Water Use and Millet Production in the Sahel

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Water-availability is an important and often critical factor for plant-production in the Sahel. The most important crop of this region is millet, which has a low water requirement and a high resistance to drought. In this article attention is drawn to the importance of properly understanding the water balance in the Sahel, and the relationship between biomass production and transpiration is discussed. An acquaintance with the magnitude of transpiration and a knowledge of the transpiration process may be important in the evaluation of plant production and water management planning. A method for estimating transpiration from a heterogeneous vegetation cover is tested, and the results are compared to Shuttleworth & Wallace's model of transpiration for heterogeneous vegetation.

Keywords: *Sahel, evapotranspiration, transpiration, biomass production.*

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During the 1970's and 1980's most of the West African countries have experienced a serious decline in economic and environmental resources. The reasons are many and illustrate an inter-related and complicated process of degradation resulting in the weakening of human resources due to increased poverty and malnutrition among large population groups.

In the semi-arid areas of West Africa which typify the Sahelian region (Fig. 1), the living conditions of the majority of the population are dependent on a short, seasonly determined, unstable precipitation. Livestock have traditionally fulfilled the dominant role in the local strategy for survival. This type of landuse is advantageous, because livestock are mobile, thus allowing the inhabitants to avoid regions which are temporarily drought-prone. Shifting cultivation has generally been the most common form of agricultural system.

Today a change is taking place in this traditional landuse system. The increased population pressure causes a need for the intensification of food production. The population pressure leads to conflicts between nomads and peasants, and the continuous use of traditional landuse systems contributes to the ecological degradation of large areas due to overgrazing, felling of trees, shorter fallow periods and periods with drought. The degradation is caused by a currently inadequate use of existing resources.

PROSPECTS FOR IMPROVED WATER CONTROL IN THE SAHEL

Drought is a central factor of importance often discussed in relation to the degradation of Sahelian resources (Adefolalu, D.O., 1983; Beran, M.A. & Rodier, J.A., 1985; Agnew, C.T., 1989). During recent decades a trend towards declining precipitation has been observed, and it may be that an irreversible degradation-process is taking place due to global climatic change (Parry, M.L. et al., 1988). Whatever the case, it is clear that the unstable

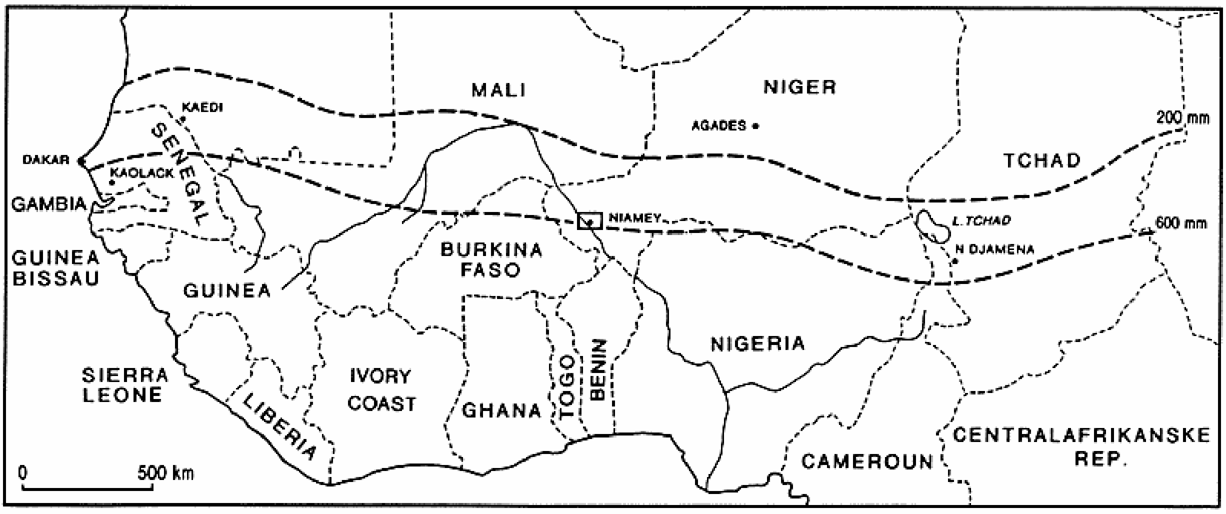

Fig. 1. Map showing the Sahelian Region and the location of the HAPEX-Sahel-experiment.

precipitation has great importance for the low investment in agriculture as well as for its direct influence on plant-physiological production.

As the majority of the Sahelian population is involved in dry-land farming, an analysis of regional sustainability should be combined with investigations on the influence of available water resources for plant production and the possibility of improving water use efficiency and the control of water resources. A complete understanding of the different water balance components is therefore essential.

In reality there are many ways of improving water use efficiency, and in many areas of the Sahel simple regulatory systems - such as the construction of small dikes and the damming of gullies - have a vital importance for agricultural production (Chleq, J.-L., 1988). In the Northern Sahel, water use efficiency is very high. Millet, which develops deep roots and has a high resistance to drought, is cultivated with only 200-250 mm of precipitation (Kowal, J.M. & Kassam, A.H., 1978). This is possible because water is collected in micro-catchments. Other methods for optimizing water use is to reduce evaporation losses by introducing windbreaks or by introducing cropping systems with a high water use efficiency - such as intercropping. Intercropping is widely used and advantageous because different crops have different periods of maximum water requirement. Windbreaks and intercropping have, moreover, many other advantages, which may be combined in alley-cropping or agro-forestry.

