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COMPARISON OF MEASURED AND MODELED RADIATION, HEAT AND WATER VAPOR FLUXES: FIFE PILOT STUDY

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ABSTRACT

This report describes preliminary findings of research conducted during the growing season of 1985 at the Agricultural Research and Development Center of the University of Nebraska and a pilot study conducted at the FIFE site near Manhattan, Kansas during July and August 1986.

For the 1985 study the primary objectives were to test the feasibility of using radio frequency receivers to collect data from automated weather stations to model fluxes of latent heat, sensible heat and radiation using routine weather data collected by automated weather stations and to compare the estimated fluxes with fluxes measured over wheat. The model Cupid was used to model the fluxes.

The 1985 study established that it was feasible to use the radio frequency transmitters and receivers to collect data from an automated weather station. In general, excellent agreement was noted between the measured and modeled fluxes of latent and sensible heat and the net radiation for the wheat during late May 1985. The comparison of fluxes at other times has not yet been done.

The objectives of the 1986 study were to utilize two or more automated weather stations, interrogated by radio frequency and other means, to examine some of the climatic variability of the FIFE site, to measure and model reflected and emitted radiation streams from various locations at the site and to compare modeled latent and sensible heat fluxes with measured values.

We were successful in 1986 in collecting data from two automated weather stations over a period of several days using radio frequency transmitters and receivers. We also collected data to compute fluxes of latent and sensible heat using eddy correlation and other micrometeorological methods at one location within the FIFE site.

We collected some bidirectional reflected and emitted radiation data from 23 locations throughout the FIFE site. Analysis of these data along with analysis of the measured sensible and latent heat fluxes is just beginning.

Biophysical measurements such as LAI by direct and indirect means, above ground plant biomass, and the transmittance and reflectance of leaves in the MMR wavebands were made for selected locations and on selected plant species. Preliminary results of some of this biophysical data are given in this report.

INTRODUCTION

The main objective of the International Land Surface Climatology Project (ISLSCP) has been stated as "the development of techniques that may be applied to satellite observations of the radiation reflected and emitted from the Earth to yield quantitative information concerning land surface climatological conditions." To accomplish this objective a major field study called FIFE - the First ISLSCP Field Experiment - will be conducted in 1987 at a site on and near the Konza Prairie in Kansas. During that experiment two types of measurements will be made, (1) long term monitoring of basic meteorological parameters and (2) extensive surface and aircraft measurements to be made during four intensive field compaigns (IFC's). Among activities to take place during these IFC's are the determination of radiation fluxes, sensible and latent heat fluxes and the measurement of selected biophysical properties. This document describes some preliminary studies that were conducted in 1985 at the University of Nebraska Agriculture Research and Development Center and in 1986 at the FIFE site to collect information helpful in making the two types of measurements described above.

Our basic overall objective in conducting these pilot studies was to document and understand certain important physical and biological conditions on a prairie. To do this we made selected meteorological, plant and soil measurements that would permit us to compare measured and modeled fluxes of radiation, sensible heat and latent heat. Specifically our objective were (1) to determine the feasibility of using radio frequency transmitters and receivers to collect data from automated weather stations to aid in determination of the meso- and micro-climatic variability on the FIFE site; (2) to measure and model reflected and emitted radiation streams from various zones within the prairie site; (3) to make reliable estimates of sensible and latent heat fluxes over the prairie employing the eddy correlation technique and other micrometeorological methods and then to (4) model the radiation, sensible and latent heat fluxes using routine atmospheric, plant and soil measurements so that aereal estimates of these fluxes can be made from a limited number of point measurements. The modeled and measured estimates of these fluxes will be compared.

The work that has been done to date and the preliminary findings, if any, for each of the four objectives specified above are presented in this report.

Objective (1) - Automated Data Collection Through Radio Frequency Communication.

In 1985 equipment was procured to perform automated data collection via Radio Frequency (RF) communication. During the summer of 1985 the equipment was installed at the Agricultural Meteorological Laboratory at Mead, Nebraska for testing. Testing was carried out with an on-site IBM computer and an existing automated weather station at a nearby, permanent location. The linkage between the computer-modem-RF radio and the data logger-modem-RF radio was established and tests indicated that communication was satisfactory.

In 1986 further equipment was purchased so that the field sites could be located on the Konza prairie. Three stations were installed in order to collect data in late July and early August 1986. A computer was installed at the Konza Prairie Headquarters building and an RF antenna was deployed on the roof. Descriptions for the 3 weather stations are given in the accompanying Table 1. Stations #1 and #2 were located on the Konza Prairie while #3 was located just southeast of the Prairie. Although the computer was only checked periodically (one to two times per week), the data collection was performed reasonably well as indicated in Table 2. The Konza #1 station utilized a CR21X data logger and performed extremely well in the RF-linkage. Konza #2 utilized a CR21 data logger and would not operate continuously in RF-linkage. Konza #3 also had a CR21 data logger but was not part of the radio communication test (its data was collected on a cassette tape). The CR21X data logger manufactured by Campbell Scientific of Logan, Utah was conveniently employed with no modifications to collect sophisticated surface weather measurements on the Konza Prairie. It would appear from this demonstration that the CR21X data logger could be easily interfaced to additional sensors and that when used with RF-communications would make a reliable weather network for the FIFE site.

Objective (2) - Measurement and Modeling Reflected and Emitted Radiation

Data collected to help meet this objective were obtained during late July and early August of 1986 at the FIFE site. This pilot study was designed to help familiarize the investigators with the topography and vegetative composition of the site and to test and develop the equipment and procedures to be employed during the IFC's in 1987.

The major focus of our effort was to obtain data concerning the reflectance and transmittance properties of some dominant vegetative species growing at the FIFE site. Additional information was collected on leaf area index (LAI) and vegetative dry matter for some sample locations.

Instrumentation used to gather data on reflectance and transmittance included the Barnes model 12-1000 modular multiband radiometer (MMR), and a LI-COR model 1800-12 integrating sphere. The Barnes MMR was used to collect reflectance data on vegetative communities along transects that may suggest differences due to topography - chiefly, slope and aspect. The integrating sphere was employed to collect data on reflectance and transmittance for individual blades of grass or leaves of forbs.

Leaf Transmittance and Reflectance

Modeling of radiation fluxes requires knowledge of the transmissivities and reflectivities of leaves of the plant types growing on the FIFE site. To this end an integrating sphere was utilized. An integrating sphere is a device used to collect electromagnetic radiation that has been reflected from or transmitted through a sample material - in this case some of the grasses and forbs found at the FIFE site. The LI-COR integrating sphere used during the pilot study was fitted with a special radiometer that allows the collection of data in the wavebands of the Barnes MMR. These channels and the wavebands are: (1) 0.45-0.52 μm, (2) 0.52-0.60 μm, (3) 0.63-0.69 μm, (4) 0.76-0.90 μm, (5) 1.15-1.30 μm, (6) 1.55-1.75 μm, and (7) 2.08-2.35 μm. Leaves of forbs or blades of grass were placed into the integrating sphere without detaching the leave or blade from the plant; that is, the plants were studied nondestructively.

Of the hundreds of species of grasses and forbs found at the FIFE site only eleven were studied (six grass species and five forb species). Table 3 lists the species name, common name of that species, whether it is a grass or forb, and the number of samples of that species for which data were collected.

Figure 1 depicts the reflectances for the top and bottom (rft and rfb, respectively) of a blade of Andropogon gerardii as well as the transmittances for the top and bottom of the blade (tft and tfb, respectively). We see that in the first three wavebands the transmittances for both the top and bottom of the blade are essentially the same and are lower than the reflectances. In waveband 4 all reflectances and transmittances are very similar. In wavebands 5 through 7 the reflectances tend to be within one or two percent of each other and in general are lower than the transmittances; except in band 6 where the transmittance through the top of the blade tends to fall between the reflectance values. Overall, the reflectances and transmittances in bands 1 through 3 are much lower than those found in the remaining wavebands. This phenomena is explained by the fact that the first three wavebands fall within that region of the electromagnetic spectrum known as photosynthetically active radiation (PAR). In this region actively growing plants are highly absorptive, while being more reflective in the longer wavelengths (bands 4 through 7). Bands 4 through 7 fall within the infrared region.

As can be seen from Fig. 2, the three samples of Andropogon gerardii exhibit similar characteristics in all bands. It is also noted here that in the PAR region that reflectance and transmittance values peak in band 2 (the green region), while in the infrared region the reflectance values peak in band 4 (0.76-0.90 μm) and the transmittance peaks in band 5 (1.15-1.30 μm). This pattern was true for all the grasses we studied.

Panicum virgatum (Fig. 3) exhibits trends very similar to Andropogon gerardii. However, Panicum virgatum transmittances are slightly higher in all bands than Andropogon gerardii, except for band 3. Reflectances for the two samples of Panicum virgatum behave very similarly, where sample one reflectances are a little greater than sample two in all wavebands (Fig. 4).

The data for Agropyron smithii (Fig. 5) depict values for transmittance and reflectance that are higher than those for Panicum virgatum but lower than Andropogon gerardii in wavebands 1 through 3. In band 4, Agropyron smithii peaks at a higher reflectance value than any other of the grasses evaluated during the pilot study. Reflectances in bands 5 through 7 for Agropyron smithii are greater than those observed for the previous two species. Reflectance values for the two samples of Agropyron smithii plotted in Fig. 6 are very similar.

Values of reflectance and transmittance for Bouteloua curtipendula are plotted in Fig. 7. Transmittances are much higher than its reflectances in the longer wavelengths, a pattern also observed for Eragrostis spectabilis (Fig. 8). B. curtipendula and E. spectabilis have the highest transmittances in the longer wavelengths of all the grasses studied.

Data for Eragrostis spectabilis are graphically displayed in Fig. 8. For the grass species studied, this one had the most irregular data but at this time it is not known if this is characteristic of this species or if we had equipment problems at the time of data acquisition.

Figure 9 is a plot of the data for Sorghastrum nutans. The reflectance in band 4 is the second highest of the grasses studied. The transmittances in the PAR are the lowest of the grasses evaluated.

All reflectances from the top of the blade for all species of grass we studied are plotted in Fig. 10. All of these species followed the same general pattern; that is, peak reflectances in the PAR portion of the spectrum in band 2 and peak reflectance in the NIR spectrum in band 4. Some species differ from each other in some wavebands, yet are similar in others. Because of this it is important that we identify the dominant grass species and characterize their reflectance and transmittance properties in order to better model the surface radiation fluxes. Our data also suggest that it may not be necessary to make measurements from both the top and bottom of grass leaves since the transmittance and reflectance values are within three to five percent of their counterparts on the opposite side of the blade.

Transmittance and reflectance data for the forbs evaluated during the pilot study period are plotted in Figs. 11-15. As was the case for grasses, the forbs display a peak reflectance and transmittance value in band 2 of the PAR region. However, in the infrared region transmittance may peak in band 5 or 4, while the reflectance usually peaks in band 4 but tends to be "flat" between bands 4 and 5.

As opposed to the case for the grasses, the reflectance and transmittance values vary according to the leaf side. For example, transmittances for Vernonia baldwinii (Fig. 12) are very different in the PAR but similar in the infrared. The reflectance for the bottom of the leaf is much lower than that for the top in wavebands 4 through 6. Rhus glabra (Fig. 14) also displays differences in reflectances and transmittances from the top or bottom of the leaf surfaces. However, some species of forbs do not display such large differences as shown, for example, by Ceanothus americanus (Fig. 15). In the longer wavebands the forbs, except for Salvia pitcheri, are very similar, but they are not very similar to each other in the PAR (Fig. 16). The forbs may not make up a very significant portion of a satellite pixel so perhaps they can be omitted from further study. Before that is done, however, we must determine the species composition of various parts of the FIFE site.

Bidirectional Reflectance and Emittance

Reflected spectral radiation from canopy surfaces in seven wavebands was measured using a Barnes MMR model 12-1000. These seven wavebands are the same as those used in the integrating sphere.

Because of restrictions placed on driving vehicles on the Konza prairie it was necessary to take MMR measurements using a portable mast. The mast allowed us to take measurements along predetermined transects, and enabled us to record changes in spectral properties of the vegetative communities due to changes in slope and aspect, or changes in species composition.

The portable mast (Fig. 17) was designed to hold the MMR approximately 3.4 m above the soil surface, which yields a spot size of about 0.75 m. In addition, the mast permits the measurement of radiation from seven different angles. These angles are nadir and zenith angles of 20°, 30°, and 50° to either side of nadir. The mast was oriented in such a way that the off-nadir readings will be made in or near the principal plane.

Data were collected on a total of twenty-three plots on two different transects in the FIFE study area. The data have not yet been analyzed.

Objective (3) - Measurement of Sensible and Latent Heat Fluxes

On selected days during the 1985 growing season, measurements were made over a winter wheat crop (Triticum aestivum L., Colt) at Mead, Nebraska. The incoming shortwave radiation (R_s) was measured with a pyranometer. Net radiation (R_n) was measured using Swissteco net radiometers. Soil heat flux was measured with heat flow sensors. Soil temperature was measured with thermocoules. Surface soil heat flux (S) was computed from soil heat flow sensor and soil thermocouple data employing a combination method. Mean wind speed profile was measured with a set of three-cup anemometers. Profiles of mean air temperature and humidity were measured with ceramic wick psychrometers.

Soil moisture was measured gravimetrically and with a neutron probe. Crop height, leaf area index and dry matter were monitored. Water potential and stomatal resistance of flag leaves were also measured.

Fluxes of sensible (H) and latent (LE) heat were computed by means of the Bowen-ratio technique. The data have been analyzed, tabulated and graphed. The following data sets were given to Dr. John Norman for comparison with his model estimates.

Variables	Measurement Dates (1985)
a) Meteorological: R_s, R_n, S, H, LE, air temperature, vapor pressure deficit, wind speed, soil temperature	May 22, 23, 25, 28, 29, 30; June 7, 8, 13, 14 and 20
b) Soil Moisture:	May 21, 23, 28; June 3, 6 8, 10, 12, 17, 18 and 24
c) Plant height, leaf width, height of most dense region, height of lowest leaves, leaf area index, dry matter:	April 20, 24; May 6, 14, 17, 20, 22, 23, 24, 28, 29, 30; June 3, 5, 7, 8, 10, 12 13, 14, 17, 18, 21 and 24
d) Leaf water potential and stomatal resistance:	May 20, 21, 22, 23, 24, 28, 29, 30, 31; June 3, 5, 6, 7, 8 and 10

Measurements were made at a tall grass prairie location within the FIFE site near Manhattan, Kansas on a few selected days during July-August, 1986. Vertical velocity fluctuations were measured with a sonic anemometer. Air temperature and humidity fluctuations were measured with fine wire thermocouples and a Lyman-alpha hygrometer. Supporting data on net radiation, soil heat flux, mean air temperature and humidity, and soil temperature were also obtained. A data acquisition system consisting of an IBM PC-XT microcomputer, amplifiers and an analog to digital convertor was used to record meteorological signals.

Computer processing of data is presently in progress. To accomplish the objectives of the pilot study, measurements of vertical velocity fluctuations will be used in conjunction with those of air temperature and humidity to compute fluxes of sensible (H) and latent (LE) heat employing the eddy correlation technique. Information on these fluxes (H and LE) will be examined in context with measured data on net radiation, soil heat flux, air temperature, vapor pressure deficit and soil moisture.

Objective (4) - Modeling Radiation, Sensible and Latent Heat Fluxes

a. Estimated LAI and Mean Leaf Angles

Experimental and theoretical studies have demonstrated that the structure of a vegetative canopy can have a significant effect on its reflective properties in the visible and NIR portions of the spectrum (Pinter 1985, cited by Jackson and Pinter 1986). Canopy architecture information can provide considerable aid in the interpretation and prediction of remotely sensed data. Direct measurements of canopy structure can be rather time consuming. The nature of the research to be conducted on FIFE will require a relatively rapid means of obtaining canopy structural measurements.

An indirect non-destructive measure of LAI and leaf angle distribution was introduced by Norman et al. (1983). The method employs the relationship between the extinction of radiation beneath a canopy and the canopy structure. The relationship described mathematically is:

$$T = e^{-k(\theta,\ \alpha)\ LAI} \qquad (1)$$

T represents the transmission of radiation for a canopy. θ is the sun or view zenith angle and k is the extinction coefficient given by:

$$k(\theta,\ \alpha) = \int_{0}^{\pi/2} g(\alpha)\ \cos\delta\ d\alpha \qquad (2)$$

$g(\alpha)$ is the fraction of leaves with inclination and angle α to the horizontal, δ is the angle between the leaf normal and the given sun direction, and θ is the zenith angle of the sun. The penetration of radiation is dependent on the number and distribution of gaps in the canopy. Thus, canopy light penetration measurements can contain a wealth of information on the vegetative structure.

Using the relationship in eq. (1) and given values of T and θ, values of k and LAI can be inferred (Norman et al., 1979; Lang et al., 1985). Recently, Norman and Campbell (1987) proposed an inversion routine describing the canopy leaf angle distribution as an elliptical distribution. The ellipsoid can vary in horizontal and vertical axes describing most leaf angle distributions. They define k, the extinction coefficient, as a function of LAI and x (the ratio of vertical to horizontal axes of the ellipse) then solve for x and LAI such that:

$$f = \sum (\ln T_i + k_i \, LAI)^2 \quad \text{is minimum.}$$

The bisection method is used to find the solution where the RMS error is minimized.

Canopy structure information has been inferred using photographic techniques and sunfleck measurements below a canopy with success in turf grass, corn and soybean canopies (Lang et al., 1985; Perry, 1985; Kopeck, 1987). The view zenith angle is varied in the photographic method while the source zenith angle is varied in the sunfleck method.

