The effects of the environmental factors on the evapotranspiration in different growth phases of soybean

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Effekte von Umweltfaktoren auf die Evapotranspiration in unterschiedlichen Wachstumsstadien der Sojabohne

1. Introduction

Since 1973 the introduction of the mass transport equation by Dalton, numerous approaches were developed for evapotranspiration (ET) calculation and hence its estimation (SCHRÖDTER, 1985). The interrelationships between the three compartments of plant-soil-atmosphere affect the ET and their theoretical developments (PEREIRA et al., 1999). Particularly, weather played a major role in determining the ET amount. According to weather variability many ET equations and models were improved by using different approaches which based on transfer theory (BRADEN, 1982; GOUDRIAAN, 1977; SAYLAN and BERNHOFER, 1993; PEREIRA et al., 1999; TODOROVIC, 1999). Most of these equations were complex, although they were physically realistic and plausible. Some researchers found the relationships between ET and relevant meteorological, soil and plant parameters for different plants. The dependence of the evapotranspiration is evaluated on climatological factors and other plant parameters through statistical analysis. BAIER (1968) provided a meaningful relation between the evaporation and meteorological parameters such as air temperature (T), global radiation (R_g), extraterrestrial radiation (R_a), wind speed (u) and vapour pressure deficit (VPD). Similarly, KRISHNAN and KUSHWAHA (1973) obtained still better relationship for typical Indian plants by using R_g, VPD and u measurements. ITIER et al. (1992) investigated the relationship between evapotranspiration and leaf water potential of soybean. TACONET et al. (1995) estimated the seasonal evaporation and stomatal conductance over a soybean field through environmental factors using radiometric temperatures. SAYLAN et al. (1998) used fuzzy logic approach to find the relationship between ET of fababean and agrometeorological parameters. Furthermore, many scientists derived different equations relating ET to meteorological, soil and plant parameters (LINDROTH and HALLDIN, 1986; SAYLAN and BERNHOFER, 1993; ROMELITO and WILLIAM, 1996).

The effects of various parameters on the ET can be changed by considering the growth phases of plants. The variations in

Zusammenfassung

Die gegenständliche Arbeit berechnet für den Standort Groß-Enzersdorf bei Wien und das außergewöhnlich warme Jahr 1992 die tatsächliche Evapotranspiration der Sojabohne in drei Wachstumsphasen – vom Aufgang zum Zweiblattstadium; von der Blüte zur ersten Hülse sowie von der Hülsenreife bis zur Ernte – nach der „Bowen-Verhältnis"-Energiebilanzmethode.

Die errechnete Energiebilanz der Sojabohne wurde in Beziehung gesetzt mit der gemessenen Evapotranspiration zusätzlich mit der gemessenen Globalstrahlung, Lufttemperatur, Windgeschwindigkeit, dem Dampfdruck(defizit), Wassergehalt des Bodens in unterschiedlichen Tiefen sowie dem Blattflächenindex bei verschiedenen Wachstumsstadien.

Es stellte sich heraus, daß die Temperatur einen wichtigen Faktor während der ersten Wachstumsphase darstellt. Globalstrahlung und Windgeschwindigkeit spielen eine zentrale Rolle für die Evapotranspiration während der ersten und zweiten Wachstumsphase der Sojabohne. Überdies beeinflußt der Blattflächenindex während aller und der Wassergehalt in 15 cm Bodentiefe während der zweiten und dritten Wachstumsphase die Evapotranspiration der Sojabohne.

Schlagworte: Evapotranspiration, Sojabohne, Bowen-Verhältnis, Agrarmeteorologie.

Summary

In this paper the actual evapotranspiration of soybean was calculated in three growth phases – from emergence to 2nd leaf, from flowering to first pod and from pod maturity to harvest- by the Bowen ratio energy balance method in Gross-Enzersdorf near Vienna/Austria during the extremely warm season in 1992. The estimated energy balance of soybean was used to investigate the relationships between the measured evapotranspiration, in addition to the measured global radiation, air temperature, wind speed, vapour pressure deficit, soil water content in different depths, and leaf area index under different growth phases. It was found that the air temperature is an important factor for the first growth phase. The global radiation and the wind speed play essential roles for evapotranspiration during the first and second growth phases of soybean. In addition, specifically the leaf area index for all growth phases and soil water content at 15 cm depth for second and third growth phases affected the evapotranspiration of soybean.

