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EVALUATION OF GROUND-BASED HOT-SPOT REFLECTANCE MEASUREMENTS FOR BIOMASS DETERMINATION OF AGRICULTURAL CROPS

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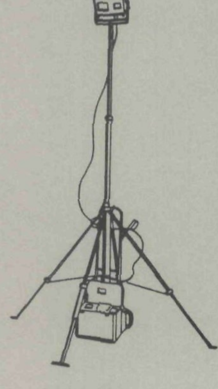

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EVALUATION OF GROUND-BASED HOT-SPOT REFLECTANCE MEASUREMENTS FOR BIOMASS DETERMINATION OF AGRICULTURAL CROPS

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ABSTRACT

Canopy reflectance simulation studies have demonstrated that a simplified relation between leaf area index and reflectance exists for the hot-spot observed at a zenith angle of approximately 52°. Based on this principle a prototype ground-based hot-spot reflectance meter (HSM) has been developed and tested. The objective of the project is to verify the performance for non-destructive determination of biomass and growth stage development of agricultural crops under standardized conditions. During 1982 and 1983 an extensive field measurement programme has been executed. Results obtained in 1983 are discussed. HSM data can be applied for biomass assessment during the vegetative phase. During the generative phase of cereals, change of biomass is detected due to the associated change of canopy colour during ripening and senescence. This new ground-based instrument can be used in agricultural research and for ground truth collection in remote sensing.

1. INTRODUCTION

An important aspect of the interpretation of multispectral data from agricultural crops is the understanding of the relationships between the distribution of the reflected solar radiation and the optical and structural properties of a plant canopy. Of particular interest is the use of multispectral remote sensing data for the determination of the evolution in time of the phenological stage of agricultural crops and its standing biomass. When such information is collected nondestructively and in a standardized manner over extended areas, prediction and assessment of crop yield and production can be improved. By numerous investigations it has been demonstrated that good correlations exist between the change of structural crop characteristics e.g. the leaf area index (LAI) and associated remotely sensed spectral estimators like for instance the brightness-greenness transform and the vegetation index. Radiative transfer models have been developed in order to improve the understanding from a physical point of view of the multispectral reflectance of plant canopies. The analysis of the relationships between structural and optical plant canopy parameters and the resulting multispectral reflectance, however, demonstrates that information about specific crop parameters can only be retrieved with limited accuracy. The non-lambertian reflectance behaviour of a complex object like an agricultural crop together with variations of the state of the atmosphere lead to a fundamental limitation of the accuracy of crop parameter retrieved by means of the use of empirical regression functions or model inversion techniques.
In agricultural research, the collection of crop parameters describing the stage of development and its condition in-situ is required. Field data collected destructively or described in a

qualitative way by human observers can be unreliable due to measurement errors and are influenced by subjective factors. The advantage of the use of spectral reflectance data is that crop characteristics can be assessed quickly, nondestructively, objectively and in a standardized manner. The stage of crop development can even be defined directly by its spectral reflectance instead of using a correlation between structural and optical parameters! In order to overcome the existing limitations of conventional ground-based spectral radiometers, which are due to changing cloud cover, the diurnal variation of the solar irradiance and the complexity of the radiation interaction process, the concept of ground-based hot-spot reflectance measurement has been developed and tested. The principle of this new instrument is based on the determination of multispectral reflectance data in the hot-spot of an active illuminant source under oblique view at a zenith angle of 52°. This principle has been worked out by Bunnik(1) and was based on the use of the canopy reflectance model of Suits(2) and his description of the reflectance in the hot-spot.
In The Netherlands a prototype instrument has been built by the Institute of Applied Physics (TNO-TH). The Centre for Agrobiological Research (CABO) carried out an extensive field measurement programme during 1982 and 1983. The results are evaluated at CABO in co-operation with the National Aerospace Laboratory NLR. Preliminary results obtained in 1982 have been presented during the second International Colloquium on Spectral Signatures of Objects in Remote Sensing(3). This article describes the principles of the hot-spot reflectance meter (HSM) and the first results of the measurement programme of 1983.

2. CANOPY REFLECTANCE IN THE HOT-SPOT UNDER OBLIQUE VIEW

In the so-called hot-spot, the direction of the incoming direct radiation is equal to the direction of observation. This results into the absence of observed internal shadow in the canopy and leads to the dominance of the single scattering contribution to the canopy reflectance. From an aircraft and on aerial photographs the hot-spot can be observed as a bright zone around the shadow of the aeroplane on the ground.

