Calculations were carried out using a simulation model calibrated for cropland, grassland and coniferous forest [9].

An important factor for the estimation of the actual evapotranspiration and biomass production is the amount of soil water available for plants in the effective root zone PAW_r. For the soils without groundwater influence PAW_r can be calculated from:

(FK (mm dm^{-1}) - PWP (mm dm^{-1})) x effective root zone (dm) with

FK - field capacity (water content at 60 hPa),

PWP - permanent wilting point (water content at 15000 hPa).

For the soils with groundwater depths higher than 1.5-2 m below soil surface, the capillary rise from groundwater to root zone has also to be taken into account [4].

RESULTS AND DISCUSSION

Relationship between available soil water and evapotranspiration

Figure 2 shows the relationship between actual evapotranspiration E_{act} and soil water available for plants of the effective root zone for cropland, grassland and coniferous forest.

E_{act} increases with an increasing amount of soil water available for plants. A comparison of E_{act} for cropland, grassland and coniferous forest in Fig. 1 shows that E_{act} increases in the following sequence: cropland < grassland > coniferous forest.

Figure 3 shows the relationship between the actual evapotranspiration E_{act} and the mean groundwater depth for sugar beets during vegetation period for a sandy soil with plant available water (PAW_r) of 70 mm. The bold line illustrates the mean E_{act} for a period of 30 years. The other curves indicate the range of evapotranspiration values which occur once in ten years. The figure shows a great influence of groundwater depth on water consumption of the plants. In years with low precipitation, a high amount of water moves upward from groundwater into the root zone in the soils with groundwater depths between ≤ 1.0 to 1.5 m.

Figure 4 shows that for the corresponding groundwater depths (≥ 1.5 m) the E_{act} increases with an increasing plant available water in the soil.

Figure 5 shows the relationship between actual evapotranspiration and groundwater depth for a coniferous forest for three different soil types with various amounts of plant available water in the root zone.

Relationship between water consumption and plant yield

The expected close relationship between the ratio $\frac{E_{act}}{\Delta e}$ and dry matter yield is confirmed by the right side of Fig. 6. Although data on the yield was obtained from various areas and for various weather periods, the relationship between the ratio $\frac{E_{act}}{\Delta e}$ and the dry matter yield can be described ina form of a simple regression equation.

Figure 7 shows that the relation between the ratio $\frac{E_{act}}{\Delta e}$ and dry matter yield on grassland is greatly influenced by the application of nitrogen fertilizer. The more nitrogen is applied (in the

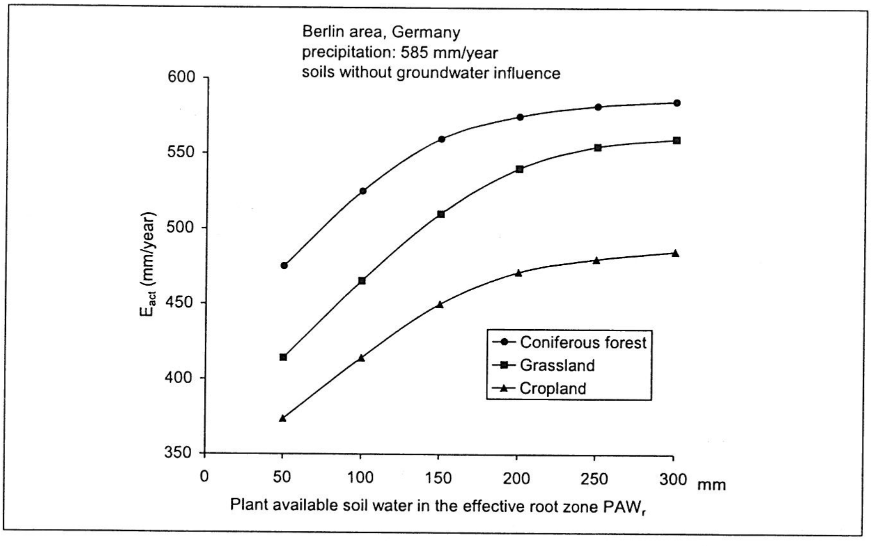

Fig. 2. Relationship between actual evapotranspiration E_{act} and plant available soil water PAW_r for cropland, grassland, and coniferous forest.