Key words: Evapotranspiration, soybean, bowen ratio, agrometeorology.

the plant factor like leaf area index and therefore ET depends on the crop resistance, weather factors, soil moisture and development periods (PETERSCHMITT and PERRIER, 1991).

The aim of this study is to determine the relationship among the parameters – leaf area index, global radiation, air temperature, wind speed, vapour pressure deficit and soil water content- with the ET of soybean during three growth phases- from emergence to 2nd leaf, from flowering to first pod and from pod maturity to harvest.

2. Material and Methods

2.1 Measurements

The soybean (*Glycine max.*, Labrador) were planted at Gross-Enzersdorf Experiment Station of the University of Agricultural Sciences in Vienna (48° 12' N; 16° 34' E; 153 m above mean sea level) during the vegetation period of 1992 in a square area of 50 m site length where the soil was variable from the loam to the sand type (SAYLAN, 1993). In Gross-Enzersdorf the annual average precipitation and the annual mean temperature from 1953 to 1987 were 739 mm and 10.1° C, respectively. The average potential evapotranspiration between 1965 and 1974 was 615 mm and average actual evapotranspiration between 1969 and 1974 was 495 mm for this research area (MÜLLER, 1993).

Soybean was planted on 28 April 1992 and harvested on 2 September 1992. The total precipitation was only 340 mm during the growth season of soybean. On the other hand, the soybean was irrigated 5 times total of 113 mm by sprinkler irrigation system. During the second and third growth phases, the soybean was irrigated twice with the total of 43 mm and 35 mm, respectively.

In this study, the actual ET was calculated by using Bowen ratio energy balance (BREB) system, which was consisted of ventilated temperature (NiFe Resistance-thermometer) and humidity sensors that were located in different heights above the canopy. The lowest temperature and humidity (TRH) sensors were fixed to 10 cm above canopy during the growth phases. The difference between the lowest TRH and the highest TRH sensors was kept 50 cm during the measurement. On the other hand, a pyradiometer and a pyranometer were used to measure the net and the global radiation amounts, respectively. The soil heat flux was measured by a pair of heat flux discs at approximately 1 cm below the soil surface. The measurement of wind speed was made at 2 m above soil surface and precipitation was measured at 1m above the surface. The consistency of the BREB method results were checked against criteria given by OHMURA (1982) and evapotranspiration values were corrected accordingly. The soil water content (SWC) was measured by gypsum blocks at a set of depths as 15 cm, 30 cm, 60 cm and 100 cm, 30 minute interval and by Time Domain Reflectometry (TDR) method 15 days interval. In addition, crop height was measured periodically 15 days interval during the growth of soybean at the site. The leaf area index (LAI) by LI-COR LAI-2000 was measured 15 days interval also. The data were logged in every 15-minute by data logger. A detailed description of the site and instrumentation were given by DIRMHIRN et al. (1991), BERNHOFER et al. (1992) and SAYLAN (1993, 1995).

The ET was calculated temporally by BREB system in the following three growth phases of soybean: 1st phase: from emergence to 2nd leaf (May 11 - May 27); 2nd phase: from flowering to first pod (June 25 – July 15); 3rd phase: from pod maturity to harvest, (July 28 – August 30).

2.2 Method

The study is based on the Bowen Ratio Energy Balance (BREB) method. This approach depends on the gains and losses of the thermal energy at the evaporating surface. Physical and biological processes in soil-plant ecosystems control the energy and mass exchange processes (CHEN and CHOUGHENOUR, 1994). The energy balance for evaporating surface can be written generally as:

$$R_n + G + H + L.E = 0 \tag{1}$$

where R_n is net radiation (Wm^{-2}), G is the soil flux (Wm^{-2}), H is the sensible heat flux in the air (Wm^{-2}) and L.E is the latent heat flux (Wm^{-2}) which might be further referred to daily ET rate (mm day^{-1}).