For a uniform Suits canopy, the single scattering reflectance in the hot-spot as a function of the view angle, Θ_o, and the wavelength, λ, is expressed by:

$$r_b(\Theta_o, \lambda) = \frac{w(\Theta_o, \lambda)}{K(\Theta_o)}\left(1-e^{-K(\Theta_o)}\right) + \rho_s(\lambda)e^{-K(\Theta_o)} \qquad (1)$$

The ratio of the single scattering coefficient, $w(\Theta_o, \lambda)$, and the extinction coefficient, $K(\Theta_o)$, is equal to the hemisperical single leaf reflectance for a zenith view angle equal to arctan $(\frac{4}{\pi})$ $\Theta_o = 52°$. The single scattering canopy reflectance becomes a linear function of the soil cover under 52° and is equal to the reflectance of the leaves when the coverage is complete. Close to this special view angle other particular angles exist. It has been found by Bunnik(1) that the radiant intensity of a Suits canopy layer is independent of the leaf angle inclination distribution function for a view angle equal to arctan $(\sqrt{2})$; $\Theta_o = 55°$. Warren and Wilson(4) and Oliver and Smith(5) proved that the soil cover is independent of the leaf inclination distribution function for a view angle equal to arctan $\left(\frac{\pi}{2}\right)$; $\Theta_o = 57.5°$. These angles are all derived from equation(1) by substitution of Suits' coefficients.
For the evaluation of the usefulness of hot-spot canopy reflectance measurements for nondestructive determination of canopy parameters, the view angle of 52° has been selected. The reflectance is not sensitive to changes of the leaf inclination distribution function. The increased probability to measure reflected radiation by single scattering from deeper layers due to the hot-spot condition, enables a determination of the leaf area index which is directly related with the standing biomass. Measurement in the near infrared will increase the sensitivity to changes of the LAI for complete coverage due to multiple scattering. Because the reflectance in the visible light region can be attributed almost only to single scattering, the hot-spot reflectance value for complete coverage can be used as an estimator of the single leaf colour.
The concept of a ground-based hot-spot reflectance meter is based on the use of an active radiant source. In order to eliminate the influence of the range between the radiant source and the canopy on the detected reflected radiant flux, spectral reflectance ratios are applied.

Three spectral bands positioned in the green, the red and the near infrared part of the spectrum have been selected. The near infrared/red ratio is the estimator of the leaf area index and the related biomass. The green/red ratio is an estimator of the leaf colour.

Verhoef(6) extended Suits' model to include the actual leaf inclination distribution function in the scattering and extinction coefficients for direct and diffuse radiant flux. This so-called SAIL-model also describes the reflectance of multi-layer canopies by using the adding method. Near-infrared/red reflectance ratios in the hot-spot have been calculated for a uniform canopy as a function of the angle of view. In figure 1 the reflectance ratio IR/RD is presented for planophile, plagiophile and erectophile canopies for LAI = 0.5 and 4 respectively. This example demonstrates that for an oblique view angle between 50° and 58°, the influence of the leaf inclination function is drastically reduced and that the IR/RD ratio increases with LAI. The variation of this ratio as a function of the angle of view could otherwise be applied as an estimator of the leaf inclination distribution function. In figure 2 a comparison is presented between the IR/RD ratio as measured during the vegetative stage of winter wheat and the IR/RD ratio determined by means of the SAIL-model. For this case the model has been modified to take into account the divergence of the active radiant flux. The IR/RD ratio has been calculated for dark and light green leaves as a function of the LAI. It is concluded that the IR/RD ratio is sensitive to the variation of the LAI up to its maximum value.

