Remote Sensing of Potential and Actual Daily Transpiration of Plant Canopies Based on Spectral Reflectance and Infrared Thermal Measurements — Concept with Preliminary Test —

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Abstract

A new concept for estimating potential and actual values of daily transpiration rate of vegetation canopies is presented along with results of an initial test. The method is based on a physical foundation of spectral radiation balance for a vegetation canopy, the key inputs to the model being the remotely sensed spectral reflectance and the surface temperature of the plant canopy. The radiation interception or absorptance is estimated more directly from remotely sensed spectral data than it is from the leaf area index. The potential daily transpiration is defined as a linear function of the absorbed solar radiation, which can be estimated using a linear relationship between the fraction absorptance of solar radiation and the remotely sensed Soil Adjusted Vegetation Index for the canopy. The actual daily transpiration rate is estimated by combining this concept with the Jackson-Idso Crop Water Stress Index, which also can be calculated from remotely sensed plant leaf temperatures measured by infrared thermometry. An initial demonstration with data sets from an alfalfa crop and a rangeland suggests that the method may give reasonable estimates of potential and actual values of daily transpiration rate over diverse vegetation area based on simple remote sensing measurements and basic meteorological parameters.

Key words: Infrared thermometry, Remote sensing, Spectral reflectance, Transpiration, Water stress.

1. Introduction

Yield and biomass production of plants have been reported to be correlated with the amount of canopy water use (Hanks, 1983; Howell, 1990). In fact, both CO₂ and H₂O exchange processes between plant leaves and the atmosphere are primarily regulated by stomatal aperture. Thus, effective water management is one of the most important issues in agricultural production, especially in arid and semi-arid regions. The more important the impact of global climate change and population growth become, the more important efficient water use will be at regional and global scales. Consequently, remote sensing techniques are expected to provide an effective method for estimating water consumption over wide areas of crop canopies as well as natural vegetation.

Although evapotranspiration (*ET*), *i.e.* the total value of evaporation from the soil surface and transpiration from plant leaves, has been estimated based on lysimeter measurements and energy balance models such as the Penman-method (Gates, 1980), it is essential to estimate transpiration separately from evapotranspiration for better understanding of water and energy exchange processes in the soil-plant-atmosphere continuum as well as for more efficient water use in plant production. However, few methods are available, for estimating the transpiration rate (*Tr*) of intact plants over wide areas (Inoue, 1990). Daily estimates of these parameters seem to be sufficient for such applications as crop diagnosis, yield prediction, management decision-making and ecological plant science. Our objective, thus, is to estimate the energy-limited potential values and actual values of daily transpiration rate (*Tr_p* and *Tr_a*) in vegetation canopies. In this paper, we

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present the new concept along with the results of preliminary tests. The method is based on a physical foundation of spectral radiation balance for the vegetation, the key inputs to the method being the remotely sensed spectral vegetation index and the surface temperature of plants.

2. Concept and Model

2.1 Basic concept

Although the term “potential” transpiration is often used, it is not well-defined, because it is determined by the interaction of the physiological status of plants and physical environmental factors. Even flooded rice plants, for example, can not always transpire at the “potential” rate. Plant water status is usually closely related to the soil water status. Nevertheless, we can easily imagine some extreme situations such as potentially transpiring plants on a completely dry soil-surface or physiologically depressed (*i.e.*, decreased transpiration) ones over a completely wet soil-surface. These situations can occur not only in imaginary extreme conditions but also in actual field conditions.

Thus, it may be better to define a meteorological “potential” transpiration based on the available energy for vaporization at the plant leaves; that is, healthy plants without water shortage are transpiring at the potential rate which is mainly regulated by the available energy. This energy limited transpiration has often been estimated by a linear function of absorbed solar radiation (Makkink, 1957) or absorbed net radiation (Priestley and Taylor, 1972). Such “radiation methods” have been widely used for the estimation of canopy transpiration (Brutsaert, 1982). In fact, Sakuratani (1987) reported a close correlation between absorbed solar radiation and transpiration of well-watered soybean plants.

