POTENTIAL AND REAL EVAPOTRANSPIRATION — THEIR USE AND PRACTICAL APPLICATION

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Introduction

Regular and increased agricultural productivity by virtue of better moisture utilization requires control over the supply of water to plants. Irrigation is relatively the simplest means of achieving this. The proper use of irrigation assumes knowledge of the water requirements of vegetation at all times. These requirements can be determined from the moisture budget. Basically, the moisture budget is as simple as a financial budget. Theoretically, it is sufficient to evaluate the debits and credits of the soil-plant system to maintain conditions of ideal moisture supply by controlling the credits in the system.

Methods of scheduling irrigation have been dealt with by various authors. To facilitate subsequent discussion on the matter, the definition and significance of terms that continually intervene in the establishment of moisture budgets viz potential evapotranspiration (ETP), and real evapotranspitation (ETR) are briefly reviewed. An attempt is also made to clarify the agronomic interest of these terms by describing their relationship with productivity.

The authors hope that out of the various systems of scheduling irrigation illustrated by the entirety of limiting factors encountered at a practical level, a clearer understanding will emerge of the essential problems to be solved.

Evapotranspiration

The term evapotranspiration includes evaporation from the soil and transpiration from plants. From a physical point of view the same phenomenon is involved in the transformation of water from the liquid to the gaseous phase with a concomitant utilization of energy (597 millithermies for 1 kg of water, or the evaporation of a layer of water, 0,001 m thick and 1 m^2 in area, or 59,7 calories per 1 mm x 1 cm of water).

Evapotranspiration, therefore, depends on the amount of energy available at the evaporating surfaces. In the absence of heating or cooling, this available energy has two sources: net radiation and advection.

(a) The net radiation of all surfaces depends on their reflective characteristics, their temperature, and on absorbed radiation from neighbouring bodies, the atmosphere, and the sun. With an increase in the number of above-ground surfaces (example : leaf area exceeding the area of soil by four times) the net radiation per unit of soil surface approaches a limit that is essentially a function of solar and atmospheric radiation.

(b) Advection, or energy brought by ambient air, for a surface of given aerodynamic characteristics depends on the relative humidity of the air, and the rate at which the air is replaced, ie wind. With an increase in the number of aboveground surfaces the amount of advective energy reaching the soil surface increases inversely to the net radia- is not independent of conditions in areas surrounding the zone considered, since the greater the evaporation in these areas the higher will be the relative humidity of the air, and the lower will be the advective energy.

The cumulative value of the two sources of energy detion that tends towards a limit. However, advective energy pends, therefore, on the climatic conditions (net radiation, windspread, humidity of the air), the characteristics of the surface (reflective capacity at different radiations) and reaching soil surface increases inversely to the net radia- because of advection, the extent of the exchanging surfaces.

Usually when one considers large surfaces like fields or regions, correlations are established between the above two sources of energy which enable the evaluation of total available energy from a limited number of terms included in the energy budget. The margins of error possible and the limits of such calculations are, however, obvious from the preceding discussion.

Evapotranspiration or the correspondent available energy will, nevertheless, be dependent on the situation of the water on the evaporating surface. Free water is in equilibrium with saturated (relative humidity H 100%) air (in the absence of evaporation or condensation); water bound by absorption to a body (capillarity) or by physico-chemical action (saline solution) is in equilibrium with non-saturated air (H 100%). Under similar conditions of the external medium, free water evaporates more easily than bound water. Evaporation may cease if the binding forces are strong enough.

In leaves the cuticle or stomatal canal provides, according to circumstances, a greater of lesser resistance to the outward diffusion of water vapour evaporated within the leaf. When the stomates are completely open the process operates as though the leaf area corresponds to an equivalent surface of almost free water. With the partial closure of stomates the process operates as though the leaf area corresponds with water partially bound to vegetative material.

Thus, evapotranspiration is expressed as a function of the size of the evaporating surface, the state of the free or bound water, and of the available energy.

ET = f (area of evaporating surface, liaison of the water, available energy)

The available energy can be assimilated according to a 'demand' imposed by the climate; the system 'surface-bound water' being an 'offer'.