This equation can be written by convenient definition of Bowen ratio, b, as (BOWEN, 1926),

$$L.E = \frac{(R_n + G)}{(1 + \beta)} \tag{2}$$

where

$$\beta = \left(\frac{H}{L\,.\,E}\right) = \frac{P C_p K_h \partial T/\partial z}{L\,\epsilon\, K_w \partial e/\partial z} = \gamma \left(\frac{\Delta T}{\Delta e}\right) \tag{3}$$

in which P is the atmospheric pressure, is $\in$ ratio of the molecular weight of water vapour and air, L is latent heat of vaporisation for water, γ is psychometric constant, K_h is exchange coefficient for sensible heat, K_w exchange coefficient for water vapour ($K_h/K_w = 1$), C_p is specific heat of air at constant pressure, ΔT and Δe are differences of temperature and vapour pressure at two heights (0.1 m and 0.6 m above canopy surface) over 15-minute intervals, respectively.

The BREB method is used in determining latent heat fluxes by many scientists (NIE et al., 1992; STEDUTO and HSIAO, 1998; SAYLAN and EITZINGER, 1998). The BREB method has been used extensively under wide range conditions and has shown very successful results. The advantage of the BREB method is that no similarity functions is necessary for the atmospheric turbulence which appear explicitly its formulation (OHMURA, 1982). However, this method requires very accurate measurements. On the other hand, disadvantages of the BREB method are analysed by OHMURA (1982) and PEREZ et al. (1999).

Both equations 2 and 3 produce a singularity for $\beta = -1$, as pointed out by OHMURA (1982). This occurs more often only when sensible heat flux is low, around sunrise, sunset and occasionally at night (BRUTSAERT, 1991). The validity of the BREB method depends critically on the similarity of the temperature and humidity profile. According to OHMURA (1982) due to one-dimensional steady-state assumptions in the BREB method, and the resolution limits of the instruments, the use of gradients of temperature and specific humidity for the ET calculation is not always justified. That's why this method requires certain rejection criteria for inappropriate data.

3. Results

The calculated ET values by BREB method were assumed to reflect the actual ET and the estimations during different growth phases of soybean were explained below. Figures 1 a, b, c represent the measured plant and meteorological parameters, the variations of energy balance components and the time series of soil water content (SWC) for different depth, precipitation and irrigation values, respectively. In Figure 1 c, it has to be noted that the number attached to soil water content (SWC) – as for instance SWC15 – shows measurement depth in cm as 15 cm. The leaf area index (LAI) scale was shown on the right hand side vertical axis (see Fig. 1a). On the other hand, R_n was considered positive when directed toward the surface, while G, H and LE were negative away from the surface. Although in Figures 1a, b, c, there were limited number of data as days, in fact time multiple regression model was based on hourly atmospheric and soil water content data. The periodically measured LAI was extrapolated to hourly data.

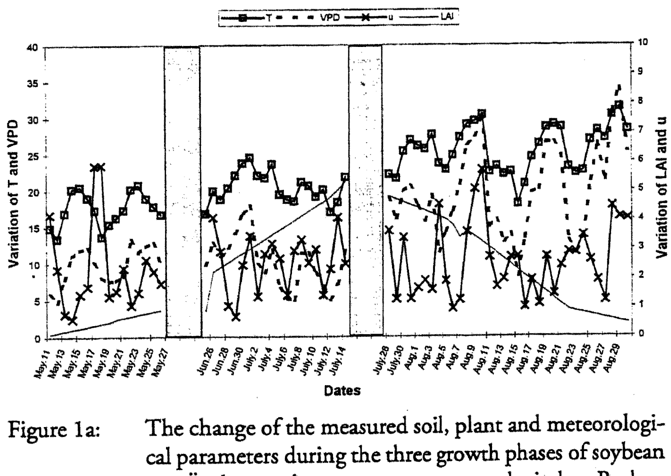

Figure 1a: The change of the measured soil, plant and meteorological parameters during the three growth phases of soybean

Abbildung 1a: Die Änderung der gemessenen meteorologischen Boden- und Pflanzenparameter während der drei Wachstumsphasen der Sojabohne