PROSPECTS FOR SPATIAL INFORMATION ON WATER BALANCE

A poor physical infra structure and a faulty information service between city and country side make it difficult to form a general picture of the problems and the potential for agricultural production in the Sahel. One of the largest obstacles for the sustainable development of Sahelian resources is indeed the lack of information. This is due to the fact that data collection from this large area is costly, time-consuming, and therefore of low priority (Prince, S.D. et al., 1990).

Regional and national monitoring is necessary for efficient landuse planning and optimal exploitation of water resources. Run-off may for instance constitute an important potential water resource, but knowledge of the correlations between regional landforms, soil types and vegetation is required for optimal utilization. Recession watering is widespread in the Sahel and often dikes are constructed upstream to retain water. Such systems may in extreme cases cause a lack of water for the population living downstream. Development plans for an area should therefore be based upon the distribution of resources within single watersheds.

Processing and analysis of satellite images could be very useful to provide a broad view of regional and national resources. Today many techniques already exist which are ready to be used in the monitoring and evaluation of regional resources. Monitoring of landuse, biomass production, erosion and population density is to some extent possible at the present time and is of particular current interest to the Sahel which, just now, is characterized by changes in landuse and biomass production due to the population pressure and the droughts in the 1970's and 1980's.

Satellite image processing is still a technique under rapid development which furthermore shows promising prospects for the physical modelling of biomass production and hydrological/atmospheric processes. Combined with geographical information systems (GIS) and standard meteorological data, satellite image processing may be a strong dynamic information and analysis facility in improving our understanding of the relationship between climate, hydrology, biomass production and landuse. This may lead to the identification of regional water resources and eventually the realization of potential agricultural production.

Physical modelling with GIS has been used for estimating potential and low water budget crop production in the EC (Bulens, J.D. et al., 1990). In temperate climates, such models are simpler than they will be in the heterogeneous Sahelian areas. Evaporation from bare soil complicates water use estimations, and intercropping complicates biomass estimates. It is therefore necessary to understand how water use influences plant production; to improve knowledge of the influence of micro-meterological conditions on transpiration in the Sahel - and to explore how these processes may be modelled on the basis of satellite images and GIS.

THE THEORETICAL RELATIONSHIP BETWEEN BIOMASS PRODUCTION AND TRANSPIRATION

Potential biomass production may be expressed as a function of a series of specifically climate and plant conversion coefficients of global radiation (Monteith, J.L., 1972). Low water budget plant production may accordingly be modelled by including a water-stress index such as ET/EP in this expression, where ET is actual evapotranspiration and EP is potential evapotranspiration (Begue, A., 1991).

The relationship between biomass production and plant water use has frequently been represented as linear until a closed vegetation cover exists or light saturation takes place (Rosenberg, N.J. et al., 1983; Onken & Wendt, 1989). In the Sahelian region a closed vegetation cover is seldom present and the dominant crop, millet, is, like other C_4-plants, able to exploit high radiation intensities. It is therefore likely that the biomass of millet may be linearly related to transpiration.

Transpiration takes place through stomatas simultaneously with the assimiliation of CO_2. As CO_2 forms the basic component in the photosynthetic process, the analogy between the transpiration and assimiliation processes causes the stated linear relationship between transpiration and biomass production.

The transpiration (T) and photosynthesis (N) for leaves have been described as (Gregory, P.J., 1989):

$$T = \frac{\rho_{st} - \rho_a}{r_{st} + r_a} \qquad N = \frac{c_a - c_{st}}{r_{st}^c + r_b^c}$$

where ρ_{st} and c_{st} are respectively the absolute humidity (kg/m^3) and CO_2 concentration (kg/m^3) in stomata; ρ_a and c_a are the absolute humidity and CO_2 concentration in the air; r_{st} and r_{st}^c are the stomatal resistance to transpiration and CO_2 assimiliation, and r_b and r_b^c are the laminary boundary resistance to vapour and CO_2 fluxes respectively.

The transpiration-efficiency is accordingly defined as:

$$\frac{N}{T} = \frac{(c_a - c_{st})\ (r_{st} + r_b)}{(\rho_{st} - \rho_a)\ (r_{st}^c + r_b^c)}$$

The relationship between the resistances of vapour and CO_2 is correlated with the diffusion coefficients and mole-weights of the two gases. It may therefore be assumed constant.

The transpiration efficiency is thus expressed as:

$$\frac{N}{T} = \frac{c_a - c_{st}}{\rho_{st} - \rho_a}$$

Often it is assumed that ρ_{st} is saturated, and that c_{st} is at or near zero, so that if the leaf temperature, air humidity and CO_2 density in the air is known, the gradient may be easily established. It has been calculated, however, that a range of c_{st}-values is dependent upon species and the response to irradiation (Rosenberg, N.J. et al., 1983).

Nevertheless, it has been shown for some species that c_{st}/c_a is regulated by the stomata function and is almost constant (Gregory, P.J., 1989). Therefore, it is often assumed, that the difference c_a-c_{st} is nearly constant, and the transpiration efficiency may then be expressed as (Gregory, P.J., 1989):

$$\frac{N}{T} = \frac{k}{e_{st} - e_a}$$

The relation between biomass production and transpiration is consequently determined by ρ_{st}-ρ_a. Accordingly, the biomass production is controlled by the plant water use when it is assumed that there are no nutrient-deficiencies or plant-diseases.

