

**STUDIES ON CANOPY REFLECTANCE AND LEAF
TRANSMITTANCE CHARACTERISTICS - AN
APPROACH TO DETERMINE CANOPY COVER,
CHLOROPHYLL CONTENT AND LEAF
WATER STATUS.**

S. HATTAPPA

**DEPARTMENT OF CROP PHYSIOLOGY
UNIVERSITY OF AGRICULTURAL SCIENCES
BANGALORE**

1989

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WATER STATUS.**

S. HATTAPPA

Thesis submitted to the
University of Agricultural Sciences, Bangalore
in partial fulfilment of the requirements
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in
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AUGUST 1989

Dedicated to
My Beloved Mother
&
Brothers.

DEPARTMENT OF CROP PHYSIOLOGY
UNIVERSITY OF AGRICULTURAL SCIENCES
BANGALORE

CERTIFICATE

This is to certify that the thesis entitled "STUDIES ON CANOPY REFLECTANCE AND LEAF TRANSMITTANCE CHARACTERISTICS - AN APPROACH TO DETERMINE CANOPY COVER, CHLOROPHYLL CONTENT AND LEAF WATER STATUS" submitted in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE (AGRICULTURE) in CROP PHYSIOLOGY to the University of Agricultural Sciences, Bangalore, is a record of research work carried out by Mr.S. HATTAPPA under my guidance and supervision and that no part of the thesis has been submitted for the award of any other degree, diploma, associateship, fellowship or other similar titles.

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LIST OF ABBREVIATIONS

ASR	-	Absorbed solar radiation
CGR	-	Crop growth rate
CRCH	-	Canopy reflectance characteristics
DAP	-	Days after planting
DAS	-	Days after sowing
ET	-	Evapotranspiration
FIR	-	Far-infra-red
IR/R	-	Infra-red/red
ISRO	-	Indian Space Research Organization
LA	-	Leaf area
LAI	-	Leaf area index
MSS	-	Multispectral scanner
NIR	-	Near infra-red
nm	-	Nanometer
PAR	-	Photosynthetically active radiation
Pfr	-	Phytochrome for red
Pr	-	Phytochrome red
R	-	Red
RCH	-	Reflectance characteristics
RWC	-	Relative water content
SAC	-	Space Application Centre
T	-	Total radiation
UV	-	Ultra-violet
IARI	-	Indian Agricultural Research Institute
SDD	-	Stress degree days

INTRODUCTION

I. INTRODUCTION

Crop yield prediction models require an estimate of certain important characteristics of the canopy. The characteristics of considerable significance are leaf area (LA), extent of light interception and rate of evapotranspiration (ET). However, to predict the production potential of the crops or ecosystems in a specific agroclimatic zone, a quick and precise measurement of canopy characters relevant to productivity have to be assessed. In this context remote sensing techniques have been shown conceptually as useful methods to obtain data on certain important crop characteristics.

The acquisition of physical data of crop canopy by adopting remote sensing techniques, therefore, became a powerful tool in understanding the crop status and thus its productivity.

Plant leaves have very specific optical properties, which were also reflected to some degree even at the canopy level (Danuse Hodanova, 1985). The radiation intercepted by the leaves are either reflected, absorbed or transmitted. The green leaves absorb the UV radiation and blue and red regions of the visible spectrum. About 10 to 20 per cent of incident

photosynthetically active radiation (PAR) and 40 to 50 per cent of near infra-red radiation (NIR - 700 to 1350 nm) are reflected by the leaves. The long wave absorption spectrum of leaves have three peaks at 1450, 1950 and beyond 3000 nm. Above 3000 nm the leaf absorbs radiation completely.

These specific characters are often used in remote sensing to assess the physiological status of the crop canopy.

Several attempts have been made to relate the spectral reflectance characters with the canopy greenness, the canopy cover and the extent of light interception (Asrar et al., 1984; Hatfield et al., 1984); (Gallo et al., 1985; Sastry and Udaya Kumar, 1986).

The remote sensing measurements cover, the visible spectrum, the near IR spectrum, the thermal IR spectrum and more recently in the microwave region. The canopy reflectance properties in visible or NIR, FIR and in microwave has been shown to reflect specifically certain plant characteristics.

Very often visible and NIR reflectances are being utilized for analysis of dry matter accumulation by the

crop. Often in many studies two approaches have been taken; (1) establishing direct relationships between spectral reflectances and biomass and (2) using the spectral reflectances to estimate the fraction of incident solar radiation absorbed by the canopy and then convert absorbed energy into biomass. The second approach which require additional information about incident solar or visible radiation, is likely to be more successful in predicting biomass in different climatic regions.

The basic approach in finding relationship between spectral reflectance and the crop canopy status is to develop initially the ground truth studies. In different crop species the canopy status is altered by varying the inputs like fertilizers, plant density and irrigation etc., and their reflectance characters are measured by using spectroradiometers.

Only recently spectroradiometers to measure reflectances at visible and IR regions are developed indigeneously. These instruments have now become useful tools not only to generate ground truth studies on reflectance properties of canopy to be used for remote sensing satellites, but are also useful in biological and agricultural research for determining crop growth characters.

One of the important crop growth character is the Leaf area index (LAI) and the extent of light intercepted by the canopy. A quick simple non-destructive assessment of in situ LAI based on reflectance characters is an immense use in several research projects in plant sciences.

In recent years not only the optical properties of leaves were used in remote sensing but are also being exploited for determining leaf constituents and water status. Such optical instruments for in situ measurements of leaf constituents will have specific advantages. Keeping this in view in the present investigation experiments were carried out with the following objectives.

1. To study the relationship between spectral reflectance of the canopy and the extent of canopy cover with the intention.
 - i) To use these ground truth studies for remote sensing purposes
 - ii) To develop a quick in situ method for measurement of LAI on reflectance characters.

2. To study the relationship between leaf transmittance characteristics and chlorophyll content.
3. To study the relationship between leaf transmittance characters and leaf water status.

REVIEW OF LITERATURE

II. REVIEW OF LITERATURE

Aquisition of physical data of crop canopies by adopting remote sensing techniques became a powerful tool in understanding the crop canopy status. To predict the production potential of crop species or an ecosystem, it is essential to assess the canopy characteristics which contribute to the growth of the plant.

The extent of canopy cover, the density of an ecosystem, the greenness of the crop or an ecosystem, the extent of disease spread and the pest infestation are a few important characteristics, which determine the production potential of a crop or an ecosystem. If this criteria can be critically quantified by acquisition of physical data of crop canopies, the productivity of ecosystem can be predicted with high degree of precision.

One of the attempts has always been to identify the growth characters directly related to biomass yield. A few important canopy characters which were shown to have relevance to biomass productivity by Sinha (1984) are:

1. Light interception is linearly related to dry matter production

2. Evapotranspiration is linearly related to dry matter production
3. Light interception is dependent upon leaf area indices
4. Evapotranspiration is dependent upon leaf area indices
5. Leaf area indices is proportionately related to nitrogen application.

The relationship of considerable significance is between leaf area index and ET (evapotranspiration). Knowing ET and the soil moisture, it would be probably possible to predict further growth of the plant.

Irrespective of the conditions of growth whether it is nonstressed or stressed conditions, the LAI is an important parameter which determines the production potential of a crop species or an ecosystem.

Therefore quick measurement of these characters (light interception, LAI and evapotranspiration) will give an idea about crop status from which the productivity can be predicted.

The two important physical characteristics of the canopy to acquire data on the extent of canopy cover(LAI), extent of light interception and evapotranspiration(ET) are (1) Canopy reflectance and transmittance characteristics and (2) the canopy temperature.

The first aspect includes the properties of the canopy in relation to light absorption, the reflectance and transmittance characters.

1. Plant characteristics in relation to radiation:

Leaf optical properties:

Since, the canopy reflectance characters are predominantly determined by the leaf optical properties it is important to know the leaf optical properties. The leaf optical properties have been extensively reviewed by Danuse Hodanova (1985). This can be summarised as follows.

The radiation incident upon the leaf surface and passing through the leaf may be reflected, transmitted, scattered and absorbed by leaf tissues, cells and their organelles. Each of these characteristics is an important indicator of leaf responsibility to radiation as it results from plant phyllogeny, adaptations to different ecological niches and the instantaneous physiological state as well.

Conventionally, radiation which is absorbed, transmitted and reflected by a leaf has been expressed as a fraction of the incident radiation and referred to either by a single wavelength, the wavelengths constituting a particular spectrum, or it may be averaged over a specific waveband.

The idealised relationship between leaf absorbance, reflectance and transmittance as a function wavelength is given in the Fig.1. The response of leaf to the ultra violet radiation (250-400 nm), PAR (400-700 nm) and infra-red (beyond 700 nm) are as follows.

UV is always absorbed by epicuticular waxes and leaf epidermis so that it hardly enters the deeper layers of leaf.

The transmission of UV radiation through leaf epidermis is generally less than 10 per cent (Robberecht and Caldwell, 1978). The leaf epidermis is thick enough to protect the mesophyll tissues from UV radiation which (a) disintegrates deoxyribonucleic acid (DNA) (McLaren and Luse, 1961, Deering, 1962) (b) inhibits enzymatic activity (Mantai et al., 1970) (c) inhibits chlorophyll synthesis, reduces cell division and enlargement and dry matter accumulation (Basiouny et al., 1978).

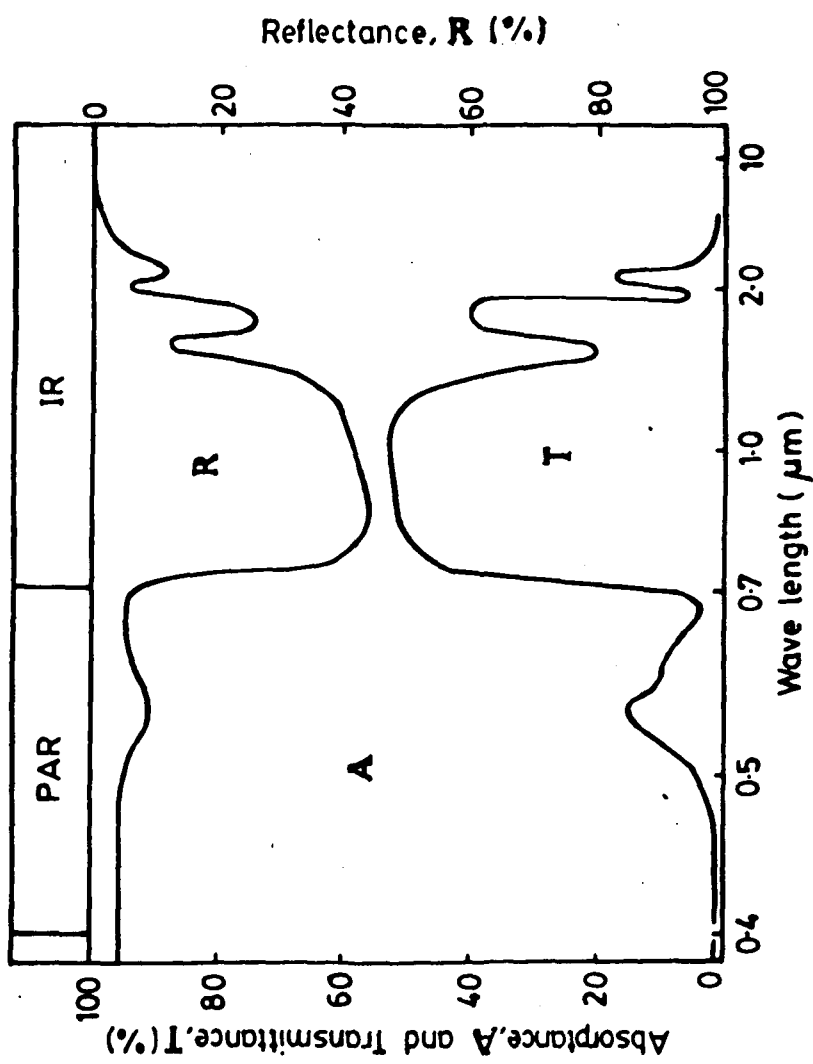


Fig. 1: Idealized relation between leaf absorbance, reflectance and transmittance as a function of wavelengths of incident radiation.

The leaves of higher plants are well disposed structurally and functionally to absorb 50 to 95 per cent of PAR and fraction of the near IR upto the 800 nm wavelength (Brandt and Tageeva, 1967; Shulgin, 1967, 1973).

In order "to prevent" the overheating of leaf tissue by excess radiation (and because of a different transparency of leaf absorbing materials to radiation of particular wavelengths), the mature leaf is capable to reflect and transmit, respectively, about 10 to 20 per cent of the incident PAR and 40 to 50 per cent of the near IR (700 to 1350 nm).

In PAR, most radiation is absorbed by the chlorophylls (which amounts to 65 to 75 per cent of the total pigments in the mature leaf) and carotenoids as accessory pigments. The blue and red absorption peaks of chlorophyll 'a' and 'b' in the ranges of 400 to 500 nm and 600 to 700 nm, respectively, and the action band of carotenoids between 350 and 500 nm are used in photosynthesis. Further, photoreceptors such as the phytochrome system Pr and Pfr (with the A (absorption action) maximum at 660 and 730 nm, respectively) and the blue-light receptors of flavoprotein type (the action maximum at 370 and 450 nm) also absorb radiation.

Once a chlorophyll molecule has been excited after receiving a quantum of desired wavelength, it must undergo certain processes before coming to the ground state. Among these processes, one is fluorescence. Normally about 30 per cent of the absorbed radiation is emitted out as fluorescence which is in the red or near infrared regions. Alternatively, the energy of the excited molecules can be dissipated as heat, which must be reflected in the change of temperature in the ambient environment.

In IR, the liquid water in cell walls and cytosol is responsible for high leaf absorbance because the vibrational absorptance bands of triatomic water molecules are at 10 to 15 times higher frequencies than the electronic absorptance bands of the other compounds and pigments mentioned. The long-wave absorption spectrum of the leaf has three peaks at 1450, 1950 and beyond 3000 nm (Allen et al., 1970, Gates, 1980). Above the 3000 nm, the leaf absorbs radiation almost completely (95 to 97%) and behaves like a black body. Owing to the rotational transitions in water molecules, some secondary leaf absorption peaks in the near IR also occur. The "visible window" between 400 and 700 nm is relatively free of absorption by water in leaf tissues but in the UV spectrum of less than 300 nm, A by water molecules becomes again important.

It can be summarised that plants receive radiation from the sun but can absorb only between 0.4 to 0.7 μm range of wavelength. These areas correspond to the absorption spectrum of chlorophyll. All the long wave radiations are reflected back from the leaves. In fact the radiation which is absorbed by plants is also not fully utilized because of limitations in cellular metabolism.

Thus, absorption and reflectance of light can indicate the functional state of the plant. When a plant is exposed to water stress, its absorption and reflectance are likely to be influenced, both at the individual level as well as the community level. For example, a reduced supply of water causes inhibition of leaf expansion. Consequently, the leaf area index of the crop canopy would be reduced, and more radiation would be reflected. This at the same time becomes a measure of the leaf area index.

2. Canopy temperature

A second remote sensing parameter, which is considered of considerable value is the canopy temperature. The canopy temperature could be used for assessing the degree of stress on the crop. The main assumption here is that when a plant experiences water deficit, it closes its stomata which reduce water loss

from the leaves. As a consequence, the leaf temperature and hence the canopy temperature raises. In other words, a well watered crop canopy maintains cooler temperature than the ambient temperature. Making use of this parameter the concept of stress degree days (SDD) has been developed and correlations with yield have been established (Idso et al., 1979). There are, however, objections to its use because many people have recorded higher temperature than the ambient temperature when plants are not water stressed. Recently this issue has been discussed by Jackson (1982) in detail. One of the main conclusions of his study is "In humid climates canopy temperatures will be near to or higher than air temperatures, with only a small range of temperatures. In arid areas, however, canopy temperatures may be more than 10°C below air temperatures and have range, perhaps, of 15°C. Thus the utility of this character has to be assessed in relation to the weather prevailing at a particular place. In addition, heat flux from the soil could considerably influence data on canopy temperature. There is now evidence that the diurnal variation in heat flux from the soil has an important effect on canopy temperature. Therefore, the time of the day becomes an important determinant for recording data.

Canopy reflectance characters

Many attempts have been made in recent years to study the spectral reflectance of the canopy to determine (a) leaf area index, (b) extent of light intercepted, (c) biomass determinations and (d) nutrient diseases and water status of the plant.

(a) Leaf area index (LAI) and light interception

In view of the importance of the LAI and amount of light intercepted (PAR basically) for development of crop yield models, several attempts have been made in recent years to develop quick methods for measurement of these parameters. Spectral reflectance characters are being used to determine the extent of canopy cover. The main objective here is to use remote sensing techniques for identifying LAI or per cent light interception.

Several methods based on multi spectral scanner (MSS) have been used to assess greenness which is taken as a measure of leaf area index. However, in many of the recent studies instead of taking spectral reflectance at all the wavelengths only the reflectance at R and IR were used to study the LAI, per cent light interception and total biomass etc. This is having a relevance mainly because of maximum absorption and

reflectance is seen at these two wavelengths respectively. The IR/R ratios, normalised difference (ND) vegetative index are computed based on reflectance on R and IR and often used as a measure of resistance properties of the canopy. Normalized difference is computed based on the formula, $ND = \frac{MSS\ 7 - MSS\ 5}{MSS\ 7 + MSS\ 5}$.

In one of the earlier studies Pollock and Kanemasu (1979) estimated the leaf area index of wheat with Landsat data wherein the following bands specifying different wavelengths were employed.

Spectral bands for the Landsat Multispectral Scanner (MSS).

Band	Wavelength (MMS)
MSS 4	0.5 to 0.6
MSS 5	0.6 to 0.0
MSS 6	0.7 to 0.8
MSS 7	0.8 to 1.1

Using the above bands Rice et al. (1980) developed the following relationship to estimate greenness and leaf area index:

$$\text{Greenness} = -0.4894 \text{ MSS } 4 - 0.6125 \text{ MSS } 5 + 0.1729 \text{ MSS } 6 + 0.5854 \text{ MSS } 7.$$

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Daughtry et al. (1983) showed conceptually how remotely sensed data could be used to obtain an estimate of the solar radiation intercepted by canopies and then converted to dry matter. Steven et al. (1983) found that the ratio of near infrared/red radiation was related to rate of growth in sugarbeets and showed that this ratio was related to interception of light by the canopy. They suggested that this procedure would be valuable for the remote assessment of crop growth. Thus, it would appear that an estimate of intercepted radiation by canopies from a remote sensing platform would be desirable for monitoring crop growth.

Kollenkark et al. (1982) found that greenness and LAI were strongly related; however, they showed an even stronger relationship between soil cover and greenness for soybeans. They also showed that greenness reached a maximum, although LAI continued to increase suggesting that at the upper values of leaf area index greenness may be saturating. Daughtry et al. (1983) also showed a similar relationship in their corn data, which suggests that greenness may not be directly related to LAI beyond a certain LAI.

Pinter et al. (1981) found that normalized difference when integrated over time from heading until maturity of wheat was related to yield. They suggested

that this integration would represent the duration of green leaf area by a crop and thus be directly transferable to yield. This approach was extended by Hatfield (1983), in which canopy temperature was used to evaluate the impact of stress on yield and a spectrally derived LAI at heading was used to determine the potential yield.

In recent study by Hatfield et al. (1984) a similar attempt have been made to estimate intercepted radiation in wheat by using spectral reflectance characters. For the leaf area growth, portion of the season the relation between PAR interception and normalized difference was the same over years and planting dates. For the leaf senescence phase the relationships showed more variability due to the lack of data on light interception in sparse and senescing canopies. Normalized difference could be used to estimate PAR interception throughout a growing season.

Hipps et al. (1983) also found the relation between per cent PAR intercepted and LAI. Such a relationship was valid upto a time of rapid senescence. A mathematical model was developed to quantify the relationship.

Systematic studies were conducted by Asrar et al. (1984) to assess the spectral reflectance characters with LAI and the extent of light intercepted in wheat. They determined the LAI, per cent light interception and the canopy reflectance characters at different stages of crop growth. They have computed the normalized difference ($ND = \frac{MSS\ 7 - MSS\ 5}{MSS\ 7 + MSS\ 5}$) and IR/R reflectance ratios. These two reflectance properties were used to relate LAI and per cent light interception.