3.1 Estimation of soybean evapotranspiration

In first growth phase the crop height changed from 2 to 15 cm. It was obvious from Figure 1a that the pattern of T and VPD were rather parallel to each other with ranges 13–21° C and 4.6–13.0 hpa, respectively. However, the wind speed reaching to 6 m s^{-1}. During this growth phase, there were continuous LAI increases from almost zero to 0.9 (Figure 1a). On the other hand, energy balance components R_n, LE and H assumed values between 168-520 W m^{-2}, 50–260 W m^{-2} and 35-293 W m^{-2}, respectively, (see Figure 1b). In this phase the amount of the total ET reached 58.5 mm with average value as 3.6 mm day^{-1}. In this early growth phase, the soil moisture had not limitation effect on the soybean growth, because the water content in the soil was almost at the field capacity. Figure 1c shows the variations of soil water content in different depth during the three growth phases. However, during this phase LE and H were negatively related to each other because high LE values correspond to low H values. Furthermore, G remains almost constant at approximately 10 % of R_n during the whole period.

In the second growth phase, it is possible to state from Figure 1a that increases were expected in the LE due to temperature increase up to 24.5° C. In addition to increase in the VPD reaching its maximum of 17.9 hpa and continuous increase in the LAI during the whole period (from 2.2 to 5.3). Initially, corresponding to the increases in T, VPD and LAI there was a decrease in wind speed to almost

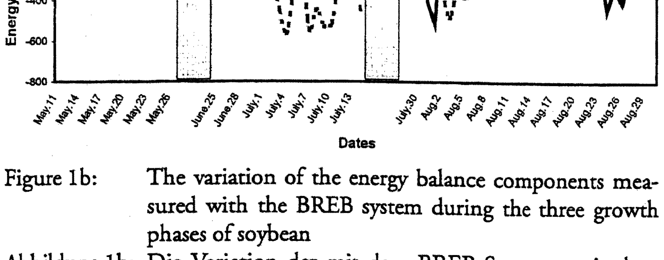

Figure 1b: The variation of the energy balance components measured with the BREB system during the three growth phases of soybean

Abbildung 1b: Die Variation der mit dem BREB-System ermittelten Energiebilanzkomponenten während der drei Wachstumsphasen der Sojabohne

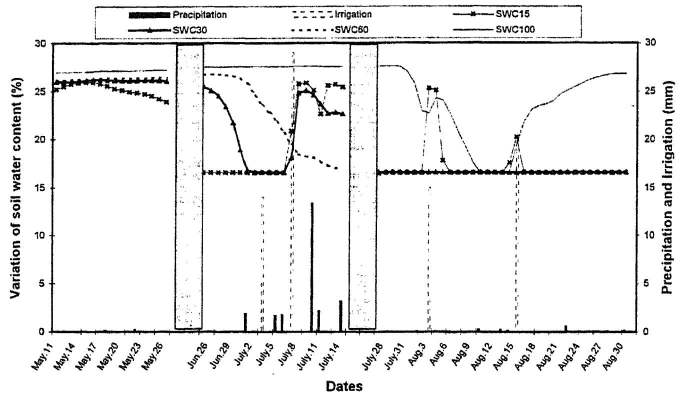

Figure1c: The variation of the soil water content (SWC), precipitation and irrigation during the three growth phases of soybean

Abbildung 1c: Die Variation von Bodenwassergehalt, Niederschlag und Bewässerung während der drei Wachstumsphasen der Sojabohne

0.7 m s^{-1}. In the second growth phase the mean crop height was 55 cm.

In this phase, the sensible heat flux shows positive values due to irrigation and precipitation (max. 190.2 W m^{-2}) especially along the middle range duration, which means that the direction of the sensible heat flux was from the air to the soil (Fig. 1b). Such an occurrence was referred commonly as the "Oasis effect" (OKE, 1978). This is explained by the fact that the atmosphere supplies sensible heat to the surface because the surface is cooler than the regional air due to evaporation cooling. Over this phase the amount of total ET was reached 145.6 mm, with maximum ET value as 12 mm per day. However, the total soil water from the surface down to in depth of 100 cm fluctuated between 220 mm and 255 mm, and consequently the plant growth was very intensive (Fig. 1c).

