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by

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FACTORS ON EVAPOTRANSPIRATION

By

K. M. King

The importance in agriculture of precipitation is well known. Not so much appreciated but of equal importance is the water loss from land surfaces. The difference of the two, the soil moisture content, is really the moisture parameter of value. Because of the difficulties involved in direct determination of the soil moisture content by sampling, or indirectly from tension or conductivity measurements, the evapotranspiration process is being studied by soil workers. The rate of evapotranspiration indicates directly the rate of decrease in soil moisture content.

It is my desire to emphasize that the soil, the plant, and the atmosphere are parts of a single system for the transfer of water from land surfaces to the atmosphere, although the title of this paper might indicate that the effects of soils, plants, and meteorological factors are distinct and different and that they could be discussed as individual topics. There is thus a great need to look at the whole soil - plant - atmosphere continuum. Much attention in the past has been given to the various parts of this system. Micrometeorologists, plant physiologists, soil physicists, and others have provided a great deal of information through investigations in their own particular fields. But since evapotranspiration is the resultant of interactions between soils, plants, and the atmosphere we must strive to see the whole system.

There is a problem here of course in finding people who can do this. In this age of specialized scientific disciplines the ability to pull together the important bits of information from several specialized fields requires a rare background of training and experience. There are very few who have good training in agriculture and meteorology, and if there are those who have they usually are biased in one direction or another. They either study the plant part as only a passive part of a physical system, or the biological and physiological aspects are overstressed and the physics somewhat neglected. In addition, few people are in an organization that will permit them to be interested in so many phases.

To be sure, detailed examination of many parts of the system is still needed. We very definitely need new techniques and instrumentation in order to get at the center of the problem. For example, workers in soil physics have tried to indicate the relation between plant growth and moisture stress in the soil. But the plant is mainly concerned with the moisture conditions and stresses in the plant. These are what effect photosynthesis, respiration, translocation of ions and so on. The water conditions in the soil may only remotely resemble water

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conditions in the plant. There is unfortunately no handy way to diagnose the moisture conditions within the plant. There is no handy way of determining what the impedance to flow is in the plant, by some measurement. Certainly we cannot predict quantitatively the various hydraulic parameters which govern the flow. In soils we are just beginning to appreciate some of the facts of unsaturated fluid flow. For example, we now realize that very rarely are equilibrium conditions reached in the soil. Field capacity and the permanent wilting point once thought to be soil moisture "constants" are now considered as being conditions respectively where downward drainage is very small compared with previous values immediately after wetting, and the condition where the flow rate of soil water to the plant is insufficient to maintain the plant. The flow of water in plants is much more complicated than unsaturated flow in soils. Yes we do need more detailed studies but we need to look at the whole system as well.

As an illustration of the need of studying the whole system and not just one part of it I would like to refer to the controversy as to whether or not growth and transpiration are independent of the amount of available water in the soil (that between field capacity and the wilting point). Some competent workers have reported that the relative growth rate is constant throughout the available water range while others have found a definite decrease in the relative growth or transpiration somewhat above the permanent wilting point (see Veihmeyer and Hendrickson, 1955). There are several things that could be proposed that might make the difference in results. A greater chance of obtaining the second relationship and not the first would be found with a greater light intensity, a lower humidity, a decreased root density, an increasing proportion of the roots subjected to stress, and a greater proportion of sand and less clay.

These factors have to do with the dynamics of the system, to a comparison of evaporative demand and the flow rate of water through the soil, across the soil-root interface, and through the plant. Under conditions of moderate light and high humidity the flow rate at lower soil moisture contents may be sufficient to maintain growth rates but with an increase in evaporative demand the flow rate may be insufficient. Failure to recognize the influence of all parts of the systems can only lead to partical success in explaining the evapotranspiration.

The Heat Budget of Crops

I believe that a study of the energy balance or heat budget at a crop surface permits us to learn much about the interaction of soils, plants, and meteorological factors in the evapotranspiration process.

In general the factors that affect evapotranspiration from land surfaces are in two classes, (a) those that affect the supply of heat to the surface and (b) those that affect the water supply at the evaporating surface.