TECHNIQUES FOR ESTIMATING PLANT WATER USE

The measurement and modelling of plant water use is much more complicated in the heterogeneous Sahelian region than in temperate regions where a complete and homogeneous vegetation cover usually exists. Most techniques for estimating water use are however almost entirely developed in the temperate regions of the world.

Techniques for measuring plant water use

There are two major methods for estimating evapotranspiration: 1) measurements of vapour fluxes above the surface, 2) calculations on the soil water balance. These techniques are suitable for estimating plant water use in the temperate regions where evaporation from bare soil only makes up a minor part of the total evapotranspiration. In the Sahelian region it is necessary to distinguish between evaporation and transpiration to evaluate plant water use. Plant-physiological techniques are available to measure transpiration. So far most progress has been accomplished since the introduction of porometers. A porometer measures a plant's ability to conduct vapour through its epidermis. Measurements of conductivity for the individual leaves may then be combined with the total leaf-area to calculate transpiration. This technique is time-consuming and not suitable for continous recordings. Recently a technique for measuring the heat-balance of the stem has attracted new attention. This technique has been used to measure sapflow during an experimental period in Niger, 1992.

The measurement of plant water use during the experiment in Niger

During the HAPEX-Sahel Experiment in Niger (17th August - 10th October 1992) transpiration was measured continuously from 6 single millet plants with the stem heat balance technique (Dynagage Inc., Models no. SGA-10ws and SGA-13ws). The recording period started 30 days after sowing and lasted until the harvest started (84 days after sowing).

The principle of the method is based on a continuous heating of a stem section over a short vertical distance. The total measurement system is insulated by a foam cylinder as seen in Fig. 2, and the partition of the radial (Q_r) and vertical conduction (Q_v) is measured with ther-

Fig. 2. Photo of Sapflow-gauges installed on millet.

mocouples. The convective heat loss through the sapflow (Q_f) is then calculated as the residual in the following energy balance equation:

$$P = Q_r + Q_v + Q_f \quad [W]$$

where P = energy-input.

Due to problems with estimating extent of heat storage in the stem at night, only daytime measurements are presently included in the analysis. Consequently, evapotranspiration at night is assumed to be equal to zero. In Fig. 3 the daily sapflow data during the experimental period are shown. It should be noted that the gauges were moved to new plants several times during the experiment owing to plant diseases and broken stems. This is the reason for the sudden irregularities between the measurements from the 6 gauges. In the last week of the experiment arose some "disorder" in the data because some of

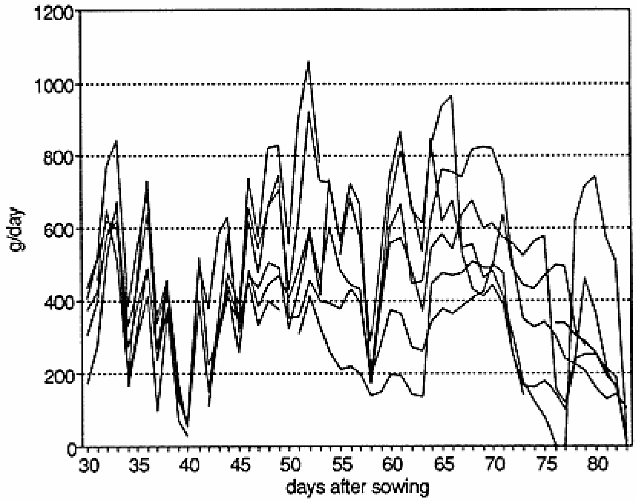

Fig. 3. Daily Transpiration (gram/day) during the experimental period, 17th Aug.- 11th Oct. 1992.

the plants had matured, and the gauges were consequently moved to late developing plants, which had a higher transpiration.

There is a high spatial variability in the state and height of millet plants within single fields in the Sahel. The 6 chosen millet plants were found to be representative on the basis of a statistical analysis of height measurements for more than 200 millet-clumps. It was, however, not possible to install the sapflow gauges on minor plants.

To allow an analysis of the sapflow measurements against above-canopy fluxes, the leaf-area of the 6 plants and leaf-area index were continuously measured. The average sapflow per leaf-area unit was then calculated for the 6 plants and hereafter multiplied with the leaf-area index (LAI).

The leaf-area was estimated by measuring the length and width of single leaves. A relationship between "length · width" and "leaf-area" was obtained by measuring the length, width and leaf-area of 30 collected leaves from the field. Leaf-area was measured with a scanning area measurement system (Delta-T Device; Model Mark 2 Area Meter). As seen in Fig. 4 the two different types of measurements have a high correlation.

LAI was estimated by measuring the transmission of diffuse radiation (blue spectra) through the vegetation cover with an optical sensor (LICOR LAI-2000). This technique has not usually been applied on heterogeonous vegetation. It was therefore tested against manual measurements and found satisfactory.

LAI are given in Fig. 5. It is clearly illustrated that the vegetation cover is very sparse since maximum LAI only reaches 0.37.