The results, from a theoretical analysis and field measurements, indicated that ND correlates with the fraction of PAR absorbed by wheat canopies. Bare soil reflectance and scattering of near infrared radiation by foliage elements were the major factors that influenced the relation between ND and PAR absorption. The estimated PAR absorption values, based on the ND, and four classes of assumed leaf angles (45, 60, 75 and spherical) were used to indirectly evaluate LAI of wheat for three different geographical locations. The standard deviation on mean predicted to measured LAI's for the three locations varied from 0.5 to 0.9 for a range of 0 to 6 LAI. The method is considerably less sensitive in predicting LAI above 6.0 since the sensitivity of ND to changes in LAI becomes small (0.01) due to small changes in canopy reflectance.

In order to develop ground truth study on the relationship between canopy spectral reflectances and greenness and canopy cover, several experiments were carried out at Indian Agricultural Research Institute (IARI), New Delhi in collaboration with Space Application Centre (SAC), Ahmadabad (Sashikumar et al., 1984; Ajai et al., 1984; Sinha et al., 1984).

In one of the studies by Sashikumar et al. (1984), the relationship between spectral parameter in the R and IR band and plant related parameter such as LAI, chlorophyll content and biomass were studied. The studies were conducted in wheat, chickpea and mustard. In all the three species at different stages of growth biometric data and reflectance characters at R and IR were recorded. In all the crops IR/R reflectance ratios showed a positive significant relationship with LAI or with leaf dry biomass. There was a close association between the predicted and measured values. Total biomass also showed a significant relationship with IR/R reflectance ratios. The spectral parameters measured during the maximum canopy cover were found to be highly correlated with biomass and grain yield.

A similar study conducted by Ajai et al. (1984) in wheat clearly demonstrated that the per cent intercepted photosynthetically active radiation (PAR)

and LAI are related with IR/R reflectance ratio. A significant linear relationship has been found between cumulated per cent light intercepted values and the final biomass production and grain yield of wheat. They developed an equation to determine per cent light interception based on reflectance properties at IR/R [Per cent interception of PAR = $-97.1 + 72.1 (IR/red) - 6.8 (IR/red)$]. This relationship can be used to estimate per cent interception of PAR by the canopies from the remotely sensed multispectral data.

In a recent study by Best and Harlan (1985). statistical model approach was used to predict green leaf area of the oats from bidirectional reflectance data collected by multiband radiometer.

Study conducted on corn by Gallo et al. (1985) also showed significant relationship between normalized difference (ND) and per cent PAR absorption. The reflectance data were acquired with a radiometer with spectral band similar to land sat MSS. These spectral vegetation indices (ratio near infra-red radiation (NIR) to red reflectance, ND and greenness index) were associated with more than 95 per cent of the variability in absorbed PAR from planting to silking.

By using an airborne thematic mapper Peterson et al. (1987) showed a strong positive significant

relationship between the LAI of closed canopy coniferous forest plants and on the ratio of NIR and red spectral band. A log linear equation fit the asymptotic characteristic of the relationship better, explaining 91 per cent of the variance. The positive relationship is explained by a strong asymptotic inverse relationship between LAI and red radiation and a relatively flat response between LAI and near infrared radiation.

An attempt was made by Bhasker Choudhury (1987) to relate vegetative index with radiation absorption and net photosynthesis.

The relationship between the vegetative indices and radiation absorption or net photosynthesis are generally found to be curvilinear and changes in the soil reflectance altered these relationships. The curvilinearity of the relationship between normalized differences and PAR absorption increases as the magnitude of soil reflectance increases.

Plant growth and biomass

Apart from identifying the leaf canopy cover several attempts have been made to use the spectral reflectance characteristics to assess the growth and development of crop canopy.

The feasibility of utilizing multispectral data for estimation of dry biomass was addressed by Aase and Siddoway (1981) who developed regression equation between canopy spectral reflectance and ground total phytomass of wheat. Their results were linear from tillering to initial flowering, but departed from linearity from the on set of senescence. Tucker et al. (1981) found that the ratio of NIR to red reflectance and normalized differences (ND) vegetation index was strongly related to above ground total phytomass in winter wheat. In a similar study Asrar et al. (1985) developed a simple model to estimate above ground total dry phytomass production of several spring wheat crops, based on multispectral reflectance and thermal emittance data of the crop canopies with conjunction with meteorological data.

In one such study (Ajai et al., 1984) The spectral signatures of three crops under irrigated and unirrigated conditions was assessed. The reflectance at red(R) and infra-red (IR) bands are found to be most suitable for describing growth pattern of the crop.

The water status of the crop was shown to be highly related with spectral parameters. They suggested the possibility of rapid and large scale assessment of water stress/drought affected areas by remote sensing. The results show that higher IR/R

reflectance ratio in irrigated crops compared to the unirrigated crops. However, such differences were mainly due to the differences in LAI, but not due to specific changes in the spectral characters of the leaf.

In another study (Sastry and Udaya Kumar, 1986) has shown that the reflectance properties of the crop canopy varied in control and moisture stress plants. In control plant IR/R ratios were significantly more than stress plants. In this experiments also difference in LAI and extent of light interception are the main contributing factors for the observed differences in reflectance values in control and stress.

Johan Kleman et al. (1987) studied the relationship between spectral signature of barley and variation in the agronomic treatment like irrigation and fertilizer application levels. Biomass water content and grain yield were measured and their connection to spectral data was analysed.

The spectral reflectances were determined from a mobile platform 15 m above the ground. Reflectance factors of single spectral bands, reflectance factor ratios, and color co-ordinates were analysed in

relation to biomass, water content of the crop and grain yield. The blue co-ordinate Z was strongly related to the different irrigation levels and relatively insensitive to the amount of biomass. The Z co-ordinate was not well correlated to the IR/Red ratio $R(0.80)/R(0.68)$. The IR/R ratio on the other hand was strongly coupled to the amount of biomass on each measurement date. In the $1.65 \mu\text{m}$ band the reflectance factor had a minimum at 500-1000 nm and a tendency to increase slightly at higher water content. Suggesting that absorption of radiation in water is only one of several factors determining the reflectance at $1.65 \mu\text{m}$.

Some of the factors like nitrogen status and the moisture status of the crop drastically affects the canopy development and its architecture and thus the canopy reflectance characteristics. In addition to this nitrogen status of the crop not only alters the LA development, but also chlorophyll content of leaves. In one of the studies jointly carried out by space application center (ISRO) and Gujarat Agricultural University (Singh et al., 1985), the spectral characters were studied throughout the crop growth status in rice crop raised at different N levels. With increase in N levels there was a significant increase in LAI and also wet and dry biomass yield. The reflectance characters were measured either in terms of

radiation ratio NIR/red or as normalised differences (ND = MSS 7 -MSS 5/MSS7 +MSS 5). The conclusions are:

1. The application of 'N' fertilizer has a significant effect on spectral response of the crop.
2. Biometric parameters like leaf area index, wet biomass, dry biomass, nitrogen content, have significant (95% level) correlation with spectral parameters (radiance ratio and normalized difference).
3. NIR/Red radiance ratio integrated over the period from 30 to 70 days after transplantation shows a linear correlation with final grain yield.

The observed differences in spectral response of the crop to nitrogen fertilizer is predominantly due to N induced increase in LAI and also due to lesser reflectance at red region due to higher nitrogen.

By using a multi band spectroradiometer with range from 400 to 1000 nm, the reflectance properties of maize plant crop grown at different nitrogen status was studied. At higher nitrogen levels there was a significant increase in chlorophyll content and LAI. This was also resulted in greater reflectance at IR and higher vegetative index (Sastry and Udaya Kumar, 1986).

Moisture status

Often attempts were also made to assess the relationship between scattering co-efficient 9.4 GHz and plant moisture status (Mohan et al., 1984).

The results of this experiment indicated that microwaves can be used for assess the water status of wheat crop.

In situ measurements on plant characteristics and leaf constituents

Plant Physiology is essentially an experimental science and instrumentation is necessary component of research in this area.

Recently in collaboration with Physicists and Engineers several new equipments have been designed and put to use for research work in Crop Physiology and Agrometeorology. For instance, development of Porometers, Portable Carbon Dioxide Analysers, radiation measurement instruments and neutron probe helped substantially to get reliable field data which was otherwise not possible a few years ago. Generally the research emphasis in Crop Physiology oriented towards developing a new concept and testing its validity for crop improvement programme either directly or indirectly. Hence, it is very essential to get reliable data under field conditions. For higher

reliability and accuracy it is necessary to make use of new equipments.

In view of this in recent years a few instruments have been developed for in situ measurements of leaf constituents. To name a few achievements in this direction are - development of neutron scattering techniques for measurement of water status in the soil, a portable porometer for determination of diffusive resistances and transpiration rates, portable photosynthetic systems, portable fluorescence measurement instruments, infra-red and moisture measurement meters and Nuclear magnetic resonance (NMR) instrument for measurement of seed oil etc.

More recently, some attempts have been made to develop optical instruments for quantitative measurement of leaf constituents based on reflectance and transmittance characters. A rapid nondestructive method was developed to determine leaf chlorophyll content using portable chlorophyll meter (SPAD 501) (Umedi Yadava, 1986). The chlorophyll have specific absorption maxima at 340 and 660 nm. This property of leaf have been used in this instrument to measure the leaf chlorophyll content. There was a significant relationship between total extracted chlorophyll determined by spectrophotometry and leaf transmittance

characteristics measured by portable chlorophyll meter (SPAD 501).

Though the leaf moisture status is an important physiological parameter there is no progress made in the development of instruments for in situ measurements. Some attempts were ^{made} for in situ measurement of water potential by using psychrometric instruments. These are not widely used due to in-built problems. Literature in this area is very scanty.

MATERIAL AND METHODS

III. MATERIALS AND METHODS

The major objective of the present investigation was to assess the relationship between spectral reflectance characteristics of the canopy and extent of the canopy cover. The other important objective was to establish relationship between leaf transmittance characteristics with chlorophyll content and water status of the leaf.

To meet these objectives a field experiment and several green house and laboratory experiments were conducted during the course of this investigation.

The experiments conducted are described separately under the three major aspects. They are;

- I. The inter-relationship between canopy reflectance characteristics, extent of light interception and the leaf area indices in different crop species (Field experiment)

The field experiment was conducted during summer 1987 (February - June) at GKVK Farm of the University of Agricultural Sciences, Bangalore.

The GKVK Farm is situated in transition tract of Karnataka at $12^{\circ} 58'$ north latitude, $77^{\circ} 35'$ east longitude and an altitude of 930 meters above sea level.

Soil characteristics

Texture	:	Red loamy
Field capacity	:	4.8
Wilting point	:	15.5% (225 m/m)
Bulk density	:	1.59 g per cc
Available NPK	:	200:20:160 kg/ha

The field experiment was conducted with four different crop species adopting a randomised block design with four replications.

Species studied:

1. Cowpea (Vigna unguiculata L. Var. C-152)
2. Soybean (Glycine max L. Meril. Var. Hardee)
3. Amaranthus (Amaranthus sp. Var. R-104)
4. Sorghum (Sorghum bicolor Var. CSH-5)

Replications - Three

Plot size - 3 x 4 meters

Cultural practices - Land preparation

The main field was ploughed, thrice by disc plough followed by harrowing. The clods were crushed and levelled. Later wooden plank was passed to smoothen the land and a fine seed bed was prepared for sowing adopting the layout.

Fertilizer application

The recommended dose of 10:20:10, 15:20: 15; 40:30:15 and 40:20:20 kg NPK per acre for cowpea, soybean, sorghum and amaranthus crops respectively was applied in furrows just before sowing in the form of urea, superphosphate and muriate of potash.

For sorghum and amaranthus, nitrogen was given in split dose, half at sowing and remaining half six weeks after sowing.

Sowing and after care

The cowpea (Vigna unguiculata L. Var. C-152) crop was sown with a spacing of 45 cm between rows 10 cm between plants.

The soybean (Glycine max L. Merril. Var. Hardee) crop was sown with a spacing of 30 cm between rows, 10 cm between plants.

The amaranthus (Amaranthus sp. var R-104) crop was sown with a spacing of 45 cm between rows, 30 cm between plants.

The sorghum (Sorghum bicolor L. var. CSH-5) crop was sown with a spacing of 45 cm between rows, 15 cm between plants.

Thinning was done two times after sowing and from 15th day one plant was maintained per hill.

Hand weeding was done at regular intervals to maintain the plots weedfree.

Plant protection measures were taken as and when required as per the recommended package of practices.

Irrigation

Plots were irrigated once in a week to field capacity.

In addition to the field experiment with four crops a micro plot experiment in raised bed with sunflower was also carried out. In this experiment plants were raised in raised bed the fertilizer applied and after care was in accordance with recommendation given in the package of practices. Objective of this experiment was to compare the per cent absorption of solar radiation (ASR) values determined for total radiation and for photosynthetically active radiation (PAR) using tube solarimeter and light meter respectively.

Observations

The data on leaf area, extent of light interception by the canopy and canopy reflectance

characteristics were determined at different stages of crop growth. The major objective is to record the canopy characteristics at different leaf area indices.

The parameters recorded at each sampling times were:

1. Leaf area(LA)
2. Leaf area index(LAI)
3. Absorption of solar radiation(ASR) (Per cent radiation intercepted by the canopy)
4. Canopy reflectance characteristics (Between 500 and 1000 nm).

The stage of the crop at which the observations were recorded and their details are given in the results chapter.

1. Leaf area(LA)

From each plot ten randomly selected plants were harvested to record the data on leaf area, care was taken to see that central four rows were not used for collecting plants for leaf area measurements. Leaf area of individual leaf was measured using a LICOR Portable Leaf Area Meter - Model LI-3000 and expressed in cm^2/plant .

2. Leaf area index (LAI)

Leaf area index was computed from the data on leaf area and the spacing occupied by plant

$$\text{LAI} = \frac{\text{Leaf area (cm}^2\text{)}}{\text{Spacing (cm}^2\text{)}}$$

3. Absorption of solar radiation (ASR)

Per cent interception of solar radiation by the canopy was determined using Tube Solarimeter.

The extent of solar energy intercepted by crop canopy is an important parameter to determine the energy utilization efficiency of the crop. The light absorption by crop canopy enhances with increase in leaf area index, the extent of coverage of inter-row and intra-row spacing and the leaf orientation and inclination. Further, the amount of reflected radiation also accounts for the light absorption capacities of the canopy.

Description of tube solarimeter

The tube solarimeter is a radiometric instrument to measure the total light intensity (global radiation). Difference in heat produced between a white surface and a black surface when radiation is absorbed is measured usually by using a thermocouple (Plate 1).

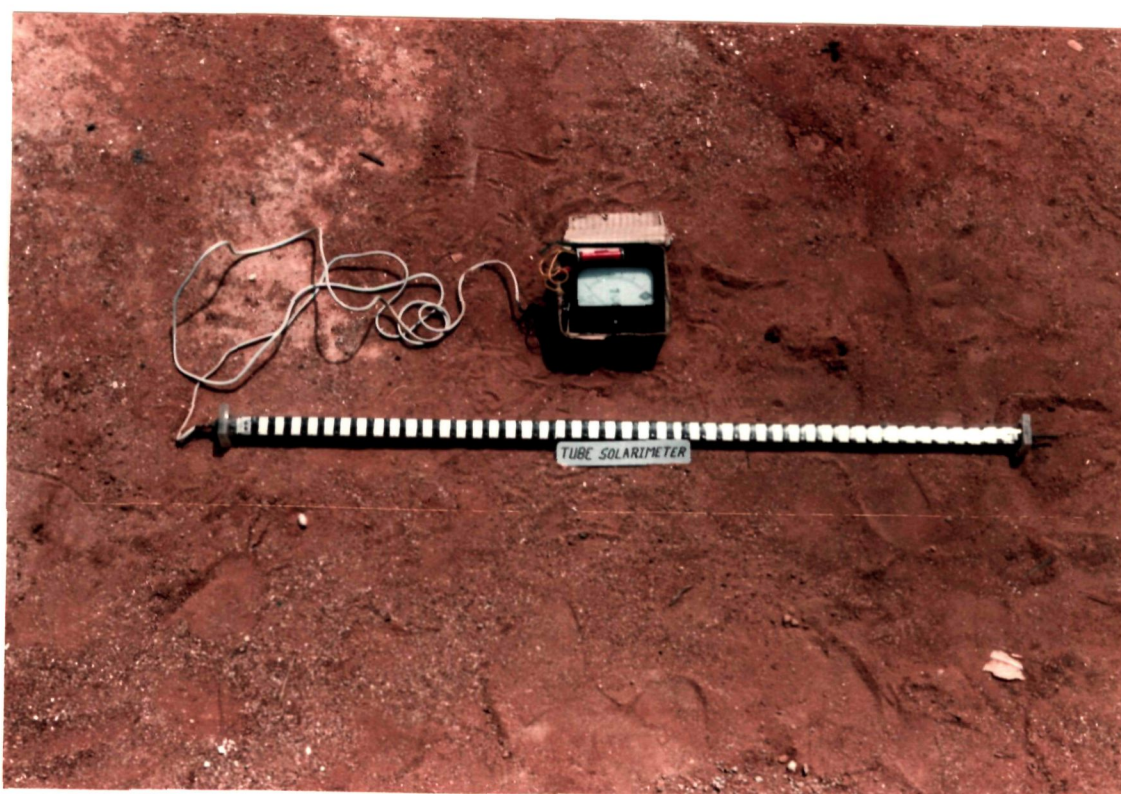


Plate 1. Tube solarimeter

Tube solarimeter is often 1 to 1.5 meters in length, so that it can cover at least 2 meter-row spaces of the canopy. The leads of the tube solarimeter (thermocouple) are connected to a multi-volt meter and the milli-volt current produced is directly proportional to the light intensity.

The tube solarimeter was calibrated with the help of a light meter (LI-170) using Pyranometer sensor. The following formula was used to calculate total radiation using tube solarimeter.

Radiation measured by tube solarimeter = (Milli-volt meter reading X K in micro volts)

Where, K is conversion factor for computing microvolts into watts m^{-2} . The radiation measured in tube solarimeter is expressed in watts m^{-2} .

The tube solarimeters are having specific advantage in determining the radiation intercepted by a canopy. In many situations the inter-row and inter-plant canopy cover will not be uniform, especially at low LAI values. As a result the extent of radiation reaching soil inside the canopy will not be uniform. Hence, by using the conventional radiation measurement instrument, it is not possible to assess the mean radiation which was not intercepted by the canopy. By

using tube solarimeter, which measures the radiation across 1 to 1.5 meters length area, the mean radiation reaching the soil surface could be accurately measured.

Procedure

1. The total radiation(T) was recorded with tube solarimeter by placing it above the canopy.
2. The radiation received on the soil surface(S) was recorded by placing the tube solarimeter at the soil surface inside the canopy, perpendicular to the rows.
3. The reflected radiation(R) was measured by reversing the instrument towards the canopy.

The total amount of solar radiation absorbed by crop canopy (ASR%) was determined by the following formula.

$$\text{ASR}(\%) = \frac{T - (S+R)}{T} \times 100$$

Where, T is total solar radiation received, S is radiation at the soil surface inside the canopy and R is reflected radiation from the canopy.

Determination of absorption solar radiation - Per cent light interception using light meter (LI-170)

In one of the experiments in sunflower, the extent of light interception was measured using light meter LI-170. The objective of this experiment was to compare the light interception values measured using tube solarimeter and light meter. The extent of total radiation or PAR intercepted was separately determined by using different sensors.

Description of light meter

Photometric instruments are usually highly spectrally selective and include such devices as photoemissive and photoconductive cells. Selenium and silicon photovoltaic cells are widely used in biological work in photometric instruments for the measurement of total radiation and photosynthetically active radiation (PAR).

Measurement of light intensity by using quantum/radiometer LI-170

This instrument is designed to measure PAR and global radiation by using different silicon photovoltaic sensors.

1. Quantum sensor

Measures quantum in the PAR between 400 to 700 nm. This is expressed as micro einstens $\text{m}^{-2} \text{sec}^{-1}$.

A silicon photodiode with an enhanced response in the visible wave lengths was used as sensor for measuring PAR.

It can be used to measure PAR within plant canopies, green houses, controlled environmental chambers and remote environmental monitoring sites. These are typical applications of this sensor.

2. Pyranometer (Radiometer) sensor

Measures global (total) radiation from sun and sky received on a horizontal surface and it is expressed in watts m^{-2} .