The supply of heat at the surface of any field for the most part comes from solar radiation although sometimes heat is extracted from the air that has been heated somewhere else and passes above or through the crop. In Southern Ontario the incoming radiation in a growing season carries sufficient heat to evaporate almost five feet of water. Of course only part of this heat is used in evaporating water. Much of the radiation is reflected or reradiated out into space or passes into the air as sensible heat. A small but important part is used for photosynthesis. The significant radiation factor is the net radiation, the difference between incoming and outgoing radiation. The net radiation is the important radiation parameter because it indicates the heat available at the surface for evapotranspiration.

The diagram of the heat budget for a crop, shown in Figure 1, indicates the terms of the heat budget equation. The various terms will change sign of course depending on time of day and other conditions. Actually when the soil is well supplied with water there is a very high correlation between net radiation and the evapotranspiration. Evapotranspiration may be 85 pct. to slightly over 100 pct. of the net radiation under moist conditions during the daytime. As the soil becomes drier and the flow of water to the plant decreases sufficiently so that evapotranspiration is decreased then a greater part of the net radiation will be transformed into the sensible heat flux. At nighttime the net radiation is negative and any evapotranspiration that does occur (and there is some) obtains the heat supply from the soil, vegetation, and air.

In the subhumid regions, over large fields, there is not an appreciable amount of heat extracted from the air. Experiments in Wisconsin (Suomi and Tanner, 1958) showed that over an irrigated pasture field a maximum of only 25 per cent of the total evapotranspiration came from heat derived from the air passing <u>over</u> the crop. Rider in England (1957) found that over a field of peas the evapotranspiration was twice that of the incoming solar radiation. This is an unusually high value.

Under arid conditions, where irrigated fields often are surrounded by very dry areas, a very large part of the net radiation goes into sensible heat flow. Because of the large temperature differences between the air and irrigated crop surface much heat may be extracted from the air as it passes over the crop. It is here that the influence of the plant factors may arise because the amount of heat transferred from air to crop surface depends not only upon the temperature difference but upon the turbulence which is a function of, among other things, the surface roughness.

This large extraction of heat from a field or plot has been described by Halstead and others (1957) as the "oasis effect". To study the influence of the "oasis effect" it is necessary to specify conditions over the "oasis", over the surrounding area, and the size of the "oasis". For a completely moist area with r.h. = 100 pct. in the area and surrounded by a dry area where the evaporation is zero, the temperature $30^{o}C$, the vapour pressure 8 mb, a net radiation of .72 ly/min, a wind gradient of 1 m/sec/25 cm. and a roughness height of $Zo = 5$ cm., Halstead finds temperature in the centre of the irrigated area would be for a 6-foot tank 30.0°C; a 50-foot plot, 28.6°C; a 100 yd. field, 23.8°C; and a one mile field 20.0°C.

The evapotranspiration would drop from .45 cm/hr in the small tank, to .26 cm/hr. in the 50 foot plot, to .19 cm/hr. in the 100 yd. field, and to .13 cm/hr. in the one mile field. This admittedly is an extreme example but when the surroundings are quite dry the oasis effect can be quite large.

In this same connection it is interesting to look at the relation between evaporation from pans and evapotranspiration from crops. In this region we have found the correlation between free-water evaporation and potential evapotranspiration is positive and reasonably high indicating that both are influenced to some degree by the same meteorological conditions.

When pan evaporation and actual evapotranspiration are compared it is often a different situation especially in arid regions. A negative correlation was obtained for part of the growing season by Staple and Lehane at Swift Current (1954) and for the whole season by Army and Ostle in Montana (1957). The high negative correlation ($r = -.82$) between evapotranspiration from wheat and a BPI pan during the period 1913-1944 at Huntley, Montana, indicates very well what happens when the soil is dry. Except for a short period at the beginning of the growth period the evapotranspiration would be lowest in a season of dry and associated hot weather. It is under these same conditions that the free-water evaporation would be the greatest. In a season of more abundant rainfall evapotranspiration would be greater and free-water evaporation lower. These results show the "oasis effect" quite well.