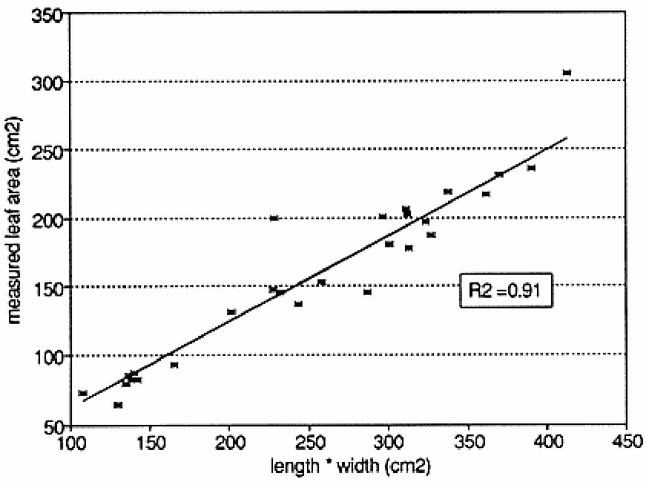

Fig. 4. Correlation between "leaf-width multiplied by leaf-length" and "scanned leaf-area".

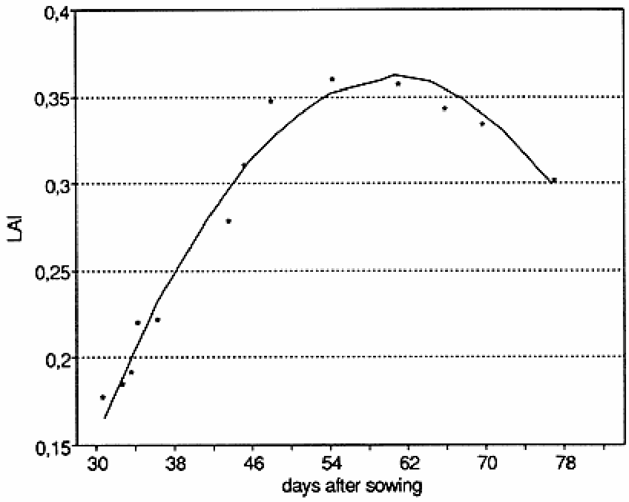

Fig. 5. Leaf-area index, 17th Aug.- 11th Oct. 1992.

The diurnal variation of transpiration is seen in Fig. 6a. Fig. 6b illustrates the important control by irradiation of stomata resistance and transpiration. The estimated daily transpiration is seen in Fig. 7. Note that the transpiration does not decline, as in Fig. 3. This is caused by diminished leaf-area of the 6 plants giving a high transpiration per leaf-area unit. At the same time, LAI does not decline simultaneously with the leaf-area of millet since alternative crops are evolving and included in the LAI measurements.

Models for estimating plant water use

Modelling evapotranspiration is usually based upon atmospheric parameters. The most widespread model used is Penmann's Formula (1948) for potential evapotranspiration (EP):

$$EP = \frac{\Delta\ (R_n - Q_G) + C_a\ (e_m - e_a)\ / r_a}{L_v\ (\Delta + \gamma)} \quad [mm]$$

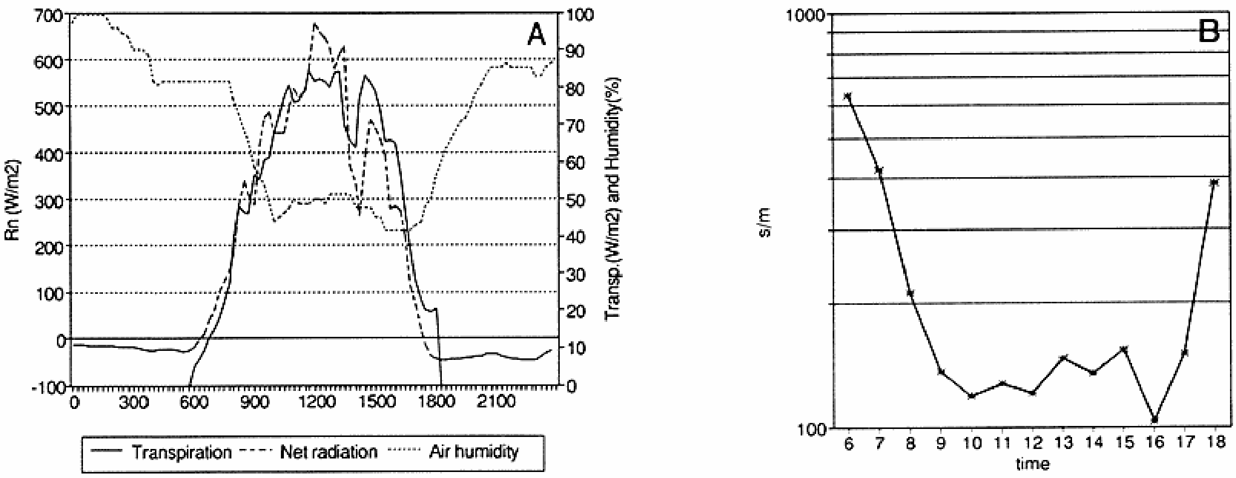

Fig. 6. a) Diurnal variation of Transpiration, Net Radiation and Relative Air Humidity, 12th Sept. 1992.
b) Diurnal variation of Stomatal Resistance, 12th Sept. 1992 (Winand Staring Centre, Wageningen, the Netherlands).