When energy is the limiting factor of ET ('demand' inferior to 'offer') ET is maximal for a given climate; potential evapotranspiration ETP is thus defined.

When the system 'surface-bound water' is the limiting factor, evapotranspiration is inferior to potential evapotranspiration.

Consequently, real evapotranspiration ETR is by definition inferior to or at the most equal to potential evapotranspiration ETP.

If one is careful to define the climatic scale of reference associated with the scale of evapotranspiration, one arrives at a definition of ETP and ETR specific to the scale considered.

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We can examine the application of these definitions to actual examples of very different scale.

A ETP

(a) By definition a free water surface evaporates at *potential evapotranspiration for a given climate at the scale considered* (eg disc of Picbe evaporimeter (a few cm^2) — class A pan (a few dm^2) — lake — sea.

(b) Bare soil with surface wet by rain evaporates at ETP.

(c) A leaf with completely open stomates evaporates at ETP since the internal cellular sap corresponds to very weakly-bound water (the permanent wilting point corresponds to H 98,6%).

(d) A dense vegetal cover in full growth and well supplied with water contains many exhange surfaces leaf area index LAI for example greater than 4). Even when there is stomatal regulation the 'offer' of the system (combination of the surfaces and bounding of water) can remain greater than the climatic demand (net radiation and advection) at the level of the total vegetal cover. The ETR of this cover is then limited by the available energy, and corresponds to ETP.

B ETR

The 'offer' is inferior to the 'demand'. This insufficency of the 'offer' may result from inadequate leaf area, from the bonding of water or a combination of these two factors.

(a) The surface of bare soil dries rapidly after rain. The slight drying of even a thin surface layer of soil results in an increase in the bonding of water and reduced evaporation. Thickening of this layer of 'mulch' only further reduces evaporation.

(b) A leaf with partially closed stomates has a lower real evapotranspiration (ETR) than the ETP at this scale.

(c) A young crop that has not reached full leaf canopy (LAI 1) is likely to have a real evapotranspiration inferior to the ETP at the scale of the cover, even if the stomates are completely open.

(d) A crop covering the soil completely (LAI 1), but with a strong bond with its water will have an ETR inferior to ETP. This strong binding of water (eg closed stomates) may result either from the degree dessication of the soil during vegetative growth, a physiological crisis, or normal evolution in the development of the crop (eg maturity).

C Evolution of ETR and ETP

In order to follow the evolution of the moisture budget with time it is possible to review the preceding considerations graphically (Figure 1). The time corresponding to a vegetative cycle is represented on the abscissa while real evapotranspiration or potential evapotranspiration expressed in height of water or equivalent energy is represented on the ordinate. We will consider an example at the scale of a crop growing in France during the spring—summer period. The climate ETP 'demand' thus has a generally increasing trend.

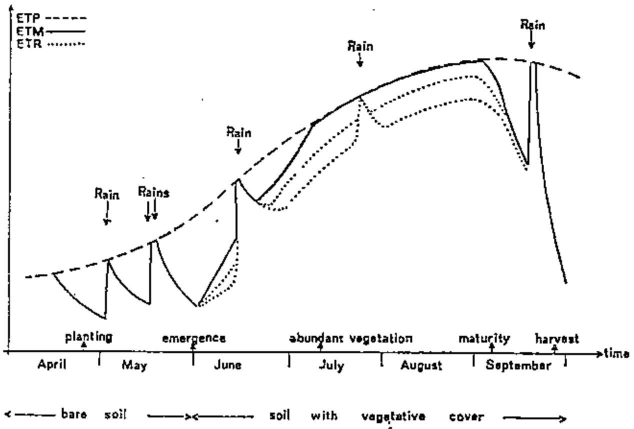

Fig 1 Evolution of the moisture budget with time

After planting the soil remains bare. In the absence of rain evaporation is weak or even negligible. After rain, evaporation is equivalent to ETP for a few hours and then diminishes very rapidly.