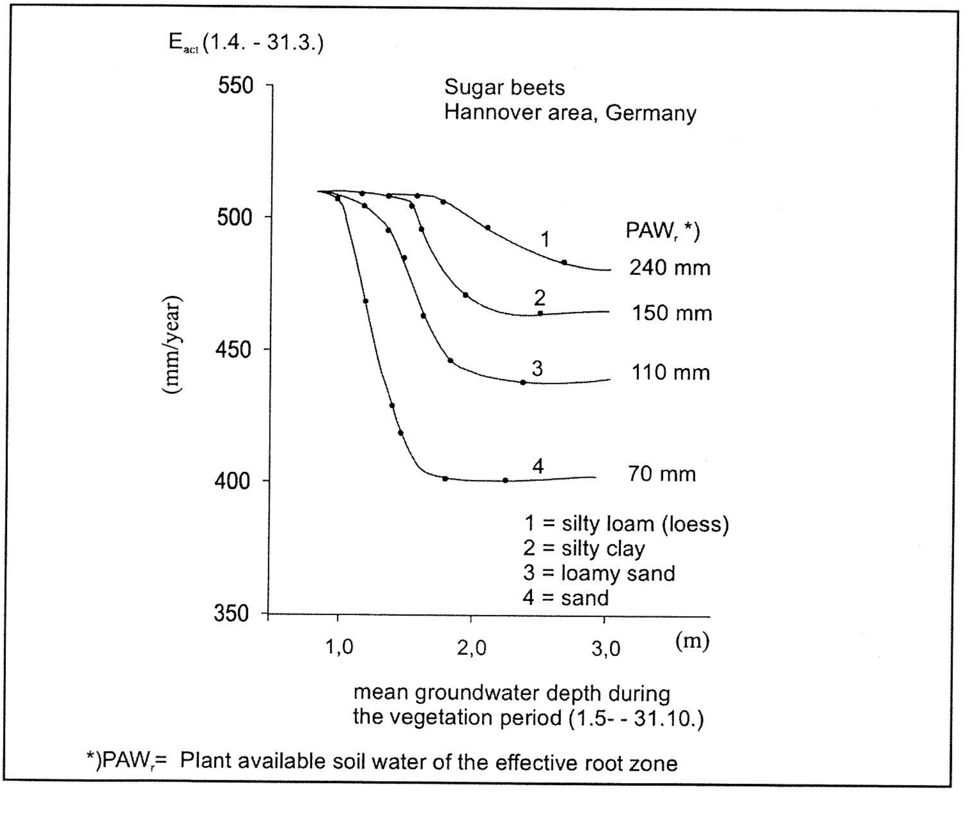

Fig. 3. Relationship between actual evapotranspiration E_{act} and groundwater depth for soils with different amounts of plant available soil water (PAW_r) for sugar beets.

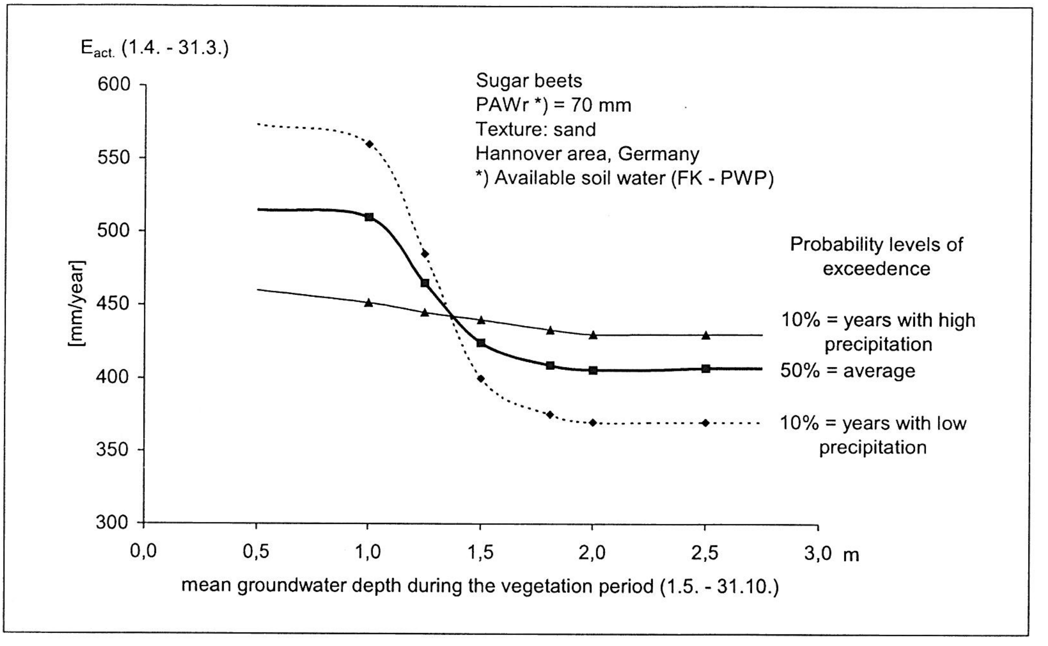

Fig. 4. Relationship between evapotranspiration E_{act} and groundwater depth for sugar beets and for different probability levels of exceedence.