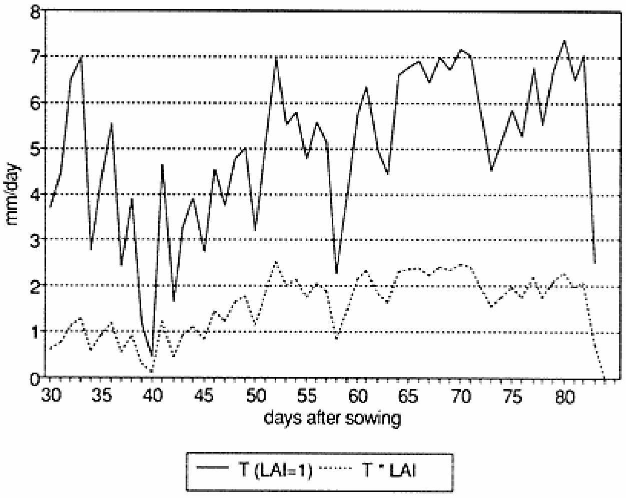

Fig. 7. Estimated Transpiration (mm/day) calculated on the bais of Sapflow-data and LAI during the experimental period, 17th Aug.- 11th Oct. 1992. Transpiration per leaf-area unit (LAI = 1) is also shown.

where R_n is net radiation; Q_G is soil-heat flux; e_m-e_a is the vapour pressure deficit of the air; r_a is the aerodynamic resistance, which is expressed as an empirical funcion of the wind-speed derived above grass, C_a is the specific heat of air, L_v is the latent heat of vaporization, Δ is the saturated vapour pressure gradient and γ is the psychrometric constant. Actual evapotranspiration is then calculated from EP, crop coefficients and the soil water balance (Doorenbos, J. & Pruitt, W.O., 1977; Agnew, C.T., 1989). The Penmann Formula has been criticized for its lack of aerodynamic effect and plant resistance to transpiration, but it is still widely used because of its simplicity and modest demand on input parameters (Agnew, C.T., 1991; Wallace, J., 1991).

Monteith (1965) modified the Penmann Formula by introducing a canopy resistance and an aerodynamic resistance based on existing roughness to substitute the empirical wind-function derived by Penmann. The Penmann-Monteith Formula is used for calculating actual evapotranspiration (ET) (Monteith, J.L., 1973):

$$ET = \frac{\Delta (R_n - Q_G) + C_a (e_m - e_a) \;/ r_a}{L_v (\Delta + \gamma (1 + r_c / r_a))} \quad [mm]$$

One practcal problem is the estimation of the canopy resistance, r_c, which is to be calculated from measurements of stomata resistance and leaf-area index.

Modelling of evapotranspiration from a hetereogenous vegetation cover requires a distinction to be made between evaporation from bare soil and transpiration from

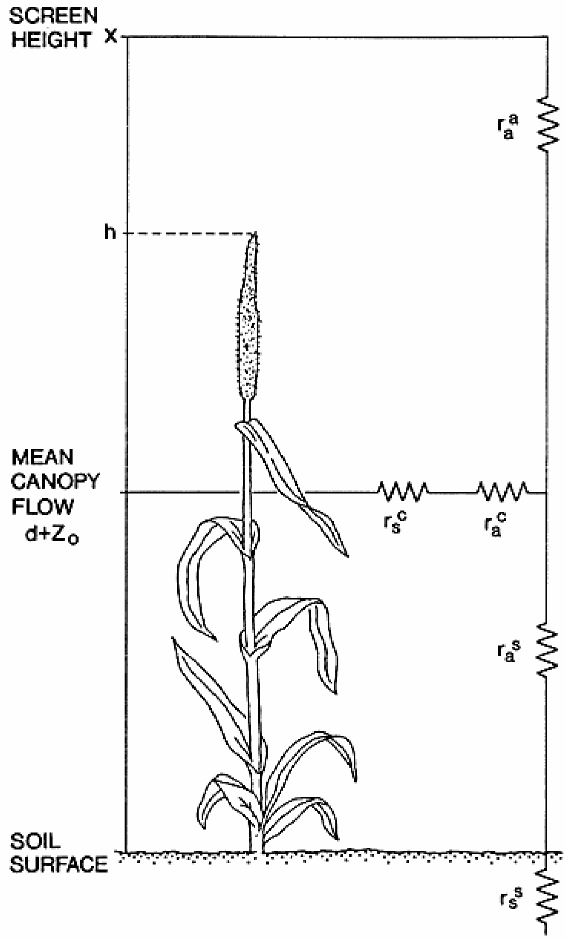

Fig. 8. Sketch of resistances to evapotranspiration in heterogeneous vegetation. See text for nomenclature and description.

plants. Evapotranspiration here takes place under altered micro-metereological conditions due to the larger turbulence around the tall well-spaced plants. Furthermore the available energy for evapotranspiration has to be partitioned between soil and plants, and separate surface resistances should be included for soil and plants.

Shuttleworth & Wallace (1985) introduced a model based on these concepts. The model is a 2-layer model based on the Penmann-Monteith Formula and applied to soil and plants respectively.

For the partition of the net radiation, R_n, between plants and soil, it is assumed that absorption by soil, R_n^s can be calculated from Beers' Law:

$$R_n^s = R_n * e^{-0.4 * LAI} \quad [W/m^2]$$

where the crop-dependent coefficient of 0.4 is estimated from an empiric relationship between LAI and radiation absorption for millet given by Begue, A. et al. (1991). The absorption by plants is calculated as R_n-Rn^s.

