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EVAPOTRANSPIRATION AND PLANT PRODUCTION DIRECTLY RELATED TO GLOBAL RADIATION

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This article is based on the thesis, that when sun radiation is not in excess and advected energy supply can be neglected, then for periods of plant cover and growth, both evapotranspiration and plant production are linearly and strongly related to global radiation.
The regression coefficients will depend also on plant, soil and other climatic factors, but global radiation will be the dominating factor for potential evapotranspiration and potential plant production in given regions.

Sun radiation provides energy for evapotranspiration and photosynthesis. The two processes are linked together due to regulation of the stomata openings. A linear relationship between transpiration and plant yield has been shown by several scientists: de Witt (1958), Penman (1962), Rijtema (1966 and 1968), McCaughey (1968) and others. Evans (1973) has reviewed work on the effect of light on plant growth and yield. From a Unesco seminar in Sweden, a number of papers on plant response to various climatic factors have been published, edited by Slatyer (1973). The present paper was presented at a seminar organized by the Nordic Association of Hydrology in January 1974.

TECHNIQUE AND METHODS

The Hydrotechnical Laboratory has a Climate and Water Balance Station 20 km west of Copenhagen where the most important climatic factors are recorded and punched on tape every 10 minutes throughout the year. For recording global radiation and reflection, Kipp & Zonen solarimeters are used as sensors, and for net radiation a net radiometer constructed at the laboratory is used. Evaporation from the water surface is recorded by the use of two types of sunk evaporimeters having 1/3 and 12 m^2 water surface, respectively. Evapotranspiration is recorded by two weighing lysimeters each having 2 m^2 soil area covered with grass and by water balance studies in lysimeter and field investigations using the neutron method for determining soil moisture. Potential evapotranspiration is estimated as evaporation from a 1/3 m^2 sunk evaporimeter nearly filled with sand to avoid convection, and by the method of Penman (1948), Aslyng (1965) and Kristensen (1971). For the Penman method is used the equation:

$$E_p = \frac{\triangle\,(R_n - Q_s)}{L\,(\triangle + \gamma)} + \frac{\gamma\, f(v)\,(e_m - e)}{\triangle + \gamma}$$

where

E_p = potential evapotranspiration, mm day^{-1} (24 hours)
R_n = net radiation, cal cm^{-2} day^{-1}
Q_s = heating of soil, cal cm^{-2} day^{-1}
L = latent heat of vaporization, 59 cal cm^{-2} mm^{-1}
$\triangle$ ≡ slope of vapor pressure curve, mb°C^{-1}
γ = psychrometer constant, approx. 0.66 mb°C^{-1}
e_m-e ≡ vapor pressure deficit at 2 m height, mb
f (v) = 0.26 (0.5 + 0.54 v), mm H_2O mb^{-1} day^{-1}
v = wind velocity at 2 m height, m sec^{-1}

Lysimeter and field investigations with well-developed and growing crops, (grass, barley and root, depending on season) have shown, that potential evapotranspiration determined by soil moisture study and estimated from the above equation gives results in close agreement with evaporation from the above-mentioned evaporimeter with sand, (Kristensen 1971).

NET RADIATION AND GLOBAL RADIATION

In Fig. 1 is shown the relation between monthly values of net radiation above short well-growing grass and global radiation, 1970–73. Different symbols for

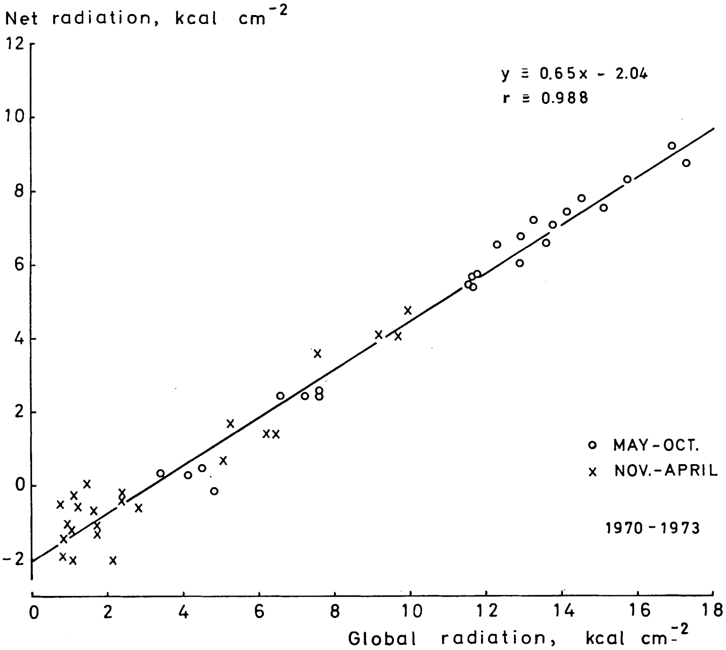

Fig. 1.
Net radiation related to global radiation, monthly, 1970–73.

summer and winter months are used. Values for November-February are small and snow cover occurs occasionally, so that deviation from the linear relationship occurs, but is of little importance in relation to evapotranspiration and plant yield with the main figures for May-September. Fitzpatrick & Stern (1973) showed net radiation as a linear function of global radiation and atmospheric transmissivity.