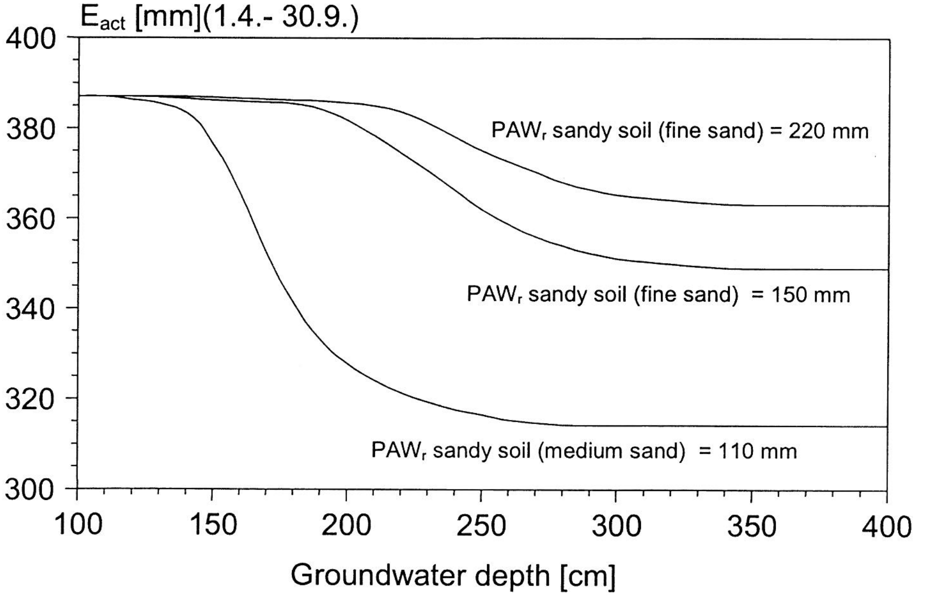

Fig. 5. Relationship between actual evapotranspiration E_{act} and groundwater depth for soils with different amounts of plant available soil water in the effective root zone (PAW_r) for coniferous forest.

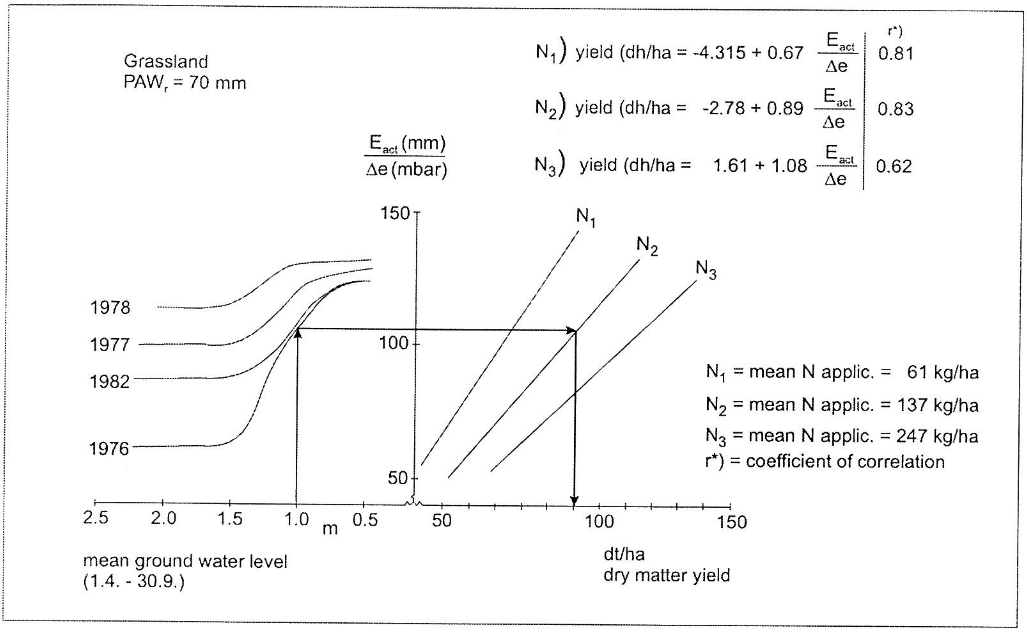

Fig. 6. Relationship between groundwater level, the quotient of transpiration E_{act}, water vapour saturation deficit Δe, and dry matter yield on grassland as a function of nitrogen fertilizer application.