Cone sensors have been developed which sense diffuse light entering at a variety of angles (Norman et al., 1983). Two cone sensors were used in this research. One was a multi-cone sensor which measures diffuse light at angles 12°, 33°, 49°, 65° and 81° (Norman et al., 1983). The second was a prototype sensor developed by LI-COR which measures diffuse light at 7°, 25°, 40° and 58°.

Ten measurements above and below the canopy were made in each plot. The LI-COR sensor required correction of raw data for corruption of light detected by one or more sensors. The ratio of corrected measurements below the canopy with measurements above represent the fraction of diffuse light penetrating the canopy. The 10 ratios from each plot were averaged to give a mean gap fraction at each angle. These values were used as input values for the inversion routine.

Part of the 1986 field experiment included testing the suitability of the multi-cone sensor in a grassland environment. LAI estimates inferred using the multi-cone sensor data were compared to LAI estimates inferred from the LI-COR cone data. Multi-cone LAI estimates were generally lower than LI-COR cone LAI estimates (Fig. 18). The lower values of the multi-cone LAIs are due, in part at least, to the height of the cone (approximately 0.1 m) so that the leaf area below the height of the cones was not viewed. Canopy heights were as low as 0.30 m in some plots. A shorter cone like the LI-COR instrument is desirable. Also the multi-cone sensor is more sensitive in the green portion of the spectrum, thereby sensing more scattered radiation. The canopy appears to be brighter at greater zenith view angles where it should be darker; this results in higher calculated values of gap fraction at these lower angles. The distribution of gap fractions with cone angle were exemplary of canopies with lower leaf area and more horizontally inclined leaves than actually existed. In most cases, the multi-cone sensor data resulted in lower LAI and lower mean leaf angle estimates than those derived from the LI-COR sensor.

The terrain posed another problem. Due to the steepness of some of the slopes, the cone sensors were oriented parallel to the surface. Results are listed in Table 4 along with additional canopy structural measurements. Inferred LAI was plotted against dry leaf weight and canopy height (Figs. 19, 20). The relationship is described with an exponential equation from Landsberg (1977) of the form:

$$LAI(s) = A(1 - \exp^{B(x+C)}) \quad (3)$$

where x is the biomass dryweight in grams or canopy height in cm. Such relationships can be useful in estimating LAI from the dry biomass or, conversely, estimating biomass from estimates of LAI which can be made quite rapidly using sensors such as the one developed by LI-COR.

b. Model Simulations of Wheat Canopy Fluxes

Coordinated measurements of agronomic characteristics, hourly climatic variables and fluxes made over a wheat canopy at Mead, Nebraska in May and June, 1985 provided an excellent opportunity to test the model, Cupid (Norman, 1982).

Cupid is a comprehensive plant-environment model, including many environmental and plant factors. It is versatile, independent of plant type but requires a minimum input of information including hourly measures of solar radiation, air temperature, water vapor pressure, wind speed, precipitation, soil temperature at 0.50 m depth and soil moisture content at some reference depth. Hourly inputs were available from the Automated Weather Data Network (AWDN) Mead station. Canopy input information make the model independent of plant type. Stomatal characteristics were taken from Denmead and Millar (1976).

To date we have examined the data for May 22, 23, 25, 28, 29 and 30, 1985. We will present the data and analysis of two of these days, May 22 and May 30. May 22 is an example of a clear day and May 30 is an example of a partly cloudy day. Results and conclusions are similar for all six dates.

The radiation, wind, temperature and vapor pressure input over the 24 hours are given in Fig. 21a,b for the dates of May 22 and May 23, 1985. No precipitation fell on either of the two days.

The measured fluxes of net radiation (R_n), latent heat flux (LE), soil heat flux (S), and sensible heat flux on May 22, 1985 - a clear day - are shown in Fig. 22. The simulated fluxes are given in Fig. 23. The measured and simulated fluxes of R_n and LE are compared in Fig. 24. There is very good agreement between the measured and simulated values during all periods of the day. The measured and modeled fluxes of H are shown in Fig. 25. The measured and simulated values agree quite well and tend to follow a similar pattern. The largest deviations tend to occur mid-morning and mid-afternoon.

The measured and simulated fluxes of R_n, LE, H and S are shown in Fig. 26 and Fig. 27, respectively, for May 30, 1985 - a partly cloudy day. The measured and modeled fluxes of R_n and LE are compared in Fig. 28 and the H fluxes are compared in Fig. 29. Very good agreement is noted for all fluxes and the simulated fluxes mimicked the measured fluxes during both clear and partly cloudy conditions.

Based on the preliminary results of the data collected during the six days in May, 1985 it can be stated that the model Cupid did very well in estimating the fluxes of R_n, LE and H for wheat. The performance of the model Cupid for estimating these fluxes from the tall grass prairie vegetation at the FIFE site is yet to be determined.

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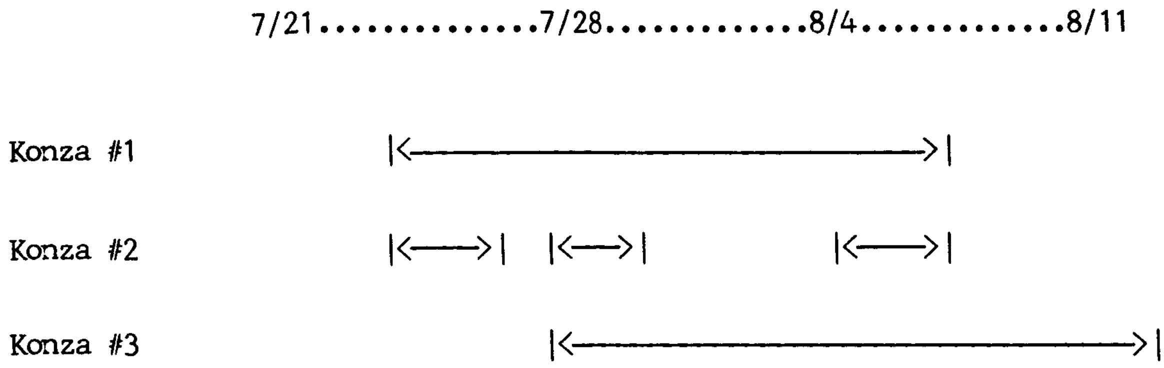
Table 1. Description of the 3 surface weather stations deployed in 1986.

Elevation (m)	Konza #1 426	Konza #2 400	Konza #3 400
Data logger	CR21X	CR21	CR21
RF-modem	yes	yes	no
RF-radio/antenna	yes	yes	no
Tape recorder	no	no	yes
Anemometer	yes	yes	yes
Wind vane	yes	yes	yes
Pyranometer	yes	yes	yes
Air temperature	yes	yes	yes
Air relative humidity	yes	yes	yes
Soil temperature	yes	yes	yes
Precipitation	yes	yes	yes
Net radiation	yes	no	no
PAR	yes	no	no
Canopy temperature-Nadir	yes	no	no
Canopy temperature-30° FV	yes	no	no

Table 2. Time period of data collection.



Experience with the CR21 in unattended mode would indicate that it worked well with the tape recorder (#3) but not good with the RF-linkage (#2). The CR21X (#1 above) performed extremely well in RF-linkage.

Table 3. Vegetation studied at the FIFE site.

Species	Common name	Grass or Forb	Number or Samples
Andropogon gerardii Vitman	Big bluestem	G	3
Panicum virgatum L.	Switchgrass	G	2
Agropyron smithii Rydt.	Western wheatgrass	G	2
Eragrostis spectabilis (Pursh) Gread.	Purple lovegrass	G	1
Bouteloua curtipendula (Michx.) Torr.	Sideoats grama	G	1
Sorghastrum nutans (L.) Nash	Indiangrass	G	1
Salvia pitcheri Torr.	Pitchers sage	F	1
Vernonia baldwinii Torr.	Ironweed	F	1
Ambrosia psilostachya DC.	West ragweed	F	1
Rhus glabra L.	Sumac	F	1
Ceanothus americanus L.	New Jersey tea	F	1

Table 4. Canopy structure characteristics, FIFE pilot study. July, August, 1986.

Plot #	Location	Dry Weight (g)	Height (cm)	Inferred LAI	Mean Leaf Angle
1	SBV	64.0	35	2.4	62.5
2	SBV	81.4	35	2.6	62.5
3	SBV	60.1	30	1.1	74.9
4	SBV	64.5	30	1.3	69.3
5	SBV	92.1	40	2.4	64.1
6	SBV	71.1	35	3.1	59.4
7	SBV	149.8	65	5.1	50.2
8	SBV	131.8	45	3.4	53.3
9	SBV	113.6	50	4.4	57.9
10	SBV	93.7	40-45	3.7	55.8
11	SBV	104.8	30-35	3.4	64.1
21	KONZA	106.7	35	2.6	46.0
22	KONZA	77.7	35	2.0	50.9
23	KONZA	160.5	70	3.7	56.7
24	KONZA	195.9	70	4.5	55.0
25	KONZA	200.4	65	2.9	62.5
26	KONZA	114.4	65	3.5	62.5
27	KONZA	129.8	60	3.4	54.1
28	KONZA	119.0	70-75	3.6*	
29	KONZA	93.7	50	2.9*	
30	KONZA	137.1	60	4.8*	
31	KONZA	112.5	45	3.5*	
32	KONZA	57.3	30	1.4*	

*Approximate LAI; values extrapolated from curve.

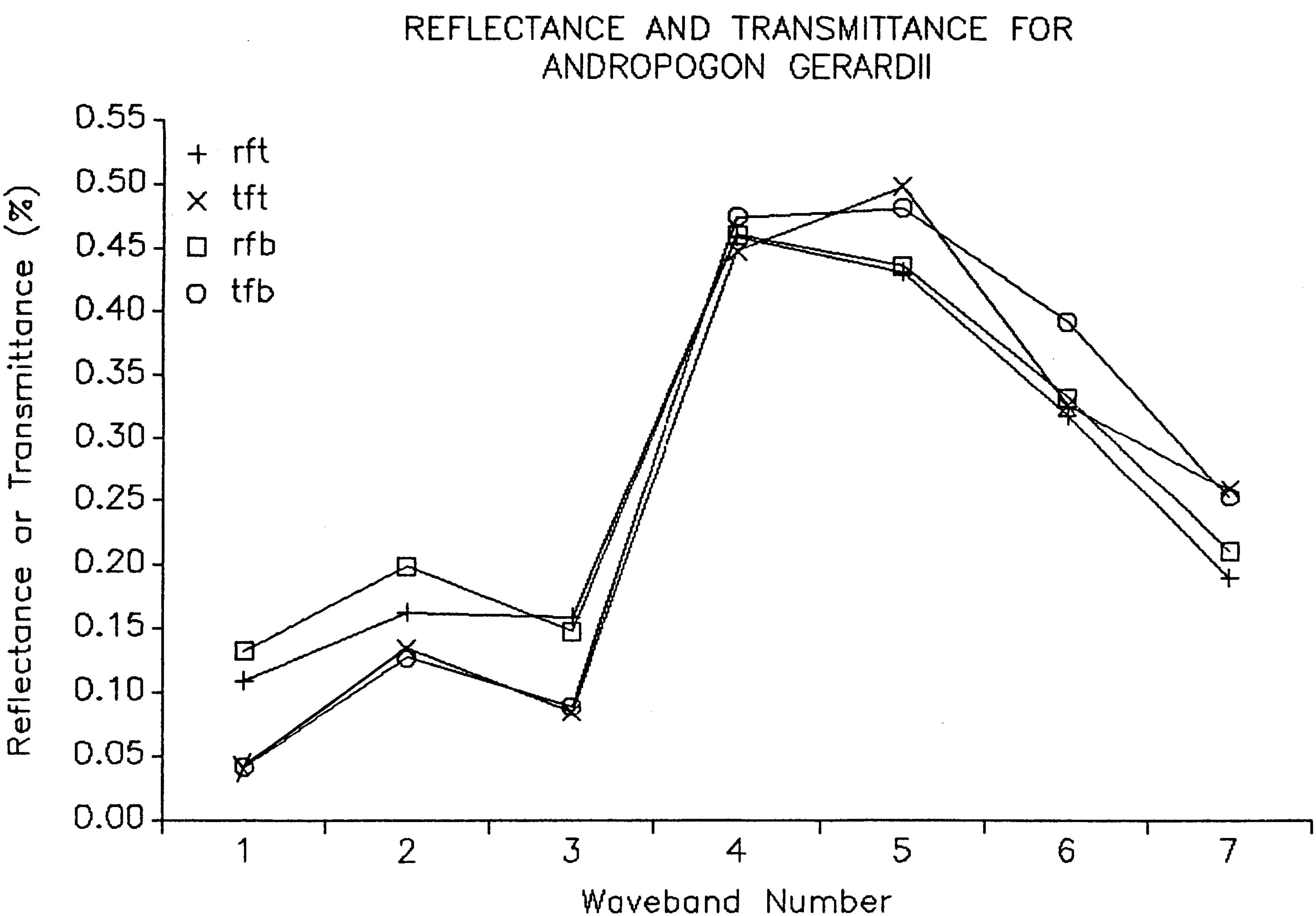


Figure 1 Leaf reflectance from the top (rft) and bottom (rfb) and transmittance through the top (tft) and bottom (tfb) in the MMR wavebands for _Andropogon gerardii_.

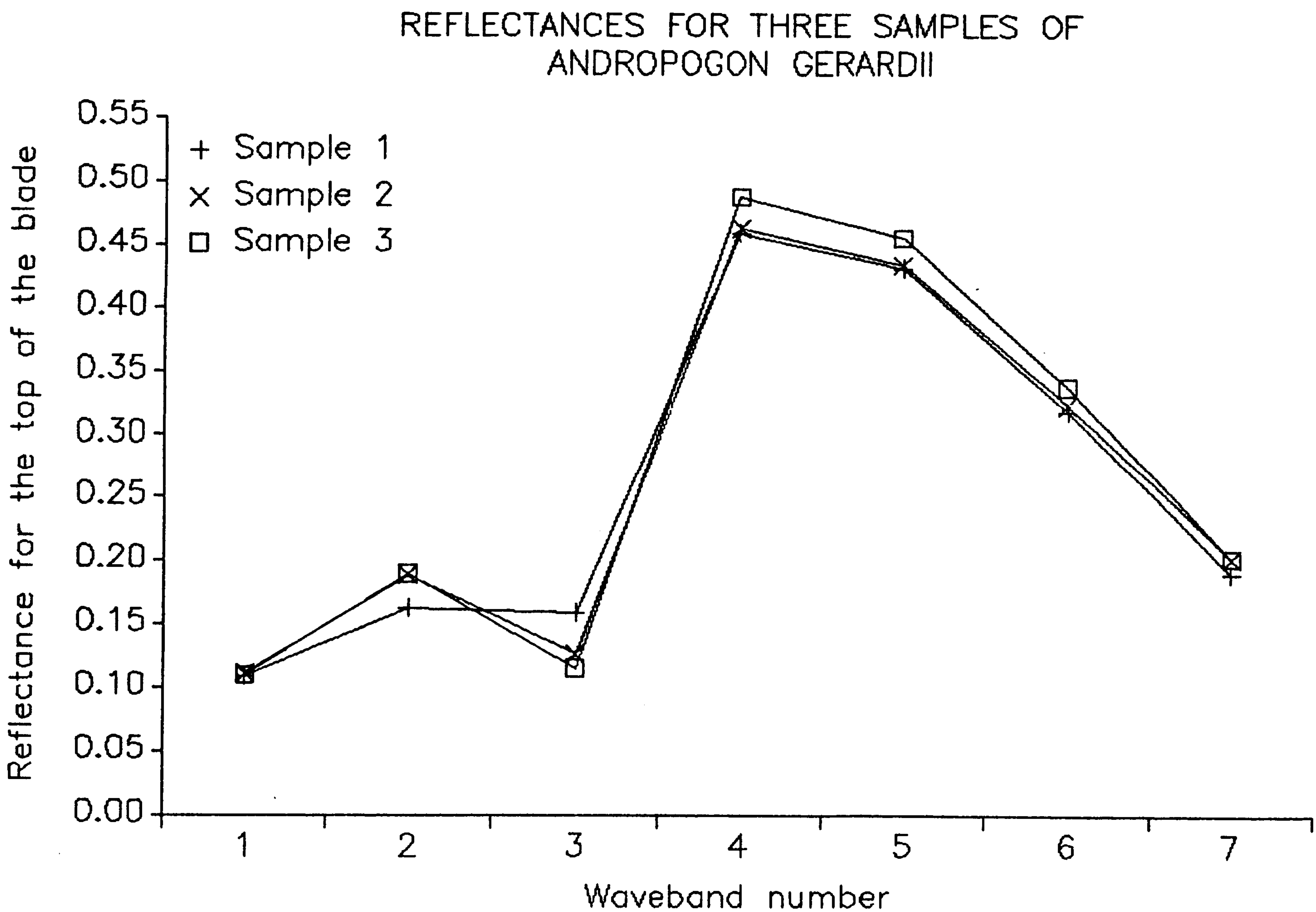


Figure 2 Comparison of leaf reflectances for leaves from 3 Andropogon gerardii plants.