3. THE PROTOTYPE HOT-SPOT REFLECTANCE METER

The HSM-instrument as used at the test area in The Netherlands in 1983 is shown in figure 3. A flash lamp with a modified reflector is used as active radiant source. The sensor system consists of a photographic camera with built-in beam splitters and spectral filters. The hot-spot reflectance is measured in three spectral bands centred at 550 and 670 mm with 10 mm bandwidth and at 870 nm with 20 nm bandwidth. The reflected radiant flux, which enters the camera aperture and is transmitted by the filters after spectral separation, is measured by means of detectors in the focal plane of each spectral band. The flash lamp and the sensor system are mounted in the HSM head together with an auxiliar TV camera which can be used for pointing of the sensor footprint. The measurement configuration is shown in figure 4. The curved footprint with a central view angle of 52° is positioned within a larger rectangular area illuminated by the flash light. Immediately before and after the measurement of the reflected radiation at the moment of maximum flash light intensity, the background radiation due to solar and sky irradiance is measured. By linear interpolation, the passive contribution to the reflected radiation during the active measurement is estimated. The response attributed to the flash light only is obtained by substraction. During the active measurement also the spectral distribution of the flash light radiation is measured. The analog detector signals are amplified simultaneously be low and high gain amplifiers in order to obtain a large dynamic range. The signals are converted to 12 bit digital data and recorded together with annotation and time and day code on digital cassette tape. After conversion to computer compatible tape, the raw data are screened for measurement errors and are afterwards preprocessed, calibrated and converted to reflectance data. The hot-spot reflectance ratios IR/RD and GR/RD are calibrated relative to the reflectance ratios for a standard white reflectance panel as determined in the laboratory. All HSM data collected during the field measurement programmes performed in 1982 and 1983 are stored in a digital data base together with the ground truth data. Plot routines are available for different graphical presentations and have been used for data analysis.

4. HSM MEASUREMENT PROGRAMME AND GROUND TRUTH COLLECTION

In 1982 at a test farm in Wageningen six plots of 10 by 10 m each were sown with one variety of winter wheat. In order to obtain biomass and yield differences, nitrogen and fungicide applications were varied over the plots. Twice a week HSM-reflectance measurements were carried out across and along row direction of the plots. In 1983 the hypothesis of the insensitivity of HSM data for differences between the leaf inclination distribution and the application to other crop types were tested by choosing a test field design with several crop types. This year the test fields were situated at a test farm in the reclaimed polder Eastern Flevoland. To increase the speed and the accuracy of the measurement procedure, the instrument was moved along the trial plots by means of a rail system (see figure 4).

Four winter wheat varieties with different canopy structure were selected. Also spring barley and oats were shown for comparison. Large differences in structure were introduced by selecting also the most important crops in dutch arable farming: potatoes and sugar beets. To complete the crop spectrum, pasture grass, maize and stembean fields were prepared. One field was kept bare throughout the growing season. For potatoes and winter wheat variety Arminda, an extra field with row direction across rail (along view direction) was added. For comparison throughout the growing season passive measurements under perpendicular view have been carried out in parallel with a hand-held radiometer developed at CABO(7). For model simulations leaf reflectance and transmittance values and soil reflectance values were measured occasionally in the laboratory.

HSM-reflectance measurements have been executed twice a week. Six samples were taken in one part of each test field. The HSM head was situated at 2.50 m above ground level. The curved footprint on the ground was about 2 m^2. The remaining part of the field was used for ground truth determination. Many parameters to describe growth and development in a more quantititive way were measured. To assess soil cover, slides were made perpendicular and under the oblique view angle of 52°. The average crop height was measured and the soil surface wetness was estimated with a 1 (very dry) to 5 (very wet) scale. For the cereals every week a sample of 2 rows of 1 m length (0.5 m^2) was taken. A subsample of 100 stems was used for dry weight and LAI assessment. After heading the subsample was split in ears, stems and individual leaves for weight and surface estimation. To describe the development of the cereals, a growth stage scale frequently applied in phytopathology was used (comparable to the Feekes scale).
For potatoes and beets every week 10 sample plants were harvested to measure above and beneath ground level the fresh weight. Three representative plants were divided in leafblade and stem material for dry weight and LAI assessment. Since reflectance measurements were done twice a week and ground truth was collected once a week, the ground truth data were interpolated and smoothed. The weighted average over a period of 10 days before and after measurement was used to assess the ground truth parameters for each HSM measurement date.

5. RESULTS AND DISCUSSION

The measurement results for two wheat varieties (Arminda and Durin), potatoes and sugar beets are summarized graphically in the figures 5 through 12. All these measurements are performed perpendicular to the row direction. The mean value of the IR/RD hot-spot reflectance ratio is plotted as function of time. LAI and above ground dry matter weight. In figures 5 and 6 (wheat), also the GR/RD ratio is included. The spread within the 6 measurements is indicated by plotting also maximum and minimum values measured that day. The low spread around the curves illustrates the advantage of having measurements independent of solar radiation under standardized conditions.