The total radiation energy absorbed is a function of the incoming solar radiation (R_s) and the interception-ability of the canopy. The intercepted solar radiation (IR_s) has been analyzed as an exponential function of leaf area index (LAI) using the relationship (Monsi and Saeki, 1953),

$$IR_s = R_s [1 - \exp(-k LAI)] \quad (1)$$

where k is an extinction coefficient that is a function of both canopy architecture and spectral features of leaf sections. Also, the intercepted

or absorbed photosynthetically active radiation ($APAR$) has been related to LAI in a similar manner, $APAR = PAR [1 - \exp(-k LAI)]$ (Asrar *et al.*, 1984), where PAR is the incident photosynthetically active radiation.

On the other hand, a number of papers have reported a close relationship between LAI or biomass and remotely sensed spectral reflectance values such as vegetation indices (VI ; *e.g.*, Wiegand *et al.*, 1991). From a theoretical point of view, however, the radiation balance of a canopy may be estimated more directly from remotely sensed spectral data than from the leaf area index, because effects of other factors such as canopy architecture, the spectral signature of the leaf and viewing/illumination geometry can be included in the spectral measurements. In fact, $APAR$ was shown to be well estimated by spectral reflectance measurements (Asrar *et al.*, 1984; Gallo *et al.*, 1985; Inoue *et al.*, 1991). Furthermore, Pinter (1993) showed that the relationship between fraction $APAR$ ($fAPAR$) and spectral indices derived from reflectance measurements was independent of solar zenith angle or time of day, though the actual values of these parameters varied with time of the day. His results suggest that the use of multispectral vegetation indices (such as $SAVI$, soil adjusted vegetation index) to estimate the proportion of incident solar energy absorbed by a plant community is promising and has biologically significant meaning.

On the basis of the above consideration, we assume that $[1 - \exp(-k LAI)]$ can be expressed as a linear function of the spectral vegetation index, skipping the estimation of both k and LAI values; that is,

$$fAPAR = 1 - \exp(-k LAI) \propto VI \quad (2).$$

Considering the radiation balance of a canopy, one can define the radiation absorbed by the canopy (AR_s) as,

$$AR_s = R_s [1 - r - (1 - r_0) \exp(-k LAI)] \quad (3)$$

where r and r_0 are the reflectances of the canopy and soil, respectively. The value of r was found to be related to the reflectance r_f of a full-cover canopy and r_0 of bare soil, respectively,

$$r = r_f - (r_f - r_0) \exp(-k' LAI) \quad (4)$$

where k' is a constant (ET research group, 1967). The value of k' was found to be similar to k . Moreover, the effects of both $r_0 \exp(-k LAI)$ and

$r_0 \exp(-k' LAI)$ are small, and the difference between these two terms is negligible. Thus, we can obtain the following equation by substituting Eq. 4 into Eq. 3,

$$\begin{aligned} AR_s &= R_s(1-r_f)[1-\exp(-k LAI)] \\ &= R_s(1-r_f)fAPAR \\ &= R_s \alpha' SAVI \end{aligned} \quad (5)$$

where α' is an accumulated proportionality constant. $SAVI$ is the Soil Adjusted Vegetation Index defined as,

$$SAVI = [(\rho_{NIR} - \rho_{RED}) / (\rho_{NIR} + \rho_{RED} + L)](1+L) \quad (6)$$

where ρ_{NIR} and ρ_{RED} are the near-infrared and red reflectance factors, respectively, and L is assumed to be 0.5 for a wide variety of LAI values (Heute, 1988). Since we assume that the “potential” daily transpiration Tr_p is proportional to the AR_s/λ , it is expressed as,

$$Tr_p = \alpha SAVI R_s \quad (7)$$

where α is a coefficient including α' and the latent heat of vaporization λ .

Next, we can estimate the “actual” daily transpiration rate (Tr_a) by combining this concept with the Jackson-Idso Crop Water Stress Index ($CWSI$; Idso *et al.*, 1981; Jackson *et al.*, 1981). The $CWSI$ is proposed as an indicator of crop water status, and $CWSI$ values can be calculated based on canopy and air temperatures (t_c and t_a) and vapor pressure deficit (VPD). The $CWSI$ for plants is defined theoretically as $CWSI = 1 - Tr_a/Tr_p$, which is discussed in detail in the next section. Therefore, Tr_a can finally be estimated by,

$$Tr_a = \alpha SAVI R_s(1 - CWSI) \quad (8)$$

based on the combination of remotely sensed spectral and infrared thermal measurements with sound physical foundation.