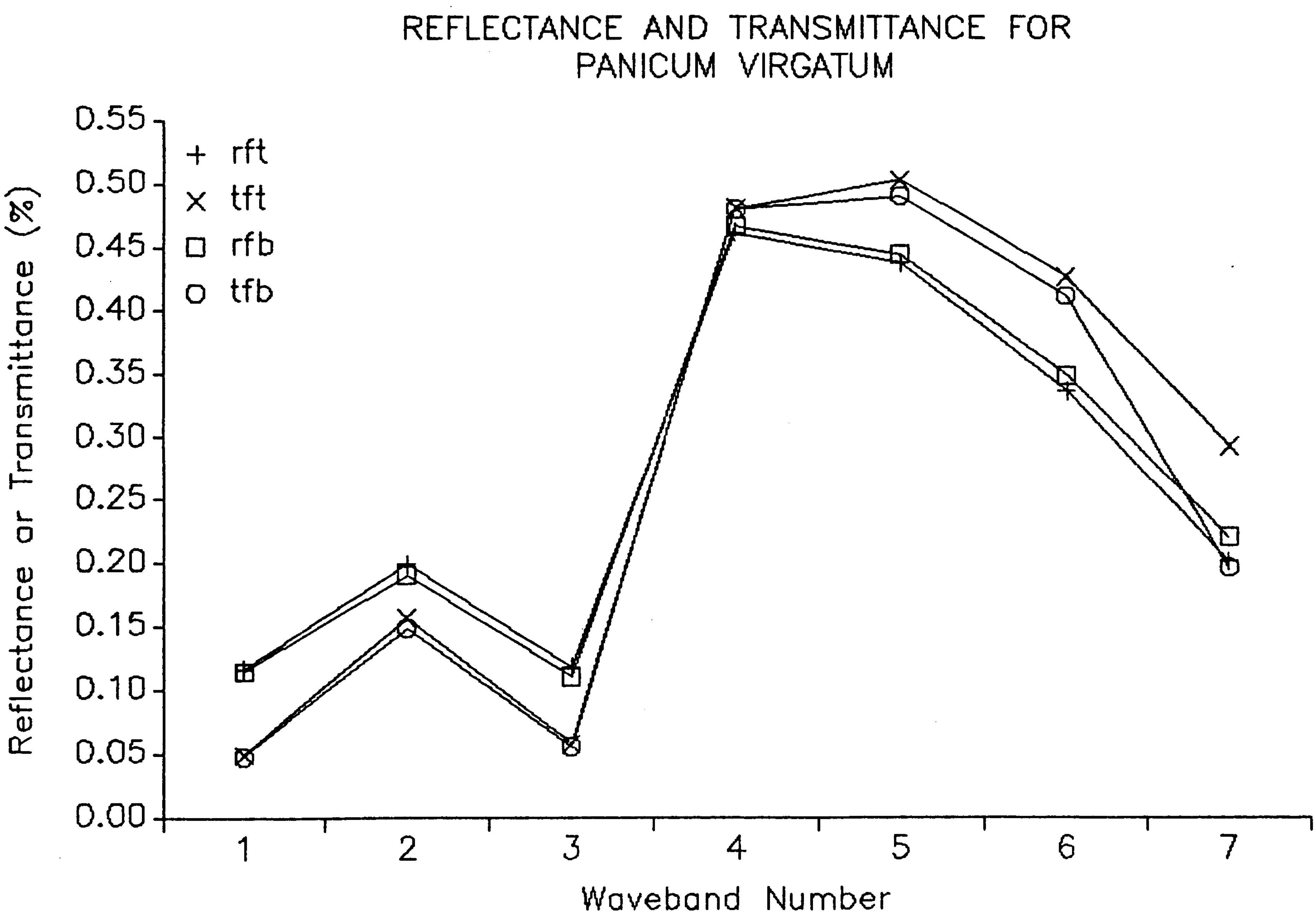


Figure 3 As in Fig. 1 for <u>Panicum virgatum</u>.

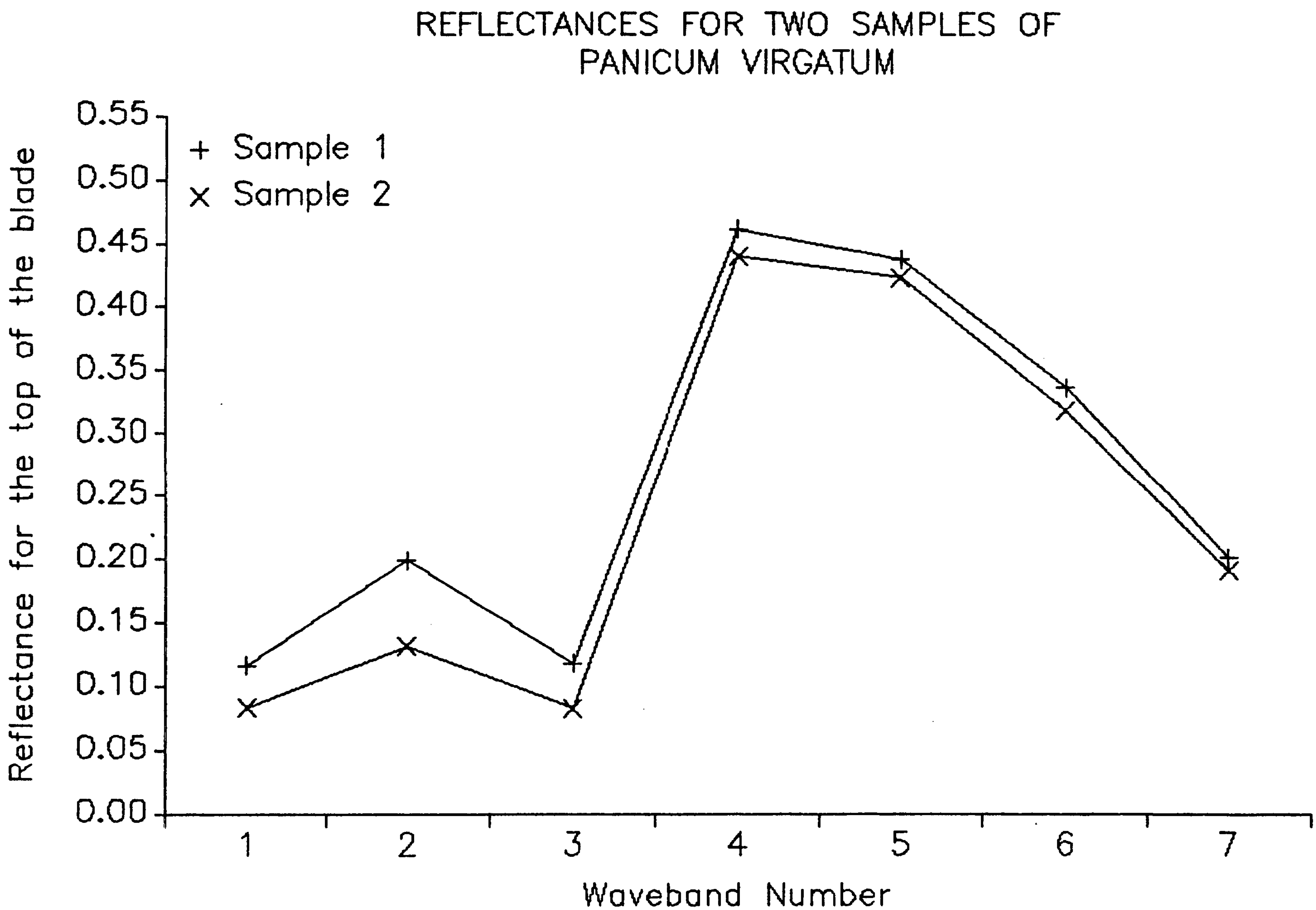


Figure 4 Comparison of leaf reflectances for leaves from 2 *Panicum virgatum* plants.

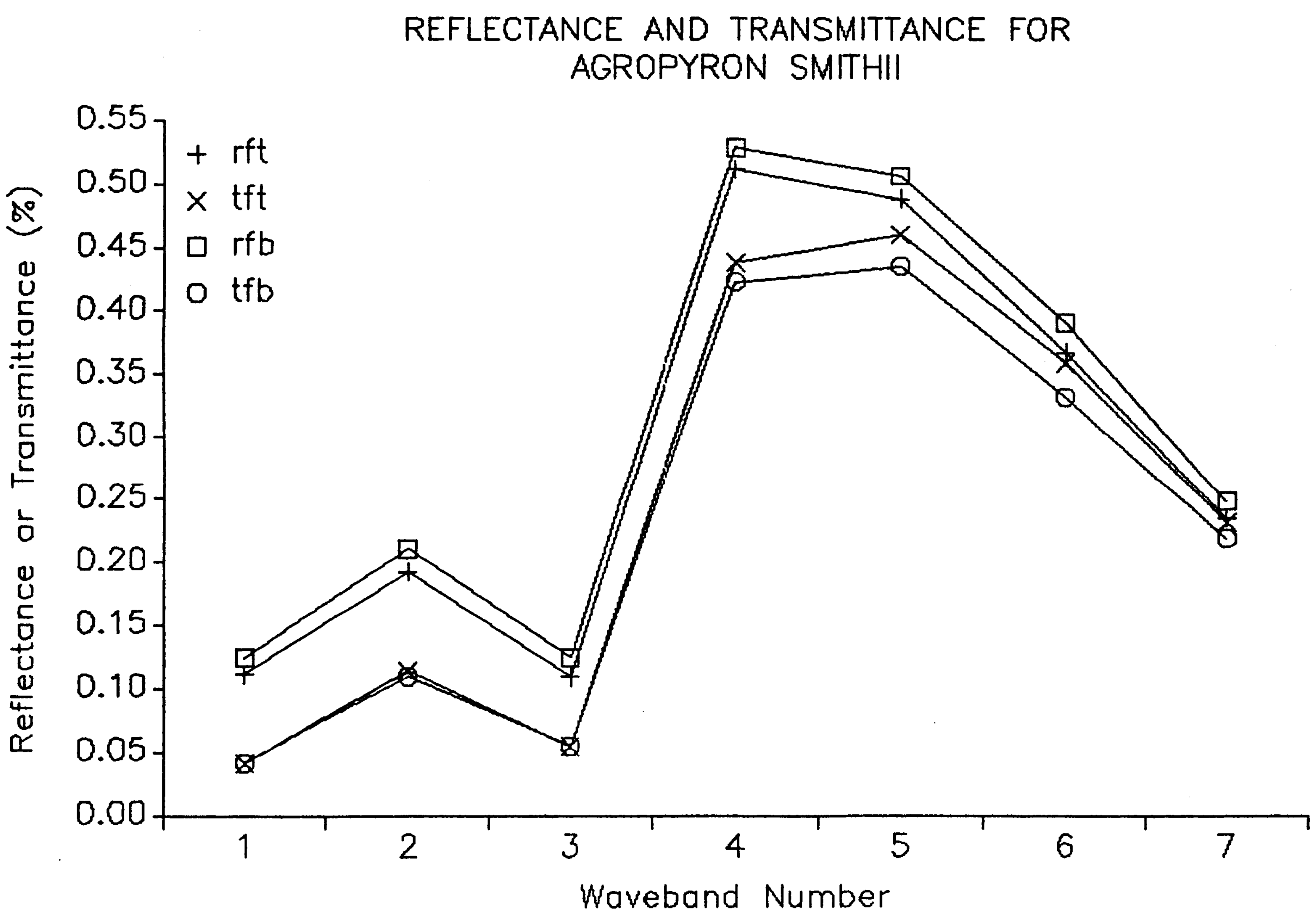


Figure 5 As in Fig. 1 for _Agropyron smithii_.

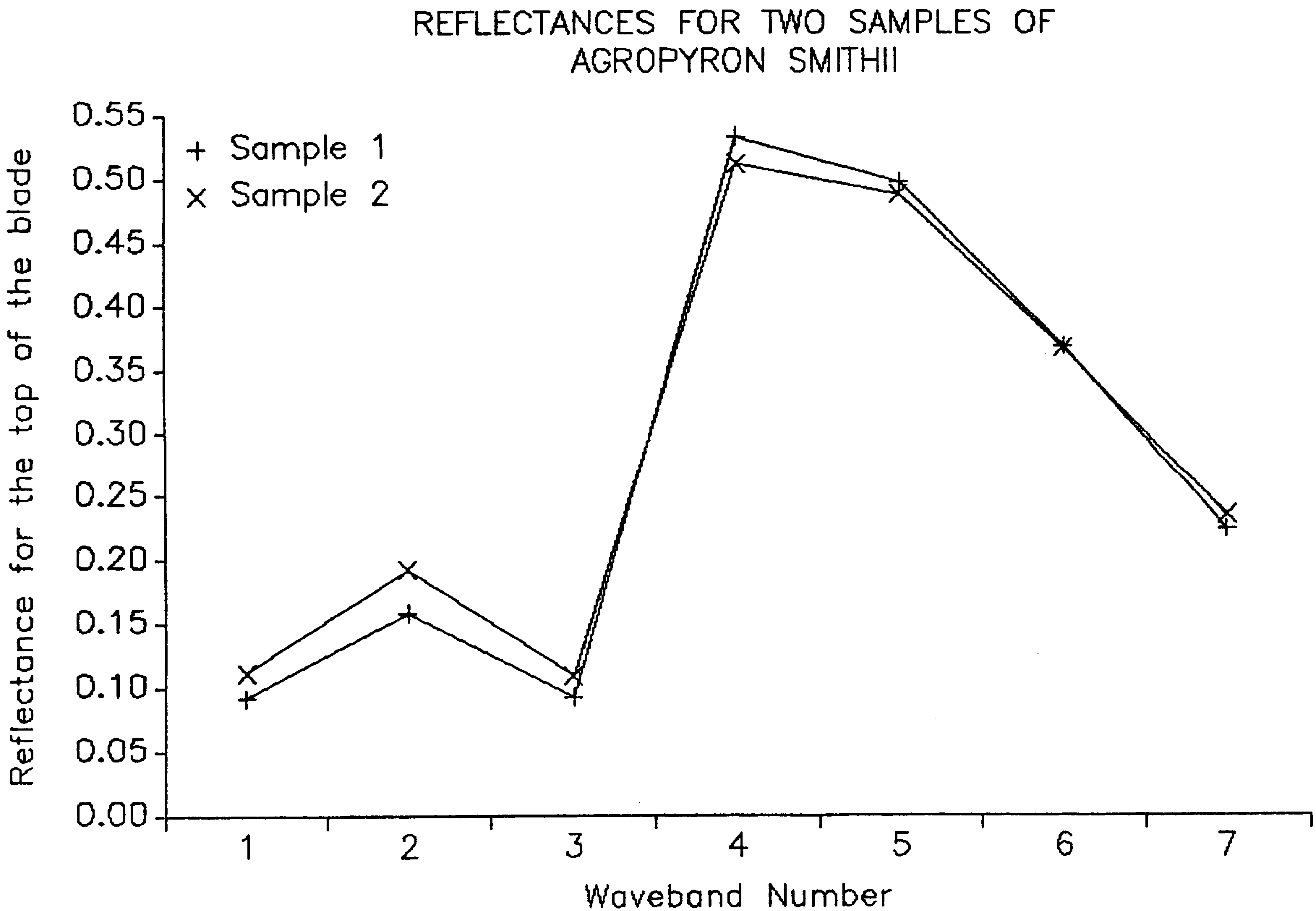


Figure 6 Comparison of leaf reflectances for leaves from 2 *Agropyron smithii* plants.

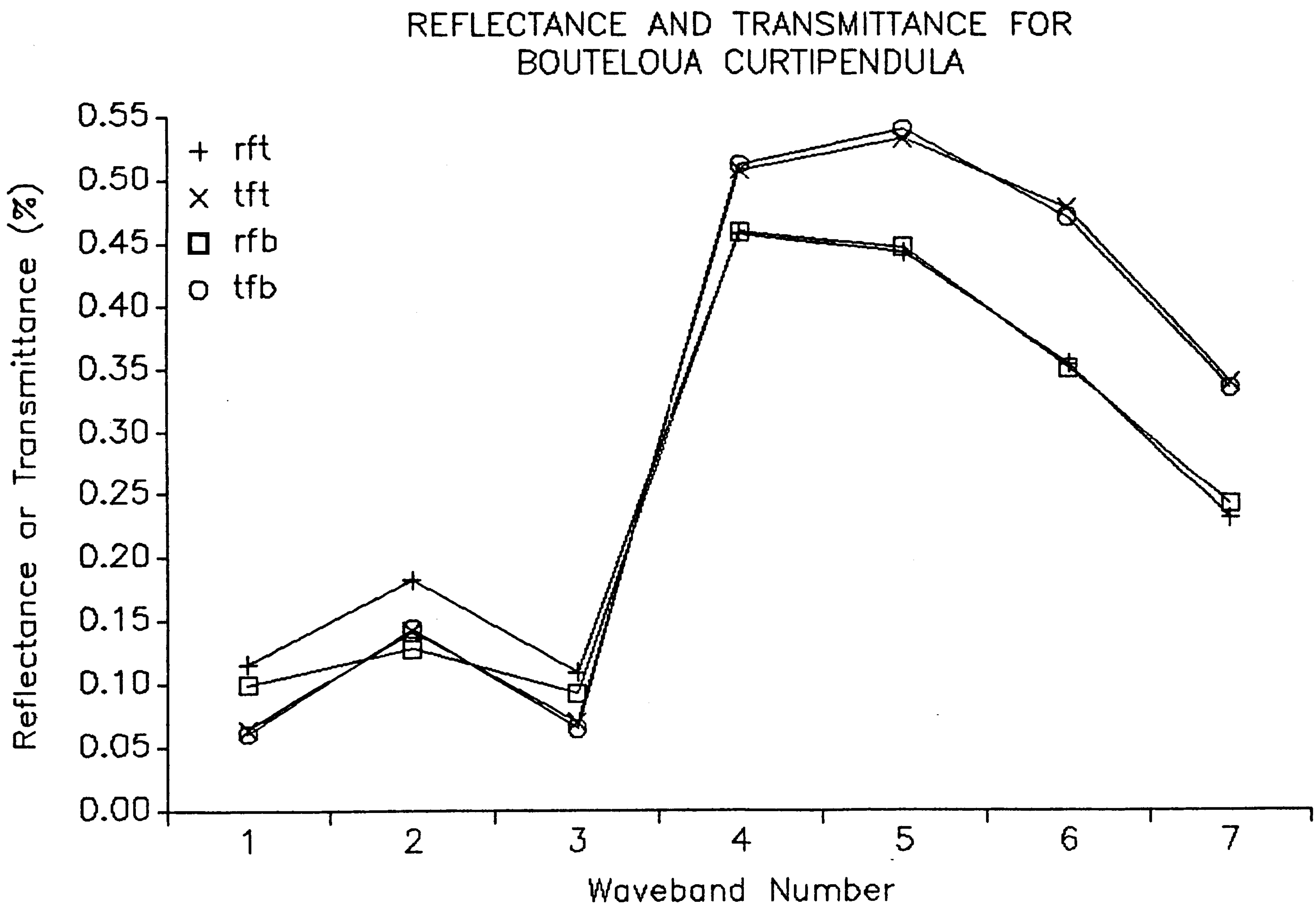


Figure 7 As Fig. 1 for Bouteloua curtipendula.