During the early stages of leaf development the total evaporating surface of the plant is limiting. Even if the stomates remain open, ETR at the scale of the crop is inferior to ETP. After rain ETR may momentarily be equivalent to ETP.

When extensive leaf development is achieved ETR can equal ETP even if stomatal regulation intervenes. Two cases are then distinguished:

1 The soil is well supplied with water, leaf area is well developed, and stomatal regulation is relatively weak: ETR = ETP.

2 The soil is poorly suplied with water, leaf area is poorly developed, and stomatal regulation is more severe ETR < ETP.

When the plant matures, events take place as though the binding of water was increasing. ETR becomes very weak or even almost non-existent, and only rains cause ETR to be momentarily equal to ETP.

One understands that when considering this representation of ETR and ETP the model terms may vary *ad infinitum* according to the duration and intensity of the factors involved (rain — climatic demands — soil moisture reserves — natural growth laws).

D Agronomic utilisation

For agronomic purposes one is thus led to define three main terms:

Potential evapotranspiration: ETP — energy being the only limiting factor, corresponds to a climatic parameter. *Real evapotranspiration: ETR* — energy is replaced by the system 'surface-bound water' as the limiting factor.

By definition ETR $\leq$ ETP. When considering real evapotranspiration ETR we shall distinguish: *maximum real evapotranspiration ETM*, the development of the exchange surfaces and the physiology of the crop when it is adequately supplied with water from the soil, defined ETM for a given climate (ETP)* ETM $\leq$ ETP.

Reduced real evapotranspiration: ETR — inadequate supply of moisture from the soil induces either a reduction in exchange surfaces, or a more severe stomatal regulation or a combination of both factors.

$$ETR < ETM \leq ETP$$

If one could dispose of plant groups with staggered periods of development, the ETP could be defined as the envelope of the ETM's (Figure 2).

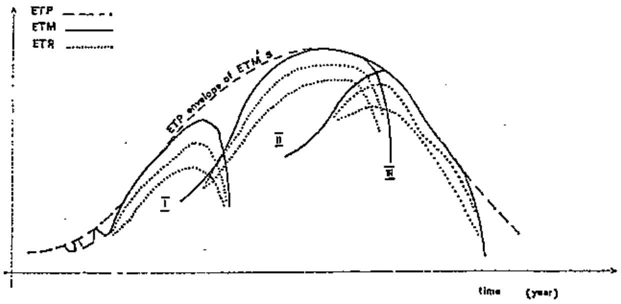

Fig 2 Potential evapotranspiration as the envelope of maximum real evapotranspiration

One notes immediately a difficulty in the measurement of ETP; the choice of a plant giving an ETM as close to ETP over an extended period of time. One must, therefore, choose a convenient type of variety.

It is moreover, important to ensure that the precisely defined surface used for measurement (lysimeter) is treated in an identical manner, to the guard area that surrounds it. Advection affecting the lysimeter would falsify the significance of results. These constitute the main difficulties in the evaluation on ETP.

Climatic formulae derived for estimating ETP generally only take a limited number of climatic parameters into consideration which are more or less correlated with the available energy. Consequently, their application on a local scale is subject to inaccuracies when compared with reality.

It is evidently necessary to limit the sources of error in the definition of ETP. It would, however, be illusory to want to define this value precisely from a formula or a plant even for periods of the order of a decade (10 days).

This evaluation of ETP is, nevertheless, an essential step. We will see later that optimum irrigation practice should be conducted, at least at certain times, with the view of achieving a consumption of water corresponding to ETM. It will, therefore, be necessary with time to establish a coefficient of flux from ETP to ETM to evaluate ETM as a function of ETP that we can already evaluate from climatic data. This coefficient characterises the development of the plant in conditions of abundant moisture supply for a given climate.

One difficulty lies in the starting point of the moisture budget. When the soil is bare evaporation depends of course on the ETP 'demand', but also on the frequency, duration and intensity of rains. Often we will have to be satisfied, for a given time and location, with a mean coefficient of reduction of ETM in relation to ETP.

Hence despite the difficulties mentioned, scheduling will be based essentially on the evaluation of ETP, and the determination of a plant coefficient enabling the evaluation of ETM.