Because of the "oasis effect" extreme caution must be taken before the results from atmometers, small tanks, small evaporimeters, and small plots which are well supplied with water are used to estimate the evapotranspiration from large fields. In the volume above such a small evaporation area there can be an abnormally large horizontal divergence of sensible and latent heat.

The edge or border effect in which air passes through the crop has been called the "clothesline effect" by Tanner (1957). The clothesline effect will be very important for plants in small tanks, for the edge of fields and for small plots as found at most agricultural experiment stations. It will also appear where fertility variables have increased growth and heights of some parts of a plot or field relative to a large plot. If one were following the soil moisture content in such an experimental area one might conclude at the end of the season that the increased fertility had increased evapotranspiration. But this would only be under the conditions of the experiment. One cannot conclude that the same thing would occur where the crop height was uniform over a larger area. It is also difficult to conclude whether or not the observed results was a plant effect or a meteorological effect.

An economical floating lysimeter which is suitable for obtaining continuous records of the evapotranspiration has been described by King et al (1956). Even with extreme care to obtain a well exposed lysimeter, it is apparent that a lysimeter is not an absolute device for determination of evapotranspiration. Its calibration depends on its area and as well its representativeness which affects the sampling errors. While the tank surface area is easy enough to determine the effective evaporating area cannot be measured directly. We defined the effective area as the volume of water lost from the lysimeter divided by the depth of water lost from the surrounding field during the same period. We have found that the effective area of the floating lysimeter in an irrigated pasture decreased markedly upon cutting of the forage. The change in the effective area may have occurred for two reasons (a) because overhanging foliage was decreased, and (b) because the microclimatic conditions were changed at the lysimeter because of exposure of the bare border area or because the tank walls extended to the level of the stubble. Even though a lysimeter is not an absolute device it is suitable for testing the reliability of various methods of estimating evapotranspiration. If the ratio of evapotranspiration by the method under test to that from the lysimeter is a constant for a wide variety of weather conditions then the method can be considered good.

Soil Factors

Let us leave some of these problems of the heat budget of a crop volume and look at a bare soil where plant factors are non-existent. After a well-drained soil has been wetted to field capacity, the evaporation rate at the beginning is largely limited by the heat available at the surface. As the surface dries the evaporation rate is limited by the moisture availability because of low transfer to the surface by capillary movement. The total water content during evaporation in a profile of a bare soil to any depth has been found by Richards et al (1956) to vary as a power function of time. Thus a log-log plot of water content against time gives a straight line as shown in Figure 2.

There is theoretical evidence (Gardner, 1957) to show the evaporation rate should decrease at first as the square root of time and then exponentially when evaporation demand or the heat available is constant. This square root of time dependency also holds for horizontal infiltration into a dry soil. The square root of time function and associated diffusion theory show that the total evaporation cannot be decreased by drying the soil out quickly to create a dust mulch on the surface. Also shown in Figure 2 is the actual measured water content changes in a soil with herbaceous cover following rainfall as reported by Carlson et al (1956). During the latter part of the dry cycle there is a close resemblance between evapotranspiration and evaporation. It appears as if the movement of water in the soil either to the root or the soil surface is the controlling factor.

Thornthwaite and Mather (1954) have also indicated the actual evapotranspiration decreases as the soil dries out. They give smooth curves which were based on the assumption that the ratio at any time of the actual to potential evapotranspiration would be equal to the fraction of available water that is present in the soil.

Halstead (1954) from work at O'Neil Nebraska in 1953 found that the fraction of net radiation used in evapotranspiration was a linear function of the soil moisture content. It is only a coincidence I believe that the soil moisture content at 10 cm. gave this relationship. The scatter might indicate the hysteresis effect on capillary conductivity. Capillary conductivity is not a single valued function of soil moisture content but can only be specified if one knows the past history of wetting and drying. It is undoubtedly capillary conductivity rather than the moisture content that controls the evaporation from the surface as the soil dries.