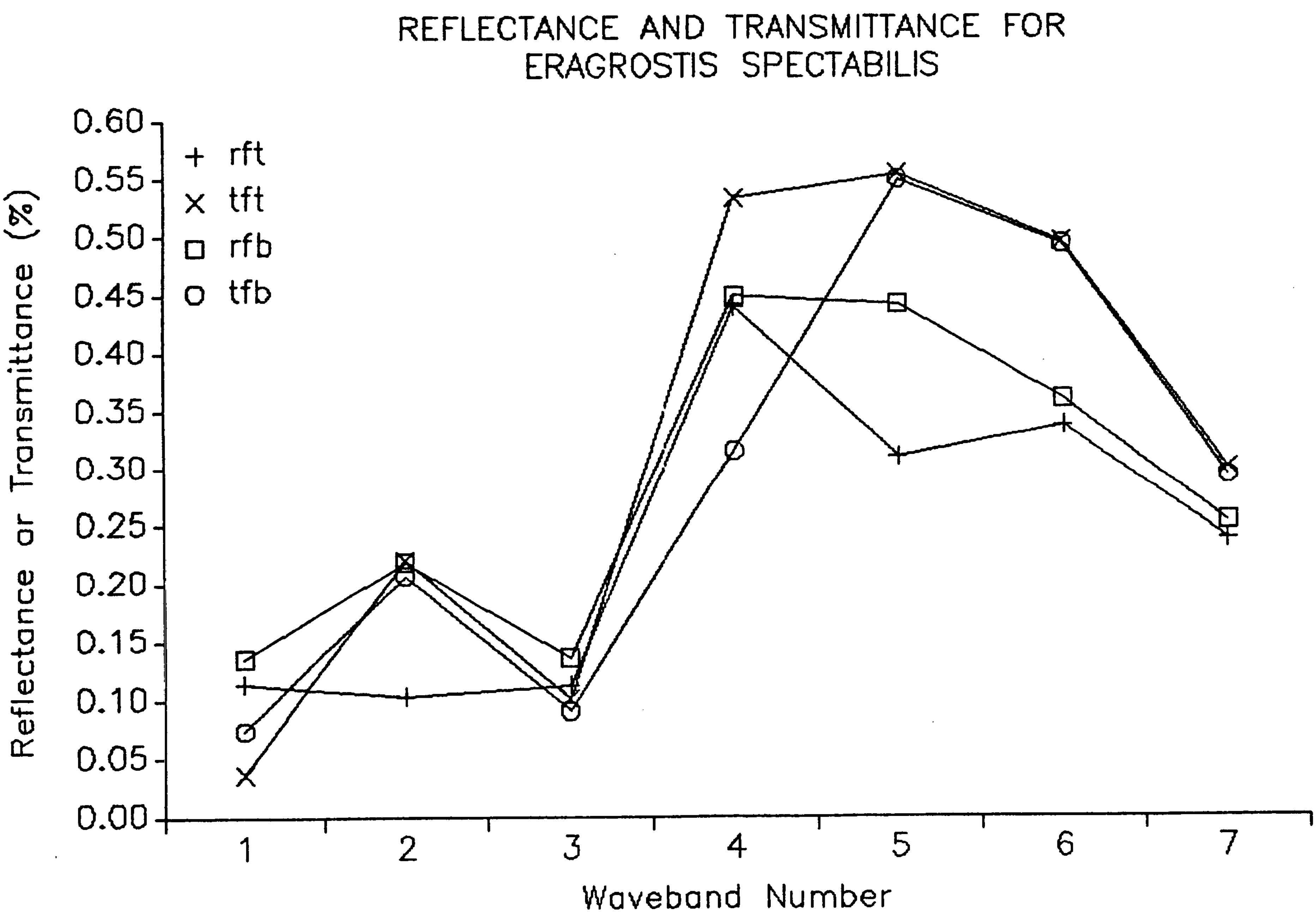


Figure 8 As in Fig. 1 for _Eragrostis spectabilis_.

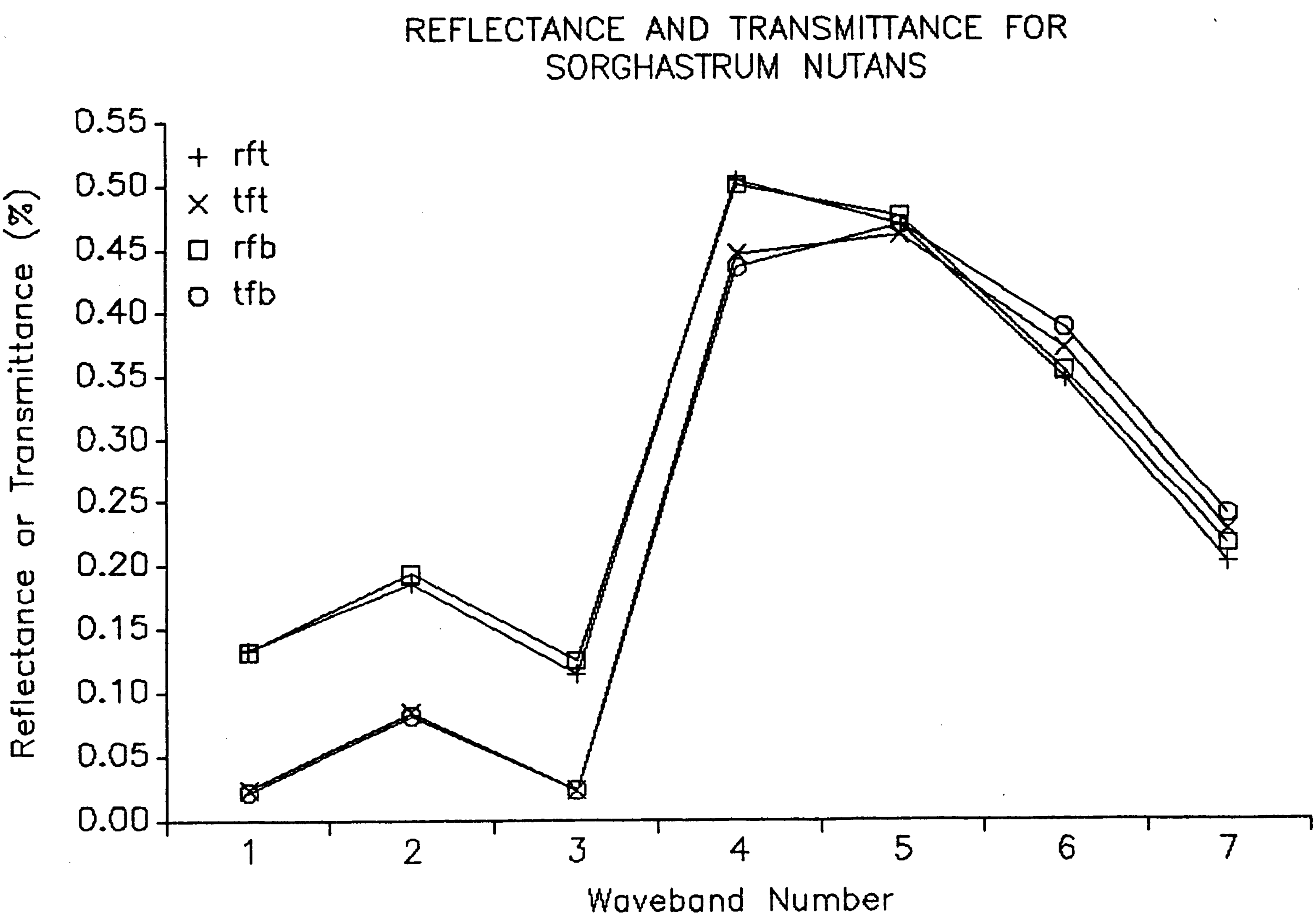


Figure 9 As in Fig. 1 for Sorghastrum nutans.

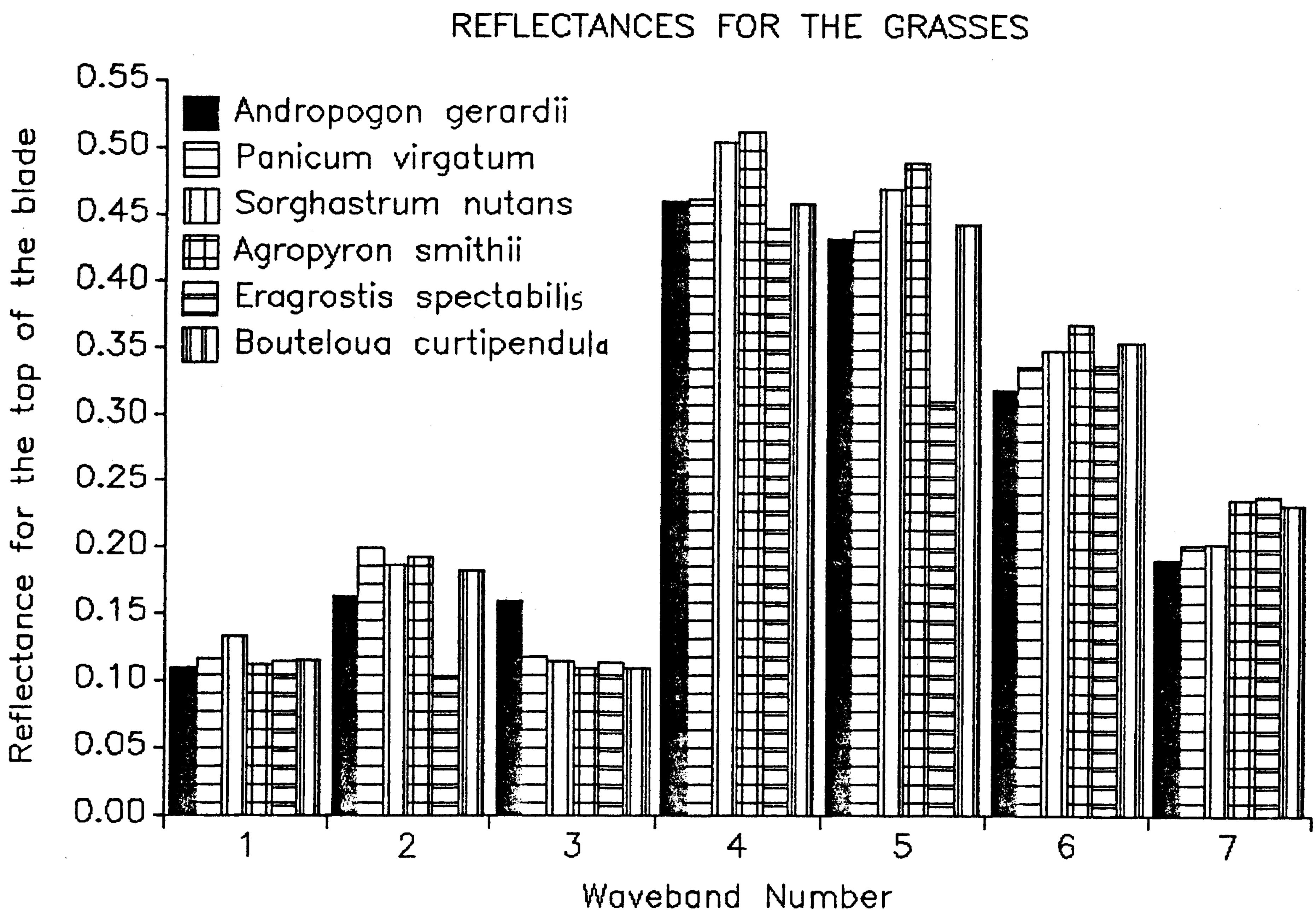


Figure 10 Comparison of reflectances in the MMR wavebands for all grasses measured in the study.

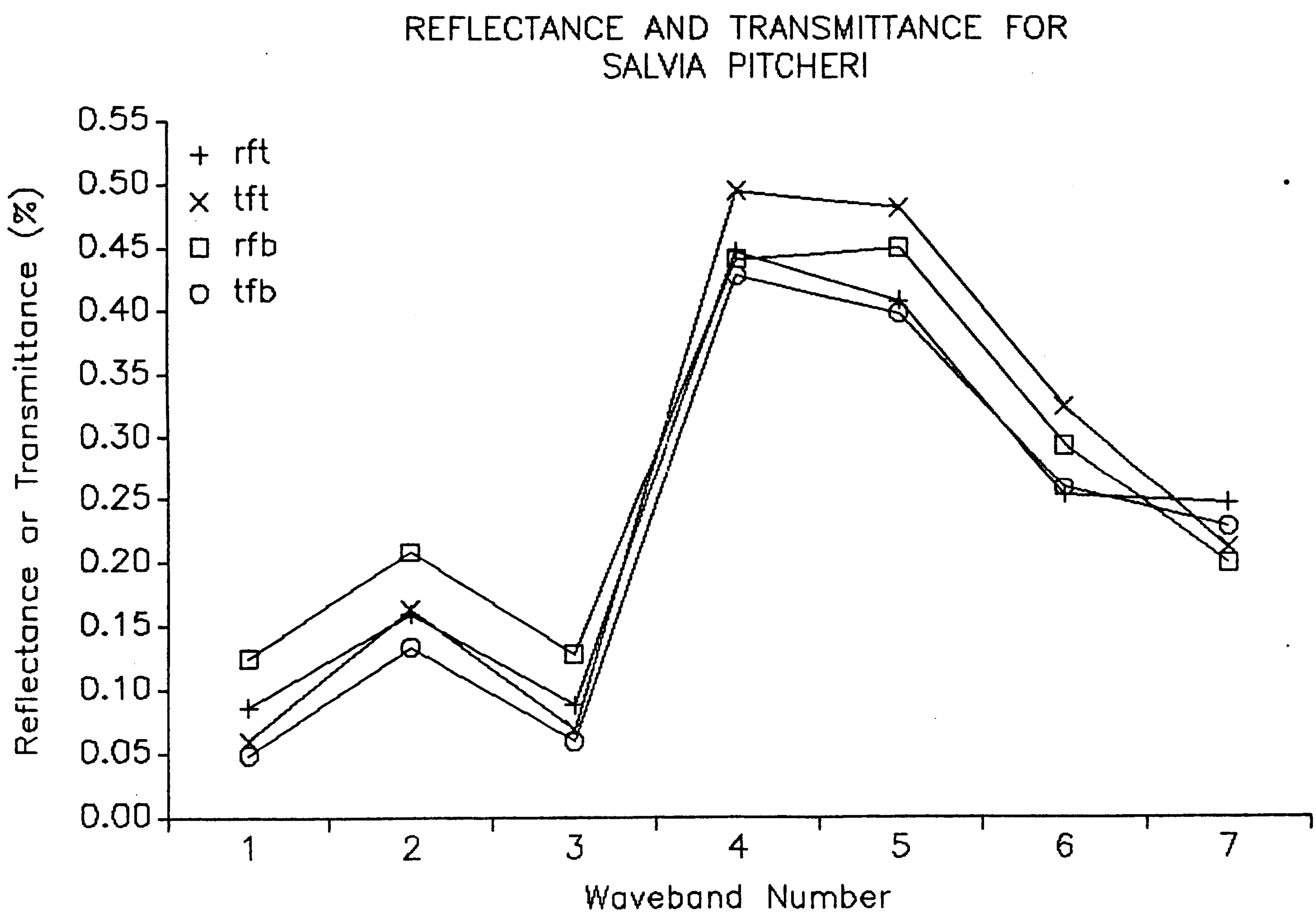


Figure 11 As in Fig. 1 for _Salvia_ _pitcheri_.