Relations and productivity

Problems and some definitions

Amongst the terms that have been defined, maximum real evapotranspiration ETM presents itself, therefore, as the basis for establishing a moisture budget on the plot. Irrigation management aims at the elimination of all forms of drought and its effects and comes back to maintaining the supply of water to the land so that the crop can achieve ETM at all times. Under these conditions maximum production is assured . . . but also at maximum expense.

One can ask oneself to what extent is it necessary to maintain water supply, at this level, and at all times to obtain this production. Similarly one can question whether water made available to, and used by the crop, maintains the same efficiency when ideal conditions of supply (ETM) are approached. This comes back to the question of marginal profitability.

These problems are simple to formulate, but complex to resolve. To avoid possible confusion in the interpretation of experimental solutions it is, therefore, important to define clearly the terms involved.

The condition of drought manifests itself, and is characterised by, the difference (Δ ET) between actual consumption (ETR) and maximum consumption (ETM)

$$ETM - ETR = \Delta\ ET$$

Δ ET is a deficit of evapotranspiration. It can be evaluated either for a complete vegetal cycle, for a period of growth or for a climatic period.

The intensity of the drought represents itself for the period considered by the relation $\frac{\Delta\ ET}{ETM}$. This index of drought can vary from 0, no drought, to I, total drought.

The influence of Δ ET or of $\frac{\Delta\ ET}{ETM}$ can be analysed from two distinct aspects

(i) influence of the functioning of the plant particularly on photosynthesis (DM) or the total production of dry matter (DM) (fruit plus leaves plus stems plus roots)

In this case, Δ ET or $\frac{\Delta\ ET}{ETM}$ will be compared with

$\Delta\ \phi = \phi\ \max - \phi$
or $\Delta\ DM = DM\ \max - DM$
or ϕ max or DM max obtained under conditions of ETM
ϕ or DM obtained under conditions of ETR

we will have the same with $\frac{\Delta \phi}{\phi\ \max}$ or $\frac{\Delta\ DM}{DM\ \max}$

an index of the reduction in production.

(ii) influence on the commercial yield R (fruit or leaves or roots) in this case, Δ ET and $\frac{\Delta\ ET}{ETM}$ will be compared with

$$\Delta\ R = R\ \max - R$$
and $\frac{\Delta\ R}{R\ \max}$

The two approaches are complementary.

A Relationships between transpiration and photosynthesis

Before examining what happens at field scale let us examine the relationship that exists between transpiration and photosynthesis at the level of a leaf or a plant.

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*Available energy and soil water are not limiting factors; the limiting factor is a physiological characteristic of the plant under consideration (growth and development).

At this level we can define maximum transpiration (TrM), which at this scale is similar to ETM. It is independent of the moisture supply and dependent on the characteristics of the exchange surface and ambient micro climate. Let us assume that moisture becomes limiting. Moisture losses from the leaves are no longer compensated by equivalent supplies to the plant and leaves would thus become more and more dessicated and would soon die if the plant did not possess an efficient method of stopping this excess transpiration. The method is well known as the closing of the orifices (stomata) for transfer of water vapour across the leaf epidermis; the mechanism is dependent on the moisture status of the leaves. Whether we reason at the scale of a plant or a leaf we arrive at a transpiration $TR < TrM$ which represents a state of drought intensity $\frac{TrM - Tr}{TrM} = \frac{\Delta Tr}{TrM}$

In terms of fluid mechanics, the plant, while closing its channels of exchange with the atmosphere to a greater or lesser degree, increases a 'diffusion resistance' called stomatal resistance (rs), the effect of this variation on the rate of exchange becomes greater as the sum of resistences encountered becomes weaker.

If one considers that the channels of penetration or carbon dioxide are the same as those for the escape of water vapour, we can accept that the supply of carbon dioxide to the chloroplasts will be reduced by an amount equivalent to the increase of resistance to flow along these communal channels. *There will consequently be a concomitant reduction in photosynthesis and transpiration.*

The problem is to know whether the relative value of the variation in photosynthesis $\frac{\Delta \phi}{\phi \text{ max}}$ will be greater than, equal to or less than that of the transpiration $\frac{\Delta Tr}{Tr \text{ max}}$

The relation describing the association of these variables can be of the type 1, 2 and 3 shown in Figure 3.