To further illustrate the influence of soil moisture tension on evapotranspiration let us look at some work described by Lemon and others (1957) of evapotranspiration from cotton in Texas shown in Figure 3.

The sensible heat and evapotranspiration terms of the heat budget are plotted against the soil moisture tension; the soil moisture tension being that averaged to two-, three-, and four-foot depths. Lemon had available five large blocks of cotton 1,150 feet by 120 feet oriented lengthwise with the prevailing wind. Three had been irrigated respectively one, 12, and 16 days previous to the observation and there were two non-irrigated plots under different moisture stress. These workers had measured the net radiation over all the plots and found that there was essentially no difference in measured net radiation although one might think there would be some variation. They determined the sensible heat flow by means of the product of wind and temperature difference above the plot (Halstead 1954). The graph shows the conditions at 1700 hours when the soil heat flow was quite small and was neglected. Thus the evapotranspiration equalled the net radiation minus the sensible heat flux. Under conditions where the soil moisture tension was 15 atmospheres (wilting point) the evapotranspiration was zero and so all of the net radiation was going into sensible heat flux to the air. In contrast, for the plot with very low soil moisture stress, evpotranspiration was about .125 cm./hour and was using more than twice the energy available to it from radiation.

Figure 3 essentially illustrates the variation of evapotranspiration with soil moisture stress. The oasis effect is also indicated. Lemon comments that similar cotton extended for 10 miles upwind so that the advected heat came from long distances. As well as the soil moisture differences there was undoubtedly a plant effect since the plants that were on the irrigated plots were taller than those on the unirrigated plots.

To summarize the soil effects we can think of three very important things. A "capacity" factor, an "intensity" factor, and a "rate" factor. The capacity factor shows the amount of stored water, the intensity factor the tension with which it is held but the rate factor is most important because it deals with the flow of water to the soil surface or the plant roots. The capillary conductivity may increase by several orders of magnitude between field capacity and the wilting point (Gardner 1957).

Plant Factors

Plant factors might be looked on (a) as those which affect the water available at a transpiring surface and (b) those which affect the amount of heat available at the surface.

Beginning with the second condition I think in looking for reasons for changes in the heat available we should go back to the original heat budget diagram. First of all, plants may influence the net radiation because of their albedo. A dark green crop like a lush pasture reflects less radiation than does a ripening grain field. A second factor which will influence the heat available is the spacing and form of a crop. We have already mentioned the possibility of extra high crops extracting more heat from the air. For an intertilled crop it is hard to predict what the evapotranspiration will be. For example, what is the evapotranspiration when the horizontal projection of the crop cover is a quarter of the whole field area? The minimum amount of evapotranspiration could be predicted by assuming that evaporation would take place from the exposed soil surface just as it would from a bare field. We could also treat the fraction of the area covered by the crop and calculate evapotranspiration from it as if it was a large field. But the sum would be the minimum amount to be expected from the field. A greater amount might occur from the plants because the part of the net radiation not used to evaporate water from the bare soil would be available for evaporation from the plants. As well because the surface of this field of part plants and part bare soil would be aerodynamically rougher than a field with continuous cover there would be greater extraction of heat from the air passing over the plants and also there would be more air passing through the plants. Differences between plant species will show up for the most part when the supply of water is not limiting. This would be under conditions where there would be the so-called potential evapotranspiration. Thornthwaite and Penman postulated that the potential evapotranspiration would be the same for all crops so long as there was a continuous green cover. One wonders how these workers defined a continuous green cover for Penman (1956) applied his equation to a watershed where there was quite a number of trees and small bushes and the Thornthwaite method is applied to practically all land surfaces. Rider (1957) has found that there were significant differences between evapotranspiration from fields of peas, grass, and brussel sprouts, all supposedly giving a continuous green cover. The areas were several acres in size and there possibly had been different amounts of heat flowing in through the crop from the side. Also changes in the growth stage of a plant and especially the stage of maturity may alter the evapotranspiration even when the soil moisture supply is adequate.