For winter wheat (Fig. 5 and 7) clearly 2 phases can be distinguished. The vegetative phase is started when the pseudo-culms formed by leafsheaths appear (Feekes-scale 4) and ends when the flag leaf emergences (F-scale 8). When oblique ground cover reaches almost 100 % after 4 May, the GR/RD ratio becomes constant due to saturation of reflectance in the visible light region. The GR/RD reflectance ratio of single green leaves was 2.5. During May the IR/RD ratio further increases because of the multiple scattering contribution in the near infrared. In the May period, the IR/RD ratio of Arminda is higher than for Durin, while on the contrary dry weight, perpendicular soil cover and LAI (see also figures 6 and 8) of Arminda are lower. This difference is likely explained by the larger leaf density within the plant rows for Arminda due to its more erectophile structure. The LAI has been measured by including the soil area between the rows. Ultimately both crops reach nearly the same IR/RD value at F8.
On "boot" (start of heading) the differences in reflectance between the wheat fields disappear. Heading itself is best identified by colour changes. The GR/RD ratio shows a sudden rise (after a small dip). The IR/RD ratio falls down to value 10 during heading. In the grain filling stage (starting end of June and ending with maturity at F11.3) the IR/RD ratio decreases with the same rate as during heading. But the IR/RD ratio shows a curvature, highly correlated with leaf senescense and water content of the crop.
Figures 6 and 8 suggest that the IR/RD ratio is sensitive during the vegetative and the generative stage. It is shown that HSM reflectance ratios are probably more accurate estimators of LAI, growth and senescence then the traditional clipping of samples in the emergence and ending phases of wheat growth. Also identification of phenological stages is possible. Adoption of a crop development scale defined by the time evolution of HSM could be considered.
The behaviour of the IR/RD ratio for potatoes is presented in figures 9 and 10. The ratio

IR/RD - infrared/red ratio
GR/RD - green/red ratio

increases upto the maximum value of the LAI. From June to end July the oblique soil cover as measured perpendicular to the rows increases till 100 %. During August the perpendicular coverage becomes complete. Both trajects are measured by the IR/RD ratio. In September and October the mean reflectance fluctuates considerably. This variation is ascribed to large within-field density differences caused by irregular lodging of stems. During the vegetative phase the IR/RD ratio increase rate with dry matter is in the same order as for winter wheat (15 to 20 gr m^{-2} per unit of IR/RD).

For sugar beets the measurement results are shown in figures 11 and 12. The increase rate of dry matter with the IR/RD ratio is smaller compared to the increase rate found for potatoes. This difference is explained by the clustered leaf mass during the crop development. At the end the IR/RD ratio saturates for LAI=4.

6. CONCLUSIONS

It is concluded that the sensitivity of the HSM IR/RD reflectance ratio to the increase of canopy biomass is high during the whole vegetative stage. During the generative stage of cereals the increase of biomass is measured because of the change of the plant colour in the ripening and senescing phase. The GR/RD ratio can be applied as an estimator of the colour of the plant components. The use of an artificial radiant source and the elimination of the reflectance contribution due to the solar irradiance significantly reduces the spread between the measurements. Compared to conventional destructive methods of biomass assessment, no real sampling problems occur to get the same or even better accuracy. HSM-ratio data can be applied as direct estimators to define the phenological stage of development.

HSM measurements are in reasonable agreement with reflectance model simulations. Existing row models should be used to analyse the influence of row (and cluster) effects. From the prototype HSM a practical device could be developed for use in agricultural research and for ground truth collection in remote sensing.

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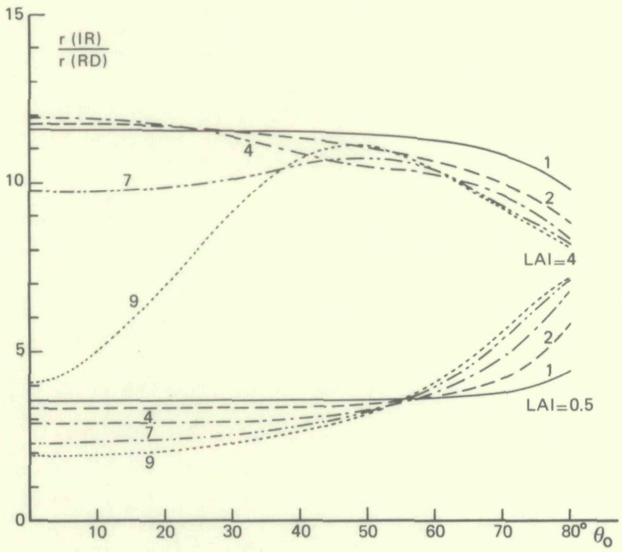