EVAPOTRANSPIRATION AND GLOBAL RADIATION

In Fig. 2 is shown the relation between monthly values of potential evapotranspiration, E_p, and global radiation, R_g, for 1970–73. It is found that $E_p = -5.32 + 7.33\ R_g$, kcal cm^{-2}, with especially good agreement during the growth period May-October. The 4 + 4 largest values shown by crosses are for April and March, respectively. The Penman E_p for grass and E_0 for water are often found larger than observed values in springtime (Aslyng 1965). The reason may be

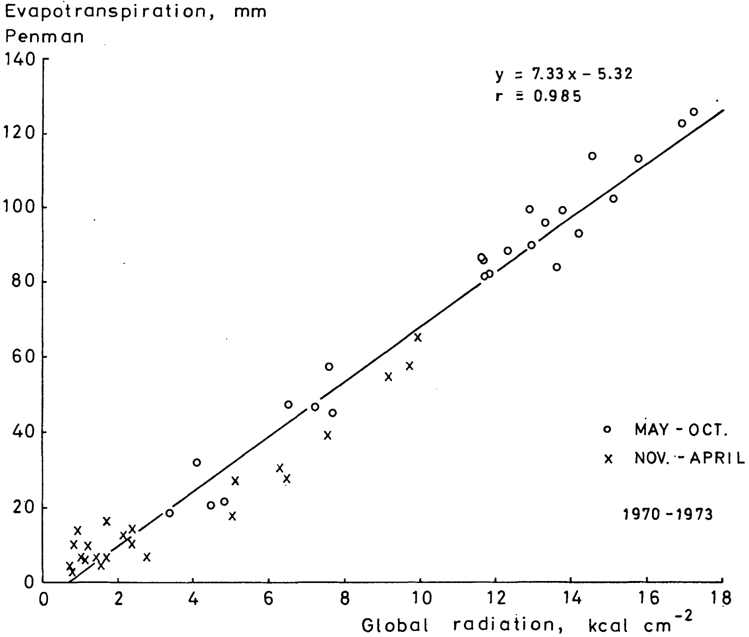

Fig. 2.
Potential evapotranspiration (Penman) related to global radiation, monthly, 1970–73.

insufficient leaf area and low air and soil temperature restricting photosynthesis and evapotranspiration. For E_0 it could be due to insufficient adjustment for energy to heat the convecting water, the tank and the surrounding soil.

During March and April most soil areas in Denmark are bare and wet, having a low albedo and a relatively large evaporation – especially in combination with spring tillage operations.

In Fig. 3 is shown evapotranspiration from lysimeter investigations with ryegrass (Jensen 1974), well-fertilized and surface-irrigated with 20 mm water when 20 mm deficit in field capacity was estimated. During periods of rainfall, the lysimeters are automatically covered by a glass roof, (Kristensen & Aslyng 1971).

The potential evapotranspiration, estimated as the linear function of global radiation and according to Penman, is also shown in Fig. 3. The evapotranspiration from ryegrass (Lolium perenne) determined by frequent soil water balance studies using the neutron method is marked, and for each of the 3 cuttings indicated by arrows, a linear relationship parallel to the E_p line is found and shown.