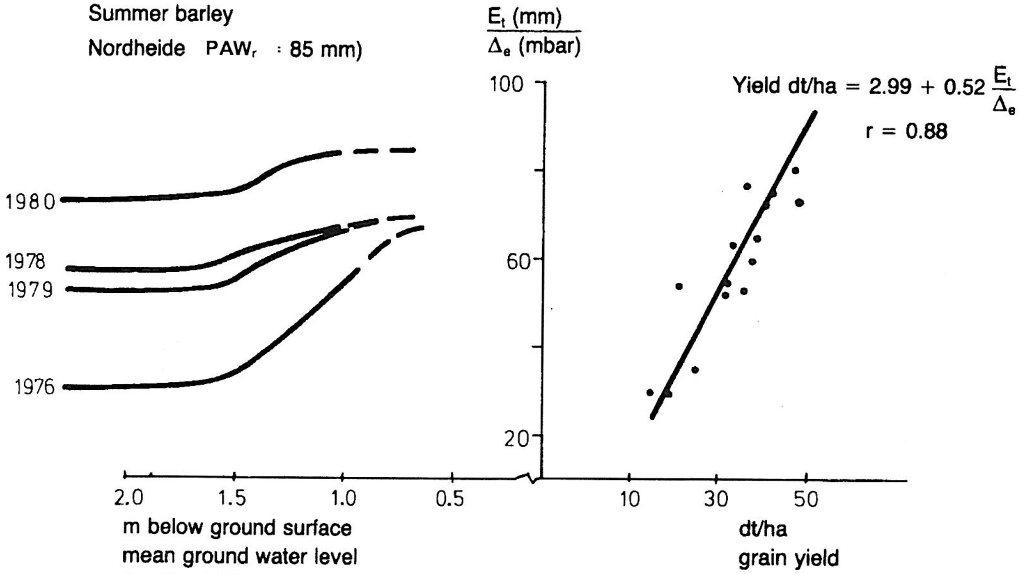

Fig. 7. Relation between ground water level, the quotient of transpiration E_t and water vapour saturation deficit Δe, and the grain yield for summer barley (mean nitrogen fertilizer application = 105 kg ha^{-1}).

range of 60 to 250 kg N ha^{-1}), the more efficient the soil water use by plants.

There is also a close relationship between the grain yield for cereal crops and the ratio $\frac{E_{act}}{\Delta e}$ (see Fig. 7). Due to a good correlation between Δe and the potential evapotranspiration E_{pot}, it is also possible to use the ratio $\frac{E_{act}}{E_{pot}}$ instead of $\frac{E_{act}}{\Delta e}$ for the calculation of plant yield. In this case E_{pot} should be calculated using the HAUDE formula [2].

For the pine forest types of Berlin, a following relationship was found between the ratio $\frac{E_{act}}{E_{pot}}$ of the actual and previous years (t-n) and plant growth, i.e., annual ring growth (RG_t):

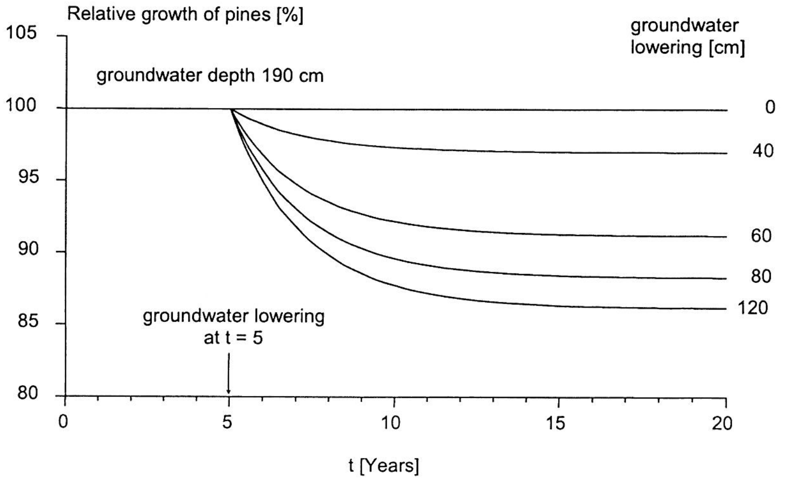

Fig. 8. Influence of groundwater lowering on the relative growth of pines (fine sandy soil, area Berlin).

$$RG_t = 24.38\ X(t) + 50.70\ X(t\text{-}1) + 36.91\ X(t\text{-}2) + 23.86\ X(t\text{-}3) + 30.23 \quad (r = 0.69)$$

with

RG_t = annual ring growth (1/100 mm),

$X(t) = \frac{E_{act}}{E_{pot}}$ of the actual year t,

$X(t\text{-}1) = \frac{E_{act}}{E_{pot}}$ of the t-1 year,

$X(t\text{-}2)\ t = \frac{E_{act}}{E_{pot}}$ of the t-2 years,

$X(t\text{-}3)\ t = \frac{E_{act}}{E_{pot}}$ of the t-3 years.