A number of flux resistances is introduced as illustrated in Fig. 8. The aero-dynamic resistance between the soil-level and the height for mean canopy conditions, r_a^s, and the aerodynamic resistance between this canopy-height and screen-height, r_a^a, is calculated from the wind-profile as described by Monteith, J. (1973): r_a^a is calculated from the prevailing wind conditions above the canopy, and r_a^s is calculated by introducing an exponentially decreasing eddy diffusion coefficient in the canopy-layer. It is not known how r_a^a and r_a^s respond to differing leaf-area indices. Shuttleworth & Wallace therefore assume a model where both r_a^a and r_a^s vary linearly with the leaf-area index between the values associated with their two limits, namely bare soil and a complete canopy. The height of mean canopy conditions is calculated from $(d+z_0)$, where d is the zero plane displacement ($d = 0.63 \cdot h$; h=plant-height), and z_0 is the roughness length ($z_0 = 0.13 \cdot h$) (Monteith, J.L., 1973).

r_s^s, the soil resistance, defines the resistance to evaporation of a wet soil underlying a dry soil layer of increasing thickness. In dry climates the soil resistance may be expressed as a function of moisture in the surface layer (Wallace,J., 1991). Various estimates of r_s^s are given in Wallace, J. (1991).

r_a^c is the bulk boundary layer resistance of the vegetative elements in the canopy. It is calculated as $r_b/(2 \cdot LAI)$, where r_b is the mean boundary layer resistance. Typical values of r_b are in the order of 25 s/m (Shuttleworth & Wallace, 1985), which is of limited numerical importance compared to the much larger stomatal resistance.

r_s^c is the canopy resistance and calculated as $r_{st}/(2 \cdot LAI)$, where r_{st} is the stomatal resistance.

The model by Shuttleworth & Wallace reveals that the available energy for transpiration may exceed the fraction of intercepted energy. This may happen when a very dry soil is present and the soil-evaporation is very low or zero, because soil-heat is transferred as sensible heat to the canopy. This implies the difficulty of defining a water-stress index (ET/EP) for modelling biomass production in a heterogeneous vegetation cover as suggested by Begue, A. et al. (1991).

A COMPARISON OF MEASURED AND MODELLED TRANSPIRATION

Measurements of sapflow are transferred to field values of transpiration as described above. The calculation of transpiration is performed by applying Shuttleworth & Wallace's model to micro-metereological data collected during the experiment.

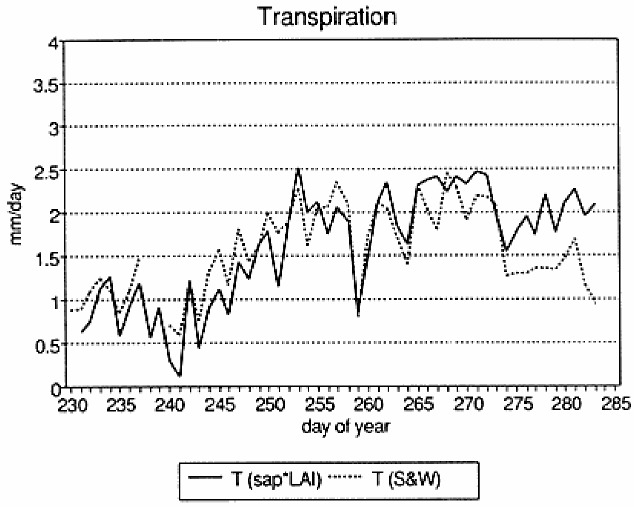

Fig. 9. Comparison between measured and calculated transpiration (mm/day) during the experimental period, 17th Aug. - 11th Oct. 1992. The calculation has been based on Shuttleworth and Wallace's model.

Net irradiance (REBS Q*6 radiometer), soil heat fluxes below millet and bare soil (REBS HFT-3), air-humidity (AANDERAA hygrometer), temperatures (thermocouples) and windspeed (VECTOR anemometers) were measured at 2 second intervals and averaged over 10 minutes. Stomatal resistance (Delta-T-Device, AP4-Porometer) were measured continuously during one "wet" day in the vegetative period (55 DAS) and one "dry" day (77 DAS) in the senescent period.

In the period 30-72 days after sowing, a stomatal resistance of 220 s/m is used as the input in the model, and for the rest of the period 500 s/m is used. It is not unusual to witness values of minimal stomatal resistance within this range for cereal crops in the vegetative and reproductive periods respectively (Taconet, O. et al., 1986; Ben Mehrez, M., 1992).

In Fig. 9 measured ("sap · LAI") and calculated ("S & W") transpiration are seen in Fig. 9 to correlate well. In the end of the period, the model, however, tends to underestimate the measured transpiration. Serious uncertainties in the method of transferring the sapflow measurements to a representative data-set of transpiration for the total field arose in the last 2 weeks of the experiment. In Fig. 5, it is seen, that LAI is reduced in the senescent period, but it is still quite high at harvest-time. This is due to the fact that weeds, cowpeas and hibiscus grow very fast during this time. The LAI of millet is therefore overestimated. Furthermore, the estimation of the leaf-area of

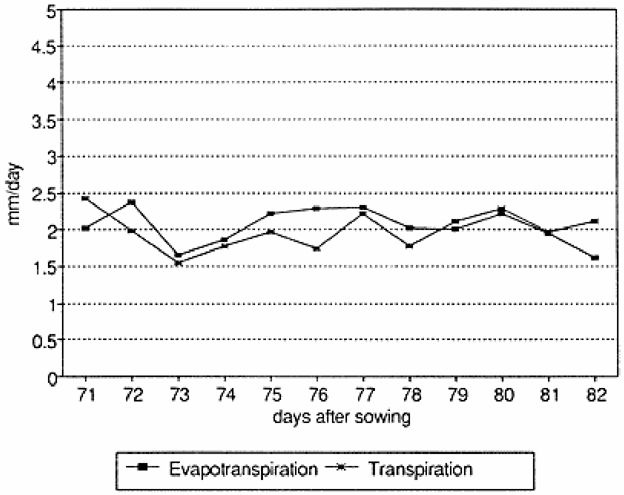

Fig. 10. Comparison of Daily Evapotranspiration, estimated by eddy correlation technique, and Transpiration during a period with presumably no soil evaporation. Last day of precipitation was 63 days after sowing.