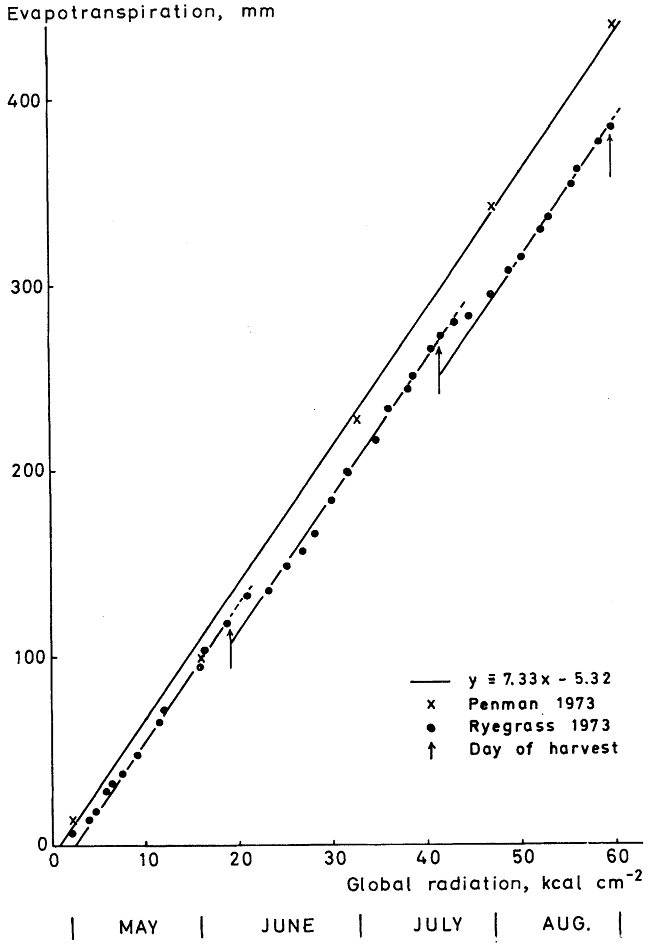

Fig. 3.
Evapotranspiration from ryegrass (Jensen) and potential evapotranspiration (Penman) related to global radiation.

Irrigation just after cutting gives evaporation from the soil which, together with evaporation from the fresh stem cuts, maintains the rate of water consumption for some time after cutting. Later, a reduced rate is observed until sufficient leaf area has developed and the evapotranspiration again has reached the potential level. For each cutting, the observed "potential evapotranspiration" is reduced by 15–20 mm, corresponding to 2–3 kcal cm^{-2}.

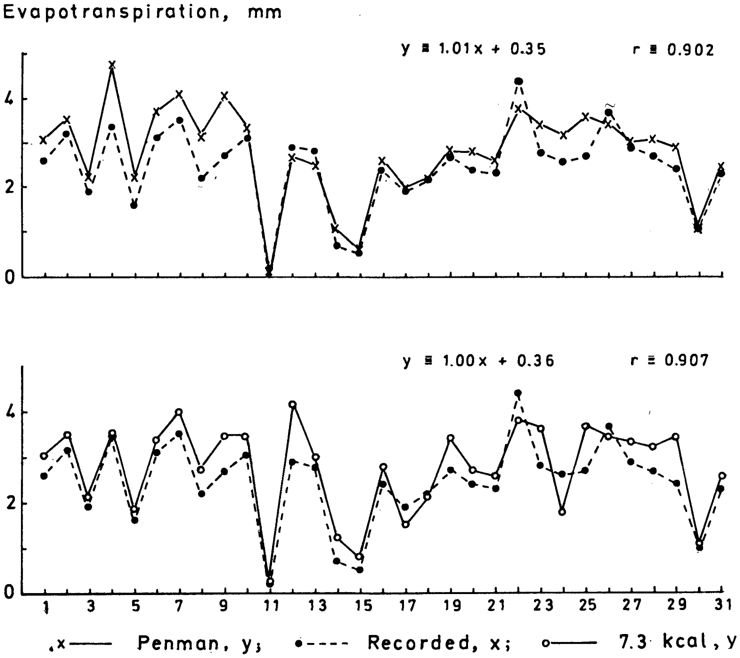

Fig. 4.
Evapotranspiration from short grass related to potential evapotranspiration (Penman) and to global radiation, daily August 1972.

In Fig. 4, daily values of potential evapotranspiration, estimated according to Penman and to global radiation, are compared with evapotranspiration from irrigated short grass (8–14 days after cutting) recorded by weighing lysimeters for August 1972. The recorded evapotranspiration may not be fully at potential level due to insufficient leaf area. In spite of large variation from day to day, good agreement is found. The two methods of estimated potential evapotranspiration are in very good agreement.