Fig. 1 The simulated near infrared/red hot-spot reflectance ratio of a uniform green leaf canopy as function of the view angle, Θ_o, for different leaf inclination distribution functions and LAI (planophile(1), plano-plagiophile(2), plagiophile(4), erecto-plagiophile(7), erectophile(9))

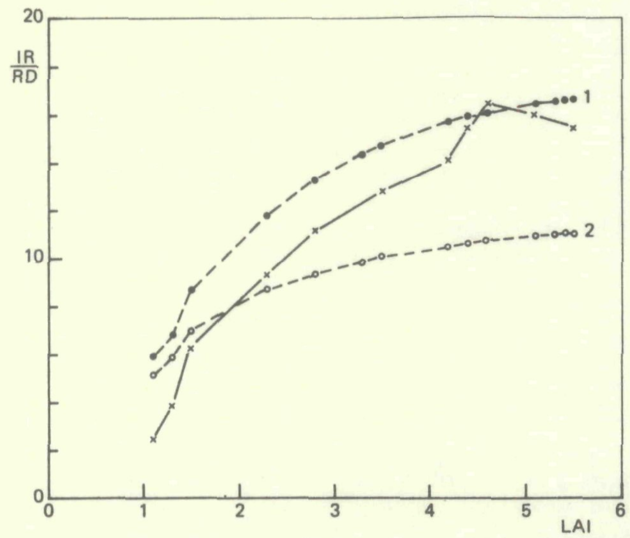

Fig. 2 Comparison between the IR/RD hot-spot reflectance ratio as measured for the vegetative phase of winter wheat (Durin) with model simulations for dark green(1) and light green(2) leaves

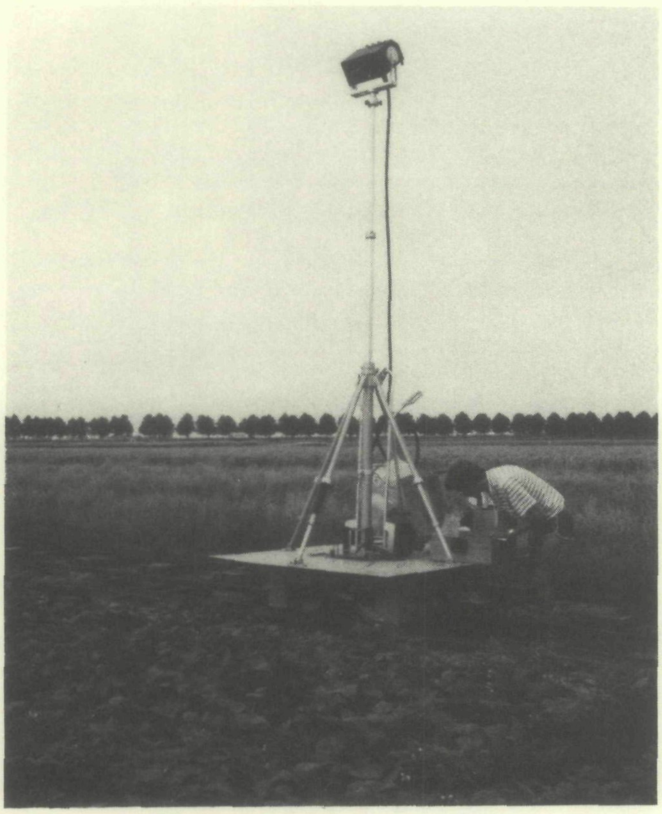

Fig. 3 HSM in use during the measurement programme at the test site in Eastern Flevoland in 1983