The equation shows that the mean ring growth can be calculated from the ratio $\frac{E_{act}}{E_{pot}}$ of the actual year and those of the three previous years, respectively.

This relation was used to calculate the influence of a decrease in groundwater level on the relative growth of pines in the area of Berlin for a sandy soil with a plant available water capacity of 150 mm. The mean growth decreases by 15 % if the groundwater depth declines from 190 to 310 cm (Fig. 8).

CONCLUSIONS

Under the same climatic conditions, actual evapotranspiration and biomass production depend on the amount of plant available water (available soil water in the root zone plus capillary rise). Both, evapotranspiration and yield, increase with an increase in the amount of plant available water, whereby the relationship between transpiration and dry matter yield is also influenced by the climate. This can be explained by expressing the processes of transpiration and photosynthesis in the form of diffusion equations. A plant specific relation exists between water consumption and biomass production, which can be quantified by the ratio: $\frac{E_{act}}{\Delta e}$ or $\frac{E_{act}}{E_{pot}}$, respectively.

The lower the water vapour saturation deficit (Δe or E_{pot}), the more efficiently water is used by the plants.

Saturation deficit should therefore be kept as low as possible. However, under the North European climatic conditions the chances for selecting saturation deficit are relatively law. In arid regions, however, saturation deficit can be made to play a more important role by selecting the species to be grown and the time of cultivation. In the arid regions it is also possible to influence saturation deficit actively by growing agricultural crops under the shade of trees.

At a given saturation deficit, the yield can only be increased by increasing transpisration. A high transpiration rate is achieved when soil water is offered to the plant in an easily absorbable form. This is an important factor in the watering of crops. In dry years with a high saturation deficit plants must be watered earlier than in average years, if a certain yield level is to be reached.

The approach described in the present paper allows for the quantification of the relation between simple parameters for the evaluation of soil water economy and plant yield. Hence, on the basis of soil physical characteristics soil scientists and plant growers are able to predict those parameters that can easily determine the probable effects of the treatments that change soil water economy on plant yield.

REFERENCES

1. **Bierhuizen J.F., Slatyer R.O.:** Effect of atmospheric concentration of water vapour and CO_2 in determining transpiration-photosynthesis relationships of cotton leaves. Agric. Meteor., 2, 259-270, 1965.
2. **Dyhle C., Glugla G., Golf W., Hoyningen-Huene J., Kalweit H., Olbrich H.D., Richter D., Wendling U., Wessolek G., Wittenberg H.:** Ermittlung der Verdunstung von Land- und Wasserflächen. DVWk Merkblätter, 238, 1996.
3. **Feddes R.A., Kowalik P.J., Zaradny H.:** Simulation of field water use and crop yield. Simulation Monographs, Wageningen, Centre f. Agricult. Publ. a. Docum, 1978.
4. **McKeague, J.A., Eilers R.G., Thomasson A.J., Reeve M.J., Bouma J., Grossman R.B., Favrot J.C., Renger M., Strebel O.:** Tentative assessment of soil survey approaches to the characterization and interpretation of air-water properties of soil. Geoderma, 34, 69-100, 1984.
5. **Renger M.:** Water consumption and plant yield. Plant Research and Development. Inst. für Wissenschaftl. Zusammenarbeit, 25, 120-127, 1987.
6. **Riek W., Wessolek G.:** Wasserhaushalt-Zuwachsverhalten von Kiefern und Eichen im Raum Berlin. Bodenökologie und Bodengenese, Heft 14, Techn. Universität Berlin, 1994.
7. **Rijtema, P.E., Enrödi, G.:** Calculation of production of potatoes. Neth. J. Agric. Sci., 18, 26-38, 1970.
8. **Stanhill G.:** The relationship between climate and the transpiration and growth of pastures. Physiology of Herbage Growth, 293-296, 1962.
9. **Wessolek G.:** Einsatz von Wasserhaushalts- und Photosynthesemodellen in der Ökosystemanalyse. Landschaftsentwicklung und Umweltforschung, Techn. Universität Berlin, 61, 1-168, 1989.