In the case of relation I it would be essential to try and eliminate even the slightest risk or drought ($\Delta \phi$ maximum in the vicinity of Δ ET zero).

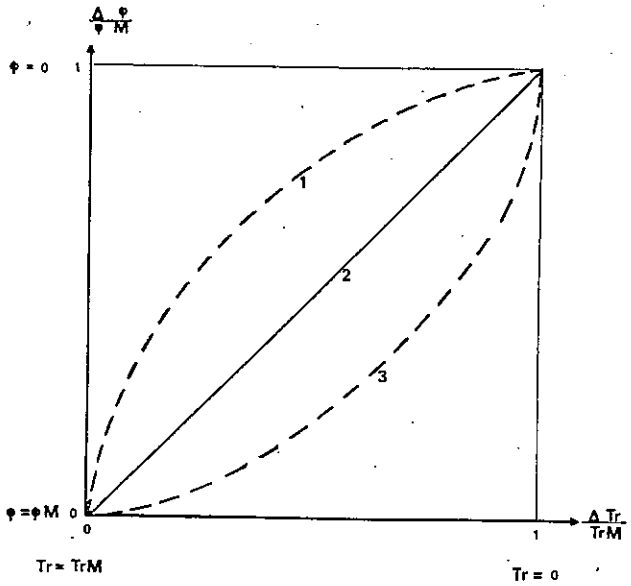

Fig 3 By hypothesis the three possible relationships between relative deficit of photosynthesis and intensity of drought.

On the contrary, with relation 3 it would become progressively less profitable to improve the possibilities for transpiration the closer one approaches maximum transpiration. This relationship is the most intriguing as it corresponds with the classical concept of Mitscherlich's law of diminishing returns.

Furthermore, from a theoretical point of view it satisfies the imagination. In effect, if one accepts that which is highly probable, viz that the sum of the resistances encountered during the transfer of carbon dioxide from the ambient air to the point where it is integrated into primary photosyntheses is greater than the total resistance encountered by water vapour passing between the surfaces of mesodermal cells and the ambient air, then one must also accept that variation in one of the resistances common to both pathways (stomatal resistance) will have less effect on the flow of CO_2 than on the flow of H_2O vapour.

Experience has, however, provided evidence for a relation of type 2; *the relative deficit of photosynthesis seems equal to that of transpiration or, the efficiency of water consumed appears constant over the entire range* of variation in consumption. In reality Mitcherlich's law applies rather loosely to the relationships studied here. The aim is not to compare a supply (amount of water for example) or a concentration (possible analogy with the moisture content of the substrate) and a process, but two processes subject to a common regulating factor.

The apparent disagreement with the theoretical reasoning suggests that the total resistance encountered along the CO_2 pathway is little different from that encountered along the water vapour pathway. The additional resistances of the CO_2 pathway are most likely related to stomatal resistance.

Let us not be delayed by this incidental physiological interpretation and retain the essential facts. There is no reduction in transpiration, without a reduction in photosynthesis and the relative deficit in photosynthesis is largely equal to the relative deficit in transpiration.

With this preliminary information let us pass on to the scale of the cultivated field.

B Relation between evaporation and production

It is considerably more difficult to analyse clearly the relation between ETR and production at field level. Invariably experimentalists restrict themselves to comparing ETR estimated with disregard to runoff or drainage losses, and a given production that can either be the commercial yield (R) or total dry matter excluding roots (DM) over a complete vegetative cycle.