It is under conditions of limited moisture supply that differences in plant species and varieties are most evident. This is because the rate of extension of new roots into moister soil regions and the control which plants exert on the stomatal openings is not the same for all plants. The closure of stoma depends upon the turgor of the guard cells surrounding the openings. This is regulated by light intensity and the amount of water present. A water loss of 10 pct. in one plant may be necessary before the stoma close whereas in others it is only three to five pct. The closure and opening is an enzymatic reaction. Starch accumulated in guard cells of closed stoma is changed to sugar when activated by light and the proper turgescence of the cells. With an increase of the cell sap concentration the osmotic value increases, water flows in, and the stoma open. Incidentally a good indication of the moisture stress conditions within a plant probably could be obtained from the ratio of available heat at a crop surface to the heat used up in evaporation of water from the crop.

Summary

In summary I wish to emphasize that a convenient way to study the effects of soil, plant, and meteorological factors is through a consideration of two main factors which influence evapotranspiration:

(1) the supply of heat at the evaporating surface and
(2) the availability of water at the evaporating surface

Certainly all the interactions of soils, plants and meteorological conditions are very complex. For the determination of evapotranspiration we must not forget that all parts of this system for the transfer of water from land surfaces to the atmosphere have an effect. In our future research we must seek more details of the role of the individual components of the soil, plant, atmosphere system with regard to the supply of heat and water. But probably the most valuable results will be obtained when the whole system is considered and the interactions of the components are made more clear. This is the apprcach we plan to take in our research work at Guelph during the months ahead.

Literature Cited

Army, T.J. and B. Ostle, 1957.
The association between free-water evaporation and evapotranspiration of spring wheat under the prevailing climatic conditions of the Plains area of Montana. Soil Sci. Soc. Amer. Proc. 21:469-472.

Carlson, C.A., K.G. Reinhart, and J.S. Horton, 1956.
Predicting moisture in the surface foot of soil. Soil Sci. Soc. Amer. Proc. 20:412-415.

Gardner, W.R. 1956.
Calculation of capillary conductivity from pressure plate outflow data. Soil Sci. Soc. Amer. Proc. 20:317-320.

Gardner, W.R. 1957.
Solution of the moisture flow equation for evaporation from a fallow soil. Soil Sci. Soc. Amer. Annual Meeting, Atlanta, in press.

Halstead, M.H. 1954.
The fluxes of momentum heat, and water vapor in micrometeorology. In Johns Hopkins Laboratory of climatology, Publication in Climatology 7: No.2.

Halstead, M.H. and W. Covey, 1957.
Some meteorological aspects of evapotranspiration. Soil Sci. Soc. Amer. Proc. 21:461-464.

King, K.M., C.B. Tanner, and V.E. Suomi 1956.
A floating lysimeter and its evaporation recorder. Trans. Amer. Geophys. Union 37:738-742.

Lemon, E.R., A.H. Glaser, and L.E. Satterwhite, 1957.
Some aspects of the relationship of soil, plant, and meteorological factors to evapotranspiration. Soil Sci. Soc. Amer. Proc. 21:464-468.

Penman, H.L. 1956.
Estimating evaporation. Trans. Amer. Geophys. Union. 37:43-46.

Richards, L.A., W.R. Gardner, and Gen. Ogata, 1956.
Physical processes determining water loss from soil. Soil Sci. Soc. Amer. Proc. 20:310-314.

Rider, N.E. 1957.
Water losses from various land surfaces. Quart. Jour. Roy. Met. Soc. 83:181-193.

Staple, W.J. and J.J. Lehane, 1954.
Weather conditions influencing wheat yields in tanks and field plots. Can. Jour. Agr. Sci. 34:553-564.

Suomi, V.E. and C.B. Tanner, 1958.
Evaporation estimates from heat budget measurements over a field crop. Trans. Amer. Geophys. Union, in press.

Tanner, C.B., 1957.
Factors affecting evaporation from plants and soils. Jour. Soil and Water Conserv. 12:221-227.

Thornthwaite, C.W. and J.R. Mather, 1954.
The computation of soil moisture. In Johns Hopkins Laboratory of Climatology, Publications in Climatology 7: No.3, 397-402.