The pyranometer sensor is a silicon photodiode sensor which makes it possible to get reasonably accurate global radiation measurements.

As in the case of tube solarimeter, the following measurements were taken both with pyranometer and quantum sensors to compute the per cent light intercepted by the canopy.

1. Radiation above the canopy
2. Radiation reflected from the canopy
3. Radiation at bottom of the canopy at soil surface level.

While recording the data using pyranometer and quantum sensors below the canopy, twenty points were measured between the rows and between the plants. The light reaching to the soil surface (light passing through the crop canopy) was recorded at all these points and means were computed.

4. Canopy reflectance characteristics

Canopy reflectance characteristics were determined by using spectroradiometer developed by Indian Space Research Organization (ISRO).

Description of Spectroradiometer - 02

This reflectance meter type of spectro-radiometer using a 100 mm mirror, could be carried on strap or located on tripods or other suitable view platforms in actual use. It can operate in temperatures of 50°C down to 5°C. It has five gain ranges to make it versatile to measure radiance right from low reflectance surfaces.

Unlike other imported radiometers which measure radiance in upto 4 specified ranges of spectra, this instrument gives a continuous spectral capability very necessary in ground truth data collection wherein even small features make important contribution to the specificity of the signatures and thus should not be

lost as is the case in integration or average type of instruments.

It is powered by two standard 9 volts batteries whose power can be monitored on the panel of the instrument.

The instrument is capable of a resolution of 2 per cent on reflectance. It comes with its own fibre glass case, rexine cover and strap (with or without tripod).

Specifications

Optics	:	t/3 newtonian telescope
Field of view _	:	10°
Spectral range _	:	0.45 - 1.01 microns
Weight	:	2.5 kgs
Size in mm	:	160 x 160 x 300
Power	:	2 nos. standard 9V Dry Cell Batteries.

This instrument has been designed for ease of operation. A simple checkout procedure and zeroing of the instrument is all that is required before the unit is ready for operation.

The instrument is fully enclosed in a rexine cover with its own carrying strap. It is not intended to take out the instrument fully from this cover. It will be only necessary to unzip the front and rear portions

of this rexine cover, during the use of the instrument. When the front circular flap is uncovered the front circular cap will become accessible. Similarly the rear rectangular flap is unzipped to get access to rear panel and all its instrument controls.

Controls and panel meter

The various controls, gains, switches and the panel meter can be identified from the Fig.2.

Procedure for reflectance measurement

The instrument was held vertically downward approximately at a height of 2 metres from the ground. The instrument was positioned in such a way to maintain about 4 feet from the surface of the crop canopy. The instrument is positioned in such a way that the front circular open area (which is often cover with a lid when the instrument is not used) is pointed towards the canopy. The optical sensor, which measures the reflected radiation is also located near the circular open area of the instrument. The instrument which is mounted on the tripod stand is adjusted so that the sensor is not in the inclined position in relation to the canopy. The instrument was held from four feet from the surface of the canopy. At this height the instrument will record the reflectance characteristic from one square meter of the crop canopy. Initially

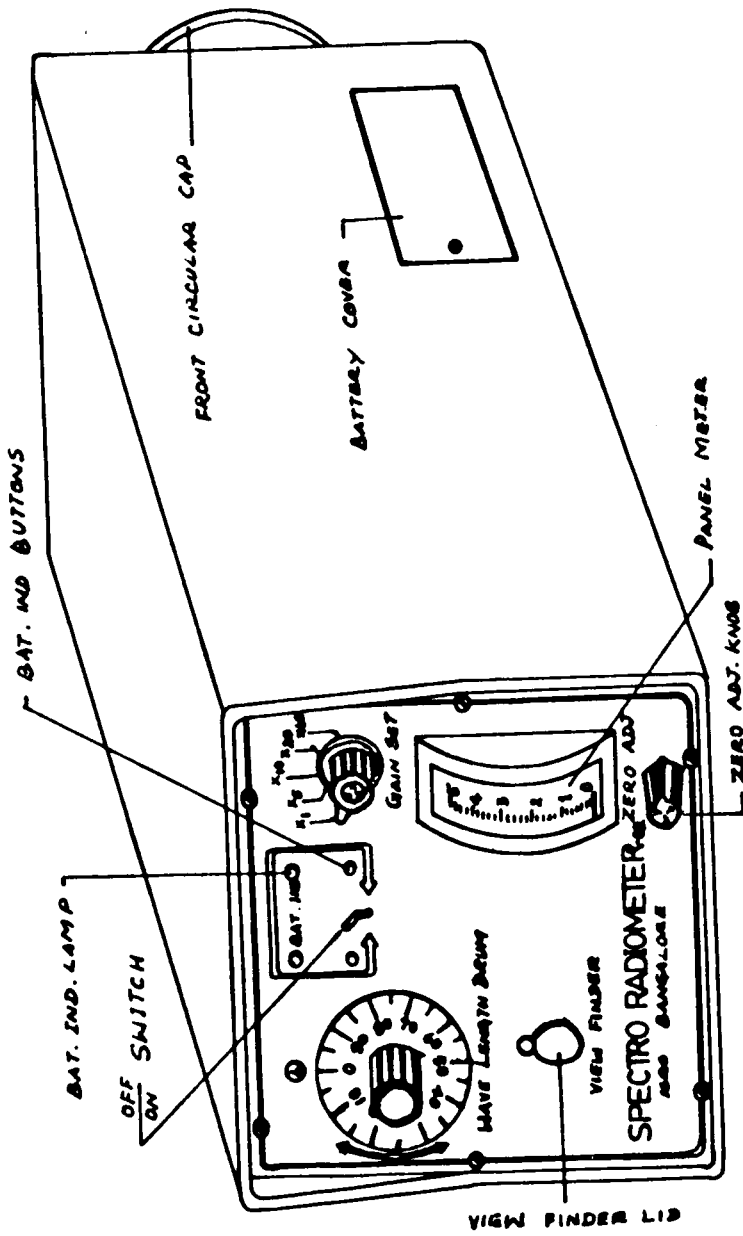


Fig.2 : COMPOSITE VIEW OF SPECTRO RADIOMETER-02.

the wavelength drum knob was adjusted to 500 nm. The reflectance measurements were taken at an interval of 20 nm, from 500 to 1000 nm on a cloud free day between 11.00 to 13.00 hrs. The measurements were recorded at three different locations in each plot. Depending on the total reflectances the gain set in the instrument was adjusted in such a way to get a reading between 1 to 4 of the meter reading (the over all scale of the meter was from 0 to 5).

The barium sulphate coated plate was used as a reference and ratio of the canopy reflectance to that of barium sulphate plate were computed for different wave lengths and presented as percentage.

The following formula was used to calculate the per cent reflectance at different wavelengths.

$$\text{Per cent reflectance} = \frac{x_1}{y_1} \times \frac{Y_2}{X_2} \times 100$$

Where x_1 is reflectance values from the canopy at a specific wave length, y_1 is gain set value for canopy reflectance, Y_2 is gain set value for reference reflectance and X_2 is reference reflectance (reflectance value from the barium sulphate coated plate at the same wave length).

Apart from recording these canopy reflectance characteristics, the reflectance properties of bare

ground was also recorded simultaneously from near by non-cropped area.

IR, R and IR/R ratios

From the reflectance values at red (640 nm) and infra-red (900 nm) regions, the ratio of infra-red to red reflectances were computed.

IR/R ratios of the canopy in relation to IR/R ratios from the bare ground

An attempt was also made to arrive at IR/R ratio of the canopy in relation to IR/R ratio of the bare ground. The ratio of these two ratios is designated as IR/R in relation to bare ground.

II. The relationship between leaf chlorophyll content and leaf transmittance characteristics

A number of green house experiments were conducted to meet the objectives envisaged under this topic.

All the green house experiments were conducted at the Botanical Garden, Department of Crop Physiology, University of Agricultural Sciences, Bangalore.

The main approach in these experiments was to develop plant materials with different leaf chlorophyll content. This was achieved by adopting the following three approaches.

1. By raising plants in sand culture with different nitrogen levels.
2. By selecting plants with different degrees of yellowing in field grown plants (bulk crops).
3. By selecting leaves of different ages (top, middle and bottom leaves) from aged pot grown plants.

Sand culture experiments

To develop plant material with different leaf chlorophyll content, several pot culture experiments were conducted with different nitrogen levels. Nitrogen concentrations in the Hoagland's nutrient solution which was fed to the plants was altered suitably. The potassium and calcium were supplemented as KCl and CaCl₂.

The crops studied and nitrogen levels tested are as follows.

Maize (Zea mays - Variety Deccan 101)

Experiment-1: The nitrogen concentrations in Hoagland's nutrient solution was;

N₁ - 84 ppm

N₂ - 168 ppm

N₃ - 252 ppm

N₄ - 336 ppm

The nitrogen concentration in Hoagland's nutrient solution was decreased by reducing KNO_3 and $\text{Ca}(\text{NO}_3)_2$ in the same proportions.

Experiment-2: The nitrogen concentration in Hoagland's nutrient solution was;

N_0 - 0 ppm
 N_1 - 84 ppm
 N_2 - 168 ppm
 N_3 - 210 ppm
 N^4 - 252 ppm

Experiment-3: The nitrogen concentrations in Hoagland's nutrient solution was;

N_1 - 84 ppm
 N_2 - 168 ppm
 N_3 - 252 ppm
 N^4 - 336 ppm
 N^5 - 420 ppm

Amaranthus (Amaranthus sp. - Variety R-104)

Experiment-1: The nitrogen concentrations in Hoagland's solution was;

N_1 - 84 ppm
 N_2 - 168 ppm
 N_3 - 336 ppm

Experiment-2: The nitrogen concentrations in Hoagland's nutrient solution was;

N₁ - 126 ppm

N₂ - 168 ppm

N₃ - 210 ppm

N₄ - 252 ppm

N₅ - 294 ppm

N₆ - 336 ppm

The details of age of the plant and leaves collected for studies are described in different experiments in the results chapter.

Selection of plants with varying amount of chlorophyll content

From the bulk plots of sunflower (Helianthus annuus L. - Variety BSH-1) grown in field conditions, plants showing different degrees of yellowing were tagged. The middle leaves from such plants were collected in polyethylene bags wrapped with wet muslin cloth and brought to the laboratory for study.

Estimation of chlorophyll from leaves of different positions of the same plant

For these experiments pot grown tobacco (Nicotiana tabacum - Variety F-210) plants were used. The tobacco plants were transplanted in to the pots and grown under normal irrigation conditions upto 75th day. On 75th

day when the plants were showing initial symptoms of senescence in the lower leaves, the leaves from different plant positions were collected to determine the chlorophyll and leaf transmittance characters. The details are given in different experiments in the results chapter.

DETAILS OF POT CULTURE EXPERIMENT:

Preparation of pots, sowing and imposition of treatments

Battery containers measuring 47 x 24 x 22 cubic cm, made out of carbonised rubber and washed with deionised water were used for this experiment. Each battery container was provided with two drainage holes and the pot were filled with 24 kg of acid (0.1 N-HCl) washed quartz sand of 16 mesh size.

Seeds of each species was sown in pots. The plants were thinned after germination and on 15th day after sowing 3 plants, 12 cm apart were maintained per pot. For each treatment there were 5 pots. The treatments were imposed from 15th day after germination. Until that period, the pots were irrigated with deionized water twice daily. From 15th day on wards, for each pot 250 ml of deionized water followed by 250 ml of Hoagland's nutrient solution containing different concentrations of nitrogen were given.

Two to four replications were maintained for each treatment.

The plants were sprayed at regular intervals with insecticides and pesticides as prophylactic measures as per the recommendation of the package of practices.

The experiment was continued upto 80th day. From these experimental pots, the leaves were taken to determine leaf chlorophyll content, leaf thickness and leaf transmittance characters.

Measurement of leaf transmittance characteristics and estimation of chlorophyll content and leaf thickness

The leaves were harvested from different treatments and after recording the fresh weight, leaf area and leaf thickness, the leaf transmittance characters at red region (660 nm) and chlorophyll content was determined. Chlorophyll content was estimated as per the method described by Arnon (1949). Leaf thickness was measured by using mechanical gauge and expressed in microns.

Leaf transmittance characters were determined by Agrophotometer by using the chlorophyll channel of the instrument.

Estimation of chlorophyll as per Arnon method

Total chlorophyll was estimated in 3rd leaf from fully expanded leaf from the apex of each species under different treatments.

Fresh leaf material (0.5 g) was mascerated with a pinch of calcium carbonate into a thin paste using a pestle and mortar. To this, 10 ml of 80 per cent acetone was added and thoroughly mixed. The mixture was filtered under suction. The filtrate was collected. If the residue was still green, 80 per cent acetone was added in drops directly over the residue continuing filtration till residue became white. The volume of filtrate was made upto known volume depending on the intensity of green colour and this extract was used for estimating the chlorophyll. The optical density of the extract was measured at 652 nm in Double Beam Spectrophotometer, UV 200S and chlorophyll content was calculated using the following formulae.

Total chlorophyll

$$\frac{D_{652} \times 1000}{34.5} \times \frac{V}{1000 \times \text{weight of leaf (g)}}$$

= mg total chlorophyll/g fr.wt. of leaf

$$\frac{D_{652} \times 1000}{34.5} \times \frac{V}{1000 \times \text{Area of leaf (cm}^2\text{)}} \times 100$$

= mg total chlorophyll/dm² leaf area

Where; D - is optical density at 652 nm

V - is total volume of 80% acetone extract

34.5 - Correction factor for chlorophyll.

III. Relationship between leaf water status and leaf transmittance characteristics (Laboratory experiments)

Relationship between leaf transmittance characteristics and leaf water status was determined in leaf tissues subjected to rapid wilting under laboratory conditions.

The leaf material for this experiment was collected for either pot grown or field grown plants. The relationship between leaf transmittance characteristics and water status was studied by adopting the quick wilting method in several crop and tree species, namely Cowpea, Dalbergia, Mahogani, Sandal wood and Pongamia.

The cowpea plants were raised in pots and in microplots. Leaves from 30 to 50 day old plants were collected during early hours of the day.

They were floated in water to attain the full turgidity. After recording turgid weight, the leaves were subjected to live wilting under laboratory

conditions (temperature $26^{\circ} \pm 2^{\circ}\text{C}$, RH $50\% \pm 10\%$ and light intensity $100 \mu \text{E} \text{m}^{-2} \text{sec}^{-1}$). At different time intervals the per cent water loss and leaf transmittance characters were determined using the water channel of the instrument. A set of leaves maintained under turgid conditions were used to calibrate (adjust) the meter reading to 100 prior to taking the transmittance values of the leaves with different water status.

In addition to the determination of fresh weight loss, relative water content (RWC) was also determined simultaneously. The RWC was determined as per the method of Barrs and Weatherly (1960).

$$\text{RWC}(\%) = \frac{\text{Fresh weight} - \text{Dry weight}}{\text{Turgid weight} - \text{Dry weight}} \times 100$$

Following the same method as described for cowpea, the relationship between leaf transmittance characters and water status was assessed in some other tree species namely Dalbergia, Mahogani, Sandal Wood and Pongamia.

The leaf material for all these species was collected from field grown plants.

Relationship between leaf transmittance characteristics and water status in sunflower plants subjected to slow wilting

The objective of this experiment was to assess the relationship between leaf transmittance characteristics and water status in plants subjected to slow wilting.

For these experiments, sunflower plants were raised in pots with 8 kg soil. The preparation of the pots sowing and after care were same as described earlier. On 40th day plants were subjected to moisture stress.

Experiment-1

In this experiment, control plants were maintained at field capacity, where as, T_1 , T_2 , T_3 and T_4 pots received 80, 60, 40 and 20 per cent of water required for field capacity respectively. The plants were irrigated with reduced amount of water daily for a period of 4 days. On 5th day leaves were harvested and fresh weight, thickness and transmittance were determined. After determining these parameters the leaf turgid weight were recorded after floating leaves in water for 6 hours. While recording the leaf transmittance values in the stress leaves the meter reading was adjusted to 100 by using turgid leaf which was brought from the nonstressed plants.

Experiment-2

In this pot culture experiment stress was imposed in 40 days old sunflower plants by with-holding irrigation. In T_1 treatment water was with-held for a period of two days, whereas in T_2 , T_3 and T_4 the water was with-held 3, 4 and 5 days respectively. On day 6th the leaves were harvested and leaf transmittance and thickness were determined as described in previous experiment.

Determination of leaf transmittance characters with Agrophotometer - Description of the instrument

In recent years several Spectrophotometric studies have indicated, the possibility of quantitative determination of leaf constituents possessing specific optical properties by studying leaf transmittance characters. This property can be conveniently used to determine the chlorophyll content by studying leaf transmittance characters. Similarly it is well established that, the leaf volumetric properties change with change in the turgidity of leaf. This inturn may alter the leaf transmittance characters, especially at near infra-red regions. Hence, transmittance measurements made at red and near infra-red regions, can be made use for the quantitative determination of leaf chlorophyll content and water status.

Containing these two features a novel low cost portable instrument - Agrophotometer was designed and developed by Indian Space Research Organization (ISRO) in collaboration with Department of Crop Physiology, University of agricultural Sciences, Bangalore. The details of the system is given below.

System details

The optical layout of the new Agrophotometer is shown schematically in Fig.3a (Plate 2). Light from the source after collimation is divided into two beams at the beam splitter level. The sample compartment is located in between the collimating and beam splitting systems. Each of these beams, after passing through the selective filters F1 and F2 is brought to focus on the two detectors D1 and D2. The outputs from these are produced separately and displayed on a digital read out to give the relative turgidity and chlorophyll content of the leaves.

Specifications of each of these are given below

Source	:	Tungsten Lamp 1.5V, 750 mw
		a) <u>+</u> 9V DC
		b) 3.5 AH Rechargeable battery
Collimating optics	:	f/1.5 refracting doublet

Fig.3a: Schematic view of Agrophotometer - CL-375.

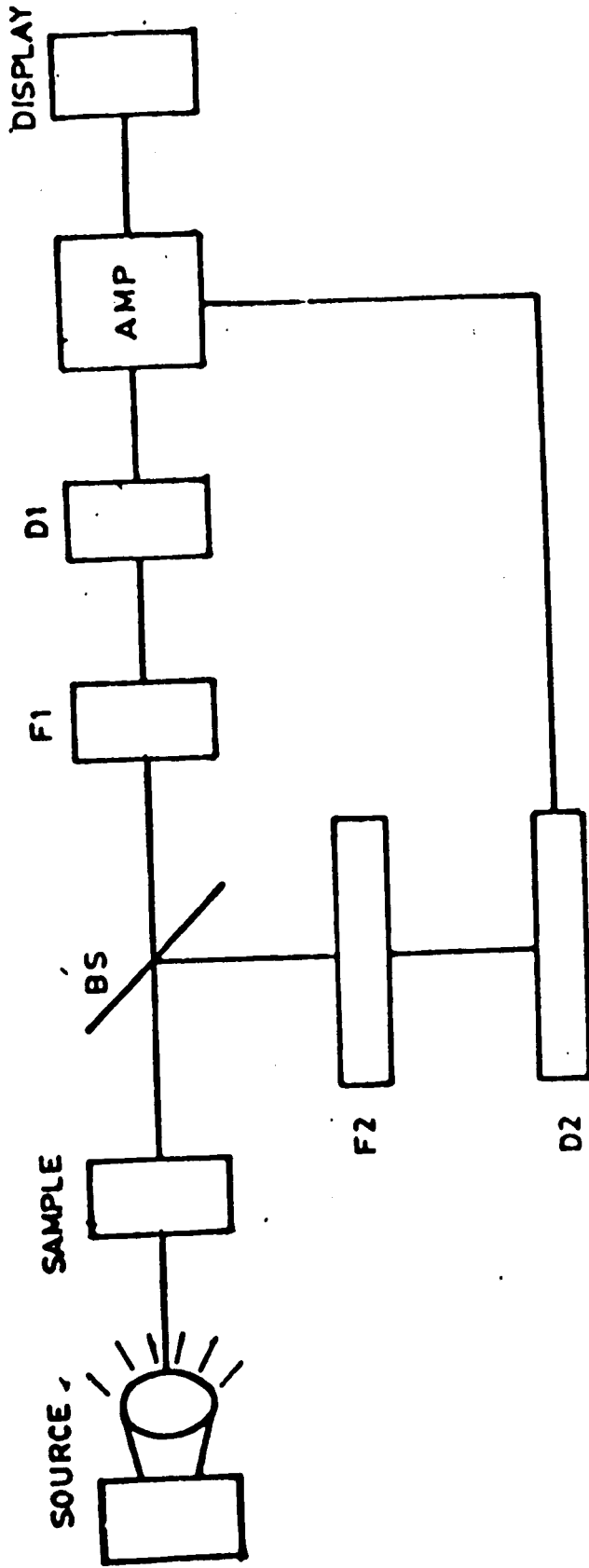


Fig. 3a



Plate 2. Agrophotometer

Spectral response of: Interfering Filters	Photographic red and intra-red band
Detectors	: Silicon photodiode
System linearity	: Better than 0.1%
Size	: 12 x 12 x 5 cubic cm
Weight	: 1.5 kg approximate
Dynamic range	: Water status 30-100% chloro- phyll content: 0.5 to 5.0 mg per dm² leaf area
Resolution	: Better than 5% for both water status and chlorophyll content

Proceedure for measurement of leaf transmittance characteristics for chlorophyll content

To estimate the chlorophyll content in situ by using Agrophotometer: The following steps are adopted.