1 ETR and 'total' dry matter

The production deficit Δ DM, established at harvesting, apparently represents a summation of the deficients established with time according to the climatic hazards (Δ ET) that occurred during the periods I to n.

$$\Delta DM = \Delta DM + \Delta DM_2 + \ldots + \Delta DM$$

with $\Delta DM_1 = f(\Delta ET_1)$

$$\Delta DM_2 = f(\Delta ET_2)$$

If we accept that the relation observed between transpiration and photosynthesis can be transposed to these conditions then for every sub-period we will have

$$\Delta DM_1 = K_1 ET_1$$

$$\Delta DM_2 = K_2 ET_2$$

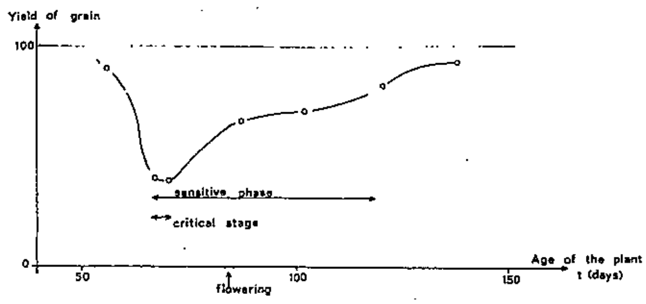

Fig 4 The influence of a drought of constant intensity on the different vegetative phases of maize.

with K_1 $\dfrac{\textit{maximum DM producing during period I}}{\textit{ETM during period I}}$

The efficiency of water varies considerably during the growth cycle (Figure 4). The response to an equivalent evapotranspirational deficit may, therefore, vary in the same proportions depending on the time of occurrence of this deficit.

For example, using the information presented in Figure 4 we can calculate that a deficient of 60 mm will result in the following production deficits

during July : 300 kg/ha

during June : 200 kg/ha

during September : 150kg/ha

and yet those 60mm deficits represent a far more severe drought during the conditions experienced in September than those experienced in July viz

$$\frac{60}{\text{ETM July}} = 0{,}34$$

$$\frac{60}{\text{ETM September}} = 0{,}83$$

The interpretation of global data (moisture budget — production) obtained over the entire growth period would, therefore, be practically impossible as far as the problems in question (desired level of ETR — profitability from water) are concerned. Cultural trials provide two types of responses (Figures 5 and 6).

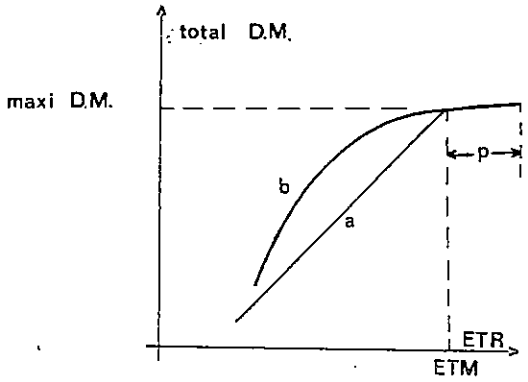

Fig 5 Typical relationship between total dry matter and ETR (on the basis of the total balance)

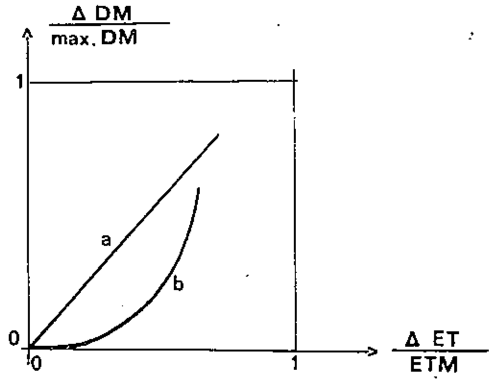

Fig 6 Typical relationship between drought and relative loss of production

Generally, linear relationships (a) are obtained when climatic conditions have been sufficiently regular to maintain the 'drought' treatment at a determined level. To enable this the natural deficit must be considerable and permanent.

The curvelinear relationship (b) otherwise divesre, more or less 'taut' and more or less regular can be obtained in the other conditions. The overestimations of ETM particularly from trials conducted on the basis of ETP lead to correlations analogous with a plateau of DM, p, (Figure 5) whose magnitude increases in proportion to the degree of overestimation.