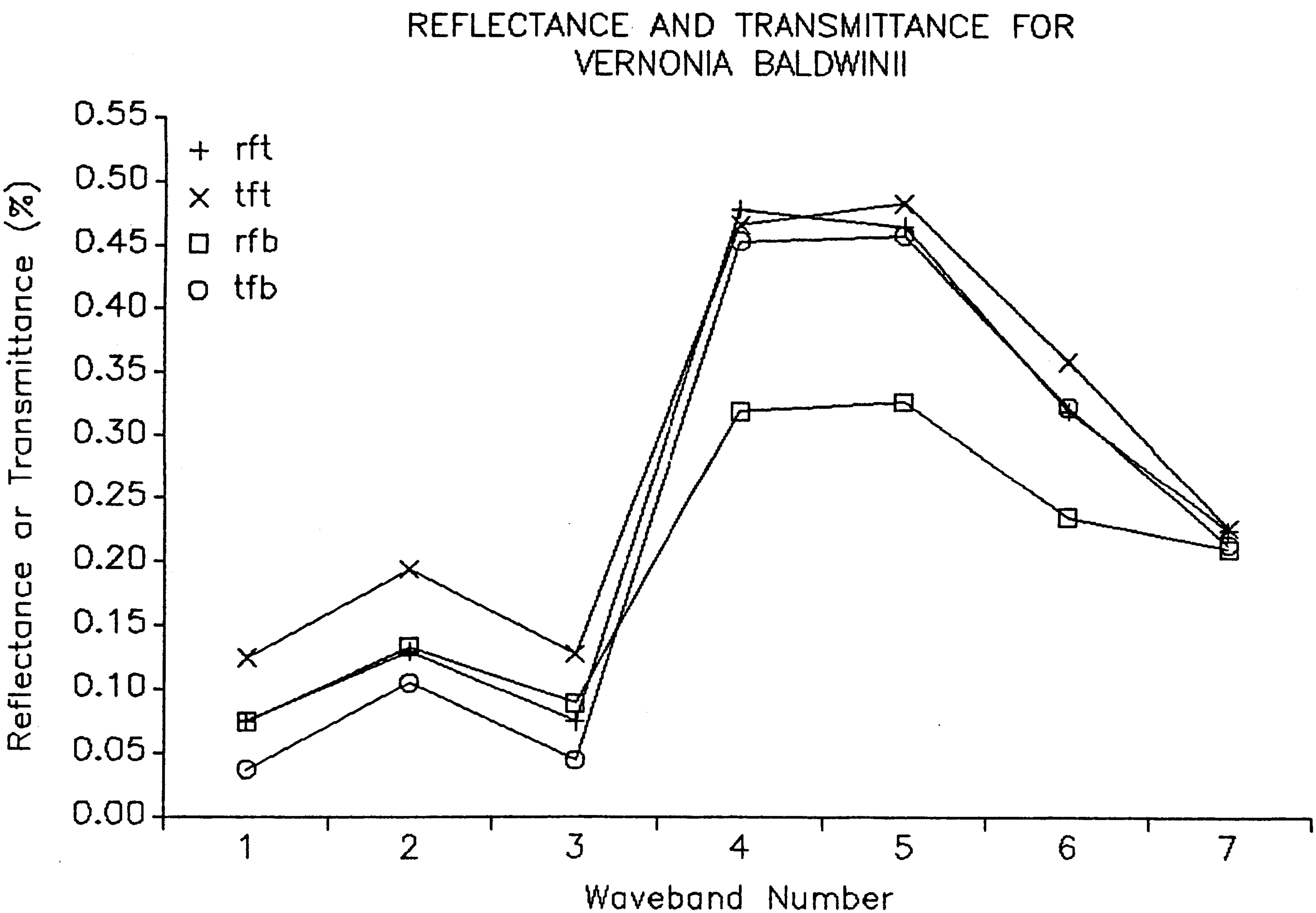


Figure 12 As in Fig. 1 for *Vernonia baldwinii*.

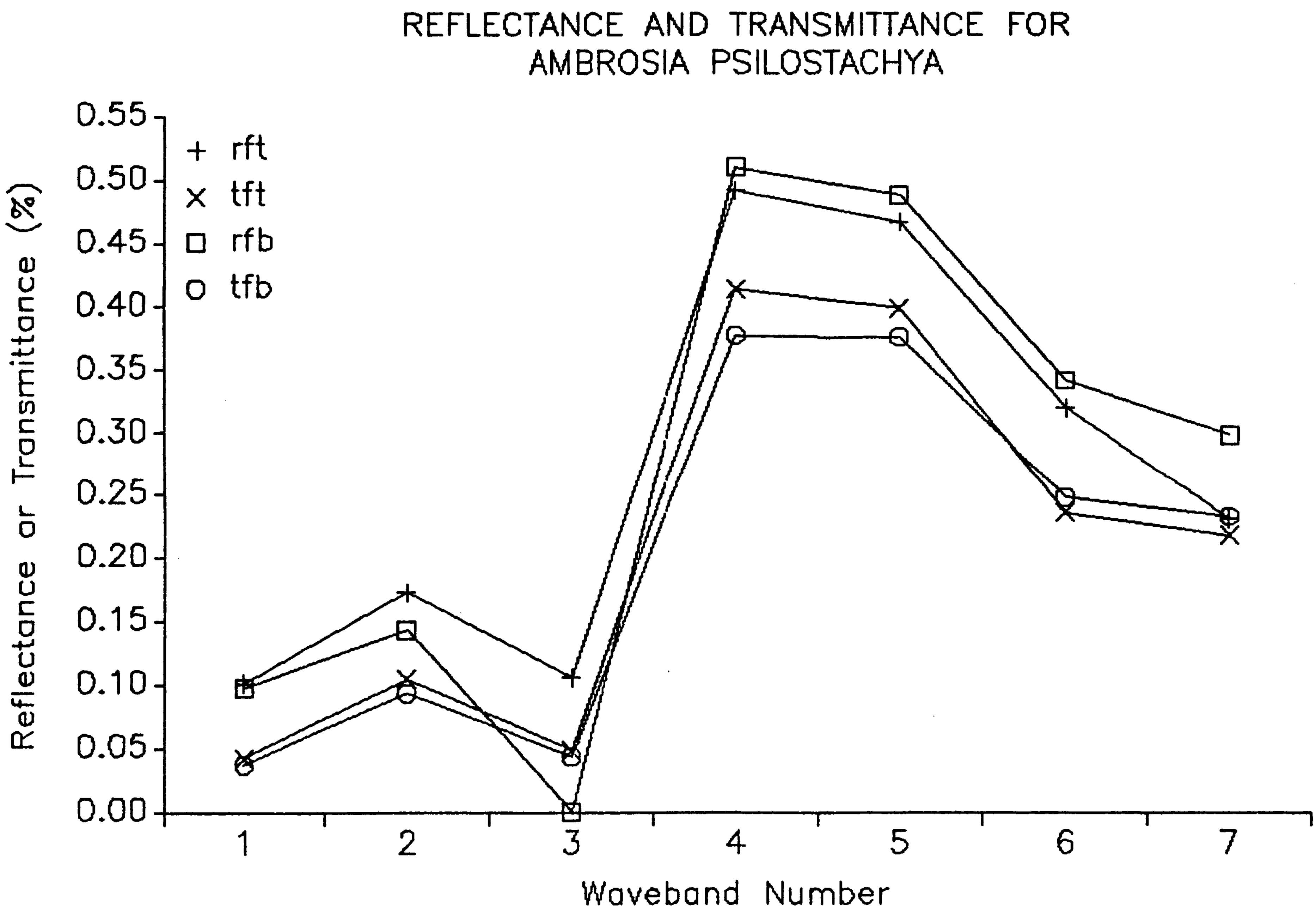


Figure 13 As in Fig. 1 for <u>Ambrosia psilostachya</u>.

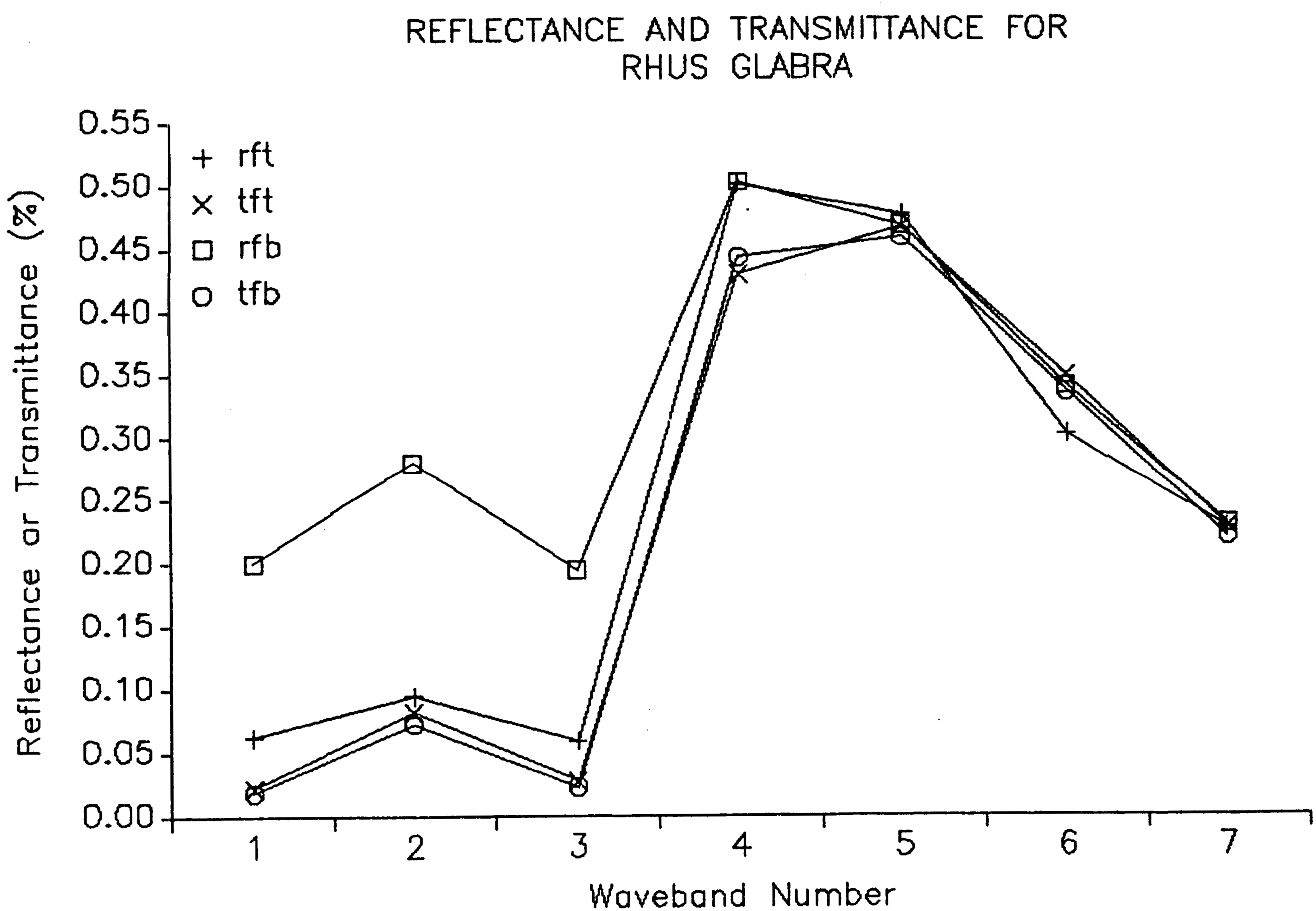


Figure 14 As in Fig. 1 for Rhus glabra.

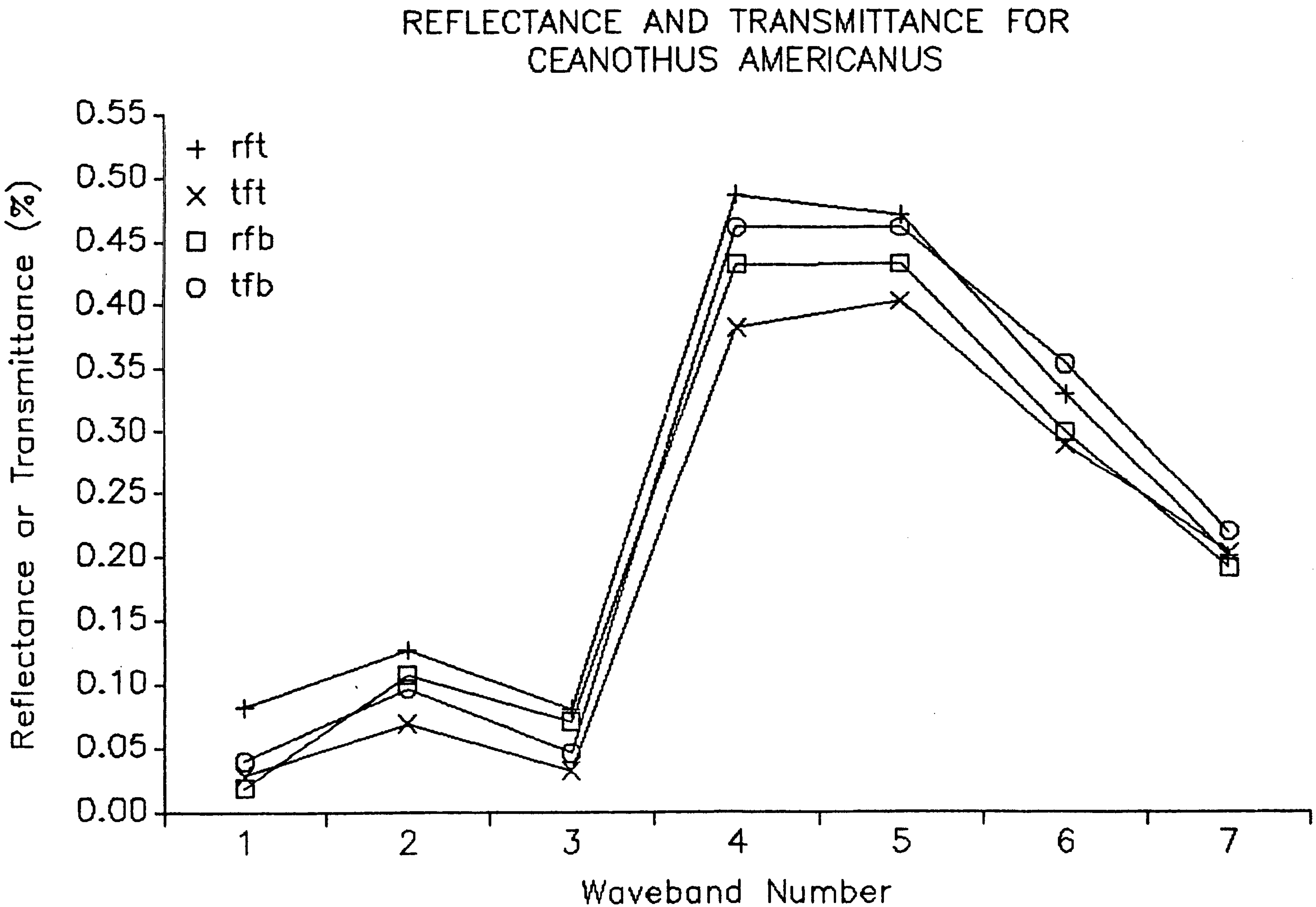


Figure 15 As in Fig. 1 for Ceanothus americanus.

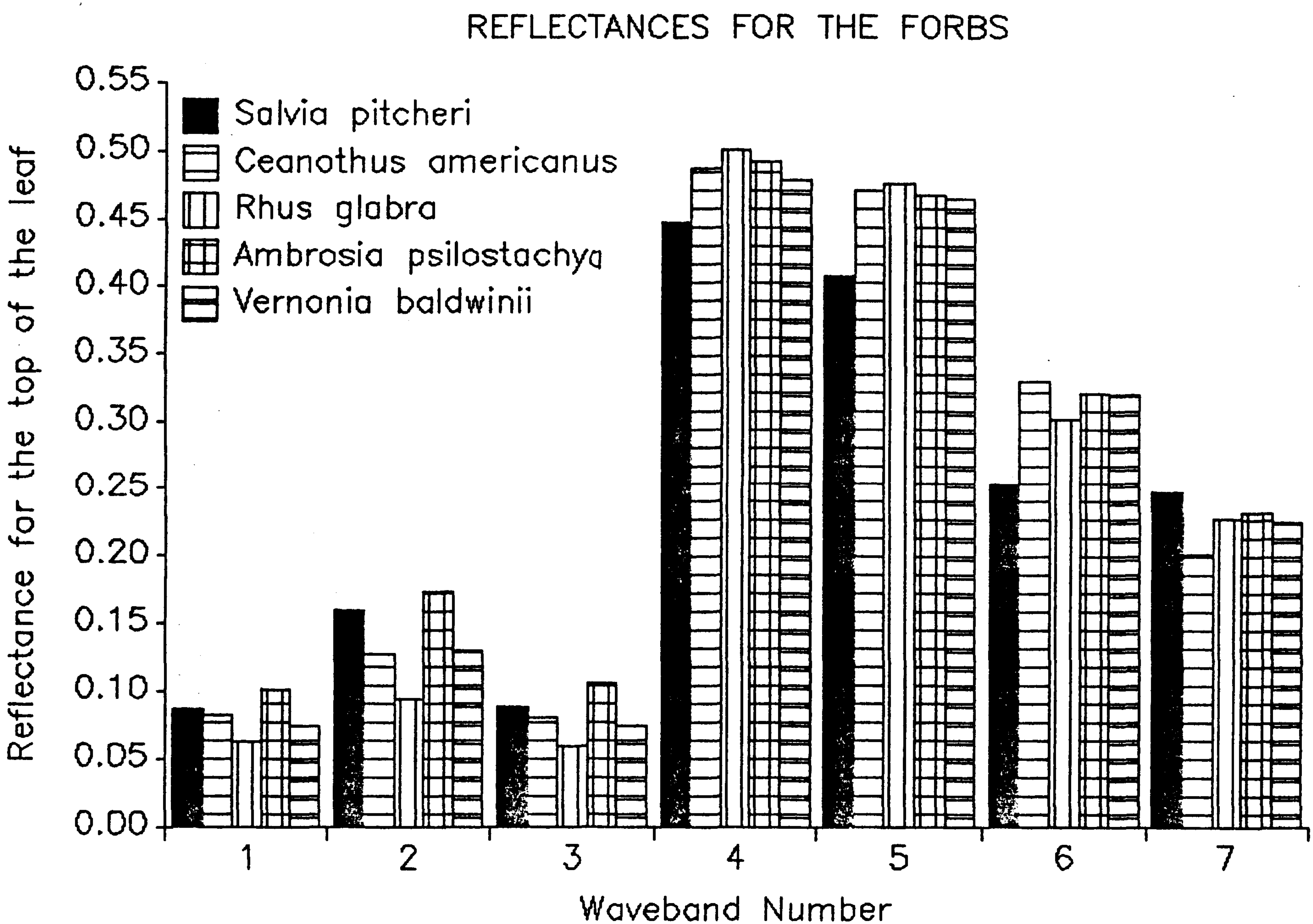


Figure 16 As in Fig. 10 for forbs.