1. Check the batteries and ensure they are in condition.
2. Select the chlorophyll channel (1.1.2) (photographic red region, 660 nm).
3. Adjust the zero setting (1.1.4) with external power source off.
4. Plug in the external power to switch on the source.
5. Adjust the gain setting (1.1.5) to read full scale of the meter (195).

6. Insert the leaf in the sample holder (1.1.7) as shown in the Fig.3b.
7. Record the reading.
8. Repeat the procedures 6 and 7 at various points on the leaf and arrive at average meter reading. If the readings are less than 20-25 use the filter (supplied with the unit) and adopt the following steps. 1-4 steps are same as detailed above.
5. Insert the filter in the sample holder .
6. Adjust the gain setting with filter to read full scale of the meter (195).
7. Remove the filter.
8. Insert in the leaf in the sample holder.
9. Repeat the steps 8-9 above at various points on the leaf and arrive at average meter reading.
10. By using calibration curve developed (based on meter reading and chlorophyll content) the chlorophyll content of the leaf can be arrived at.

Procedure for measurement of leaf transmittance characteristics for water status

To measure the water status of the leaf in situ using Agrophotometer: The following steps are adopted.

Fig.3b: Manual diagram of the front view of Agrophotometer.

- 1.1 Agrophotometer
 - 1.1.1 Power/off
 - 1.1.2 Chlorophyll/water status
 - 1.1.3 Display On/Off
 - 1.1.4 Set zero
 - 1.1.5 Gain
 - 1.1.6 Trigger
 - 1.1.7 Sample holder

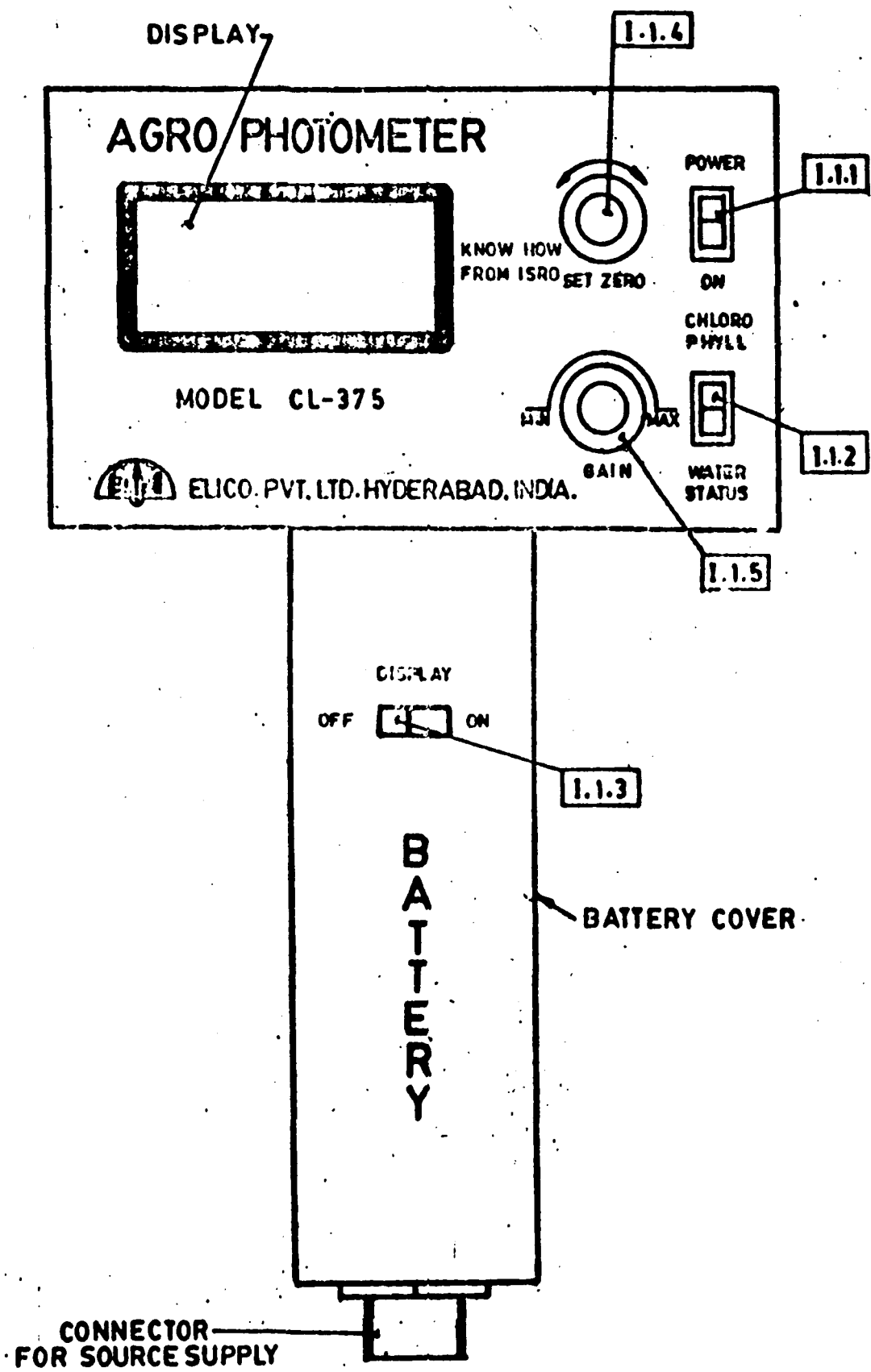


Fig.3b

1. Check the batteries and ensure they are in condition.
2. Select the water channel (NIR band).
3. Adjust the zero setting (1.1.4) with external power source off.
4. Plug in the external power to switch-on the source.
5. Insert the turgid leaf in the sample holder (1.1.7) as shown in the Fig.3c and adjust the gain setting to read 100 (One of the leaf from the treatment plant was brought to the turgid condition by floating in water for required period and this leaf was used to adjusting the meter reading to 100 for that species).
6. Insert the sample leaf with different water status in sample holder and record the meter reading.
7. Record the reading.
8. Repeat the procedures 6 and 7 at various points on the leaf and arrive at average meter reading.

The actual water status of different leaves were determined either as RWC or as per cent water content of the leaf and plotted against respective meter readings.

Fig.3c:Manual diagram of the side view of
Agrophotometer.

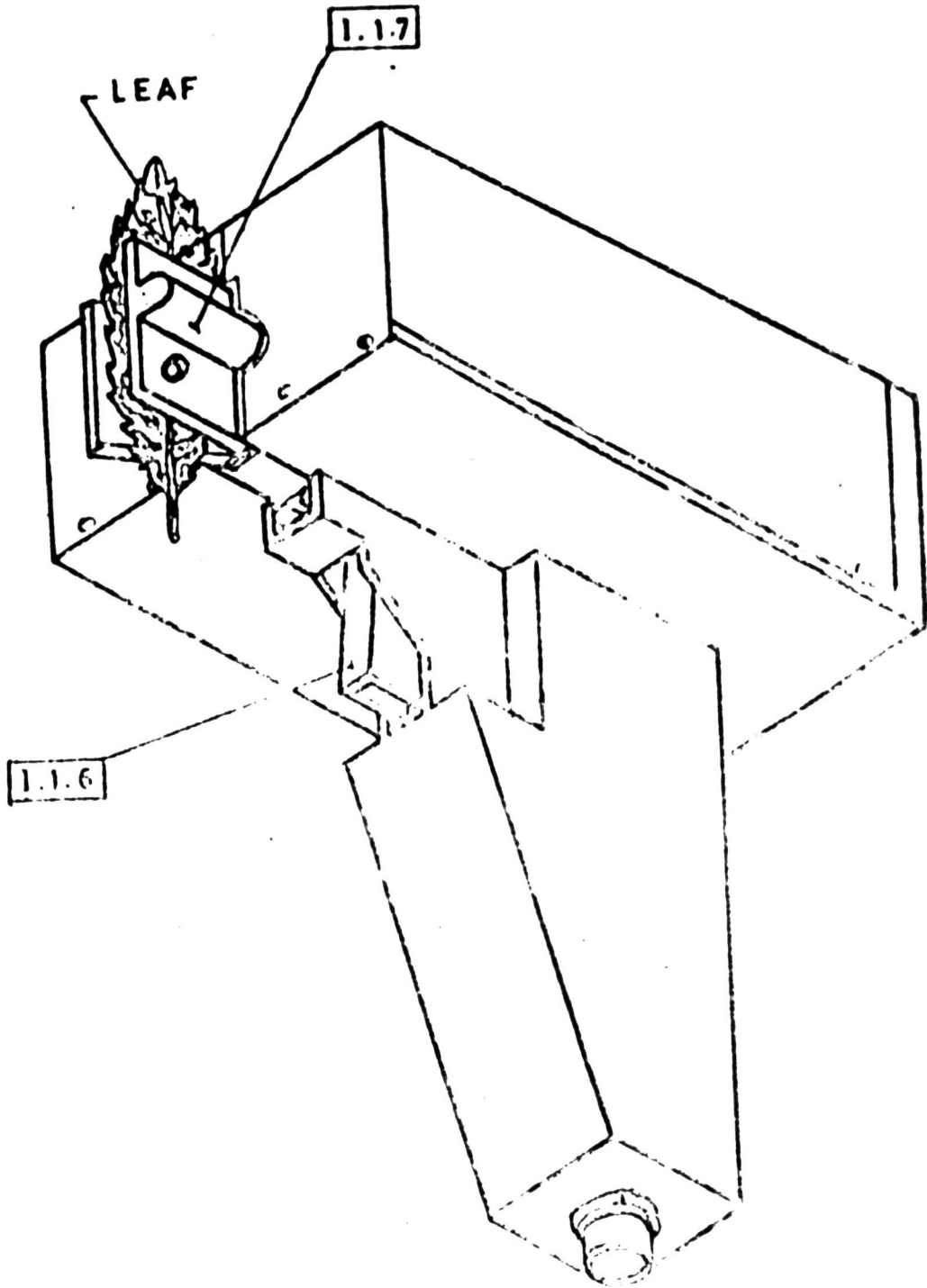


Fig.3c

EXPERIMENTAL RESULTS

IV. EXPERIMENTAL RESULTS

The experiments conducted on three different aspects are presented in this chapter.

I. The relationship between spectral reflectance of the canopy and the extent of canopy cover

One of the objectives of the present investigation is to find out the relationship between canopy reflectance characteristics and the extent of the canopy cover. In field grown cowpea, soybean, sorghum and amaranthus crops, the leaf area indices, per cent light interception and the canopy reflectance characters were determined at different stages of the crop growth. Such an approach will facilitate to study the extent of light intercepted and the canopy reflectance characteristics at different leaf area indices.

The results obtained on canopy reflectance characters at different stages of crop growth in different crops are described here.

All the crops were raised during summer under irrigated conditions. The main purpose of growing these crops during summer was to take observations of canopy reflectance characters (CRCH) during clear sunny days.

COWPEA

In cowpea, leaf area data was taken on 40th, 50th and 70th days from different plots. In the same plots simultaneously, the data on per cent light interception and the CRCH was determined using tube solarimeter and Spectroradiometer respectively. These observations were recorded between 11.00 to 13.00 hours.

The CRCH were determined at the spectral range from 500 to 1000 nm at every 20 nm intervals. Simultaneously the reference reflectances (reflectance from barium sulphate coated plate) at different wavelengths were determined. In addition to this reflectances from the bare ground from an adjacent non-cropped area with similar soil characters were also determined.

The canopy reflectance values were arrived based on the actual reflectance values of the canopy and the reference reflectance values at the given wave lengths and expressed as percentage value at each wave length the reference reflectance values are considered as 100.

The per cent reflectance (in relation to the reference) was minimum at red region (620 to 660 nm) and from 700 nm there was gradual increase in per cent reflectance and maximum per cent reflectance was

observed at infra-red region between 880 to 960 nm (Fig.4). From 960 on wards there was slight decrease in per cent reflectance.

The characteristic reflectance curve of bare ground is given in Fig.5. Unlike in cropped area the reflectance characters (RCH) were different in the bare ground. In general the per cent reflectance was less at all the wave lengths compared to crop canopy except at the visible spectra. For instance, per cent reflectance at 900 nm was 27.50 from bare ground where as it was 54.17 for crop canopy. The results on reflectance on bare ground further suggested that, the nature of the curve and the magnitude of reflectance did not vary much, when it was recorded at different dates (refer Appendices). Therefore, it can be inferred, that the bare ground reflectance values basically depends on soil physical and surface properties.

Since, the minimum and maximum canopy reflectance values were obtained at 640 and 900 nm respectively, the CRCH only at 640 and 900 were considered for arriving at the relationship between leaf area index (LAI), per cent absorption of solar radiation (ASR) with CRCH. Further, IR/R ratios were also computed and their relationship with LAI and per cent ASR was

Fig.4: Characteristic reflectance (from 500-1000 nm) of crop canopy).

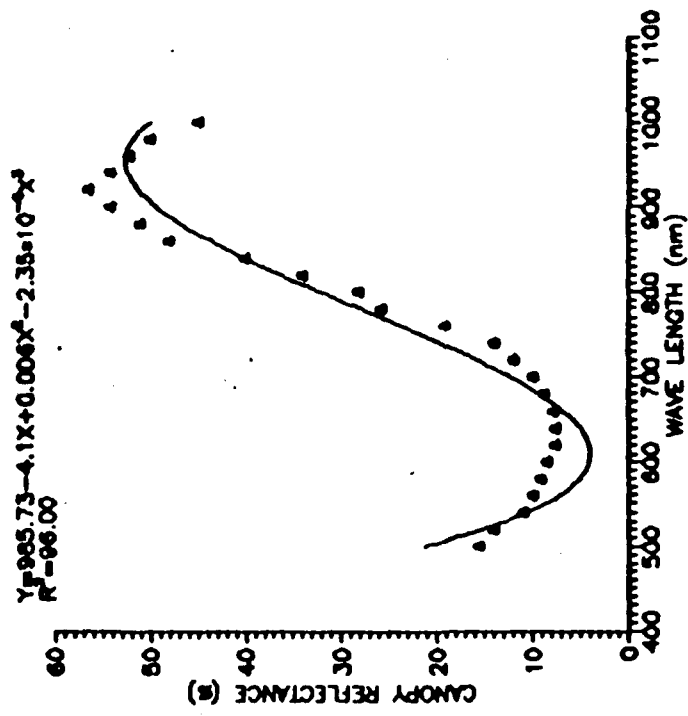


Fig. 4

Fig.5: Characteristic reflectance (from 500-1000 nm) of
bare ground.

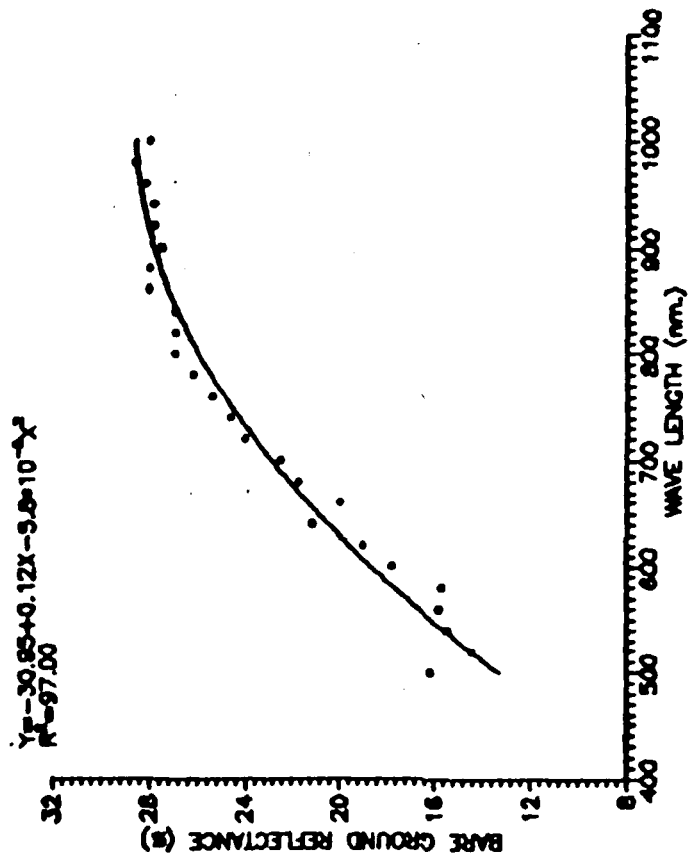


Fig. 5

assessed. An attempt was also made to arrive at IR/R ratio of the canopy in relation to IR/R ratios of the bare ground. The ratio of these two ratios is determined as IR/R in relation to bare ground.

The data on LAI, per cent light intercepted, canopy reflectance values at 640 and 900 nm, IR/R ratios and IR/R ratios in relation to bare ground recorded at different stages of cowpea crop are given in Table 1.

There were significant differences in all the canopy characteristics. The range in LAI in this experiment was from 2.20 to 3.23. With increase in LAI the per cent light intercepted was also increased. The CRCH at IR region also increased with increase in LAI. But the per cent reflectance at 640 nm showed a declining trend. For instance at LAI of 2.20 the per cent reflectance at red region (640 nm) was 14, where it was 41.67 at IR region (900 nm). But the corresponding reflectance values at LAI 3.23 were 7.65 and 54.17 respectively.

The IR/R ratio also increased an increase in LAI values.

Correlations

There was a positive significant relationship between LAI and per cent light intercepted indicating

Table 1. Canopy reflectance characters and per cent absorption of solar radiation of cowpea crop differing in leaf area indices.

Treat- ment (DAS)	LAI	Per cent ASR	Per cent reflectance		IR/R	IR/R in relation to bare- ground
			640 nm(R)	900 nm(IR)		
40	2.20	45.16	14.00	41.67	2.98	2.00
	2.27	46.74	14.00	41.67	2.98	2.00
	2.41	47.20	14.00	43.50	3.11	2.08
50	2.45	48.20	12.94	33.50	3.36	2.35
	2.50	48.30	12.40	45.85	3.70	2.59
	2.50	50.30	12.50	47.82	3.85	2.70
70	3.20	51.40	8.82	54.17	6.14	4.73
	3.21	51.40	8.82	54.17	6.14	4.73
	3.23	51.40	7.65	54.17	7.08	5.45
Mean:	2.29	46.37	14.00	42.28	3.02	2.03
	2.48	48.93	12.58	45.72	3.64	2.55
	3.21	51.40	8.42	54.17	6.45	4.97
CD at 5%	0.12	1.69	0.87	3.72	0.72	0.46

that the extent of light absorption by the canopy is linearly related to LAI (Fig.6).

A negative significant relationship was observed between canopy reflectance values at red region ($r = -0.984$) and a positive significant relationship at near infra-red region ($r = 0.960$). IR/R ratios ($r = 0.977$) and also IR/R ($r = 0.984$) ratios in relation to bare ground also showed a positive relationship with the extent of canopy cover (LAI) (Fig.6).

The relationship between the extent of light intercepted and CRCH was also computed. Per cent light intercepted showed a negative significant relationship with canopy reflectance at red region ($r = -0.899$) and a positive significant relationship with canopy reflectance at IR region ($r = 0.909$). IR/R ratios and IR/R ratios in relation to bare ground also showed a positive significant relationship with per cent light interception by the canopy.