Veihmeyer, F.J. and A.H. Hendrickson, 1955.
Does transpiration decrease as the soil moisture decreases? Trans. Amer. Geophys. Union 36:425-448.

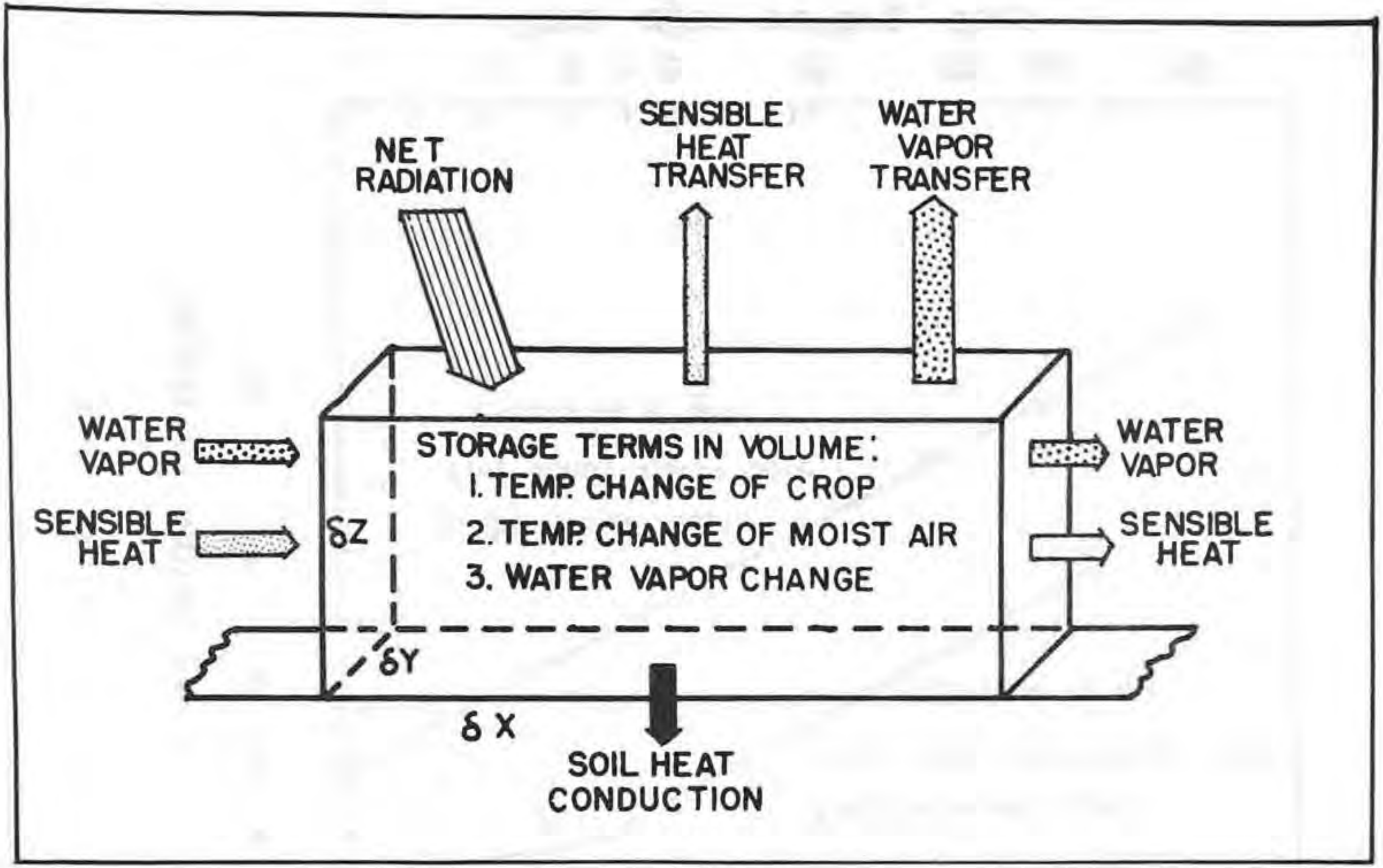

Figure 1. The complete heat budget for a crop volume.