2.2 Evaluation of $CWSI$

The crop water stress index has proved useful for estimating the stress status of crop canopies (Idso *et al.*, 1981; Jackson *et al.*, 1981). A number of scientists have examined the $CWSI$ and/or related methods for various crops over a wide range of environmental conditions and confirmed the effectiveness of such methods (*e.g.*, Diaz *et al.*, 1983; Heilman *et al.*, 1987; Hattendorf *et al.*, 1988). The usefulness and limitations of the $CWSI$ are summarized by Jackson (1982), O'Toole *et al.* (1984), Hatfield (1990) and Choudhury (1989).

According to Jackson (1981), $CWSI$ was ex-

pressed empirically as

$$CWSI = (t_c - t_{cl}) / (t_{cu} - t_{cl}) \quad (9)$$

where t_{cu} is the maximum crop temperature at which no transpiration occurs, and t_{cl} is the lower limit of crop temperature when the plants are potentially transpiring. Also, Jackson (1982) showed the theoretical background of the index based on the plant canopy-air relationship,

$$\begin{aligned} CWSI &= 1 - ET/ET_p \\ &= [(\gamma(1+r_c/r_a - \gamma) - \gamma^*) / (\Delta + \gamma(1+r_a/r_c))] \end{aligned} \quad (10)$$

where $r_c/r_a = [\gamma r_a Rn_c / (Cv) - (t_c - t_a)(\gamma + \Delta) - VPD] / [\gamma \{(t_c - t_a) - r_a Rn_c / (Cv)\}]$, ET and ET_p are the actual and potential evapotranspiration, γ is the psychrometric constant ($kPa \text{ } ^\circ C^{-1}$), γ^* is $\gamma(1 - r_{cp}/r_a)$, r_{cp} and r_a are the canopy resistance at the potential transpiration and the aerodynamic resistance, respectively, Δ is the slope of the saturated vapor pressure versus temperature curve ($kPa \text{ } ^\circ C^{-1}$), VPD is the vapor pressure deficit (kPa), and Cv is the volumetric heat capacity of air ($J \text{ m}^{-3} \text{ } ^\circ C^{-1}$). Although $CWSI$ is expressed as $1 - ET/ET_p$ in Eq. 10, as Jackson (1982) warned, “it is important that the soil background *not* appear in the field of view of the infrared thermometer. Plant temperature only is desirable for the calculation of $CWSI$ ”, the $CWSI$ is calculated with an assumption that the surface is full-vegetation canopy. In other words, $CWSI$ can be expressed as $1 - Tr/Tr_p$ in his context because the difference between ET and Tr is minor for full-vegetation canopy. This is the main reason why application of the $CWSI$ has been hampered by the difficulty of measuring foliage temperature in partially-vegetated fields.

All input parameters necessary for $CWSI$ can be computed using theoretical and/or empirical equations. As for the aerodynamic resistance which is one of the most important parameters in the above equation, a variety of published equations are available, ranging from simple (a function of windspeed (u) only; *e.g.*, Thom and Oliver, 1977) to quite rigorous (accounting for atmospheric stability and based on values of u , the surface and air temperature difference, surface “aerodynamic” roughness and other parameters; *e.g.*, Kustas *et al.*, 1989).

Further improvements of the index have been suggested for extending its applicability or for simplification (Clawson *et al.*, 1989; Moran *et al.*,

1993).

3. Data used for an initial test

Two data sets used for an initial test of the method were from 1) an experiment in an alfalfa field at the U.S. Water Conservation Laboratory, Phoenix in 1985, and 2) another experiment in a semi-arid rangeland (Walnut Gulch Experimental Watershed) near Tombstone, Arizona in 1992. Methods and results from these measurements have been presented by Moran *et al.* (1989, 1993) and Kustas *et al.* (1991). Because actual transpiration measurements were not made in either the alfalfa or the rangeland experiments, the results from these comparisons do not validate but simply demonstrate the feasibility of our new concept. Estimates of daily transpiration can be compared with measurements of evapotranspiration to determine if the results are reasonable.