From the results of this experiment it can be concluded that the extent of canopy cover (LAI) and per cent light intercepted by the canopy can be determined by measuring the reflectance characters of the canopy at red (R) and infrared (IR) regions.

Fig.6: Relationship between LAI and CRCH in cowpea: (a) LAI v/s ASR, (b) LAI v/s Canopy reflectance at R, (c) LAI v/s Canopy reflectance at IR, (d) LAI v/s IR/R and (e) LAI v/s IR/R in relation to bare ground.

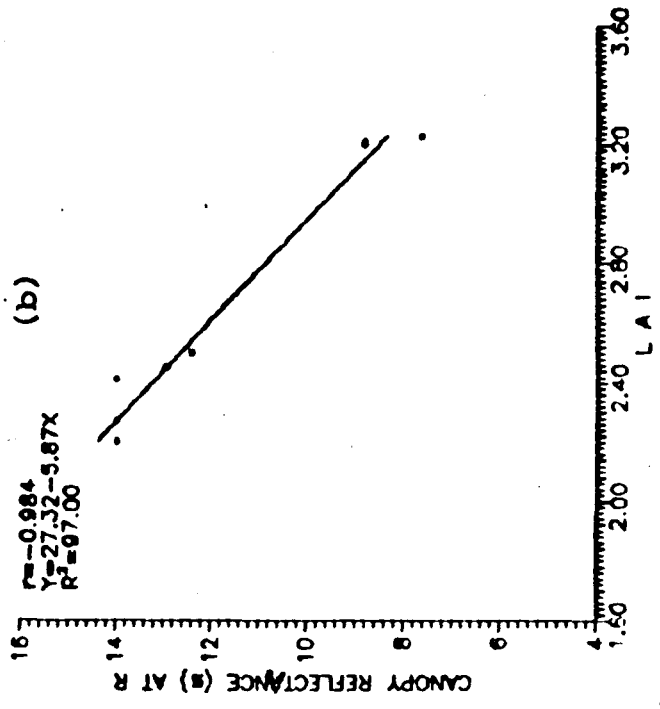
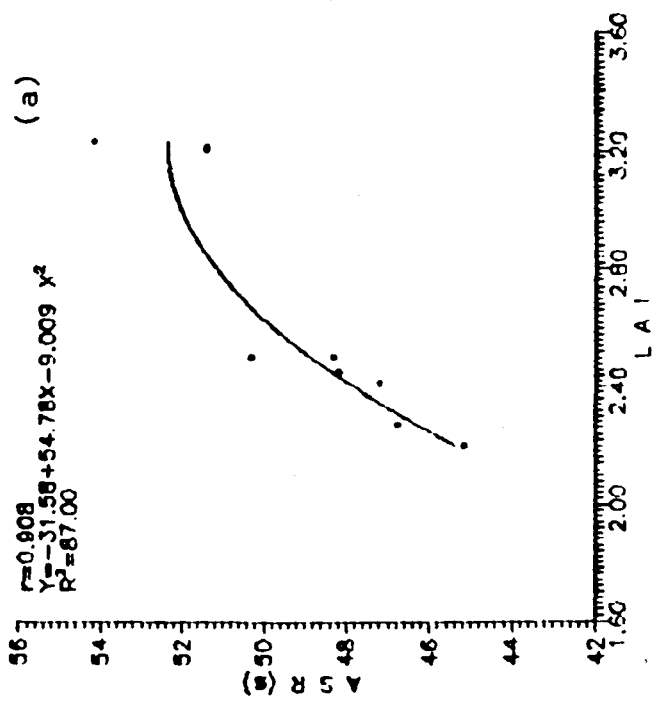
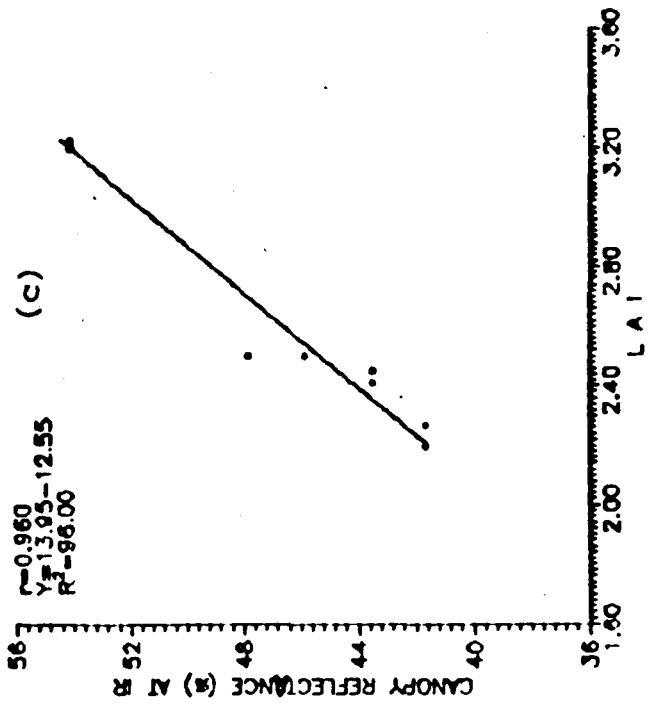
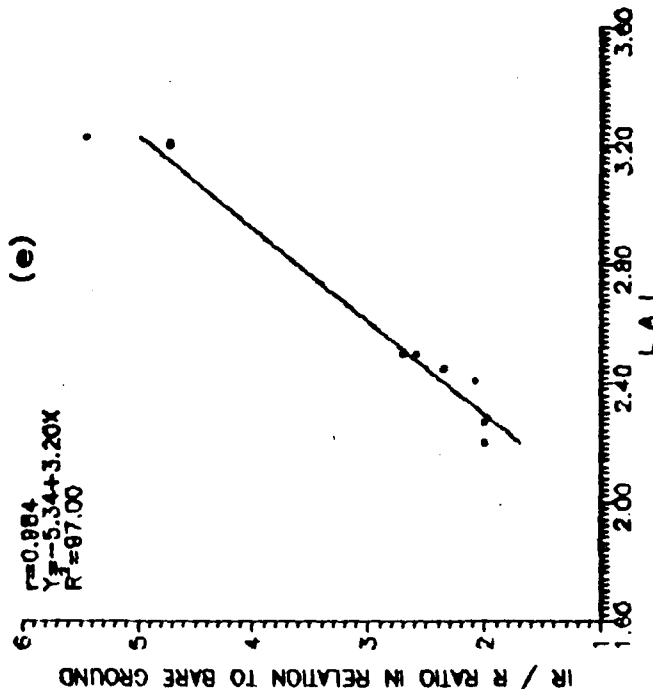
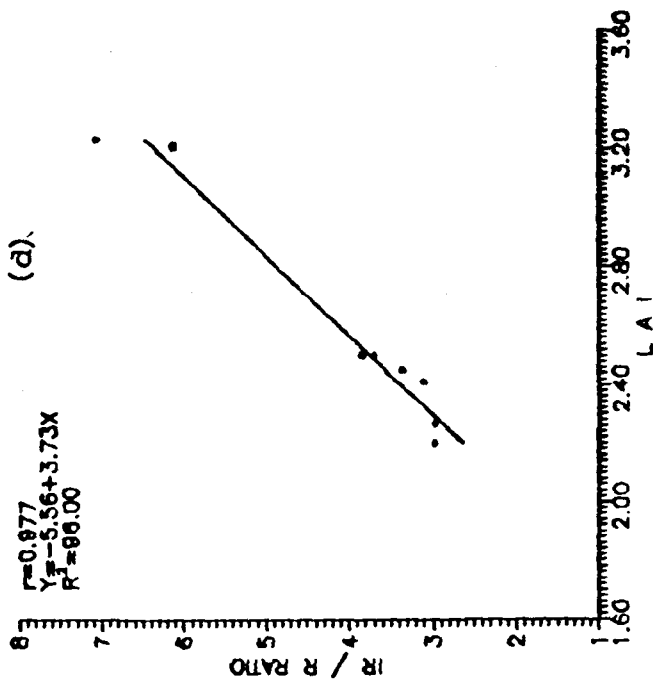


FIG. 6

Fig.6 contd.



SOYABEAN

The objective of this experiment in soybean was also to relate CRCH with the leaf area indices and extent of light intercepted by the canopy. In this experiment the observations on different parameters were recorded on 40th, 50th and 60th day after sowing. After taking observations on per cent light intercepted and canopy reflectance values, the leaf area was determined in randomly selected plants. While determining observations on the canopy reflectance characteristics, the reflectance characters from the bare ground were also determined.

The leaf area indices increased from 40th day to 60th day. With increase in leaf area there was linear increase in per cent light interception. For instance on 40th day when the LAI was 2.13, the per cent light intercepted was 36.70 where as when LAI was 3.37, the per cent light interception was 49.40. The reflectance at IR (Infra-red) and R (Red) regions also varied depending on leaf area indices. At high leaf area indices, the per cent reflectance at R region significantly decreased, where as per cent reflectance values at IR region increased proportionately. There was a marked increase in IR/R ratios at a higher LAI values. When LAI increased from 2.13 to 3.10 IR/R

ratio increased from 2.97 to 4.03 (Table 2). Even when IR/R ratios were computed in relation to bare ground reflectance a similar trend was existed.

Canopy reflectance characters at IR and LAI were positively related ($r = 0.853$) to per cent absorption of solar radiation (ASR). the reflectance at IR and IR/R ratio in relation to bare ground also showed a positive significant relationship with LAI. A negative significant relationship was seen between LAI and canopy reflectance at R region (Fig.7).

The relationship between per cent ASR verses per cent reflectance at IR, IR/R and IR/R ratios in relation to bare ground were positive and highly significant.

The results obtained in this crop is also very similar to the data obtained in cowpea crop. Therefore even in soybean also the extent of canopy cover can be determined by the canopy reflectance characters measured at R and IR regions. The relationship between the reflectance characters and LAI was more marked, when IR/R ratios in relation to bare ground was used. This suggest that, bare ground reflectance also has to be considered while taking data on reflectance characters of the canopy.

Table 2. Canopy reflectance characters and per cent absorption of solar radiation of soybean crop differing in leaf area indices.

Treatment (DAS)	LAI	Per cent ASR	Per cent reflectance		IR/R	IR/R in relation to bare- ground
			640 nm(R)	900 nm(IR)		
40	2.13	36.70	14.00	41.70	2.97	2.00
	2.23	37.70	13.00	43.50	3.35	2.24
	2.23	37.70	12.40	43.50	3.51	2.35
50	3.00	46.75	12.40	43.50	3.51	2.45
	3.10	46.75	12.40	50.00	4.03	2.82
	3.72	48.33	11.00	50.00	4.55	3.18
60	3.37	49.40	10.00	58.33	5.83	4.49
	3.37	49.40	10.00	58.33	5.83	4.49
	3.37	49.90	9.41	58.33	6.20	4.77
Mean:	2.30	37.37	13.13	42.90	3.28	2.20
	3.12	47.28	11.93	47.83	4.03	2.82
	3.37	49.40	9.80	58.33	5.95	4.58
CD at 1%	0.16	1.97	1.78	4.39	0.73	0.50

Fig.7: Relationship between LAI and CRCH in Soybean:
(a) LAI v/s ASR, (b) LAI v/s Canopy reflectance at R, (c) LAI v/s Canopy reflectance at IR, (d) LAI v/s IR/R and (e) LAI v/s IR/R in relation to bare ground.

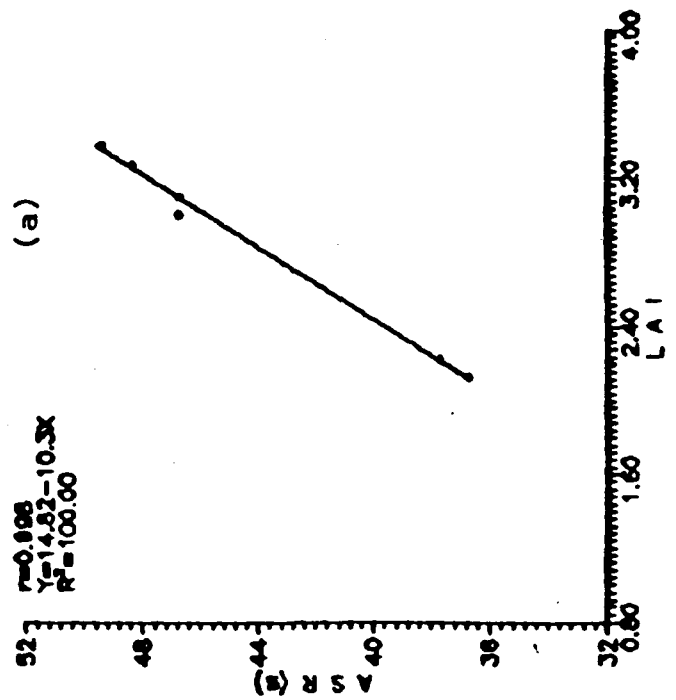
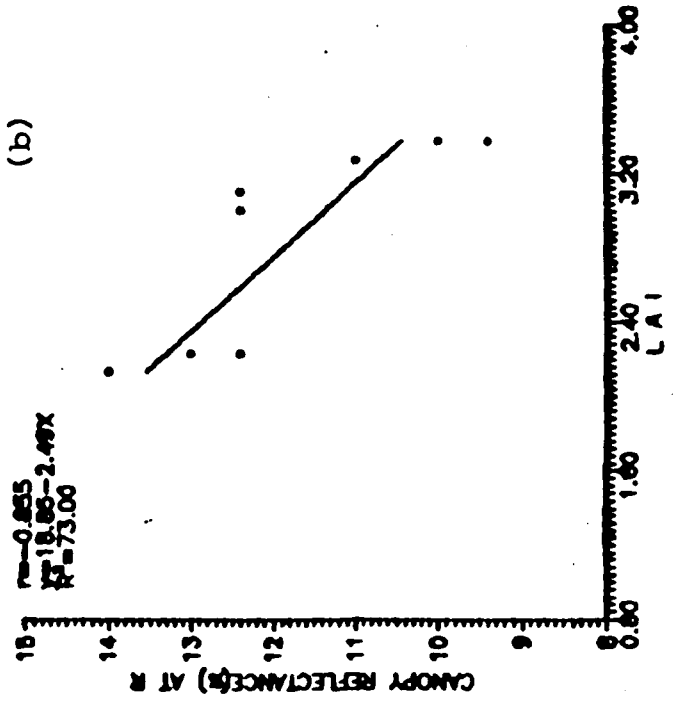
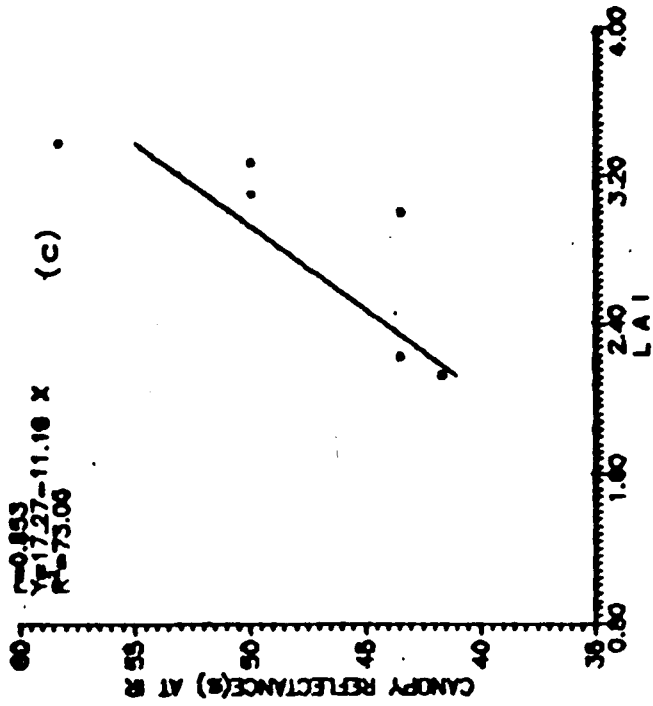
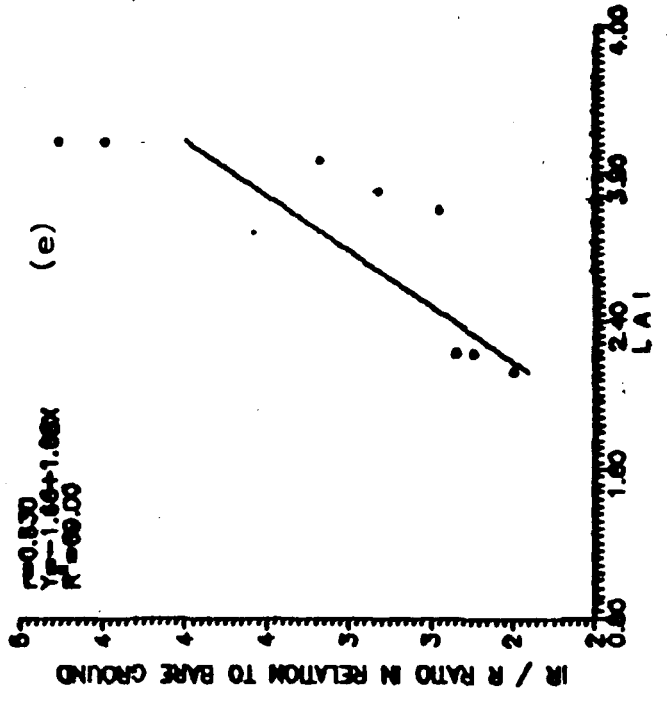
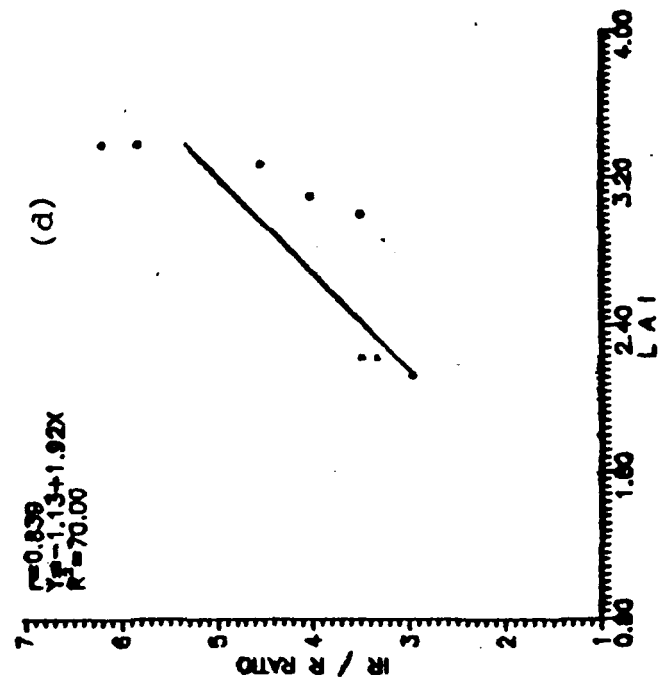


Fig. 7 contd.



SORGHUM

In field grown sorghum crop observations on LAI and other parameters were recorded on 32nd, 38th and 45th days after sowing (DAS). The range in LAI was relatively less compared to previous experiments on cowpea and soybean. The objective in this experiment was to determine CRCH at a narrow range of leaf area indices. Though differences in LAI were less, with increase in LAI from 2.10 to 2.40 a significant increase in per cent light interception was noticed. Even reflectance values at R and IR regions also showed a significant relationship with LAI in this crop. For instance with an increase in 0.3 LAI per cent, reflectance at IR region increased from 33.33 to 51.85. The range in IR/R ratios was from 2.08 to 5.04 (Table 3), even with marginal differences in LAI.

The regression values between LAI, extent of light intercepted and canopy reflectance values are given in Fig.8. There was a positive significant relationship between LAI and per cent ASR. Further, LAI showed a positive significant relationship with IR, IR/R and IR/R ratio in relation to bare ground. These results further emphasised the possibility of determining the extent of canopy cover (LAI) based on CRCH.

Table 3. Canopy reflectance characters and per cent absorption of solar radiation of sorghum crop differing in leaf area indices.