At the beginning of second phase, the topsoil layer had not enough water for plant use and SWC at 15 cm varied with the increase in crop growth. For a fully developed green cover of soybean, although LE nearly equals R_n, but G and H were almost negligible apart from irrigation days.

Contrary to the first two phases, LAI decreased steadily during the third period (July 28-August 30) where plant height varied between 70 cm and 80 cm. This phase was very warm, dry and the SWC remained almost constant. In this phase, there was a measuring error at 100 cm depth in the SWC (Fig. 1c). These were indications of drought and, therefore, the soybean field was irrigated twice in this phase. Air Temperature and VPD values followed each other more closely than previous phases with respective ranges of

18.1° C – 31.4° C and 8.2 hpa – 34.0 hpa. The average wind speed was 2.6 m s^{-1} (Table 1). Figure 1b indicates the daily mean energy balance components that were observed in the third growth phase which are checked according to OHMURA (1982). R_n changed between 126 W m^{-2} and 595 W m^{-2} with H having often positive fluxes during this phase.

Table 1: The daily mean and standard deviation (σ) values of the meteorological, soil and plant parameters
Tabelle 1: Tagesmittel und Standardabweichung von meteorologischen, bodenkundlichen und pflanzlichen Parametern

Factors	Soybean					
	1st Phase		2nd Phase		3rd Phase	
	Mean	σ	Mean	σ	Mean	σ
T (° C)	17.41	3.38	20.42	4.91	25.61	6.41
Rg ($W \cdot m^{-2}$)	456.5	317.3	424.5	327.0	386.0	307.0
U ($m.s^{-1}$)	2.41	1.87	2.61	1.54	2.57	1.85
VPD (hpa)	9.63	5.42	10.19	6.22	19.72	11.21
SWC15 (%)	25.01	0.83	20.26	4.29	17.23	2.51
SWC30 (%)	26.14	0.05	20.81	3.43	16.55	0.0
SWC60 (%)	26.42	0.06	22.09	3.81	16.55	0.0
SWC100 (%)	27.16	0.05	27.54	0.0	*	*
LAI ($m^2.m^{-2}$)	0.48	0.23	3.61	0.81	2.68	1.42

* Missing value

Although before the end of leaf (20 August) LE had values between 100 and 484 W m^{-2}, later it decreased down to 25 W m^{-2}. During this last growth phase, the influence of the irrigation gave rise to a positive convection flux from the air to the soil.

3.2 Relationships between evapotranspiration and various factors

The following relationships were considered for different growth phases of soybean. In order to obtain appropriate relationships between LE and other parameters, stepwise which is the most widely used of the automatic search methods developed to economize on computational efforts, while arriving at a reasonably good subset of independent variables and multiple regression analysis techniques were applied with variables R_g, T, VPD, u, LAI and SWC at a set of depths as stated previously (NETER et al., 1983). According to the partial F-test criterion, if the variable made a significant contribution to the model considered, it was included in the multiple regression equation. This procedure was carried out until P prediction errors were less than 0.05. After taking the necessary steps through a computer software strong correlations were observed between L.E and some of these variables.

In the early vegetative period (first phase), all data were used to predict soybean L.E, which had a high coefficient of determination with R_g only. However, still better relationship was obtained by considering four parameters, namely, R_g, T, LAI and u for which the overall coefficient of determination was equal to 0.82 (Tables 2 and 3). In order to assess the validity of the multiple regression, BREB and L.E values from the model were plotted on a Cartesian coordinate system as in Figure 2a.

Table 2: Coefficient of determination (r^2), significance test (F-test) and error probability (P), standard deviation (σ)
Tabelle 2: Bestimmtheitsmaß (r^2), Signifikanztest, Irrtumswahrscheinlichkeit (P) und Standardabweichung

Plant	Phases	r^2	F-test	P<	σ
Soybean	1	0.82	160.44	0.021	29.5
Soybean	2	0.80	154.12	0.011	61.5
Soybean	3	0.60	21.36	0.004	79.5

Table 3: Regression analysis results between daily average evapotranspiration and soil, plant and meteorological parameters for three growth phases of soybean
Tabelle 3: Ergebnisse der Regressionsanalyse zwischen durchschnittlicher täglicher Evapotranspiration und meteorologischen, bodenkundlichen sowie pflanzlichen Parametern für drei Wachstumsphasen der Sojabohne