3.1 Alfalfa experiment

An 80 × 60 m field was segmented into 18 plots in which alfalfa seeds (*Medicago sativa*, L.) were broadcast planted. The field was tended for one year, during which all 18 plots were irrigated uniformly. After one year's growth, some of 18 plots were flood irrigated at different intervals to vary levels of water stress and biomass. Four different irrigation regimes were applied to the alfalfa: the WET treatment received two irrigations between cuttings; the EARLY treatment was irrigated once, immediately after harvest; the LATE treatment received water midway between cuttings, and the DRY treatment received no supplementary water by irrigation from one harvest until the next. The growth interval between harvests ranged from 3.5 weeks in the summer to 9 weeks during winter.

Crop canopy reflectances were measured using handheld radiometers (Exotech MSS and Barnes MMR*) with a 15° field-of-view. The radiometers had the similar spectral bands to those of the Landsat Multispectral Scanner (MSS) and the Landsat Thematic Mapper, respectively. Multi-spectral observations were made several times a week at a morning time period. MMR data were acquired at 10:30 Mountain Standard Time to

coincide with the time of the Landsat overpass. Canopy surface temperatures were measured with an infrared thermometer (Everest*). Above-ground dry biomass was determined from four cuttings of 0.25 m² in each treatment. Evapotranspiration rates were measured with 1 m × 1 m × 1.5 m lysimeters in three different plots. Throughout the experiment, the lysimeters were irrigated by hand at the same times and with the same amounts of water as the surrounding plots. A multitude of other meteorological parameters were monitored every 30 min. during the experiment, including air temperature, wind speed, reflected and incoming solar radiation, canopy and soil temperatures, and vapor pressure.

3.2 Rangeland experiment

The Walnut Gulch '92 (WG '92) experiment was conducted in a semi arid rangeland over an entire growing season from April to November 1992, with a variety of soil moisture conditions and vegetation densities. The size of the main study site was about 50 km², at the eight locations of which both general meteorological conditions and surface energy balance were measured. Data used here were from a grassland site (Kendall). The spectral data used here are based on ground-based measurements using yoke-mounted Exotech MSS and Barnes MMR radiometers and infrared thermometers (Everest). On five line transects of 30 m each, vegetation parameters such as percent cover, average plant height and volume by species, total LAI and biomass, litter standing and lying, and plant water content were measured. Evapotranspiration flux densities were measured with eddy-correlation apparatus.

4. Results and discussion

4.1 Alfalfa experiment—Single harvest period

This initial analysis was limited to one harvest period from the day of year (DOY) 154 to 184, when reflectance and temperature measurements were made nearly every day and clear-sky conditions persisted for 28 of 30 days. During this period, two lysimeters were subjected to EARLY and WET irrigation treatments, respectively. Results presented here are for spectral and meteorological measurements centered on 10:30 each day.

The values of α in Eq. 7 was computed based

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on evaluation of the relation between $SAVI$ at 10:30, R_s and ET_a (measured using lysimeter) for full-cover and well-watered canopies on clear days. Under these circumstances, we can assume that $Tr_p = ET_a$. The α value for alfalfa was computed to be 1.50. Based on this value of α and the $CWSI$ calculated using surface temperature measurements, the values of Tr_a were computed for all treatment plots. The values of Tr_a for the EARLY and WET plots correspond as expected with the ET_a values measured by lysimeters in each plot (Fig. 1). That is, Tr_a is substantially lower than ET_a when vegetation density is low (DOY 158–170), and Tr_a is nearly equal to ET_a for full-cover canopy. Furthermore, the trend of decreasing ET_a with time in the EARLY treatment is reflected in the Tr_a estimates. The extremely low ET_a values observed in the EARLY plot for DOY 179–183 was caused presumably by some unusual condition of the lysimeter.

Fig. 1. Comparison of estimated Tr_a and measured ET_a for the EARLY and WET alfalfa treatment plots. Symbols ▼ with plots' initials indicate the dates of irrigation in each plot.

Estimates of Tr_a for the eight treatments (two replicates of WET, EARLY, LATE and DRY) were also reasonable (Fig. 2). That is, the Tr_a in the WET plots remained high throughout the harvest cycle; Tr_a in the EARLY plots was similar to the WET plots early in the cycle and decreased late in the cycle; the Tr_a in the LATE plots was low until the late irrigation; and in the DRY plots it remained lower than all others throughout the harvest cycle.