Treatment (DAS)	LAI	Per cent ASR	Per cent reflectance		IR/R	IR/R in relation to bare- ground
			640 nm(R)	900 nm(IR)		
32	2.40	36.66	16.00	33.33	2.08	1.40
	2.43	40.00	16.00	37.50	2.34	1.57
	2.01	36.60	16.41	34.33	2.07	1.59
38	2.45	42.22	13.33	37.50	2.81	1.89
	2.53	50.75	13.33	45.83	3.44	2.41
	2.55	50.79	12.86	45.83	3.56	2.49
45	2.60	50.79	10.29	51.85	5.06	3.88
	2.70	53.00	9.41	51.85	5.10	4.24
	2.70	53.00	10.29	51.85	5.04	3.88
Mean:	2.28	37.75	16.14	35.05	2.16	1.52
	2.51	47.86	13.17	43.05	3.27	2.26
	2.67	52.26	10.00	51.85	5.63	4.00
CD at 5%	0.36	5.46	0.89	5.95	0.53	0.39

Fig.8: Relationship between LAI and CRCH in sorghum:
(a) LAI v/s ASR, (b) LAI v/s Canopy reflectance at R, (c) LAI v/s Canopy reflectance at IR, (d) LAI v/s IR/R and (e) LAI v/s IR/R in relation to bare ground.

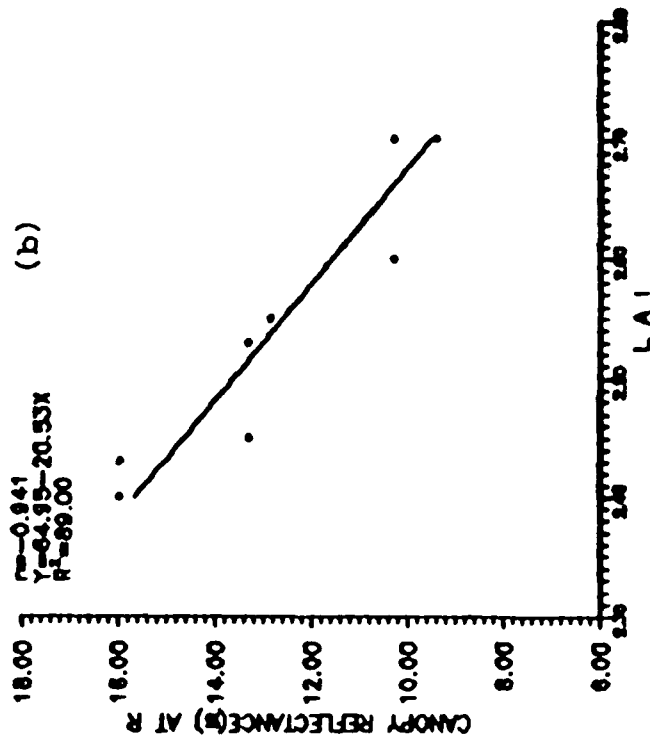
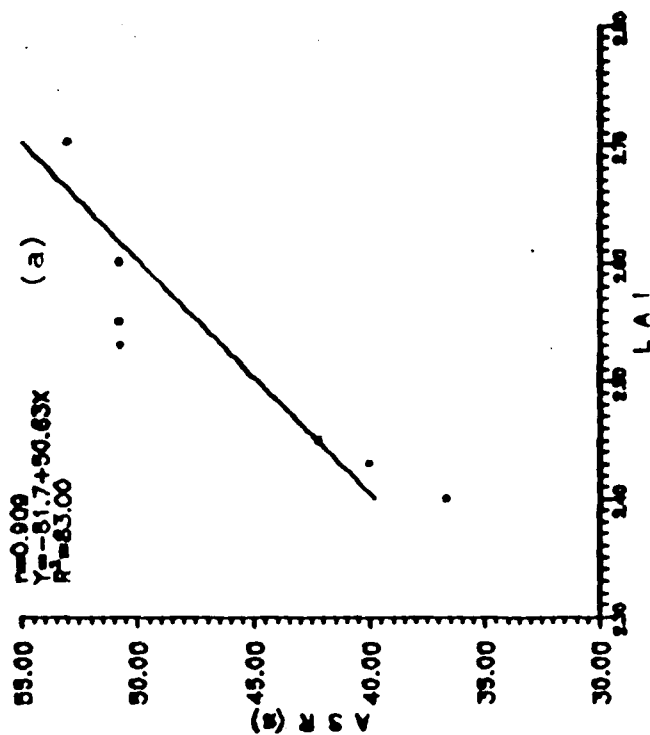
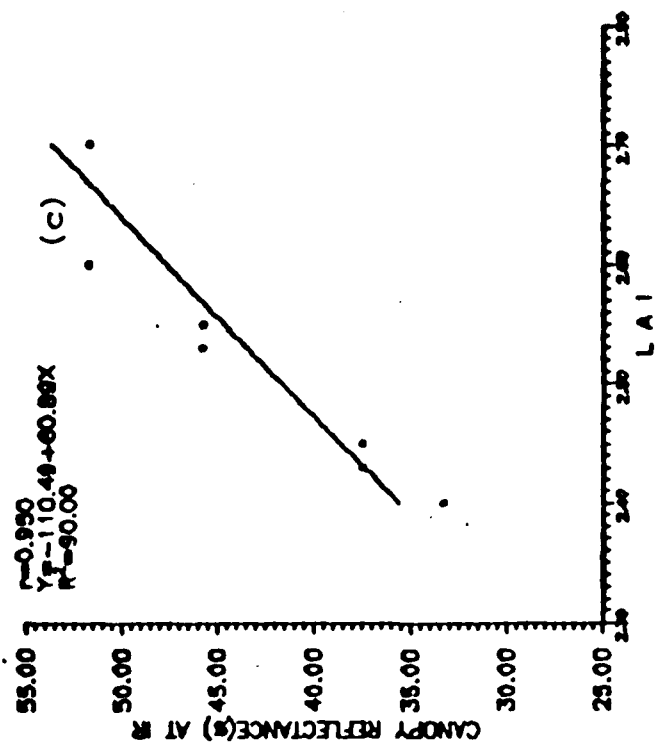
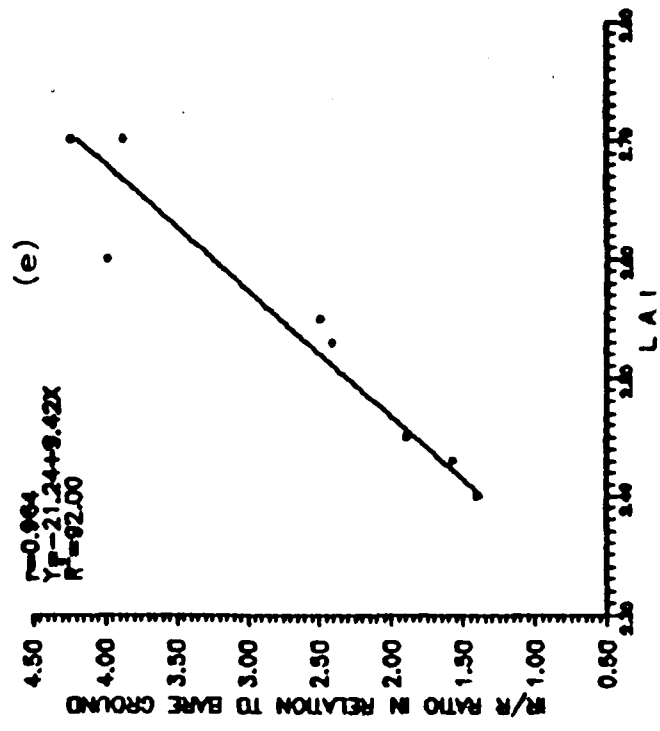
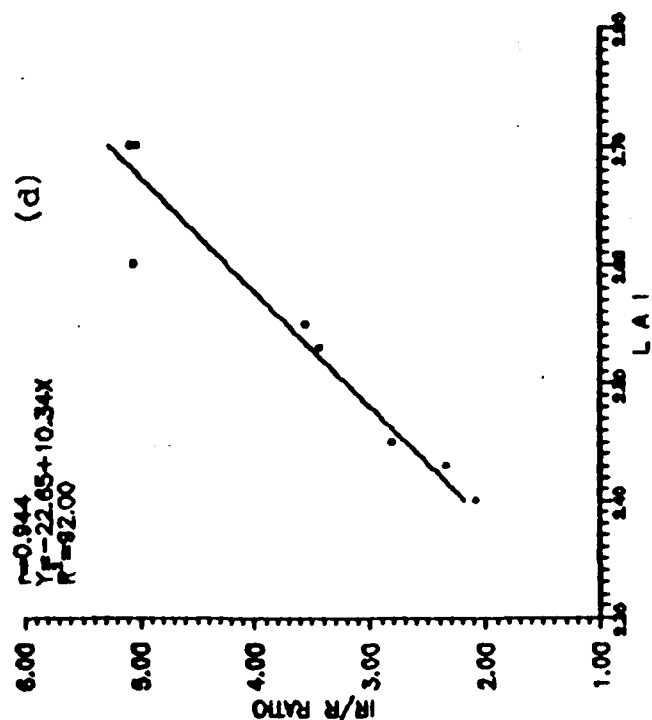


Fig. 8

Fig.8 contd.



AMARANTHUS

In this experiment observation on LAI, per cent light interception and other CRCH were recorded on 20th, 25th and 32nd days. The objective here was to see the inter-relationship between LAI and other CRCH, when the canopy (LAI) was less than 2.5. In amaranthus though the LAI was relatively less, the extent of light interception was more.

The range in LAI was from 2.06 to 2.70. However, the per cent light intercepted was 41.60 when LAI was 2.06, where as it was 54.44 when the LAI was 2.70 (Table 4). Per cent reflectance at R region decreased with increase in LAI, whereas, per cent reflectance at IR region increased with increase in LAI. The IR/R ratios also showed an increasing trend with increase in LAI.

As in the other crops (cowpea, soybean and sorghum) in amaranthus also a positive significant relationship was noticed between LAI, extent of light intercepted and per cent reflectance values at IR region. Even IR/R ratios also showed a highly positive significant relationship with extent of canopy cover (Fig.9).

Table 4. Canopy reflectance characters and per cent absorption of solar radiation of amaranthus crop differing in leaf area indices.

Treatment (DAS)	LAI	Per cent ASR	Per cent reflectance		IR/R	IR/R in relation to bare- ground
			640 nm(R)	900 nm(IR)		
20	2.06	41.60	21.20	44.44	2.10	1.41
	2.10	41.60	21.20	44.44	2.10	1.41
	2.10	42.20	21.20	44.44	2.10	1.41
25	2.33	45.40	17.00	50.17	2.95	2.06
	2.46	48.50	17.00	52.20	3.07	2.15
	2.50	49.50	14.00	52.20	3.73	2.61
32	2.50	52.22	13.33	52.20	3.92	3.01
	2.60	53.33	13.33	54.17	4.06	3.13
	2.70	54.44	30.33	54.17	4.06	3.13
Mean:	2.09	41.80	21.20	44.44	2.10	1.41
	2.43	47.80	16.00	51.52	3.25	2.27
	2.60	53.33	13.33	53.51	4.01	3.09
CD at 1%	0.21	4.61	4.77	3.18	1.11	0.77

Fig.9: Relationship between LAI and CRCH in Amaranthus:
(a) LAI v/s ASR, (b) LAI v/s Canopy reflectance at R, (c) LAI v/s Canopy reflectance at IR, (d) LAI v/s IR/R and (e) LAI v/s IR/R in relation to bare ground.

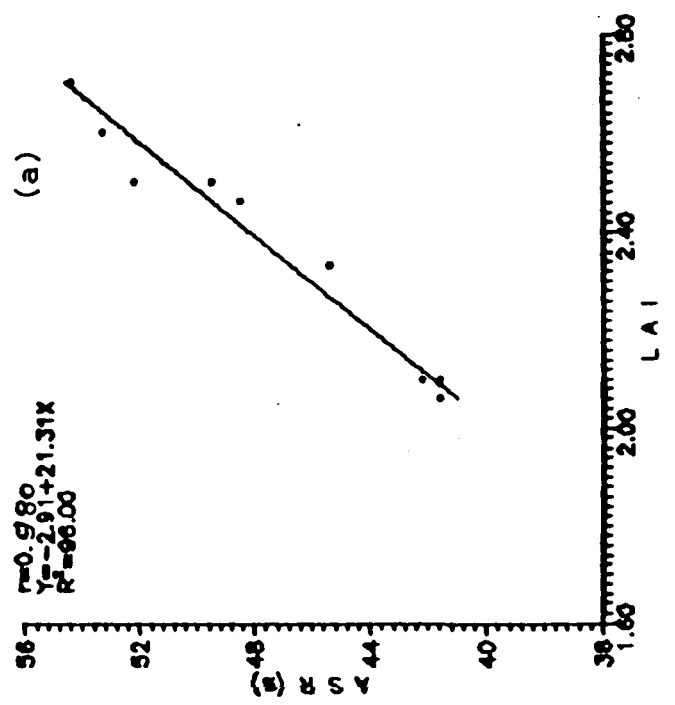
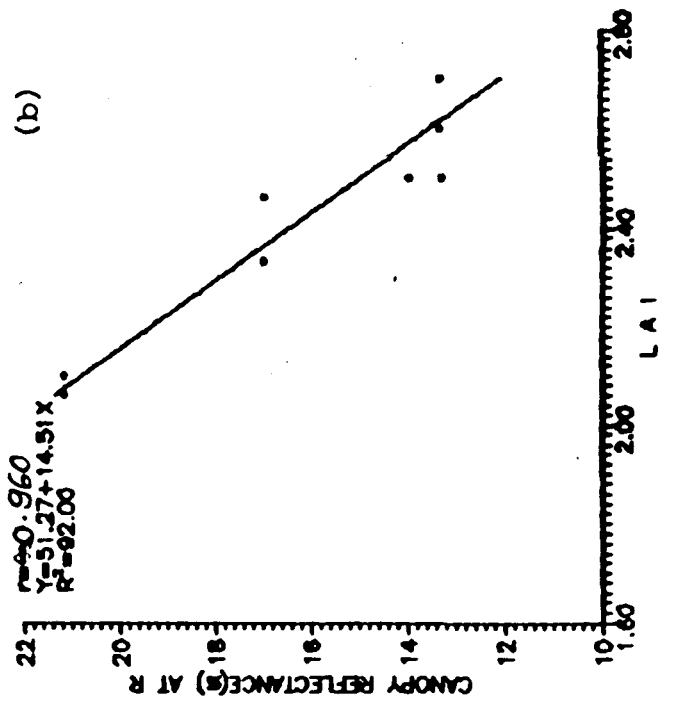
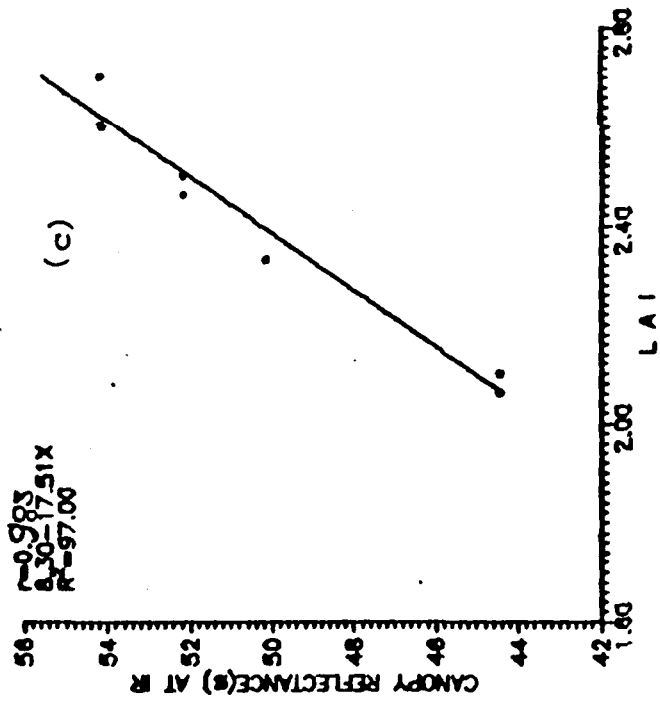
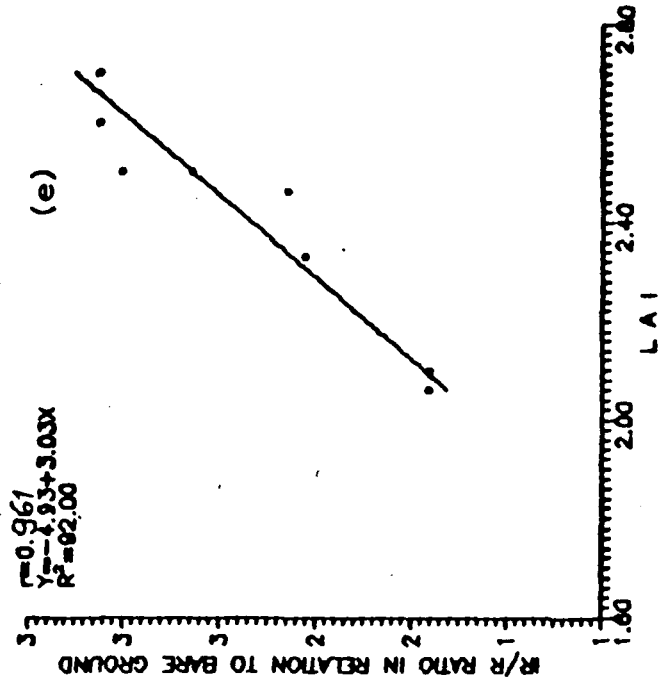
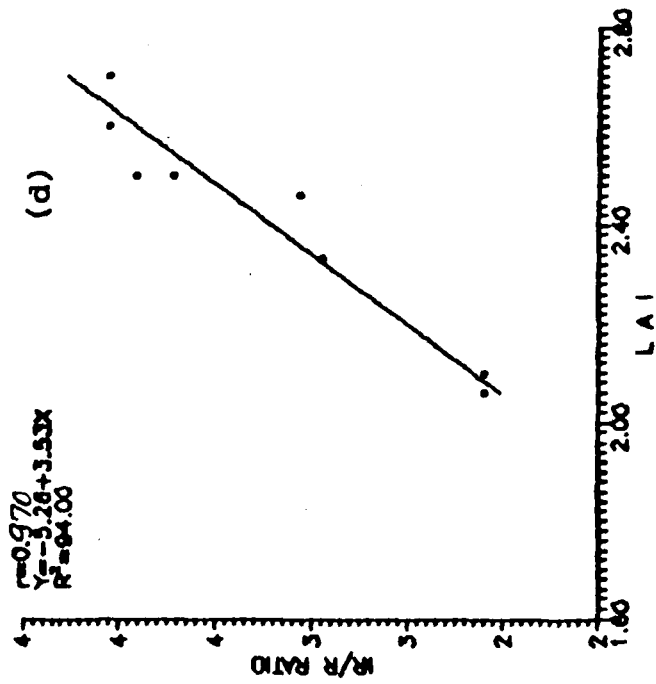


Fig.9

Fig.9 contd.



Per cent light interception - Comparison between total radiation intercepted and the interception of PAR

In all these experiments it was observed that even at an LAI of 3.0 - 3.5, the per cent light interception was only 50 to 60 per cent. In all these studies light interception was measured by tube solarimeter, which records the total radiation. An experiment was conducted to compare the extent of interception of PAR and the total radiation. In field grown sunflower crop, the per cent interception of PAR, was determined by using light meter with spectrally selective quantum sensor, which measures the radiation between 400 to 700 nm. Simultaneously the data on total radiation intercepted was also recorded using light meter with pyranometer sensor and also with tube solarimeter. The LAI of the crop was 2.43, the extent of total radiation intercepted was 66 to 67 per cent. The per cent total radiation intercepted was same when the total radiation was determined either with tube solarimeter or with light meter with pyranometer sensor. However, at the same LAI the per cent interception of PAR was 91.37 (Table 5). This suggests that, the per cent interception of PAR was relatively more compared to total radiation by crop canopies. This probably explains the relatively low values obtained when light interception was recorded by using light meter with pyranometer sensor or with tube solarimeter.

Table 5. Per cent light interception by the sunflower canopy (per cent absorption of total solar radiation and PAR by sunflower canopy).