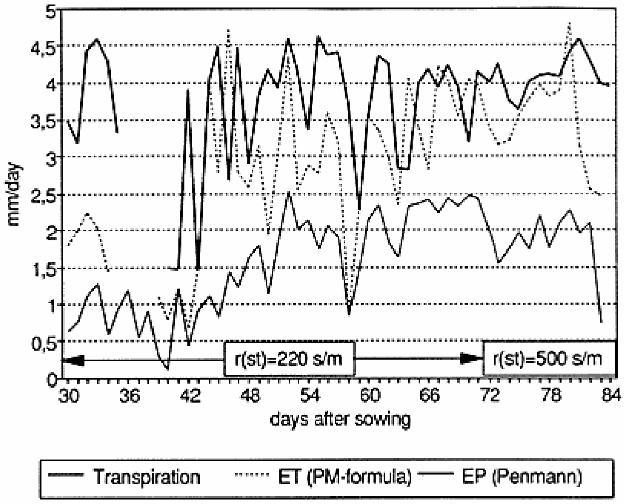

Fig. 11. Transpiration compared to potential evapotranspiration calculated from Penmann's Formula and actual evapotranspiration calculated from the Penmann-Monteith-Formula.

the 6 senescent plants became more difficult. The area of yellow spots and gaps in the leaves were estimated roughly by eye and subtracted from the calculated leaf-area. At the same time, the leaf-area of millet diminishes rapidly giving a transpiration per leaf-area unit, which is too very high. Uncertainties in this period are increased even further since transpiration per leaf-area unit is calculated and measured on the basis of the largest plant of a millet clump, while LAI includes leaf-areas of smaller and later developed plants. As the stomatal resistance is dependent upon both the age of leaves and plant height (lower plants are shadowed), the measurements will not represent transpiration from lower and late-maturing plants correctly.

To examine the validity of the transpiration data (T), these were compared to fluxes of evapotranspiration (ET) during a period when soil-evaporation is assumed to be at zero. Evapotranspiration was estimated by use of the eddy-correlation-technique (GILL SOLENT 3D anemometer combined with a KRYPTON hygrometer). The results are seen in Fig. 10. Despite the above stated uncertainties at the end of the growing season, the transpiration and evapotranspiration data seem to correlate very well.

Evapotranspiration has been calculated from the Penmann-Monteith Formula. These results are shown in Fig. 11, which clearly demonstrates that the SW-Model has introduced some concepts of utmost importance to the modelling of transpiration above heterogeneous vegetation.

Potential evapotranspiration has been calculated using Penmann's Formula and the results are seen in Fig. 11. The difficulty of utilizing calculations of potential evapotranspiration for description of the state of water-stress is indicated by making a comparison with the transpiration data. During the experimental period there was a well-distributed precipitation lasting until 63 days after sowing. The calculation of the soil-water balance and the analysis of plant temperature indicate that water-stress did not arise until the last 10-14 days of the recording period. In Fig. 12 the relationship between plant temperature (KT-17 Heimann IR-thermometre) and transpiration is shown. The results demonstrate that a very high

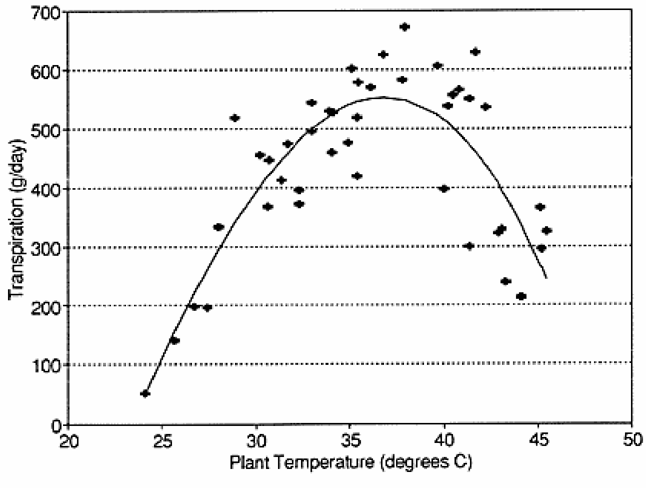

Fig. 12. Relationship between Transpiration (gram/day) and plant temperature (brightness-temperature) (°C).

plant temperature coincides with low transpiration. This happens in the last 10 days of the measurement period and is caused by high stomatal resistance and low evaporative cooling. At moderate plant temperatures the transpiration increases with an increase of leaf temperature which, in turn, increases the leaf's internal vapour pressure and causes an increased e_{st}-e_a.

APPLYING CONCEPTS TO REGIONAL ANALYSIS

The division of radiation and aerodynamic resistance in the canopy and the introduction of separate surface resistances for soil and vegetation have proved to be necessary concepts for modelling transpiration from heterogeneous vegetation. Unfortunately it is a very cumbersome process to estimate the applied surface resistances. If these components could be estimated by remote sensing techniques, it would be a assistance to the model.