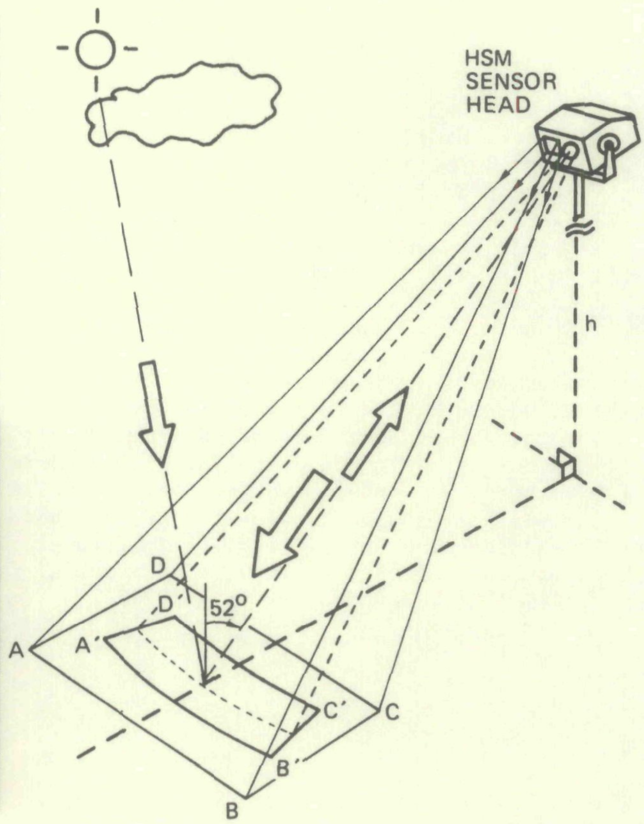

Fig. 4 HSM-measurement configuration. The area ABCD is illuminated by the radiant source. Hot-spot reflectance is measured within the sensor field of view with footprint A'B'C'D'

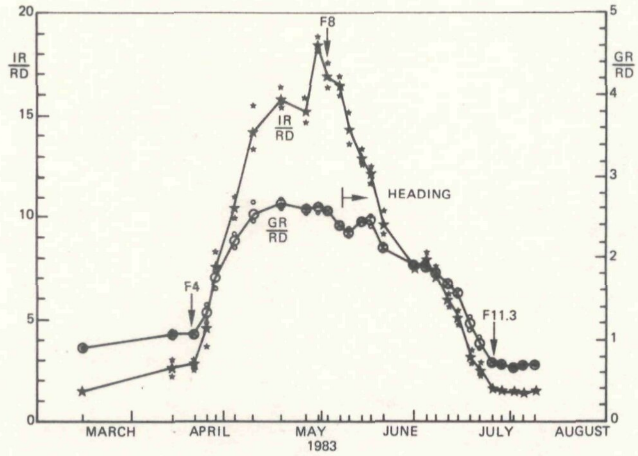

Fig. 5 HSM IR/RD and GR/RD reflectance ratio of winter wheat (Adamant) during crop growth. For each average value of six measurements, maxima and minima are plotted

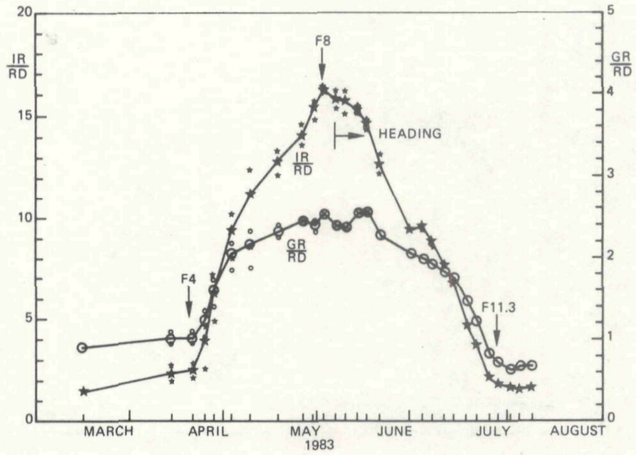

Fig. 6 HSM IR/RD reflectance ratio of winter wheat (Durin) during crop growth

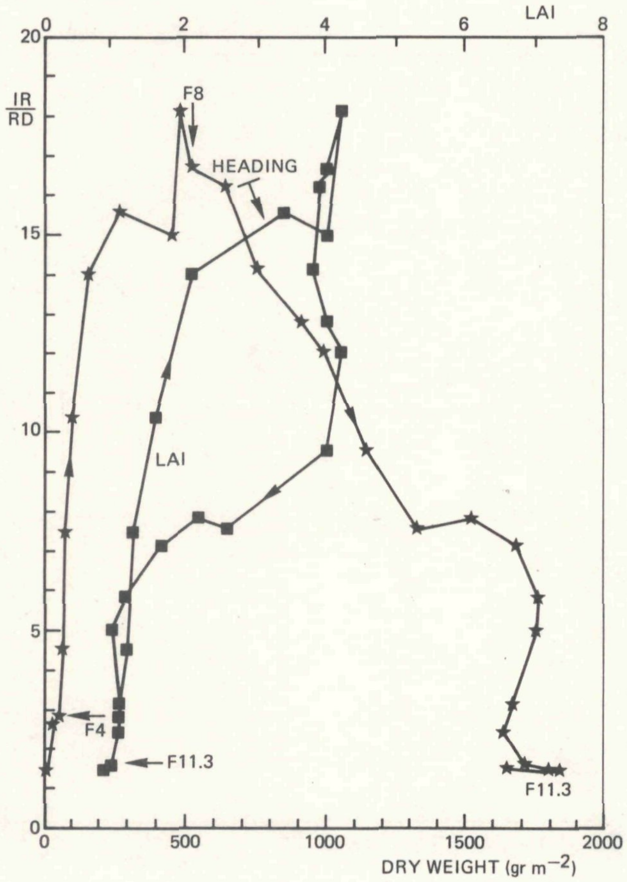

Fig. 7 HSM IR/RD reflectance ratio of winter wheat (Adamant) as a function of the measured LAI and total dry weight