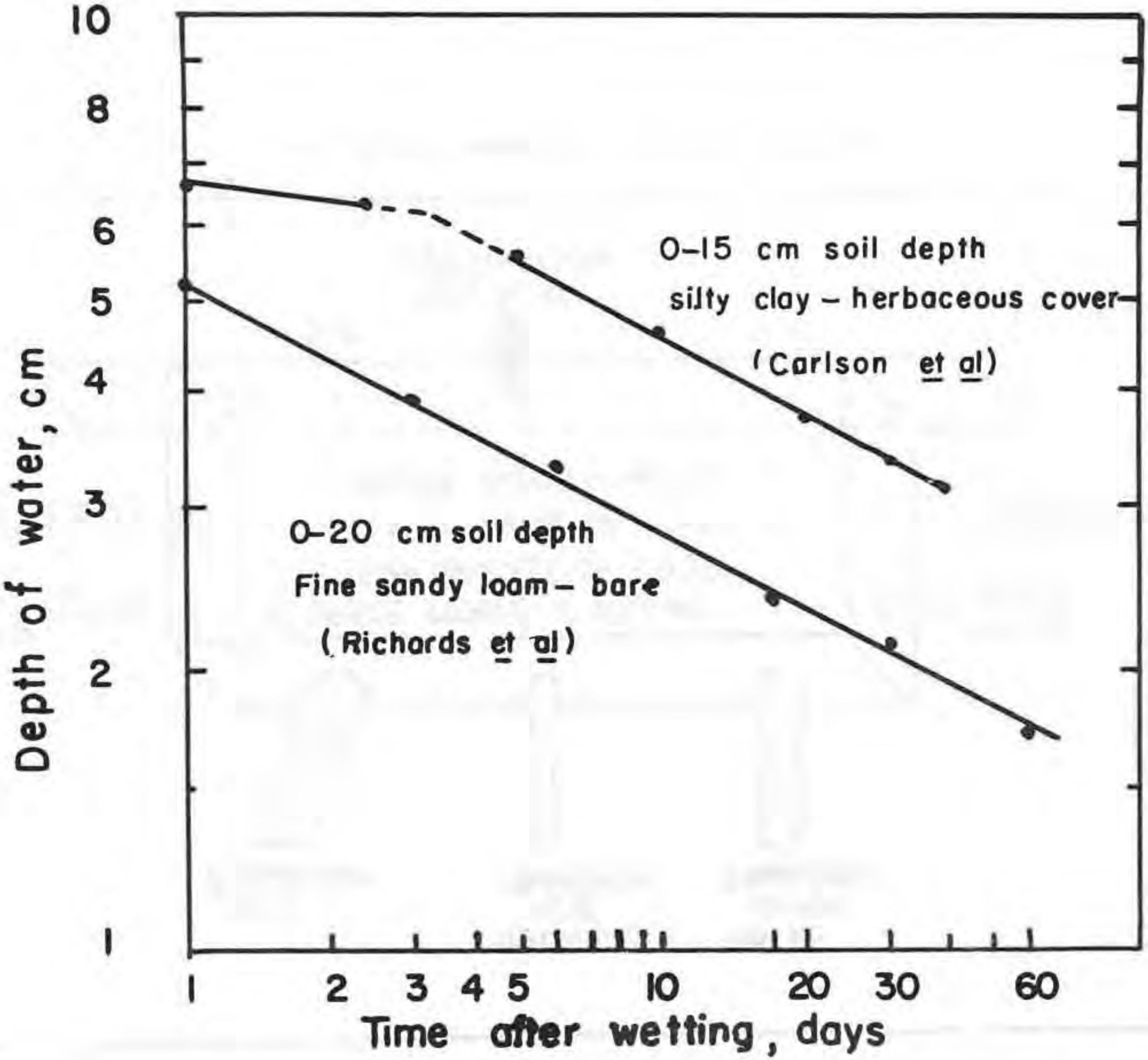

Figure 2. The change with time of water stored in a soil with and without vegetative cover.