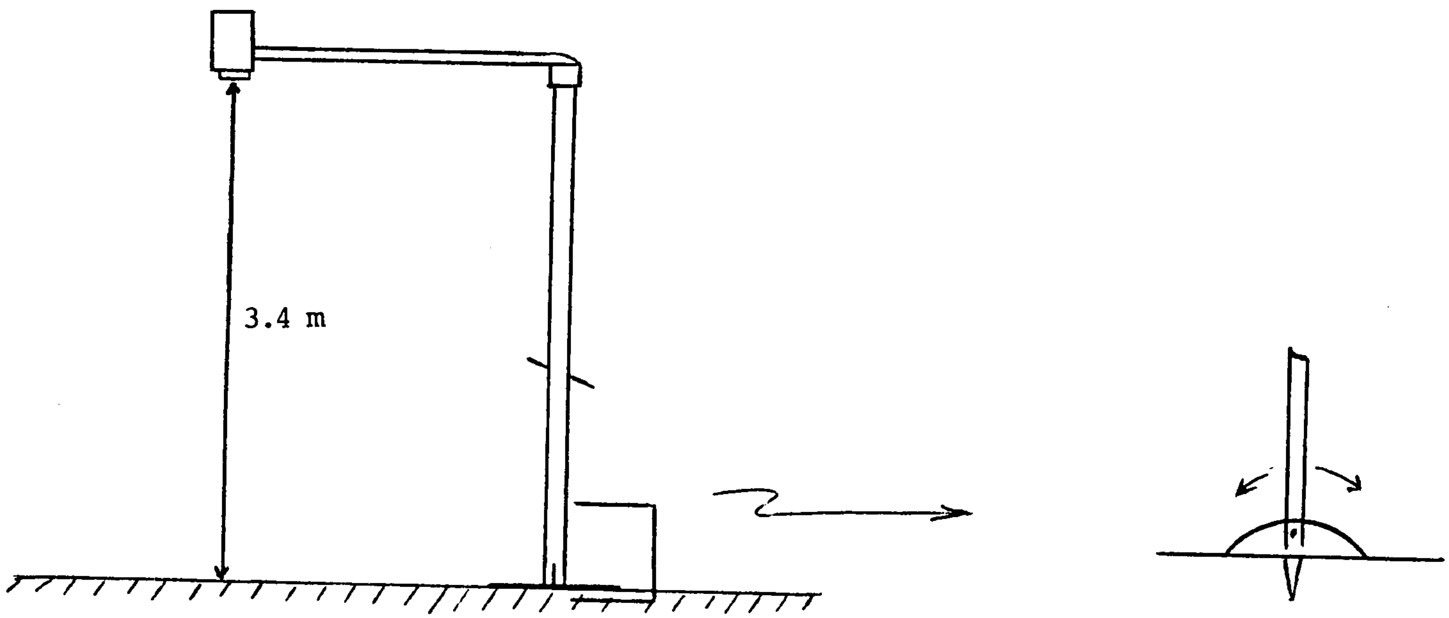


Fig. 17. Schematic of portable mast for the Barnes MMR. At right is a drawing of the base of the mount, which allows measurements off-nadir.

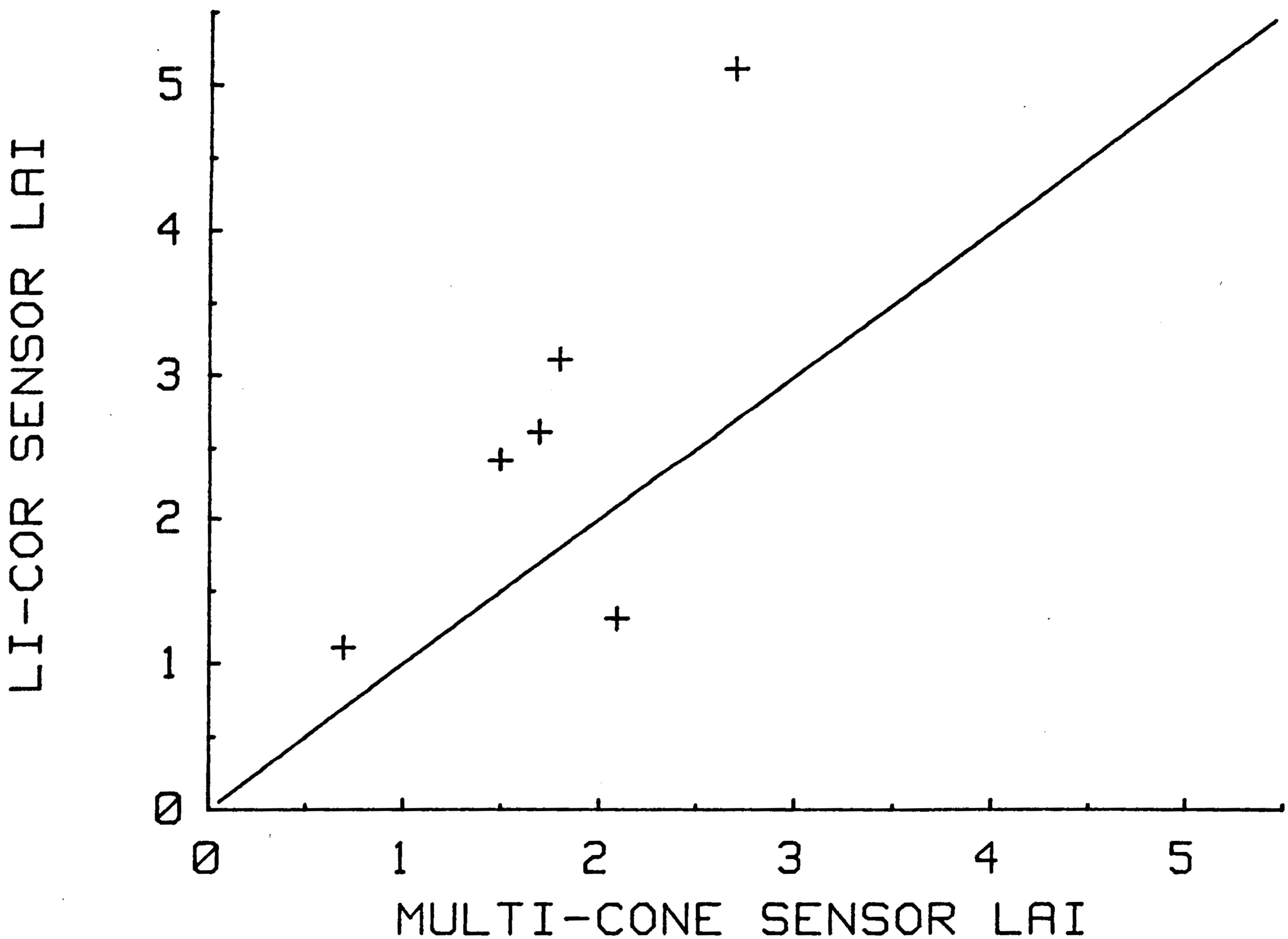


Fig. 18. Comparison of estimated LAI values from the multicone sensor with the LI-COR sensor.

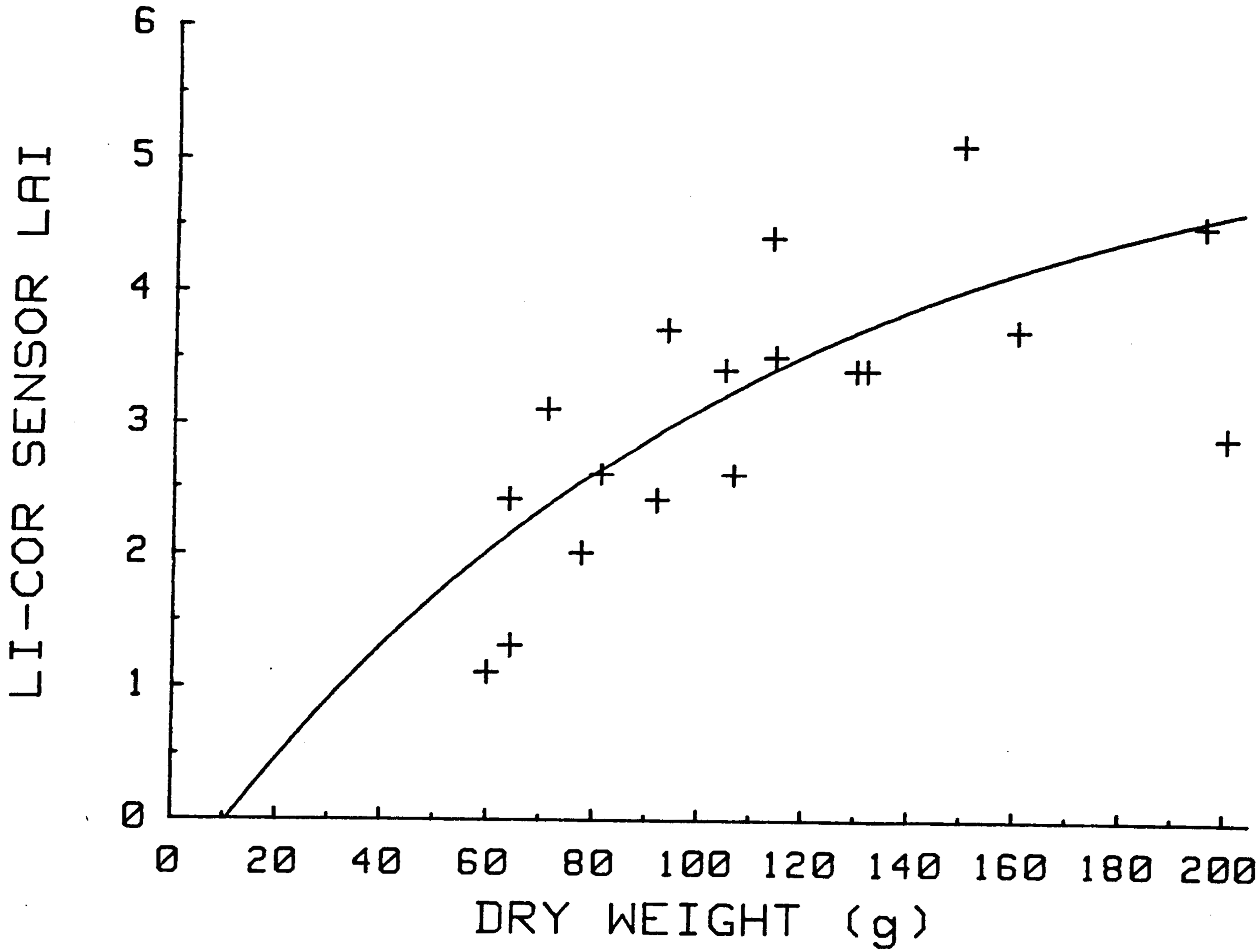


Fig. 19. Relationship between measured dry weight of plant biomass and estimated LAI from LI-COR sensor.

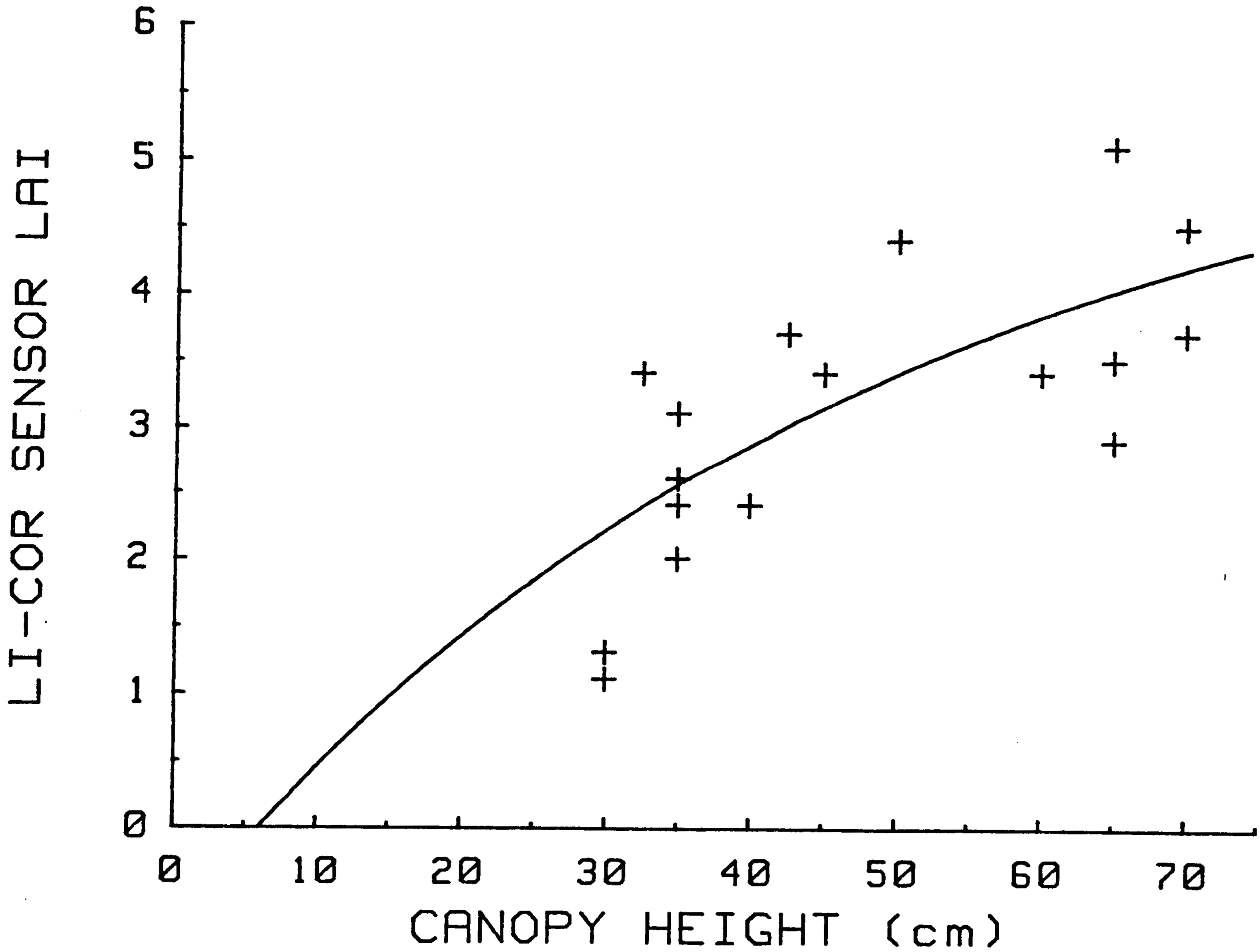


Fig. 20. Relationship between measured canopy height and estimated LAI from LI-COR sensor.

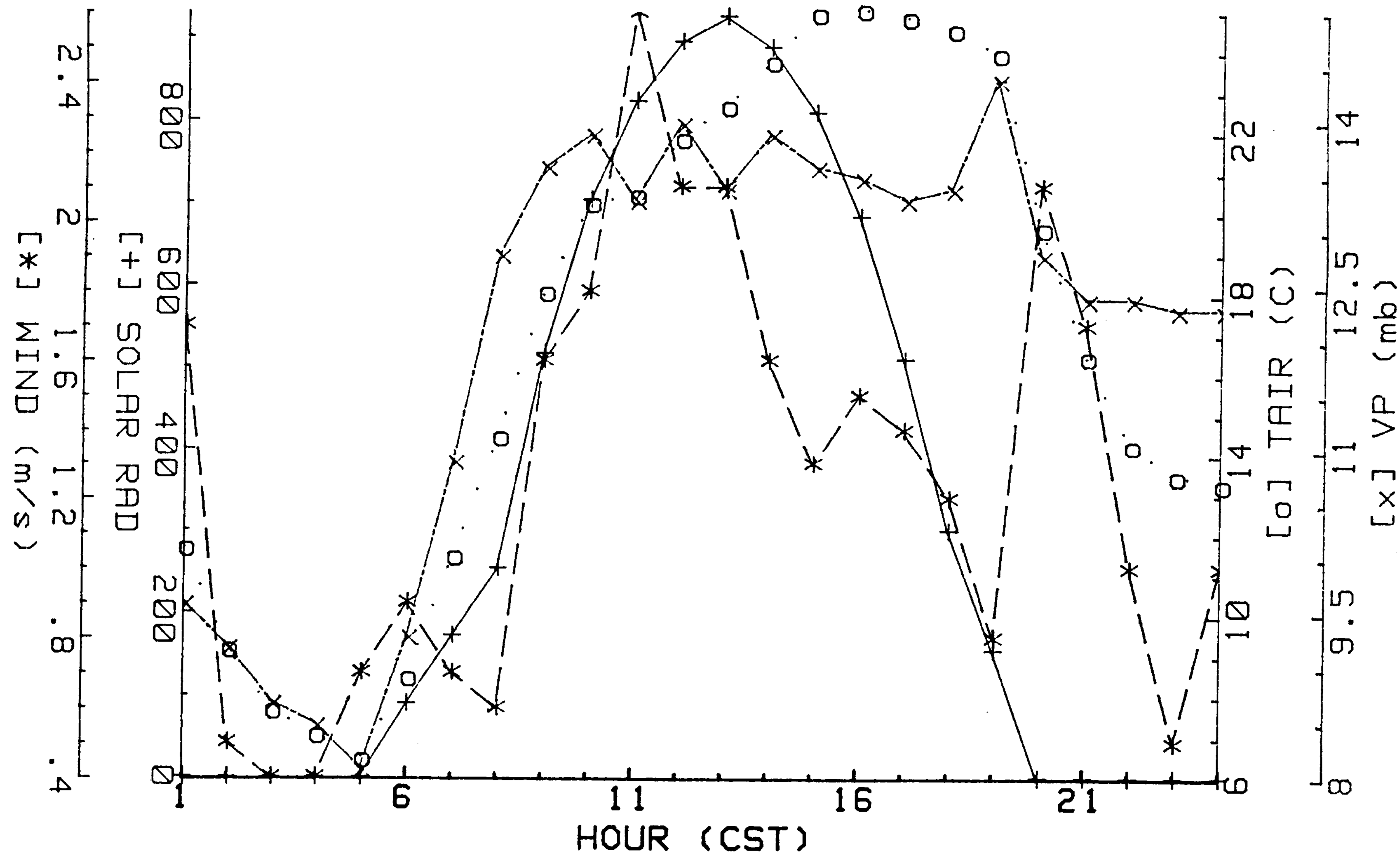


Fig. 21a. Hourly values of solar radiation, wind speed, air temperature and vapor pressure on May 22, 1985.