Nemani & Running (1988) demonstrate that the expression T_s/NDVI may represent a collective surface resistance for aerodynamically rough surfaces (T_s = surface temperature; NDVI = Normalized Difference Vegetation Index). Other investigations suggest that the soil resistance may be estimated from remote sensing analysis of microwaves (Chanzy & Bruckler, 1991). Further examination of T_s, NDVI and microwave reflection may induce techniques for the estimation of separate surface resistances.

The division of radiation-absorption is based upon LAI and may therefore be determined from NDVI. R_n may be estimated from the analysis of T_s and surface-albedo by remote-sensing techniques as shown by Soegaard (1988).

The influence of the spatial heterogenity of vegetation density to aerodynamic resistance is poorly known. The heterogenity of the millet fields results in large aerodynamic roughness and therefore contributes to little aerodynamic resistance. The roughness of heterogeneous surfaces is however at present insufficiently expressed as an increasing linear function of LAI. This relationship was originally derived above homogeneous vegetation (Monteith,J.L., 1973). Its application to low-density spatially heterogeneous vegetation such as millet probably leads to an under-estimated roughness and an over-estimated aerodynamic resistance.

Another uncertainty in the estimation of aerodynamic resistance is the assumption of similarity between the resistance of momentum fluxes and heat fluxes.

Ben Mehrez et al. (1992) estimated a flux-division parameter in the canopy on the basis of NDVI. The calculation of this factor is based on an empirical relationship given by Thom (1972). More knowledge about intra-canopy aerodynamic transfer is required for the improvement of this method.

CONCLUSION

In the semi-arid areas of the world it is necessary to dis-tin guish between soil evaporation and transpiration to evaluate plant water use. Recently the stem heat balance technique has attracted fresh attention for the analysis of transpiration in the Sahel. Combined with measurements of leaf-area and LAI, a method for obtaining continuous data on transpiration from a millet field was tested during two consecutive months in Niger, 1992. The transpiration data were compared to measurements of vapour-fluxes during a period with presumably no soil evaporation. Despite several uncertainties in exactly this period, the transpiration data correlate very well with the data of evapotranspiration.

The transpiration data were furthermore compared to calculations of transpiration by the SW-model and evapotranspiration by the Penmann-Monteith Formula. It was shown that a division of net radiation and flux resistances in the canopy and the introduction of separate surface resistances for soil and vegetation led to considerable consistency between measured and calculated transpiration. Towards the end of the experimental period the modelled transpiration (S & W) was under-estimated. This may have been caused by the input of a stomata resistance which was too high, since this parameter was only measured on the senescenting millet plants. One important obstacle for the use of the SW-model is the estimation of surface-resistance of soil and plants, while all other input parameters may be provided by a standard micro-metereological station.

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plant temperature coincides with low transpiration. This happens in the last 10 days of the measurement period and is caused by high stomatal resistance and low evaporative cooling. At moderate plant temperatures the transpiration increases with an increase of leaf temperature which, in turn, increases the leaf's internal vapour pressure and causes an increased e_{st}-e_a.

APPLYING CONCEPTS TO REGIONAL ANALYSIS

The division of radiation and aerodynamic resistance in the canopy and the introduction of separate surface resistances for soil and vegetation have proved to be necessary concepts for modelling transpiration from heterogeneous vegetation. Unfortunately it is a very cumbersome process to estimate the applied surface resistances. If these components could be estimated by remote sensing techniques, it would be a assistance to the model.

Nemani & Running (1988) demonstrate that the expression T_s/NDVI may represent a collective surface resistance for aerodynamically rough surfaces (T_s = surface temperature; NDVI = Normalized Difference Vegetation Index). Other investigations suggest that the soil resistance may be estimated from remote sensing analysis of microwaves (Chanzy & Bruckler, 1991). Further examination of T_s, NDVI and microwave reflection may induce techniques for the estimation of separate surface resistances.

The division of radiation-absorption is based upon LAI and may therefore be determined from NDVI. R_n may be estimated from the analysis of T_s and surface-albedo by remote-sensing techniques as shown by Soegaard (1988).

The influence of the spatial heterogenity of vegetation density to aerodynamic resistance is poorly known. The heterogenity of the millet fields results in large aerodynamic roughness and therefore contributes to little aerodynamic resistance. The roughness of heterogeneous surfaces is however at present insufficiently expressed as an increasing linear function of LAI. This relationship was originally derived above homogeneous vegetation (Monteith,J.L., 1973). Its application to low-density spatially heterogeneous vegetation such as millet probably leads to an under-estimated roughness and an over-estimated aerodynamic resistance.

Another uncertainty in the estimation of aerodynamic resistance is the assumption of similarity between the resistance of momentum fluxes and heat fluxes.

Ben Mehrez et al. (1992) estimated a flux-division parameter in the canopy on the basis of NDVI. The calculation of this factor is based on an empirical relationship given by Thom (1972). More knowledge about intra-canopy aerodynamic transfer is required for the improvement of this method.

CONCLUSION

In the semi-arid areas of the world it is necessary to distin guish between soil evaporation and transpiration to evaluate plant water use. Recently the stem heat balance technique has attracted fresh attention for the analysis of transpiration in the Sahel. Combined with measurements of leaf-area and LAI, a method for obtaining continuous data on transpiration from a millet field was tested during two consecutive months in Niger, 1992. The transpiration data were compared to measurements of vapour-fluxes during a period with presumably no soil evaporation. Despite several uncertainties in exactly this period, the transpiration data correlate very well with the data of evapotranspiration.

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