Considering Eq. 8, it is apparent that this approach for estimation of Tr_a accounts for both differences in vegetation density and stress response of the plants. As such, it is informative to look at both biomass and $CWSI$ in relation to estimates of Tr_a . For example, Fig. 3 shows a pair of data from WET and EARLY treatments, both of which have similar biomass values. The transpiration of the WET plot was lower than that of the EARLY plot for the first half of the growth cycle

Fig. 2. Comparison of estimated Tr_a values for the two replicates of WET, EARLY, LATE and DRY alfalfa treatment plots. Symbols ▼ with plots' initials indicate the dates of irrigation in each plot.

Fig. 3. For WET and EARLY treatments over a single alfalfa harvest period, a) estimates of daily transpiration (Tr_a) and measurements of b) biomass and c) $CWSI$.

Fig. 4. For WET and DRY treatments over a single alfalfa harvest period, a) estimates of daily transpiration (Tr_a) and measurements of b) biomass and c) $CWSI$.

and higher during the second half (Fig. 3a); yet the biomass measurements taken in the two plots over the growth cycle were nearly identical (Fig. 3b). The differences in Tr_a between the two plots were due to corresponding differences in $CWSI$ (Fig. 3c). A similar example presenting differences in both biomass and $CWSI$ for WET and DRY plots is shown in Fig. 4.

4.2 Alfalfa experiment—Data from three harvest periods

The analysis presented here covers three harvest periods from DOY 40 to 151. Three lysimeters were subjected to EARLY treatment during the period from DOY 40–90 (a), from DOY 91–130

(b), and from DOY 131–154 (c), respectively. The other two lysimeters were treated as WET plots in each growth cycle. Results here are based on the spectral and meteorological measurements centered on 10:30 each day. The value of α in Eq. 8 was assumed to be 1.5, based on the analysis in section 4.1. The r_a value was computed with the simple formula (Thom and Oliver, 1977), accounting for variations in plant height and wind-speed. Based on this value of α and the $CWSI$ computed using Eq. 10, Tr_a values were calculated for the WET, EARLY, LATE and DRY plots, and each lysimeter plot (a, b and c) regardless of treatment.

The values of Tr_a for the three lysimeter plots correspond as expected with the ET_a values measured by lysimeters in each plot (Fig. 5). That is, Tr_a was substantially lower than ET_a when vegetation density was low (after harvest), and Tr_a was nearly equal to ET_a for full-cover canopy. Similar to results presented in Fig. 4, the differences in transpiration rates between WET and DRY plots were directly correlated with biomass and/or stress differences (Fig. 6).

4.3 Rangeland—Data from single growing season

The test presented here was limited to a grassland site from DOY 114 to 290, during the dry, monsoon and post-monsoon periods.

Fig. 5. For three alfalfa harvest periods, comparison of Tr_a in three differentially irrigated plots (a, b, c) with actual daily ET values (ET_a) measured by lysimeters in each plot. Arrows and symbols ▼ indicate the dates of harvest and irrigation, respectively.

Deriving the α value for the WG '92 site was more difficult than for the alfalfa due to the lack of a well-watered, full-cover canopy at any time during the season. The α value was computed from data acquired on DOY 267. Based on soil temperature measurements made at the site, it was apparent that the soil surface was very dry. Since the vegetation was still relatively lush, we assumed that ET_a was equal to Tr_a on this day. Thus, α was calculated using the spectral vegetation index $SAVI$ measured at 10:30 and ET_a computed from eddy-correlation measurements on site. The α estimate for WG '92 was 1.47, which was close to the α value for the alfalfa crop. For most of the

Fig. 6. For WET and DRY treatments over three alfalfa harvest periods, a) estimates of Tr_a and measurements of b) biomass and c) $CWSI$. Arrows and symbols ▼ indicate the dates of harvest and irrigation, respectively.

growing season, the test site was characterized by large expanses of hot, dry soil with sparse vegetation; thus, an equation accounting for the additional resistance induced by the exposed soil as a function of windspeed and surface temperature (Kustas *et al.*, 1989) was introduced for the estimation of r_a (Fig. 7b).