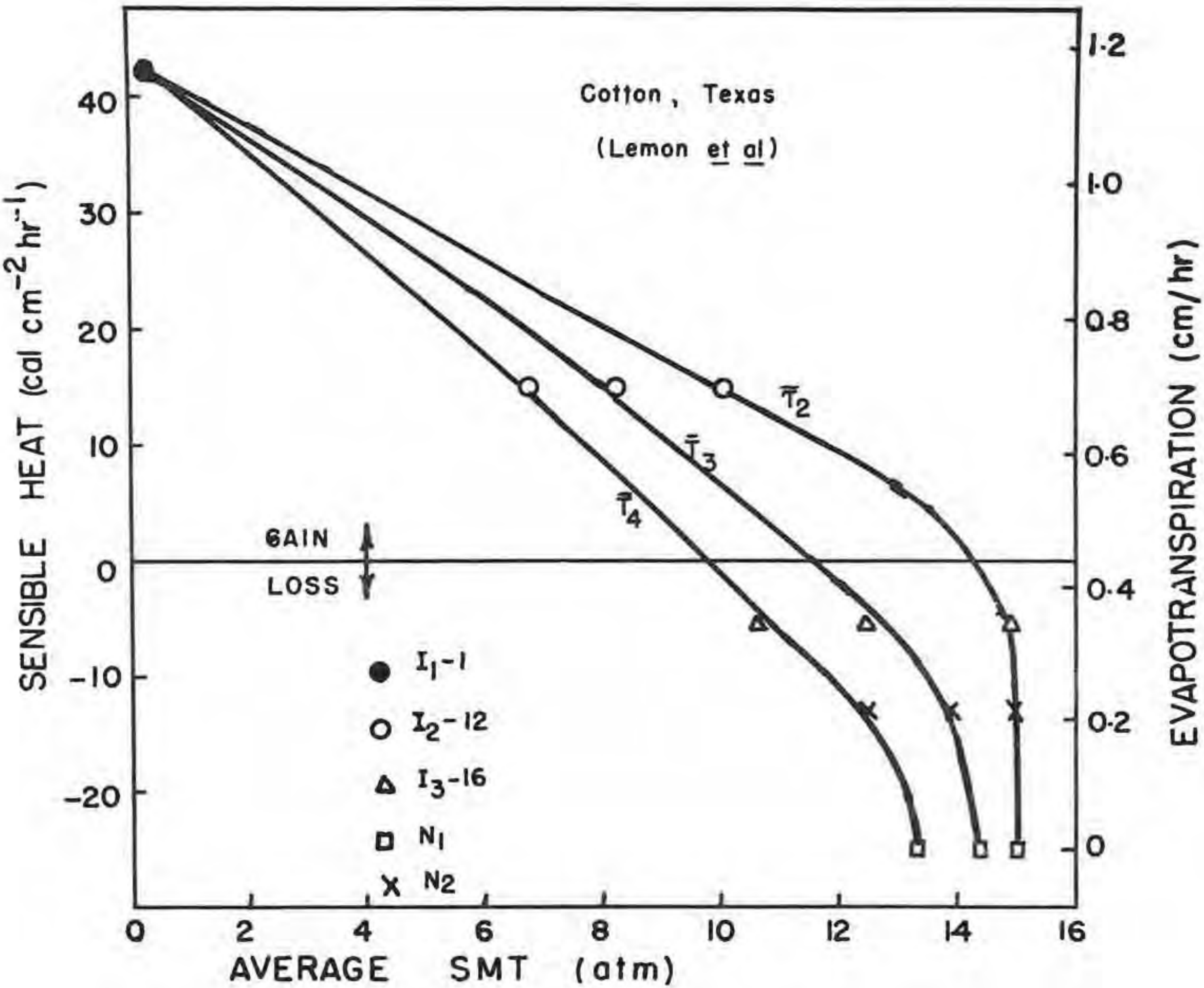

Figure 3. The variation in the sensible heat flux and evapotranspiration from a cotton crop under different conditions of soil moisture tension (SMT).