LAI	Per cent absorption of total radiation		Per cent absorption PAR (quantum sensor reading)
	Tube solarimeter reading	Pyranometer sensor reading	
2.43	67.68	66.85	91.37

The relationship between canopy reflectance characteristics and the extent of canopy cover across the species

The primary objective of the experiment was to assess the extent of canopy cover (LAI) based on the CRCH at a specific wave length. Keeping this in view, the relationship was worked out between LAI and per cent CRCH at IR region. The regression value ($r = 0.522$) clearly indicated that, there was no relationship between LAI and CRCH at IR region when all the crops were used for computation. Similarly there was no relationship between LAI and extent of light interception, when these two parameters were related across the species ($r = 0.391$). This suggests that the reflectance characters of crop canopy are crop specific. For instance at given LAI of 2.20 (Cowpea), 2.13 (Soybean), 2.40 (Sorghum) and 2.06 (Amaranthus). Canopy reflectance values at IR region were 41.67 (Cowpea), 41.70 (Soybean), 33.33 (Sorghum) and 44.44 (Amaranthus). This indicates that for each crop, specific reflectance curves at different LAI have to be developed.

II. Leaf transmittance characters in relation to leaf chlorophyll content

In a series of experiments, the leaf transmittance at photographic red region (660 nm) was determined by using a portable instrument - Agrophotometer and the

extent of leaf transmittance was compared with the chlorophyll content, estimated calorimetrically.

The main objective of these experiments was ultimately to develop a non-destructive method for in vivo estimation of chlorophyll content under field conditions.

To obtain leaf materials with different chlorophyll content, crop species were grown at different nitrogen levels in sand culture.

In some experiments, field grown plants with different degree of yellowing (chlorosis) were used to assess the relationship between leaf transmittance characteristics and chlorophyll content.

IIa) The leaf transmittance characters and chlorophyll content in maize and amaranthus

In this set of experiments maize and amaranthus plants were raised in sand culture with different nitrogen levels.

MAIZE

Experiment-1: In this experiment plants were raised with four levels of nitrogen, the concentration of nitrogen in Hoagland's nutrient solution given to the plants was 84, 167, 250 and 330 ppm for in N_1 , N_2 , N_3

and N_4 respectively. Forty days after sowing leaf chlorophyll content and leaf transmittance characters were determined in third fully expanded leaf of the plant.

While recording the leaf transmittance characters using Agrophotometer, the blank meter reading was adjusted to full scale (195) without using any filter.

The chlorophyll content per unit fresh weight or per unit leaf area showed significant variation amongst the N treatments. With increase in chlorophyll content, the leaf transmittance values decreased. For instance, the leaf transmittance was 33.3 when the chlorophyll content was 0.13, whereas transmittance values were 29.8 and 19.50 when the chlorophyll contents was 0.45 and 2.10 mg g fresh weight respectively (Table 6)

The leaf transmittance values showed a negative significant relationship with leaf chlorophyll content. Such a relationship was seen both when chlorophyll content was expressed per unit fresh weight of leaf ($r = -0.696$) or per unit leaf area ($r = -0.789$) (Fig.10).

Table 6. Leaf transmittance characters at red region (660 nm) and chlorophyll content and leaf thickness in maize plants grown at different nitrogen levels.

Treat- ments	Chlorophyll content		Leaf thickness (μ)	Leaf trans- mittance with- out filter
	mg g^{-1} fr.wt. of leaf	mg dm^{-2} LA		
N ₁	0.13	0.20	17	33.3
	0.17	0.20	18	30.2
N ₂	0.45	0.70	17	29.8
	0.75	1.10	19	22.5
N ₃	0.98	1.20	17	22.4
	1.13	1.30	18	22.2
N ₄	1.66	3.50	18	20.9
	2.10	3.90	19	19.5
Mean:				
N ₁	0.15	0.20	17.5	31.75
N ₂	0.60	0.90	18.0	26.15
N ₃	1.06	1.25	17.5	22.30
N ₄	1.88	3.70	18.5	20.20
CD at 5%	0.21	0.16	NS	0.70

N₁ - 84 ppm nitrogen
 N₂ - 168 ppm nitrogen
 N₃ - 252 ppm nitrogen
 N₄ - 336 ppm nitrogen

Fig.10: Relationship between chlorophyll content and leaf transmittance characteristics at red region (660 nm) in maize. Chlorophyll content per unit fresh weight (a) and per unit LA (b).

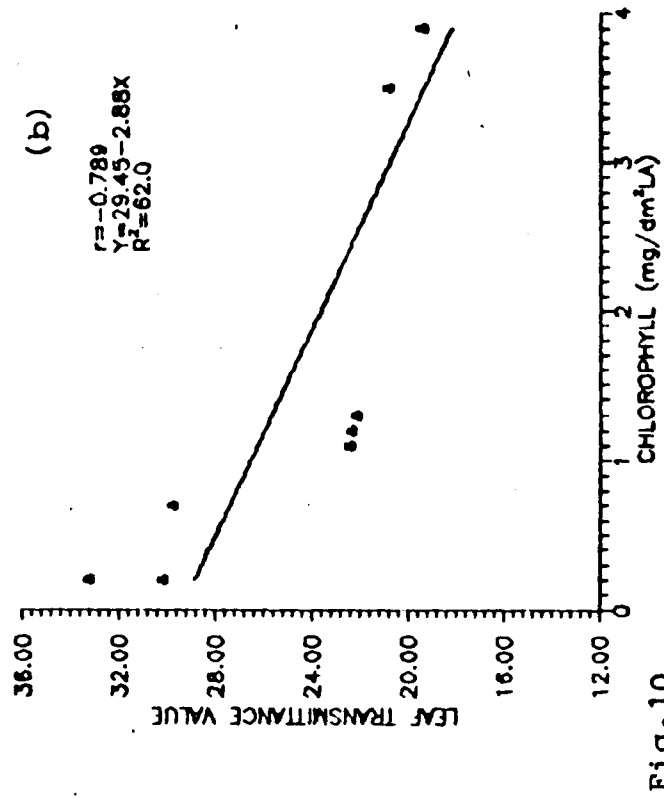
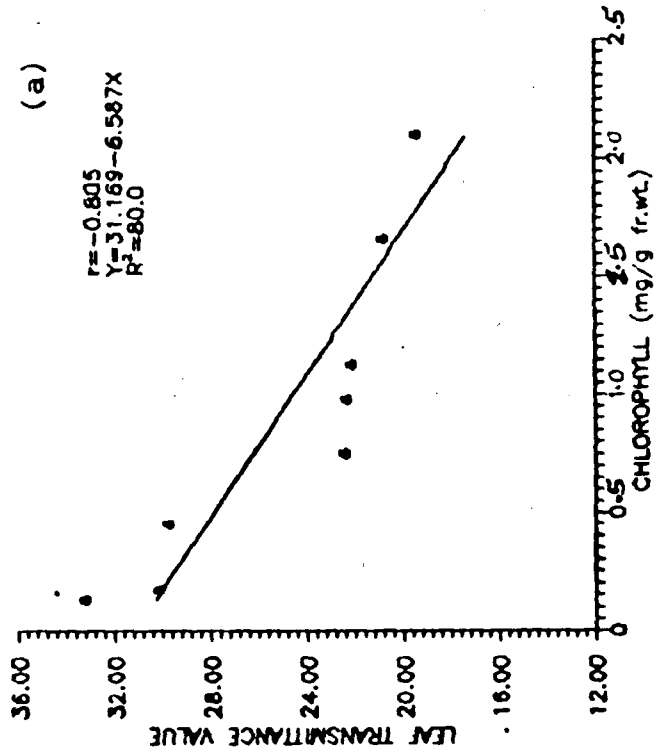


Fig. 10

Experiment-2

Nitrogen levels in this experiment were five. The plants were provided with 0, 84, 168, 210 and 252 ppm of nitrogen in Hoagland nutrient solution in N_0 , N_1 , N_2 , N_3 and N_4 respectively. As in the previous experiments chlorophyll content and leaf transmittance characters were determined on 40th day after sowing. The range in the chlorophyll content was 0.06 to 2.10 mg dm^{-2} leaf area (Table 7). Though the leaf thickness showed variations, there was no specific trend between leaf thickness and transmittance values. In this experiment, to obtain larger variation in the leaf transmittance values, the instrument gain was adjusted using the filters. Yellow gelatin paper with different thickness (17 and 25 μ) were used as filters. While recording the transmittance value without filter and with filter, the blank meter reading was adjusted to full scale of the meter.

The transmittance characters of the same leaf was recorded at three different gain sets of the instrument, first the instrument blank meter reading was adjusted to full scale of the meter without filter and transmittance characters of all the leaves were determined. After wards by using a thin yellow gelatin paper (thin filter), the gain was readjusted to full scale and transmittance values of all leaves were again

Table 7. Leaf transmittance characters at red region (660 nm) and chlorophyll content and leaf thickness in maize plants grown at different nitrogen levels (Leaf transmittance characters were measured at three different gains of the instrument).

Treat- ments	Chlorophyll content		Leaf thickness (μ)	Leaf transmittance values		
	mg g ⁻¹ of leaf	fr.wt. mg dm ⁻² LA		Without filter	With thin filter	With thick filter
N ₀	0.04	0.06	20	33.0	64.1	90.9
	0.04	0.06	22	32.9	64.8	91.2
	0.04	0.07	22	32.8	64.9	91.8
	0.06	0.09	20	30.2	60.5	83.6
N ₁	0.09	0.09	20	30.1	64.2	91.4
	0.10	0.09	19	30.1	60.0	83.0
	0.17	0.21	18	30.0	59.9	81.3
	0.17	0.21	21	26.6	59.8	82.0
N ₂	0.34	0.60	20	26.6	51.0	77.0
	0.36	0.60	22	26.4	50.1	77.0
	0.39	0.60	21	26.4	44.4	76.9
	0.40	0.80	21	26.3	49.8	77.0
N ₃	0.73	1.20	22	26.3	44.8	64.0
	0.76	1.20	21	22.6	40.0	64.0
	0.86	1.30	20	22.5	45.2	63.7
	0.86	1.50	22	22.4	46.2	63.8
N ₄	1.23	1.90	21	20.8	40.4	60.0
	1.26	2.00	20	20.4	40.2	59.0
	1.33	2.00	23	20.5	40.4	58.8
	1.35	2.10	23	20.7	39.8	59.0
Mean:						
N ₀	0.05	0.07	21.0	32.23	63.58	89.38
N ₁	0.13	0.15	19.5	30.70	63.98	84.43
N ₂	0.37	0.65	21.0	26.40	48.83	76.98
N ₃	0.80	1.30	21.3	22.47	44.05	63.88
N ₄	1.29	2.00	21.8	20.60	40.20	59.20
CD 5%	0.07	0.15	NS	1.44	3.34	4.68

N₀ - 0 ppm nitrogen
 N₁ - 84 ppm nitrogen
 N₂ - 168 ppm nitrogen
 N₃ - 210 ppm nitrogen
 N₄ - 252 ppm nitrogen

determined. Similarly the gain was further increased with thick yellow gelatin paper (thick filter) and after adjusting the meter read to full scale the leaf transmittance characters of all the leaves were determined.

Without using the filter (gain 0) the leaf transmittance values ranged from 20.4 to 33.0 in leaves differing in chlorophyll content (range in chlorophyll content was 0.06 to 2.1 mg dm⁻² LA), when gain was increased by using a thin filter (gain 1) the range in leaf transmittance values was from 39.8 to 64.9. The range in the transmittance value further increased, when the full scale meter reading adjusted by using a thick yellow gelatin filter (Gain 2). With thick filter leaf transmittance values ranged from 58.8 to 91.8.

This clearly indicated that the differences in the leaf transmittance values were more pronounced, when the instrument gain was increased by using a filter. However, relationship between chlorophyll content and leaf transmittance characters did not show a significant deviation, when the instrument gain was altered by using different filters.

In this experiment also there was significant negative relationship between leaf transmittances and

chlorophyll content. The regression value with chlorophyll content per unit leaf area was -0.959, 0.916 and -0.959 with gain 0, gain 1 and gain 2 respectively. Similarly the regression values of chlorophyll content per unit fresh weight of leaf with leaf transmittance values at gain 0, 1 and 2 were -0.949, -0.911 and -0.954, respectively (Fig.11).

However, in this experiment, there was no significant relationship between leaf transmittance and leaf thickness values.

Experiment-3

In this experiment six levels of nitrogen were tried to develop plant material with different chlorophyll content. The nitrogen levels in Hoagland's nutrient solution were 84 ppm (N_1), 168 (N_2), 252 (N_3), 366 (N_4) and 420 (N_6). Since, the range in the leaf transmittance values were higher with gain 2, in this experiment leaf transmittance values were determined by adjusting the full scale blank meter reading with thick yellow gelatin filter. The range in the chlorophyll content was 0.97 to 3.09 mg g fresh weight and the range in the transmittance values was 53.8 to 72.0 (Table 8). As in the previous experiments a significant negative relationship was seen between chlorophyll content and leaf transmittance values (Fig.12).

Fig.11: Relationship between chlorophyll content and leaf transmittance characteristics at red region (660 nm) in maize. Chlorophyll content at gain 0(a), 1(b) and 2(c). Chlorophyll content per unit LA at gain 0(a¹), 1(b¹) and 2(c¹).

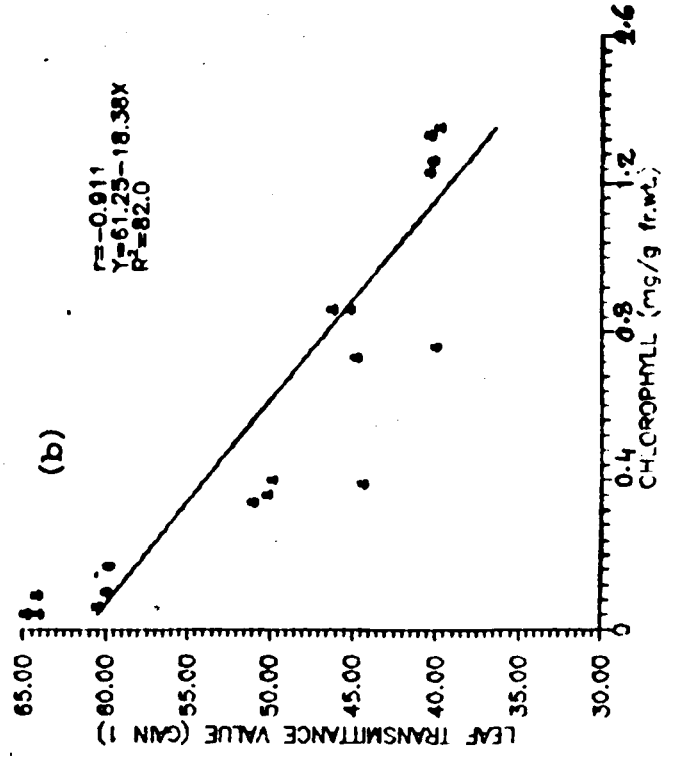
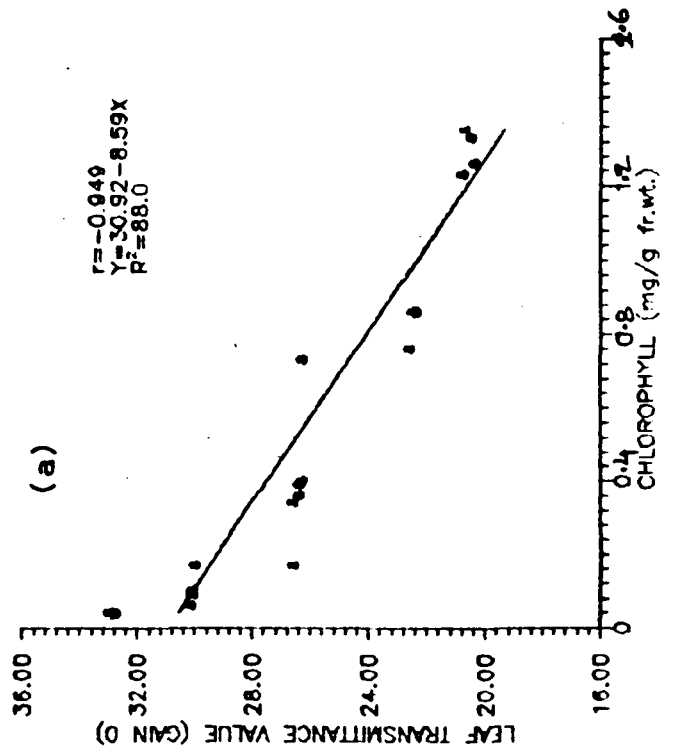
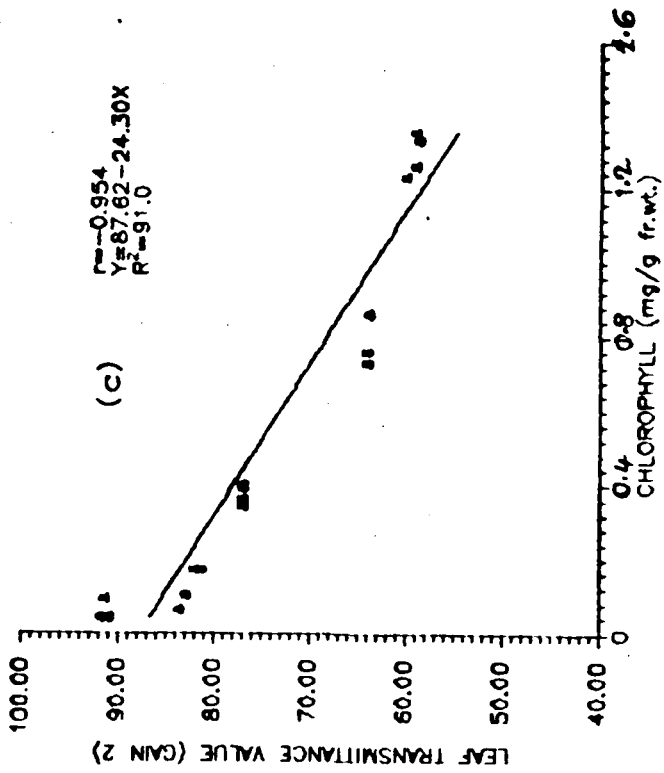


Fig. 11

Fig. 11 contd.