PLANT PRODUCTION AND GLOBAL RADIATION

In Fig. 5 is shown data from lysimeter investigations on ryegrass (Lolium perenne) yield in two parallel series each with cutting intervals of 4 and 6 weeks from May 1 to October 15, 1968, (Kristensen 1974). The grass was amply fertili-

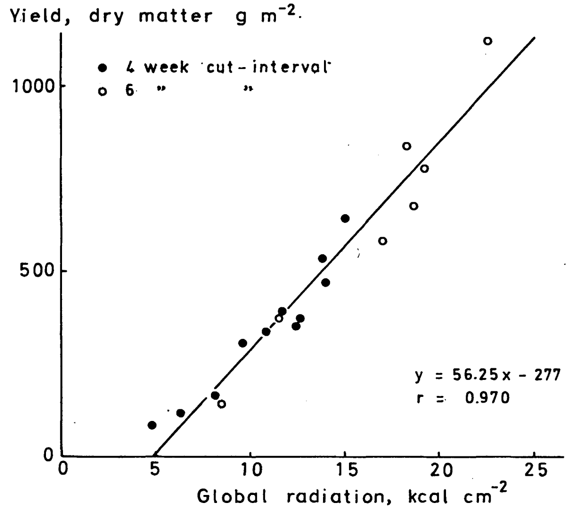

Fig. 5.

Yield of dry matter of ryegrass for periods of 4 and 6 weeks (Kristensen) related to global radiation May 1 to October 15 1968. The 4 smallest yields are harvested in August, September or October.

zed and irrigated. It appears that the dry matter harvested is a linear function of the global radiation, independent of cutting interval and time of season. For each cutting, however, there is a "loss" of about 5 kcal cm^{-2} which must be due to insufficient leaf area in the period after cutting.

The global radiation from May 1 to October 15 was 63 kcal cm^{-2} and the total dry matter harvest was 2.0 and 2.3 kg m^{-2} at 4 and 6 week intervals, respectively. With totals of 6 and 4 cuttings and a loss of 5 kcal cm^{-2} per cutting, the loss amounts to 30 and 20 kcal cm^{-2} and an effective amount of global radiation of 33 and 43 kcal cm^{-2}, respectively.

The ratios $33 \cdot 100^2/2.0$ and $43 \cdot 100^2/2.3$ indicate a global radiation requirement of about 165 000 and 187 000 kcal, respectively, for each kg of dry matter harvested. If one kg of dry matter represents 3500 kcal, it corresponds to a global radiation energy yield of 2.1 and 1.9 %. Without reduction for cutting loss it would be 1.1 and 1.3 % for 4 and 6 week intervals, respectively. The optimum cutting interval cannot be concluded from this. That would be better chosen on the basis of quantity of global radiation than on a period of weeks. Respiration increases absolutely, but also relative to crop size. Crop quality should also be considered.

DISCUSSION

The high correlation found between potential evapotranspiration estimated by the Penman method and from global radiation on a daily basis, is not fully explained by the linear relationships between net radiation and global radiation. It indicates that the aerodynamic part also is correlated with the global radiation.

McCaughey (1968) found for alfalfa in Ontario a strong correlation for daily E_p estimated by the Penman method and from net radiation R_n, which supports the present findings. He found that 82 % of R_n was used for E_p – and states 80–90 % – which also agrees with the present findings. Here it is found that 43 % of global radiation is used for E_p, since 0.43 cal cm^{-2} $R_g \equiv 59 \cdot E_p$ and $E_p = 7.3$ kcal cm^{-2}. As net radiation in summer months amounts to about 50 % of global radiation, the consumption corresponds to about 85 % of R_n.

Arkley (1963) and Rijtema (1968) found, for given crops, very firm correlation between yield and transpiration obtained in different years and regions and under different conditions, when transpiration was corrected for differences in atmospheric humidity, which supports the assumption that the aerodynamic part of the Penman equation is also closely related to the global radiation. Under conditions where appreciable amounts of advected energy are received, the Penman and the global radiation method will not give results in agreement with the real potential evapotranspiration. The aerodynamic part of the Penman equation is, however, sensitive to advection. The global radiation principle combined with soil and plant factors may also be applied in estimating actual evapotranspiration under conditions of restricted water supply if combined with plant and soil factors.

The photosynthetic active fraction (0.4–0.7 μm) of the global radiation is almost constant, being about 50 % of the global radiation. When light energy is a yield limiting factor, a linear relationship between yield and global radiation can be expected. For different regions, the regression coefficient for the same crop may differ due to other factors. Under comparable conditions different plant species and strains will result in different regression coefficients due to differences in genetic abilities.

CONCLUSIONS

1. Potential evapotranspiration determined by soil water balance study under well-developed and growing crops and by the Penman method is found to be strongly correlated even for daily values.

2. Potential evapotranspiration is found to be satisfactorily determined directly from global radiation.

3. The dry matter yield of a grass crop is found to be a linear function of global radiation throughout the growth period May-October. For each cutting, about 5 kcal cm^{-2} is found to be ineffective due to insufficient leaf cover. Cutting intervals of 4 weeks gave a lower total yield than intervals of 6 weeks.

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