It seems that the deficit in growth at each phase of development is related in a simple, probably linear, way to the deficit in evapotranspiration. Maximum total production will be obtained when the vegetative cover is allowed to function constantly at ETM; but, if during each period of growth all increases in ETR and consequently in production occur with the same efficiency of water consumed, this efficiency varies considerably from one period to the other. Maximum response in absolute values will be obtained by intervening during periods of intense growth. This has practical application for forage crops where total dry matter constitutes the criterion of productivity. This assumes knowledge of the growth curve of each particular crop.

We would like to point out a recently discovered characteristic of the sugar beet. This plant exhibits a certain degree of compensation if subjected to alternating periods of drought and abundant water during its growth phase. Drought usually causes a decrease in dry matter gain, but when the plant returns to an ETM regime, growth resumes at a greater rate than that of a plant maintained under favourable conditions. Growth seems to progress as though the period of stress maintained the beet root as a younger stage. At least for this crop we can now advocate 'intermittent' irrigation.

This observation would also seem to be an acceptable explanation for certain relations of the curvelinear type such as the supply of water- and production. We shall, however, avoid drawing a general conclusion from a specific type of behaviour which is certainly related to the type of crop.

2 ETR and useful production (R)

The variations in growth rates of plants, the importance of which we pointed out in relationships between water supply and total dry matter production, must also be considered when we become interested in the development of a particular organ. The growth curves of each plant organ

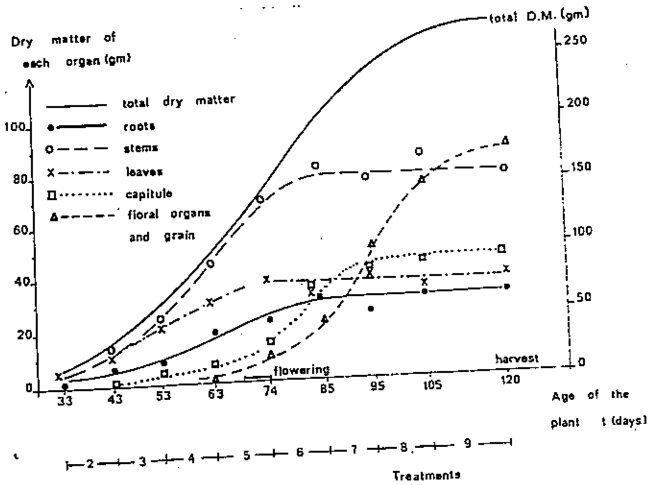

Fig 7 Growth of different organs and the evolution of total dry matter of the sunflower

or groups of organs (vegetative — reproductive) are staggered in time (Figure 7). In a preliminary phase the structures of manufacture and trans-location are developed, followed by those of storage, and finally of storage proper. These different phases can partially overlap.

Logic suggests that the depressing effect of an unfavourable factor like drought on the development of a particular organ will be most markedif it coincides with the period of most active growth of that organ. At the same time, this observation demonstrates its shortcomings particularly when we consider the reproductive organs (Figure 8 and 9). On the one hand the condition of the structure of supply or manufacture (roots, leaves) is not altogether unaffected by the development of other organs. On the other hand, however, the harvest of fruit or grain will to a large extent depend on the number of flower initials and flowers that will have been been formed during a specific stage of development more or less limited in time but sometimes very short. This period is moreover of greater importance the shorter it is, which for example is the case with maize. We will qualify it as the *critical stage* which is followed by the period of growth and storage or *sensitive stage*.

In these conditions the yield will not only depend on the intensity of drought $\frac{\Delta ET}{ETM}$ but especially on its location in time.