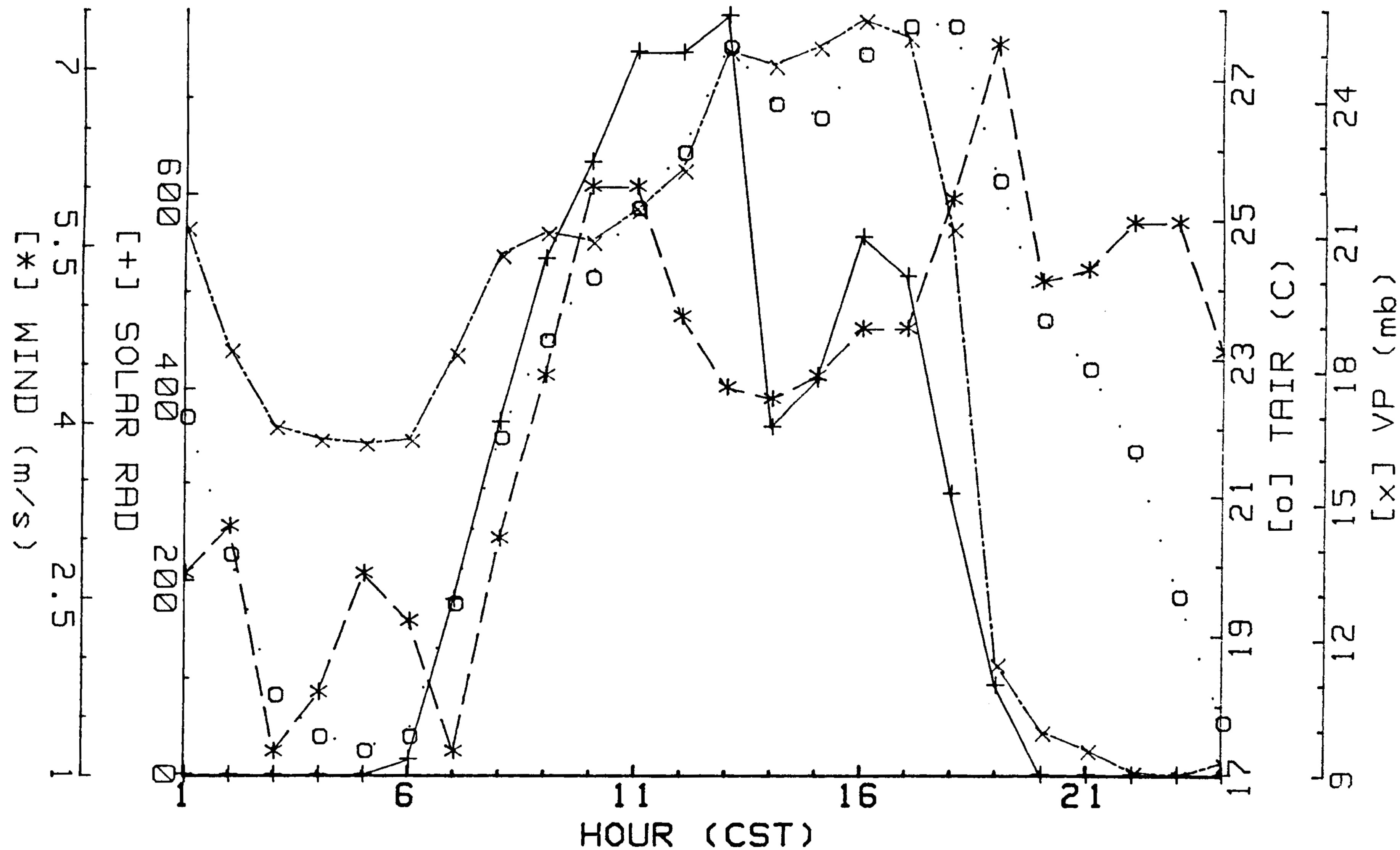


Fig. 21b. Hourly values of solar radiation, wind speed, air temperature and vapor pressure on May 30, 1985.

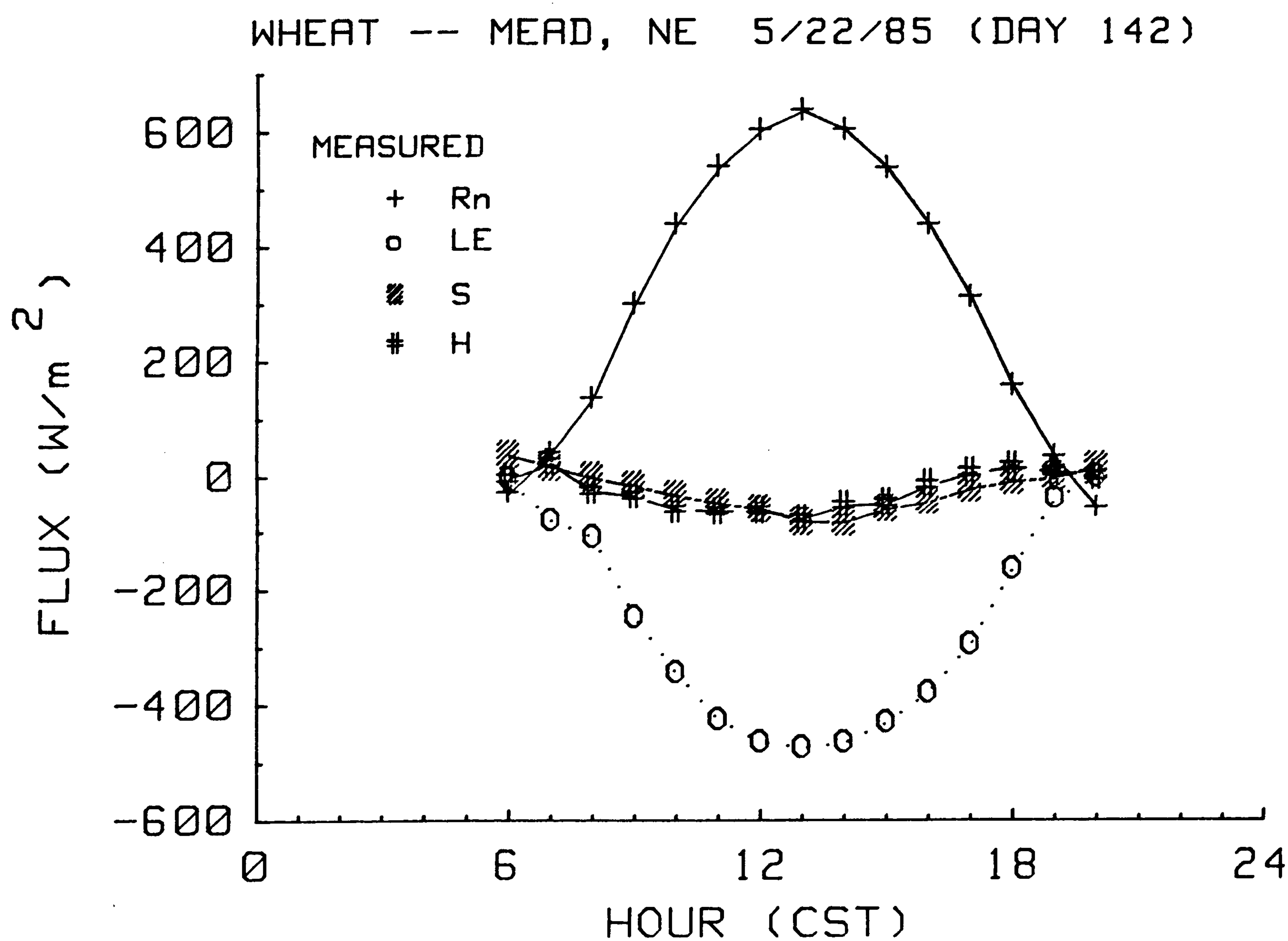


Fig. 22. Measured hourly values of net radiation (Rn), latent heat flux (LE), soil heat flux (S) and sensible heat flux (H) for May 22, 1985.

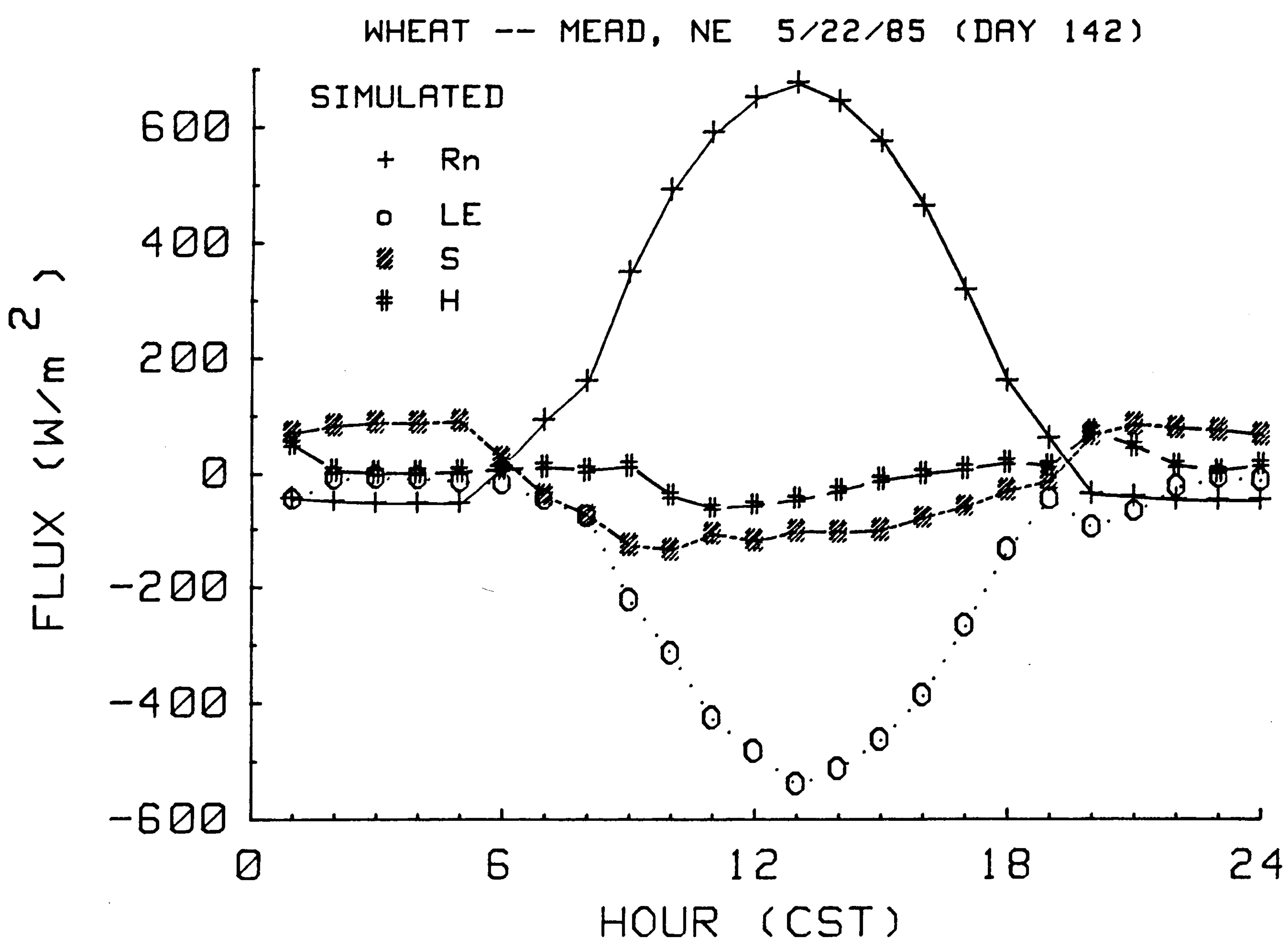


Fig. 23. Simulated hourly values of Rn, LE, S and H on May 22, 1985. Values similated using the model Cupid.

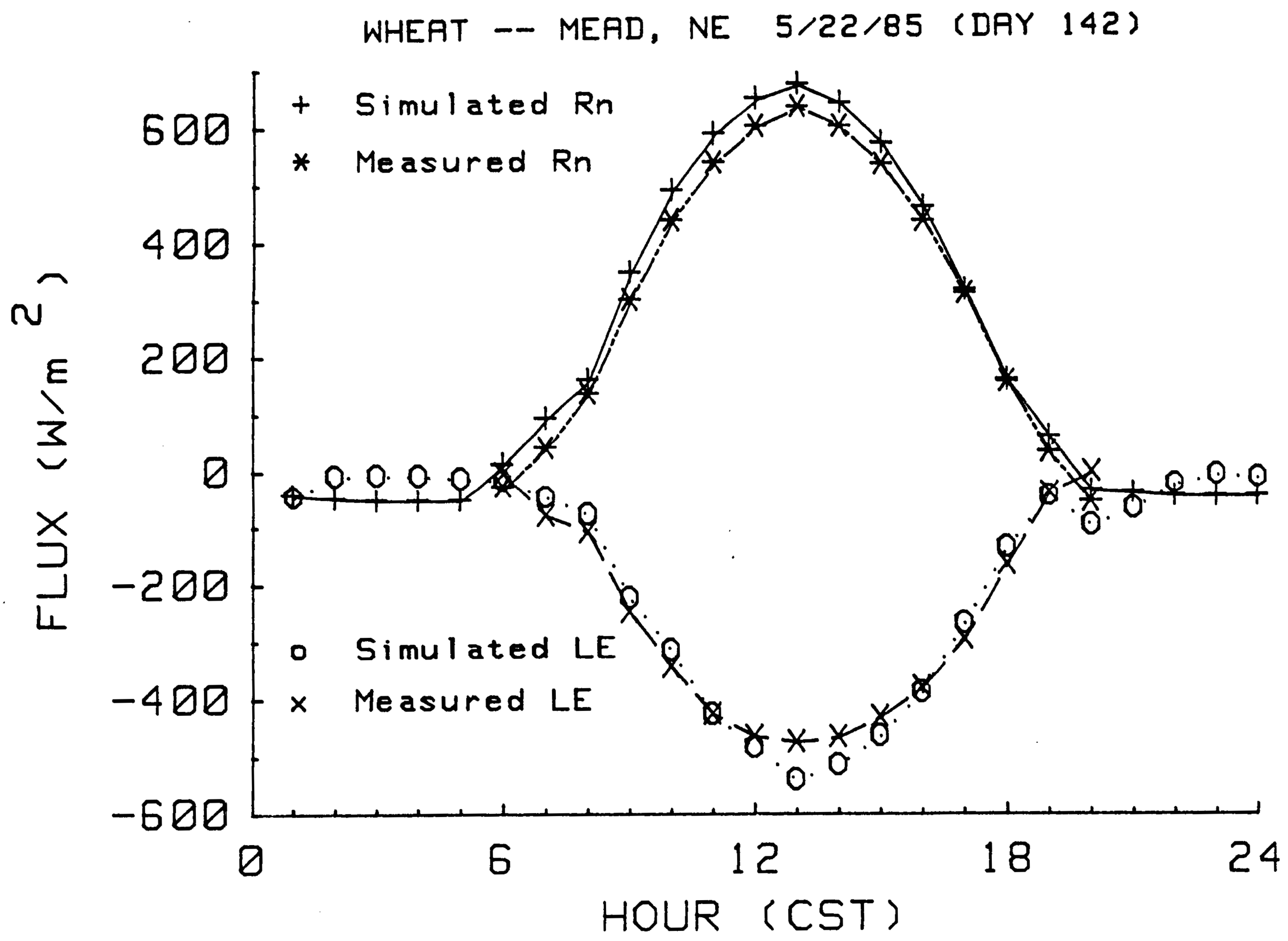


Fig. 24. Comparison of measured and simulated Rn and LE fluxes on May 22, 1985.