Plant	Phases	Equations
Soybean	1	LE = -305.1 + 21.6T - 0.63 R_g + 8.64u + 28.3 LAI
Soybean	2	LE = 194.9 -1.38 R_g - 43.1 u + 24.9 VPD + 10.3 SWC15 - 91.7 LAI
Soybean	3	LE = 348.2 -23.6 SWC15 - 42.5 LAI

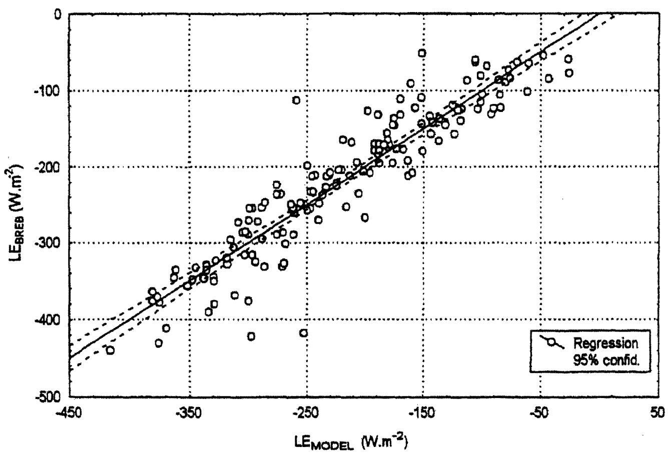

Figure 2a: The relationship between calculated (LE_{BREB}) and statistically estimated L.E (LE_{MODEL}) of soybean, first phase
Abbildung 2a: Die Beziehung zwischen errechneter (LE_{BREB}) und statistisch geschätzter LE (LE_{MODEL}) der Sojabohne, erste Phase

In the second growth phase, the R_g was the most important factor for the L.E with the second significant parameter as VPD, because L.E increased in connection with VPD. On the other hand, similar to the first measuring season LAI and u yielded a better relationship with measured L.E. The final important factor was the SWC at 15 cm depth, because at the top, the soil was extremely dry and the gypsum block sensor at 15 cm depth was affected quickly by the irrigation, the L.E and the meteorological parameters (Tables 2 and 3). Figure 2b shows the relationship between the model (LE_{MODEL}) and calculated (LE_{BREB}) hourly values.

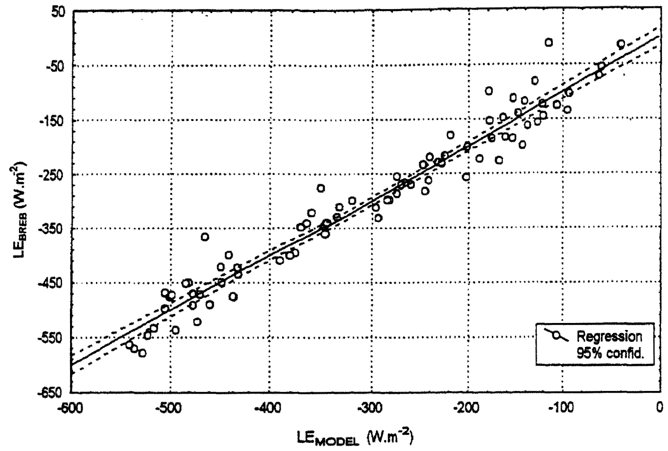

Figure 2b: The relationship between calculated (LE_{BREB}) and statistically estimated L.E (LE_{MODEL}) of soybean, second phase

Abbildung 2b: Die Beziehung zwischen errechneter (LE_{BREB}) und statistisch geschätzter LE (LE_{MODEL}) der Sojabohne, zweite Phase

During the last season of soybean, a satisfactory relationship was not observed between the soybean L.E and all the other variables. It was noticed that only the LAI and the SWC15 explained the L.E better than the other variables because during this period LAI had coefficient of determination as $r^2 = 0.54$ (see Fig. 2c).