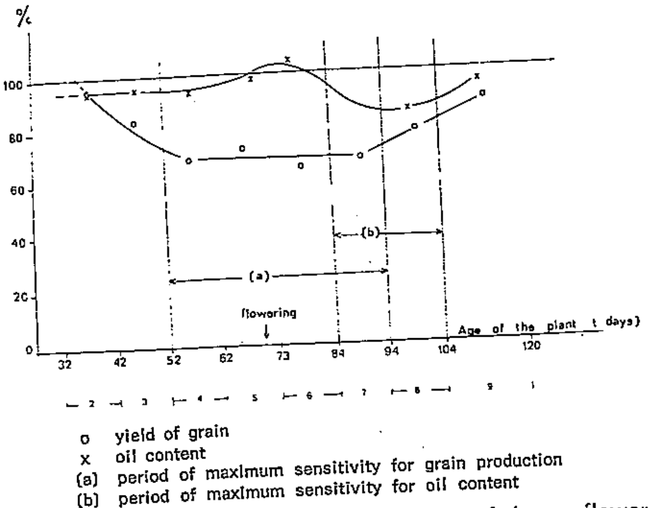

Fig 8 Evolution with time of the sensitivity of the sunflower.

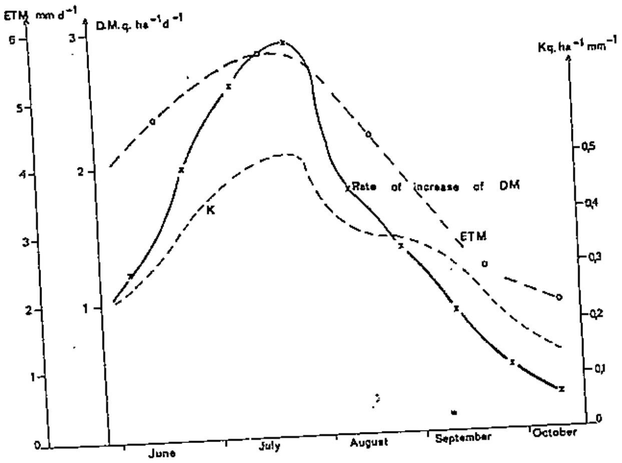

Fig 9 Comparative evolution of the rate of growth and maximal evapotranspiration of sugar beet with time (average value for 3 years). Consecutive variation of the coefficient of water use efficiency

One can expect to find a diversity of relationships between ETR and total R.

The most favourable correlation from an economic point of view would be maintained by maintaining the crop at an ETM regime from the critical stage to the end of the sensitive phase (usually the beginning of the maturing phase). The plant can be left to undergo a certain amount of stress before and after this period.

NB: Thus far we have only taken climatic (ETP) criteria, and characteristics of normal plant cover development into consideration to give a definition of ETM, and have considered the problems between ETR and production in a relatively importance both in connectio with the level of ETM and the simple manner. These factors are, however, of considerable efficiency of ETR.

ETM variations always tend to decrease under sub-optimal cultural conditions, but they are less apparent than production variations which involve a decrease in water-use efficiency. Under conditions of intensified production implicitly admitted in irrigation, variation attrbutable to cultural errors must disappear. Irrigation scheduling, should therefore, not be considered in the same terms as cultural practices.

TABLE 1 Examples of the effect of some cultural techniques (Clermont-Ferrand — Agronomy)

	Total ETM in mm	Efficiency of ETM	
		kg of DM/m³	kg dry grain/m³
Plant density 30 000 plants/ha (medium early maize)	485	1,63	0,81
50 000 plants/ha	520	2,09	1,11
70 000 plants/ha	572	2,74	1,33
Nitrogenous fertilization 0	332	1,18	0,60
(Spring oats) 60 units/ha	417	2,52	1,03

Conclusion

We have tried successively to define potential evapotranspiration and real evapotranspiration by resorting to specific definitions for different scales considered viz: ETP: energy, factor limiting, ETM: soil water being sufficient, the limiting factor is intrinsically related to growth and development of the plant, ETR: inferior to ETM, clearly demonstrates the inadequate moisture supply.

These reflect in a similar manner on evapotranspiration and production. Maximum yield is obtained when water supply eliminates all possibility of a deficit in evapotranspiration. However, the efficiency of water consumed varies with the rate of growth if one considers the total dry matter produced, and with stages and phases of development if one considers the production of a particular organ. Optimum economic yield is obtained by maintaining conditions of ETM during a restricted period of the growth cycle.

Knowledge of the growth characteristics of each cultivated species therefore, appears essential for the evaluation of ETM as well as for its use in irrigation.

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