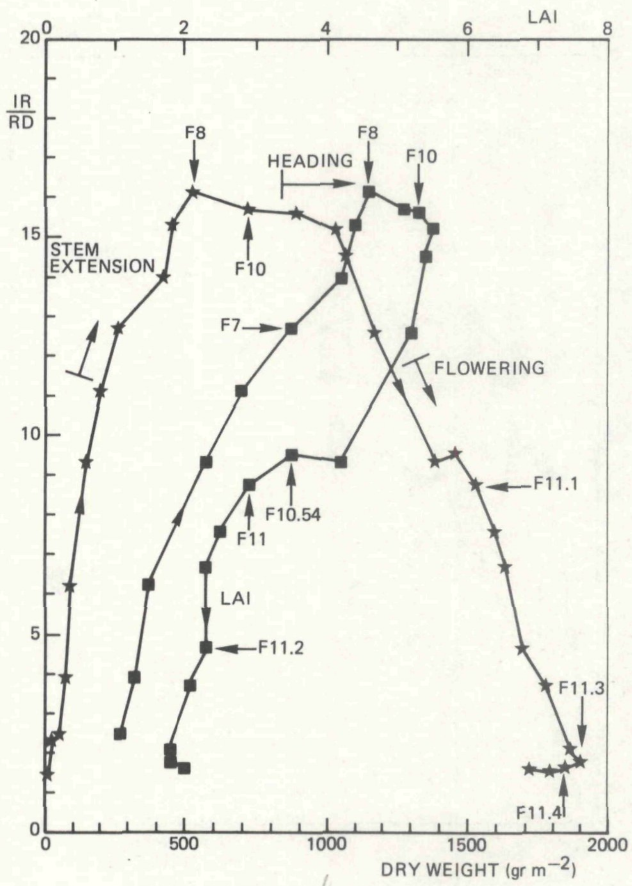

Fig. 8 HSM IR/RD reflectance ratio of winter wheat (During as a function of the measured LAI and total dry weight. Some Feekes scale values are indicated