4. Discussion

In this study, the influence of global radiation, air temperature, wind speed, vapour pressure deficit, soil water content in different depths, and leaf area index parameters were investigated on the soybean ET in three different development periods. The overall relationship was satisfactorily

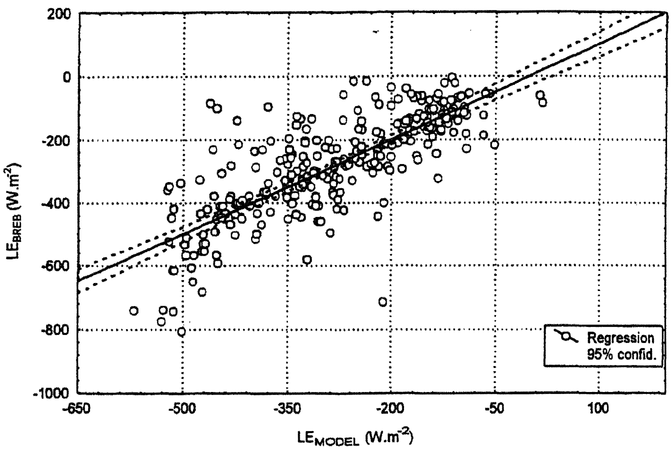

Figure 2c: The relationship between calculated (LE_{BREB}) and statistically estimated L.E. (LE_{MODEL}) of soybean, third phase

Abbildung 2c: Die Beziehung zwischen errechneter (LE_{BREB}) und statistisch geschätzter LE (LE_{MODEL}) der Sojabohne, dritte Phase

good because during the first period of soybean the soil moisture was at field capacity, with no limitation on L.E. The scatter of BREB and model L.E values appeared around the regression model. This implied that the model was valid on the average without any bias. Another distinctive characteristic of this scatter diagram was that the first period points were the closest regression to line whereas the third period points had the greatest variability, i.e., deviations from this line were bigger (Fig 2 a, b, c). Furthermore, during the vegetation period radiation and naturally the temperature increases gave rise to plant growth and LAI value. In this connection, these parameters explained the soybean L.E better than the other parameters during the first growth phase. On the other hand, the SWC affected on the ET in some phases with the crop water consumption increase.

Particularly, the growth of soybean was related to photosynthesis increase during the second and third phases with the radiation increase. In addition, SWC at 15 cm depth, decreased with the plant growth and it was related to the increase in L.E. Thus the plant root zone was very important for the L.E when the soil surface dried or the soil water limited the rate in the L.E decrease. This was because of the top layer of soil of about 15 cm was effected easily by the atmospheric variations because of the main plant root growth in this layer. Similarly, LAI tended to decrease like L.E during the third growth phase. Hence, the L.E increased directly with LAI, especially, after the end leaf attains the value of L.E as zero.

It was found that R_g was one of the major parameters for most of growth phases of soybean ET. The reason for this was due to the radiation provided the main energy to plant growth because of the thermal effects coupled with photosynthesis. The second important parameter was the LAI for all periods of soybean. In this connection, the interception of radiation depends on the LAI but also on the geometry of leaves, which had a major role for the plant growth. The other significant parameter was the variability of soil water, which affected both plant growth and availability of water for ET process. The temperature affected ET during some portions of the measuring period for plants but T might influence ET through its direct relation to stomata.

The ET might be affected by many parameters and their influences could vary temporally and spatially. This was the main reason why it was necessary to find the relationships between the ET and various parameters for different development periods of plants. If there is a limiting factor for plant growth in a phenological period or ET, this limitation needs to be considered in the ET estimations. The results of this study may give the erroneous ET when applied to different cases wherein some significant parameters other then suggested here are overlooked. The developed approach can fail when applied to the other climatological conditions, which varies from year to year. That's why, for generalisation of the results the well defined large data sets and relevant factors are needed.

Acknowledgments

The author wishes to thank Prof. Dr. Inge Dirmhirn, Prof. Dr. Christian Bernhofer, Prof. Dr. Zekai Sen, Prof. Dr. Ülgen Gülcat and Dr. J. Eitzinger for their helpful comments, particularly Ing. W. Laube, Ing. Wieslaw Mikielewicz and W. Klug for technical assistance and two anonymous reviewers.

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Eingelangt am 1. Juli 1999
Angenommen am 28. Dezember 1999