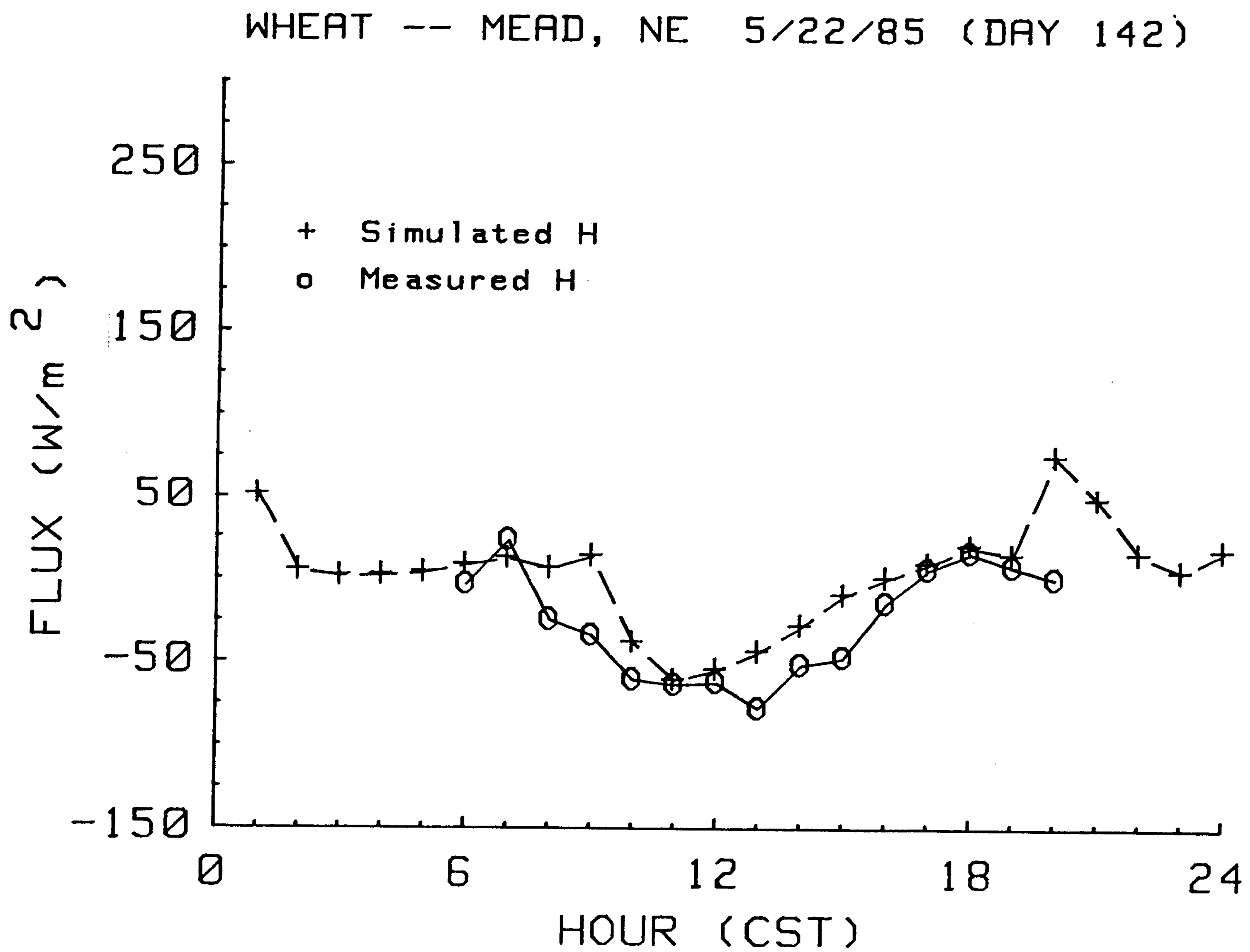


Fig. 25. Comparison of measured and simulated H fluxes on May 22, 1985.

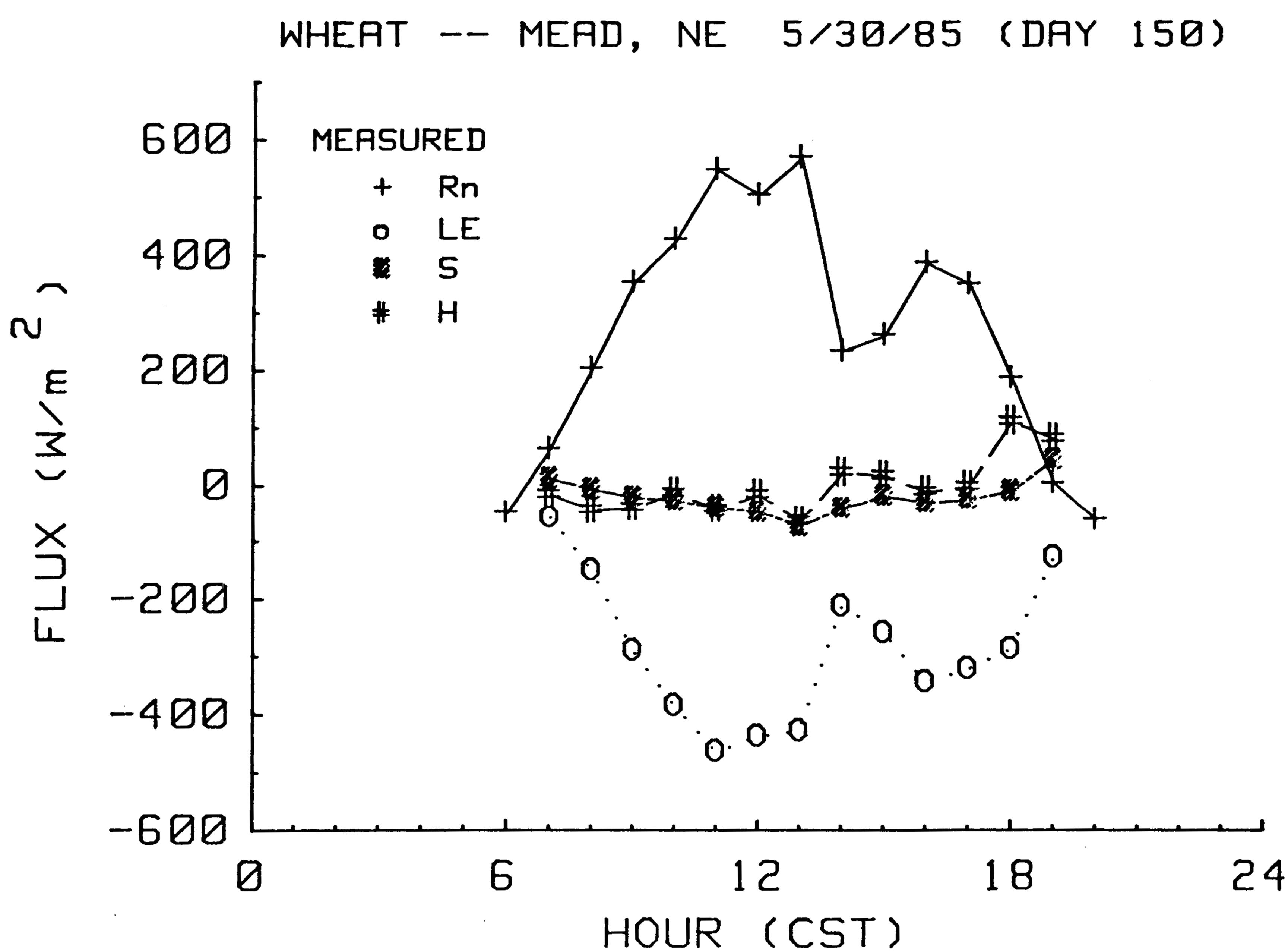


Fig. 26. As in Fig. 22 for May 30, 1985.

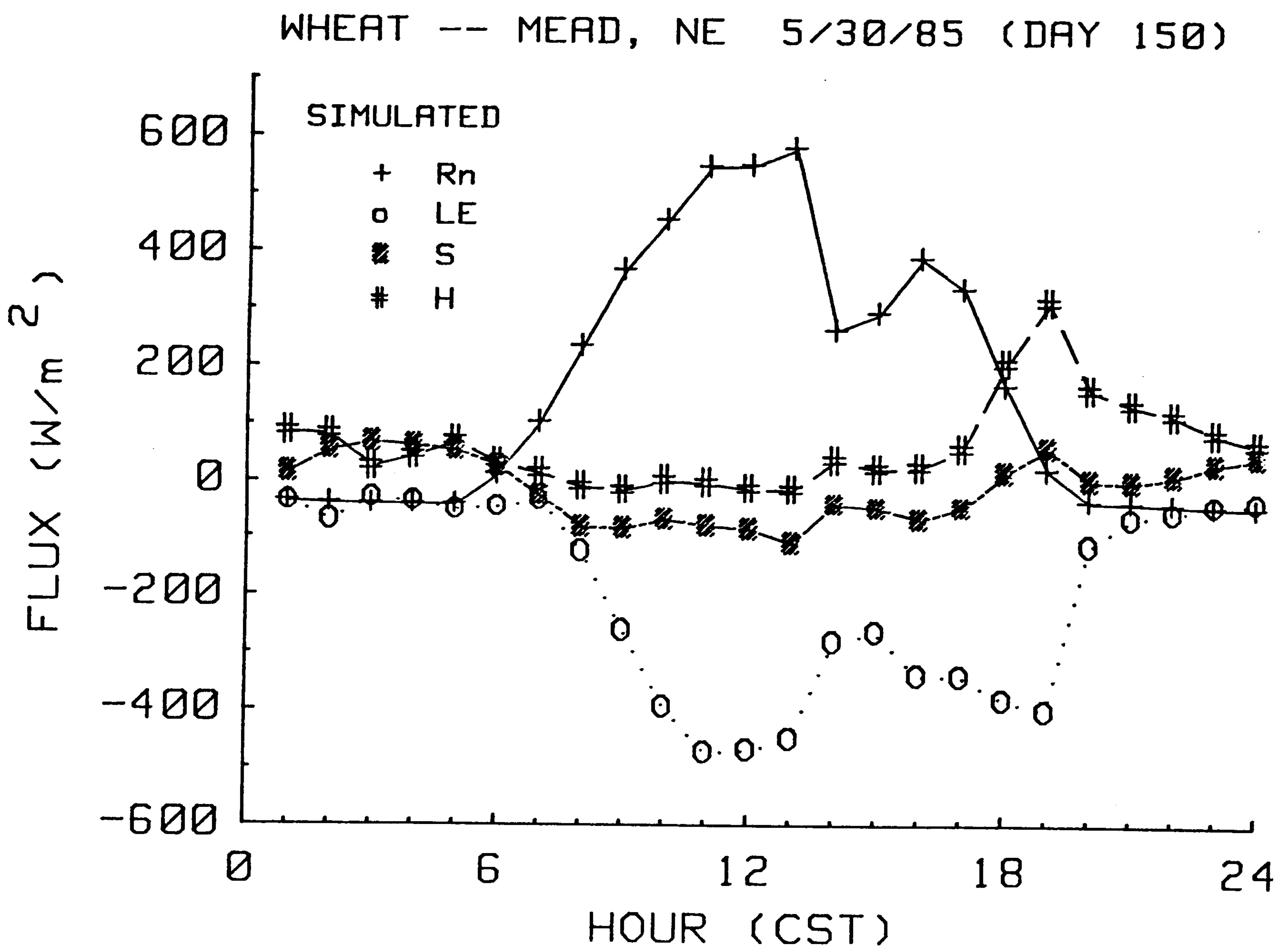


Fig. 27. As in Fig. 23 for May 30, 1985.

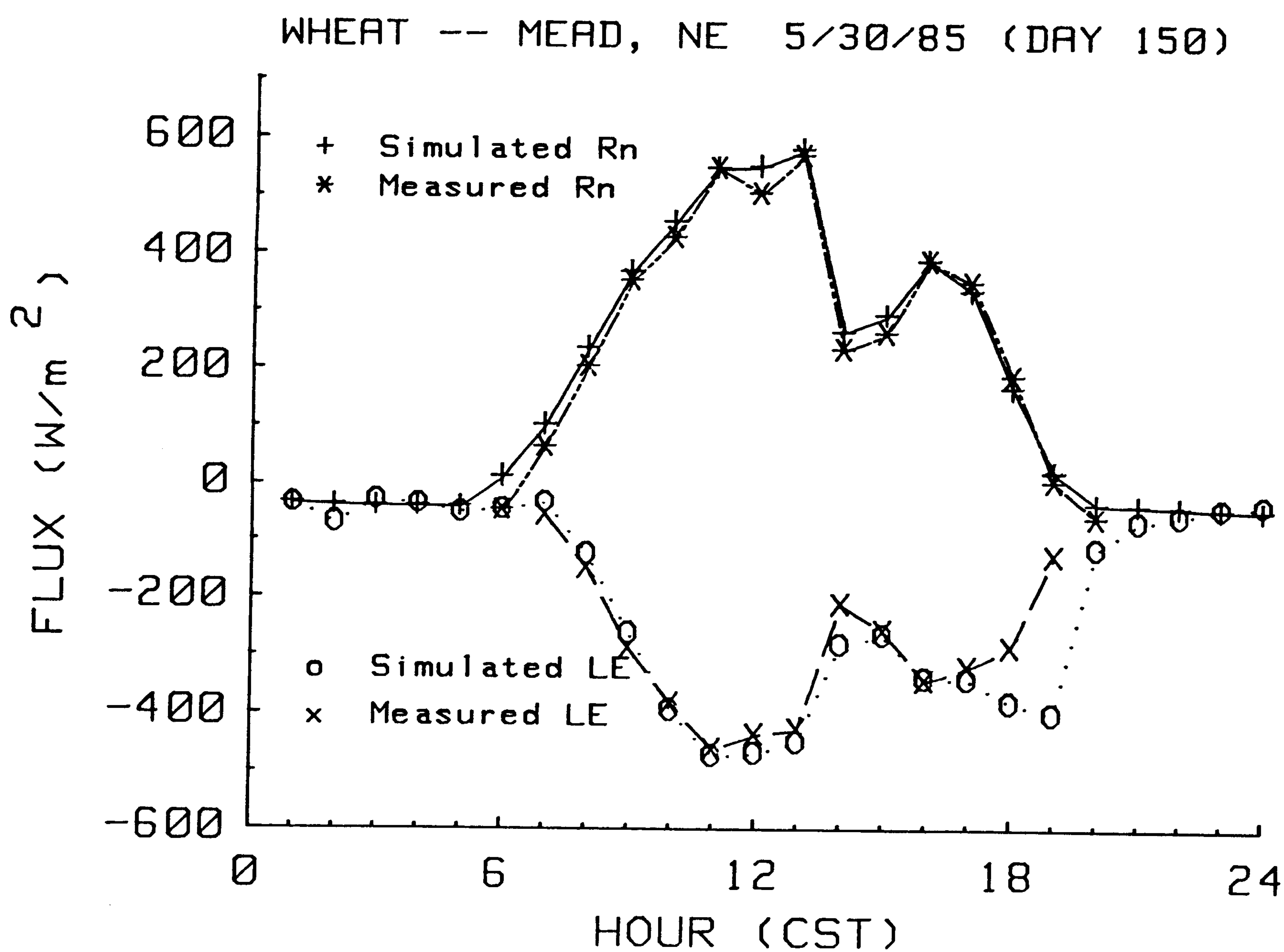


Fig. 28. As in Fig. 24 for May 30, 1985.

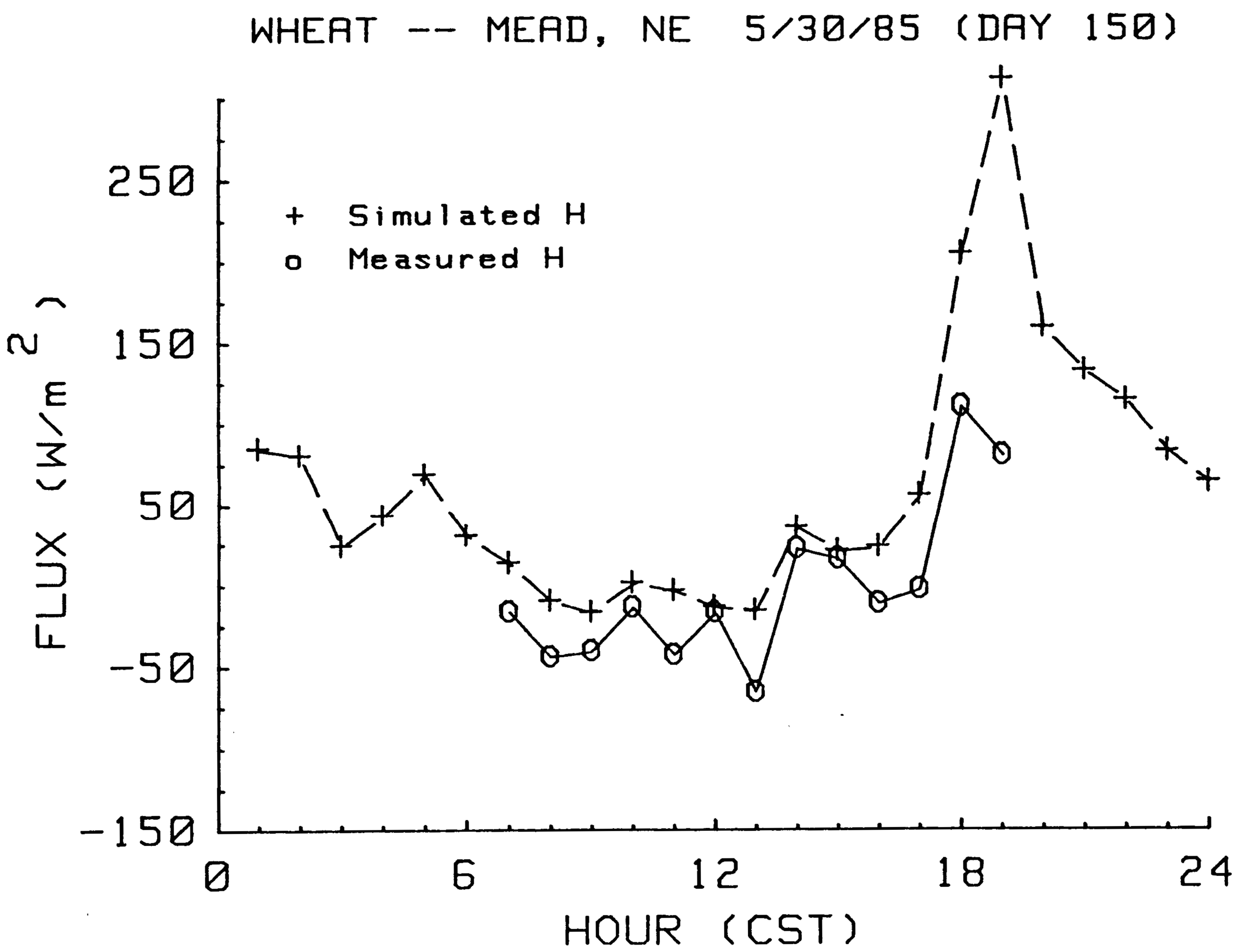


Fig. 29. As in Fig. 25 for May 30, 1985.