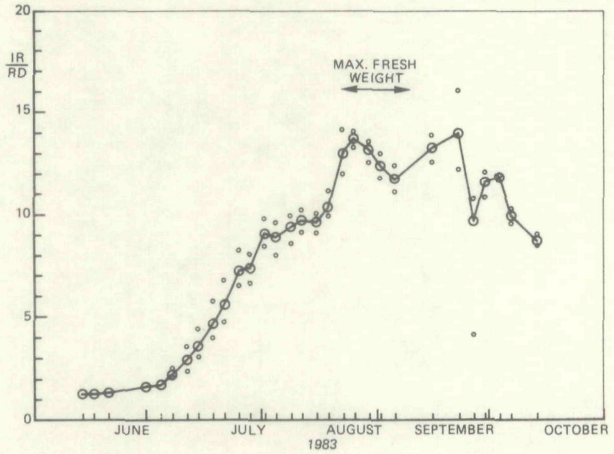

Fig. 9 HSM IR/RD reflectance ratio of potatoes during growth

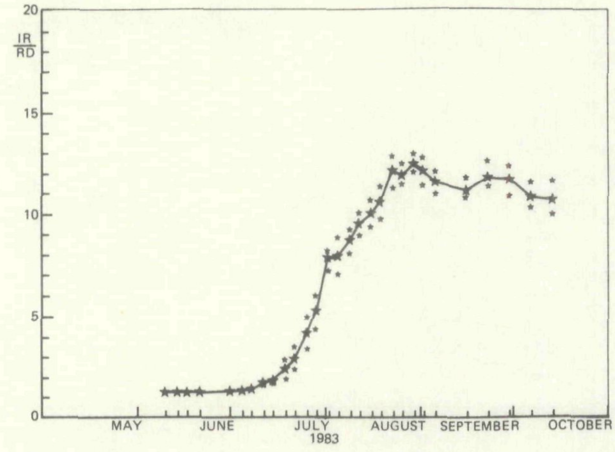

Fig. 10 HSM IR/RD reflectance ratio of sugar beets during growth

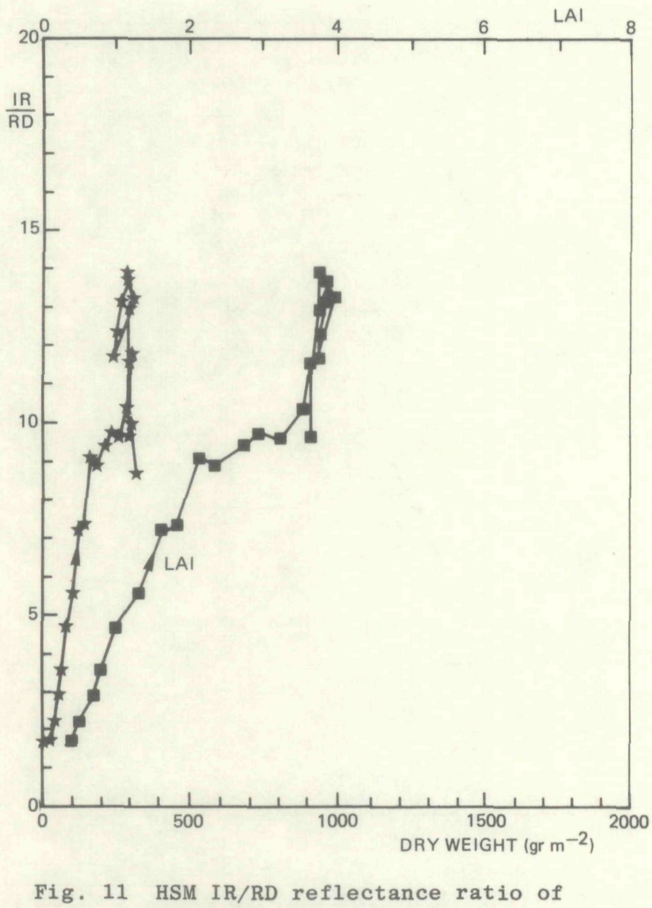

Fig. 11 HSM IR/RD reflectance ratio of potatoes as a function of LAI and total dry weight

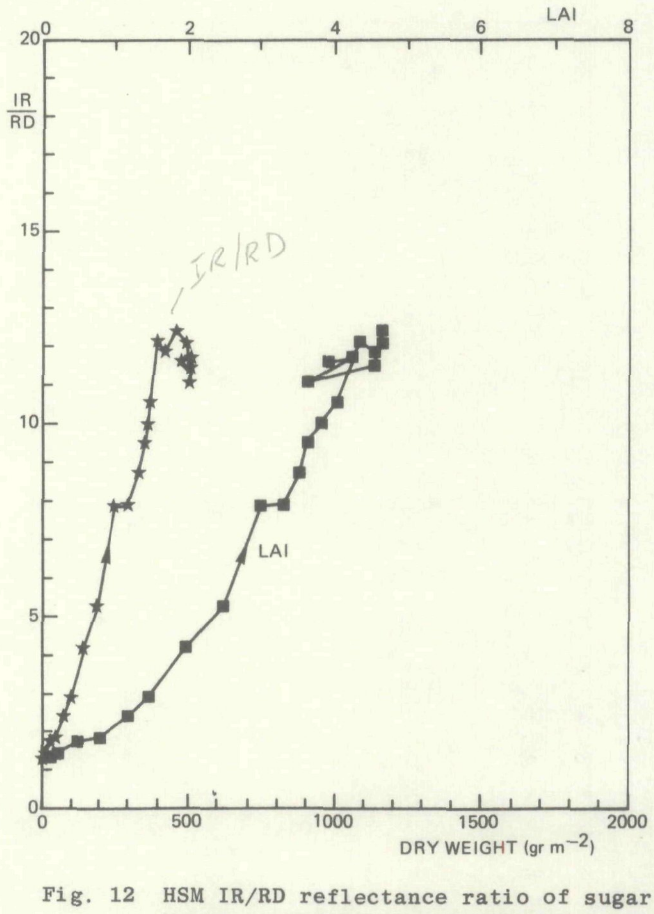

Fig. 12 HSM IR/RD reflectance ratio of sugar beets as a function of LAI and total dry weight

leaf area index — wat type wat onderzoek?

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