Values of Tr_a , Tr_p and ET_a for all measurement days at the site were compared (Fig. 7). Two different estimates of aerodynamic resistance r_a were used for the calculation of these parameters. It is apparent that the water stress was overestimated using r_a without excess resistance and was more reasonable when the excess resistance was included. As expected, the Tr_a values were lower than ET_a values in nearly all cases. The Tr_p values were also lower than ET_a , especially in the early growing season with lower vegetation amount. However, it is difficult to make any conclusions about the feasibility of the application to the

rangeland site due to the questionable methods of deriving α . It may be possible to derive α in a more justifiable manner using simultaneous measurements of $fAPAR$, albedo and spectral reflectances made by Daughtry during 1990 at WG site (personal communication, 1993).

4.4 Concluding remarks

We have presented a new concept for evaluating the potential and actual daily transpiration from vegetation based on remote sensing. On the basis of the initial results presented here and the technique's sound theoretical foundation, it is likely that this approach will be successful for evaluating potential and actual daily transpiration.

Several points require further investigation. 1) Behavior of the coefficient α will have to be examined in detail from experimental and theoretical points of view, because it may not always be consistent for various crops and sites. This α value is, by definition, determined as a function of full-cover reflectance and the slope of the $fAPAR$ and $SAVI$ relation as long as the proportionality between the absorbed solar radiation and the "potential" transpiration is assumed. From a practical point of view, nevertheless, both the full-cover reflectance and the slope are not expected to vary much for most crop canopies, and that is why α values for alfalfa and rangeland were similar (1.5 and 1.47, respectively). 2) Several questions related to the estimation of $CWSI$ values for sparsely-vegetated sites or immature crops still need to be answered; a) Which formulation should be used to estimate r_a in computation of ET_p and $CWSI$?, b) How can we calculate a $CWSI$ value using t_s (composite surface temperature) rather than t_c (plant canopy temperature)?, or how can we derive t_c from t_s ? It is possible that the new stress index devised by Moran *et al.* (1994) may provide a good solution for such questions. Also, high-resolution infrared thermal imagery will be useful, providing pixel-by-pixel temperatures over the area of soil and plant mixture (Inoue, 1990). We will be able to replace the present $CWSI$ by future improved stress indices. 3) The estimates of Tr_p and Tr_a values should be compared with "true" values directly measured using the stem flow gauge. Since measurements of Tr_a were not available in either the alfalfa or rangeland experiments, we used, instead, ET_a values in the well-

Fig. 7. Comparison of estimated values of potential and actual daily transpiration (Tr_p and Tr_a) with measured values of ET_a at Walnut Gulch site. $CWSI$ was calculated using two estimates of aerodynamic resistance r_a : a) without excess resistance, and b) with excess resistance.

watered full-cover canopies. Therefore, these results represent simply a demonstration, not a verification, of the approach. New experiments in which transpiration will be measured directly with stem-flow gauges (Sakuratani, 1984) will be conducted for further examination of the concept.

The potential and actual values of daily transpiration rate may be estimated over wide vegetation areas with simple remote sensing measurements and basic meteorological parameters. The method may also provide information on biomass and stress status, because it accounts for the differences in both vegetation density and stress response of the plant canopy.

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反射スペクトルおよび熱赤外計測に基づく植生からのポテンシャルな日蒸散量と実日蒸散量のリモートセンシング——理論と予備的検証——

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要 約

リモートセンシングによって植物個体群からの日蒸散量のポテンシャルおよび実際の値を評価するための新しい方法論を提示し、実測データによる予備的検討を行った。本方法は、植物個体群のポテンシャルな蒸散量が主に吸収放射量によって規定されており、かつ個体群の放射吸収能は葉面積指数から求めるよりも分光学的な遠隔計測によってより直接的に評価できるとの考え方に基づいている。すなわち本方法では、遠隔計測される反射スペクトルから求めた植生指数(SAVI)と日射量からポテンシャルな蒸散量を求め、さらに、熱赤外放射計測に基づく

ストレス指標(CWSI)を組み込むことによって、ストレス状態と実蒸散量を同時に評価する。各種の灌漑処理を行ったアルファルファ圃場、および自然草地において測定した反射スペクトル計測、赤外線放射計測、ライシメータ、渦相関法、および植物サンプリングによるデータを用いた予備検証の結果、本手法の概念に基づいて、分光データと基本的な微気象データの計測情報から、広域にわたる植生のポテンシャルおよび実際の日蒸散量を評価できる可能性が示唆された。

キーワード：蒸散，熱赤外計測，反射スペクトル，水ストレス，リモートセンシング。