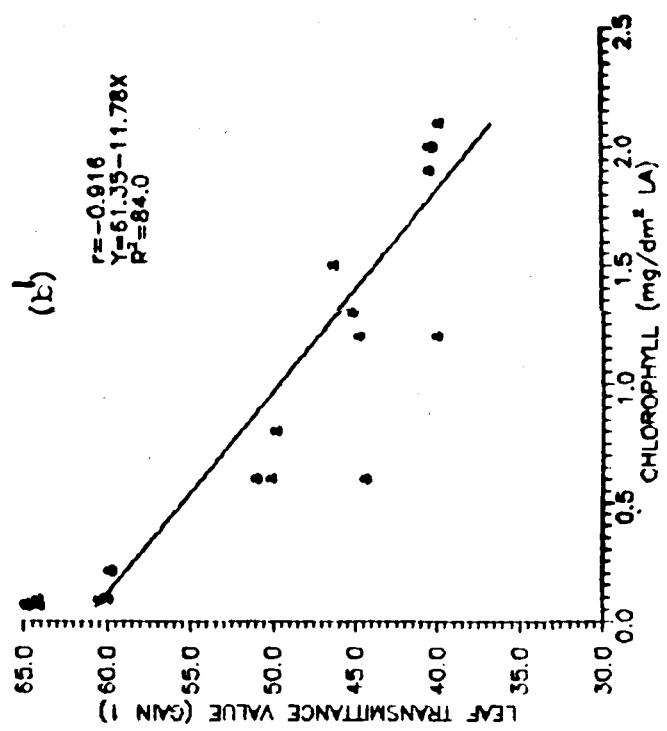
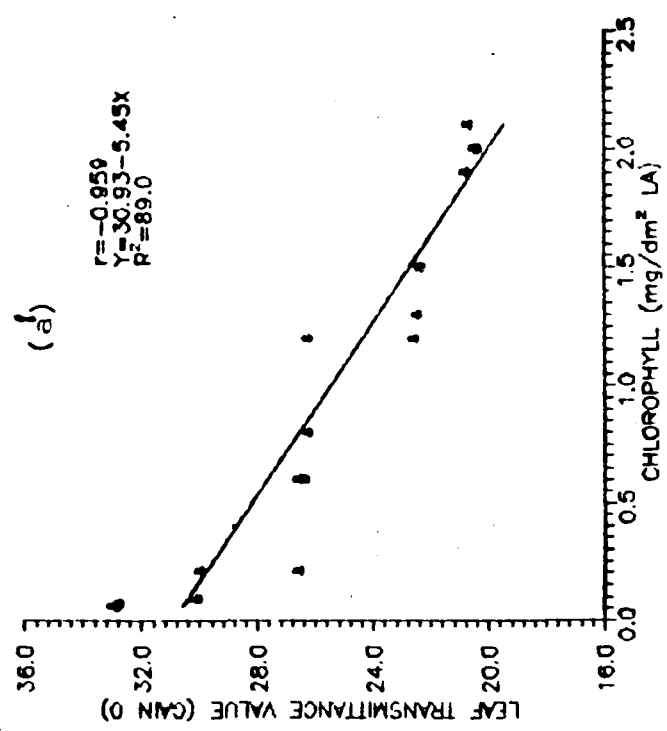
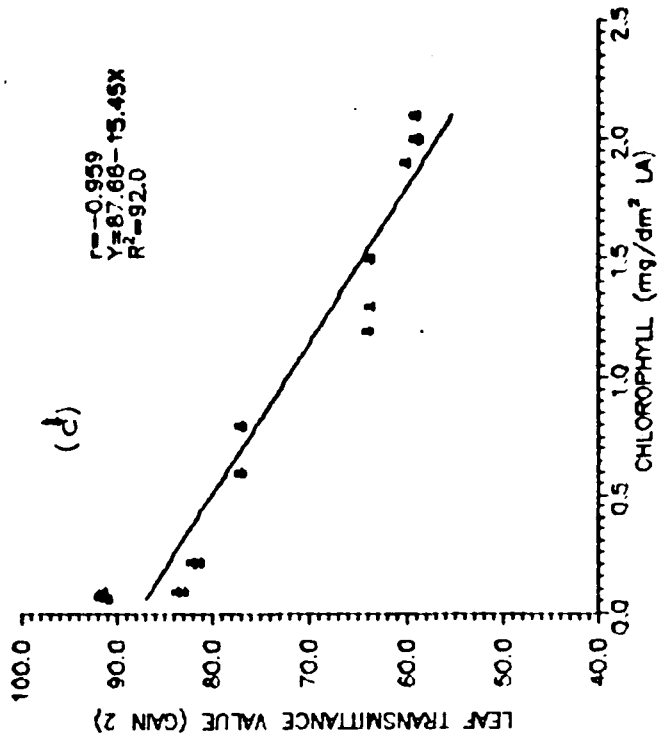


Table 8. Leaf transmittance characters at red region (660 nm) and chlorophyll content and leaf thickness in maize plants grown at different nitrogen levels.

Treatments	Chlorophyll content mg g ⁻¹ fr.wt. of leaf	Leaf thickness (μ)	Leaf transmittance values with thick filter
N ₁	0.97	16	72.0
	1.00	15	68.6
	1.01	15	68.8
N ₂	1.51	15	70.0
	1.54	16	68.0
	1.58	15	68.6
N ₃	2.08	15	68.1
	2.08	16	67.0
	2.09	15	67.8
N ₄	2.56	17	64.0
	2.69	15	64.0
	2.70	17	62.7
N ₅	3.00	17	54.5
	3.08	18	53.8
	3.09	17	54.4
Mean:			
N ₁	0.99	15.3	69.8
N ₂	1.54	15.3	68.7
N ₃	2.08	15.3	67.6
N ₄	2.65	16.3	63.6
N ₅	3.06	17.3	54.2
CD at 5%	0.10	NS	2.3

N₁ - 84 ppm nitrogen
 N₂ - 168 ppm nitrogen
 N₃ - 252 ppm nitrogen
 N₄ - 336 ppm nitrogen
 N₅ - 420 ppm nitrogen

Fig.12: Relationship between chlorophyll content and leaf transmittance characteristics at red region (660 nm) in maize. Chlorophyll content per unit fresh weight at gain 2.

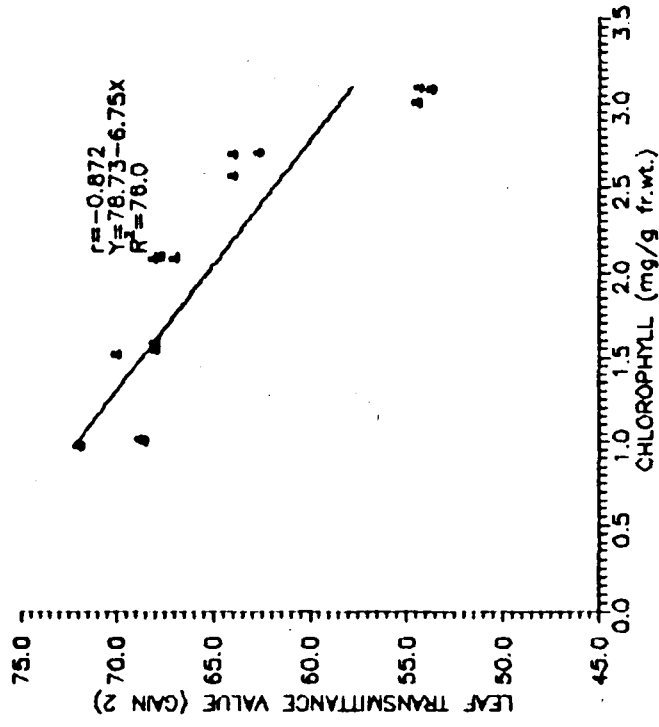


Fig. 12

AMARANTHUS

Experiment-1: In this experiment, amaranthus plants were grown at three different nitrogen levels in sand culture. The plants were fed with Hoagland's nutrient solution with 84 or 168 or 336 ppm N from 5th day after emergence. The chlorophyll content and leaf transmittance values at gain 0 and gain 1 were determined on 60th day after sowing. Chlorophyll content and leaf transmittance values were significantly differed amongst the treatments (Table 9). Though only 3 nitrogen levels were tried the differences in chlorophyll content was from 0.20 to 2.70.

There was a negative significant relationship between chlorophyll content and leaf transmittance values in amaranthus also. The regression values between chlorophyll content per unit fresh weight of leaf and transmittance values at gain 0 and gain 1 were -0.871 and -0.855 respectively. Similarly regression values between chlorophyll content per unit leaf area and leaf transmittance values at gain 0 and gain 1 were -0.791 and -0.756 respectively (Fig.13).

Experiment-2

With an objective to get greater ranges in leaf chlorophyll content, plants were grown at six different

Table 9. Leaf transmittance characters at red region (660 nm) and chlorophyll content and leaf thickness in amaranthus plants grown at different nitrogen levels (Leaf transmittance characters were measured at two different gains of the instrument).

Treat- ments	Chlorophyll content		Leaf thickness (μ)	Leaf transmittance value	
	mg g^{-1} of leaf	fr.wt. mg dm^{-2} LA		Without filter	Within filter
N ₁	0.10	0.20	21	24.6	48.0
	0.19	0.20	20	23.3	44.4
N ₂	0.22	0.30	18	22.6	45.8
	0.58	0.20	21	22.2	42.4
N ₃	1.43	2.40	19	21.0	40.0
	1.70	2.70	19	21.3	41.4
Mean:					
N ₁	0.15	0.20	20.5	24.20	46.2
N ₂	0.40	22.40	19.5	22.40	44.1
N ₃	1.57	2.55	19.0	21.15	40.7
CD at 5%	0.41	0.64	NS	1.69	8.6

N₁ - 84 ppm nitrogen
 N₂ - 168 ppm nitrogen
 N₃ - 336 ppm nitrogen

Fig.13: Relationship between chlorophyll content and leaf transmittance characteristics at red region (660 nm) in amaranthus. Chlorophyll content per unit fresh weight at gain 0(a) and 1(b). Chlorophyll content per unit LA at gain 0(a¹) and 1(b¹).

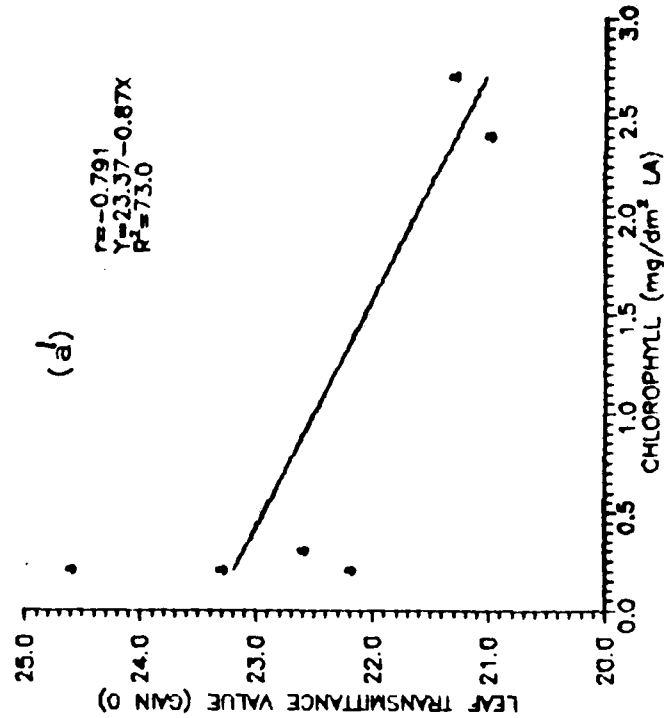
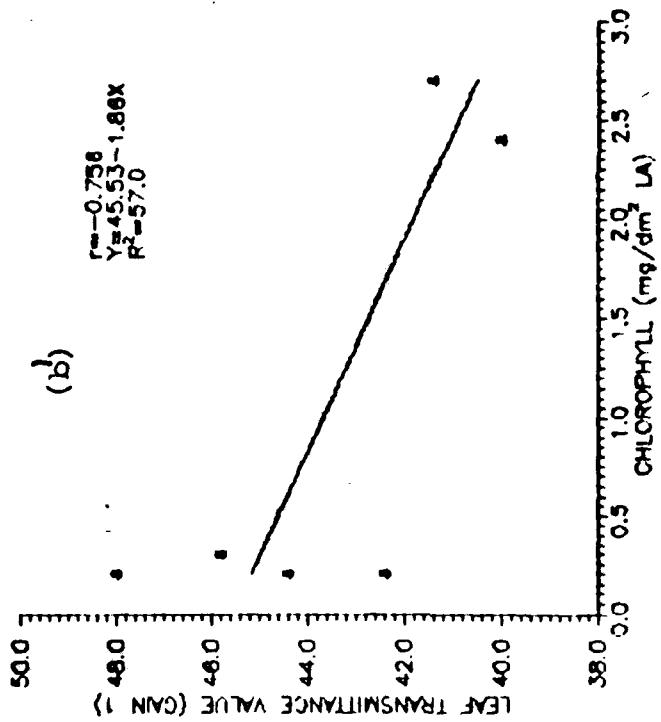
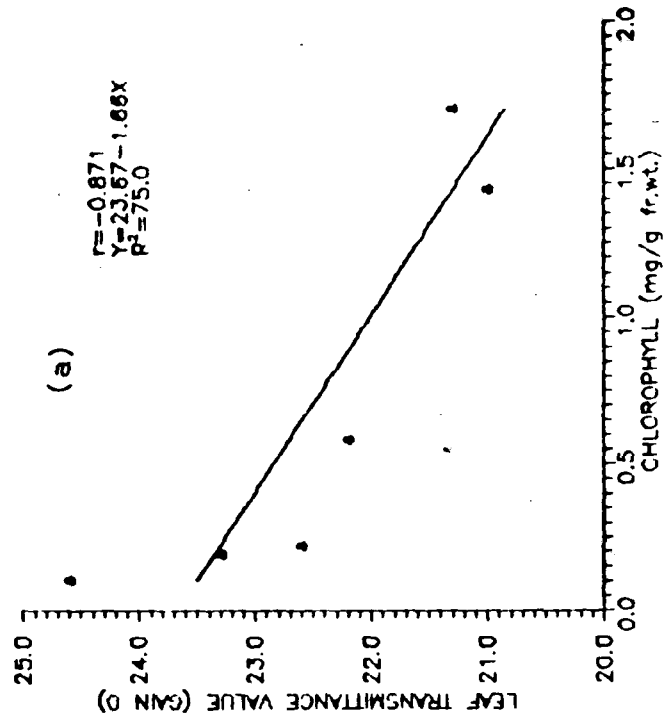
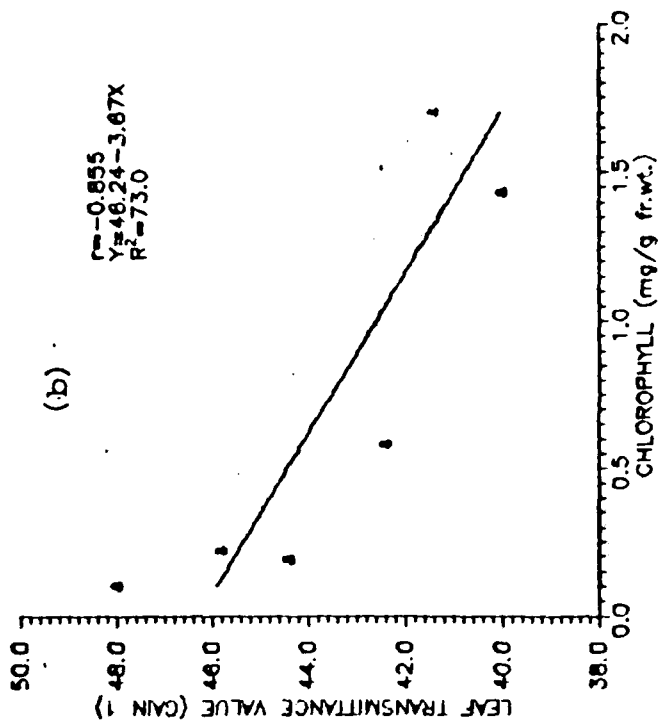


Fig. 13

N levels. The N levels tried were 126, 128, 210, 252, 294 and 336 ppm in Hoaglands nutrient solution.

On 60th day the chlorophyll content and leaf transmittance characters were determined at gain 1 by adjusting the blank meter reading to full scale using a thin yellow gelatin filter. The range in chlorophyll content and also leaf transmittance values were distinct compared to previous experiment of amaranthus (Table 10). There was a negative significant relationship between chlorophyll content and leaf transmittance values ($r = -0.815$) (Fig.14).

Leaf thickness varied from 25 to 29 μ . But differences in thickness were not associated with transmittance values.

SUNFLOWER

Experiment-1 The relationship between chlorophyll content and leaf transmittance characters were also studied in sunflower. In this experiment sunflower plants were randomly selected from field bulk plants, which were showing different degrees of yellowing. For this study only middle leaves were used. Depending on intensity of yellowing and chlorophyll content four different categories of plants were identified and designated as T_1 , T_2 , T_3 and T_4 . Chlorophyll content in T_1 was maximum where as in T_4 the chlorophyll was minimum.

Table 10. Leaf transmittance characters at red region (660 nm) and chlorophyll content and leaf thickness in amaranthus plants grown at different nitrogen levels. amaranthus.

Treatments	Chlorophyll content mg g ⁻¹ fr.wt. of leaf	Leaf thickness (μ)	Leaf transmittance value with thin filter
N ₁	0.50	25	38.45
	0.57	25	35.65
	0.61	26	31.75
N ₂	0.66	26	30.00
	0.72	27	27.75
	0.76	26	26.50
N ₃	0.79	27	27.90
	0.81	27	29.85
	0.86	26	24.25
N ₄	0.96	26	27.20
	1.03	26	26.10
	1.21	27	25.65
N ₅	1.27	28	25.00
	1.34	27	22.15
	1.34	28	24.50
N ₆	1.37	28	24.50
	1.51	29	23.50
	1.54	29	23.50
Mean:			
N ₁	0.56	25.3	35.62
N ₂	0.71	26.7	28.08
N ₃	0.82	26.7	27.00
N ₄	1.07	26.3	26.32
N ₅	1.32	27.7	23.88
N ₆	1.47	28.8	23.67
CD at 1%	0.12	NS	4.47

N₁ = 126 ppm nitrogen; N₂ = 168 ppm nitrogen;
 N₃ = 210 ppm nitrogen; N₄ = 252 ppm nitrogen;
 N₅ = 294 ppm nitrogen; N₆ = 336 ppm nitrogen.

Fig.14: Relationship between chlorophyll content and leaf transmittance characteristics at red region (660 nm) in amaranthus. Chlorophyll content per unit fresh weight at gan 1.

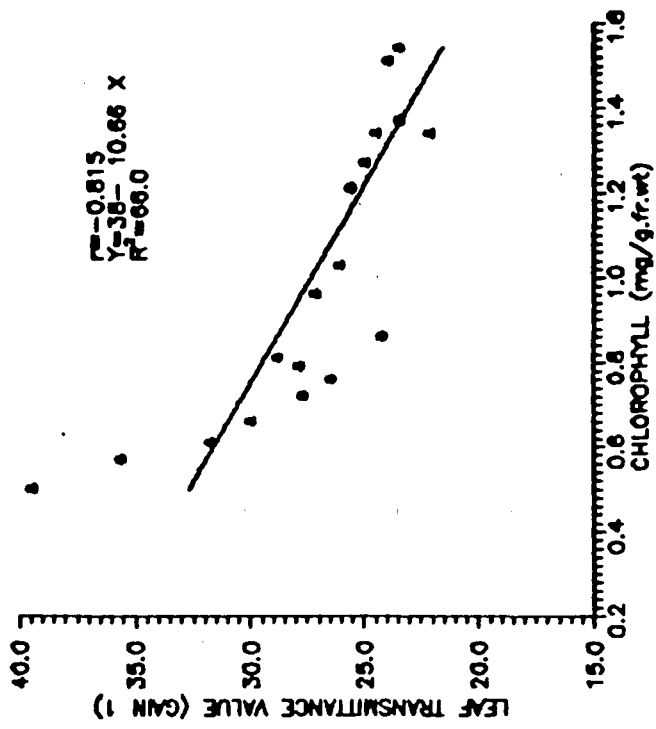


Fig. 14

The leaves from the field grown plants were brought to the laboratory in turgid condition and chlorophyll content and leaf transmittance values were determined at gain 0 and gain 1 as detailed in the previous experiments.

The differences in the chlorophyll content and leaf transmittance values were significant amongst the treatments. However, the leaf thickness did not vary significantly.

Negative significant relationship between chlorophyll content and leaf transmittance values were observed when chlorophyll content was expressed per unit fresh weight of leaf or per unit leaf area and also leaf transmittance values obtained at gain 0 or gain 1 (Table 11).

Results obtained in this experiment using sunflower clearly indicated that even in field grown plants the chlorophyll content showed a negative significant relationship with leaf transmittance values (Fig.15).

Unlike the previous experiments plants were not raised at different nitrogen levels, but when the plants were chlorotic due to several factors, the

Table 11. Leaf transmittance characters at red region (660 nm) and chlorophyll content and leaf thickness in field grown sunflower crop (Leaf transmittance characters were measure at two different gains of the instrument).

Treat- ments	Chlorophyll content		Leaf thickness (μ)	Leaf transmittance value	
	mg g^{-1} of leaf	fr.wt. mg dm^{-2} LA		Without filter	With thin filter
T ₁	0.25	0.40	34	24.6	49.0
	0.28	0.50	34	24.1	48.0
T ₂	0.35	0.70	34	21.3	41.2
	0.48	0.90	35	20.5	40.1
T ₃	0.50	1.00	35	20.9	39.9
	0.72	1.40	35	20.6	38.4
T ₄	0.95	2.10	36	20.5	37.9
	1.09	2.20	36	20.4	36.4
Mean:					
T ₁	0.27	0.45		24.35	48.50
T ₂	0.42	0.80		20.90	40.65
T ₃	0.61	1.20		20.75	39.15
T ₄	1.02	2.15		20.45	37.15

CD at 5%	0.17	0.47	NS	0.68	0.60

T₁ - Leaves from bottom whorl of the plant
T₂ - Leaves from middle whorl of the plant
T₃ - Leaves from top whorl of the plant
T₄ - Leaves from top whorl (just fully expanded youngest leaf) of the plant.

Fig.15: Relationship between chlorophyll content and leaf transmittance characteristics at red region (660 nm) in sunflower. Chlorophyll content per unit fresh weight at gain 0(a) and 1(b). Chlorophyll content per unit LA at gain 0(a¹) and 1(b¹).

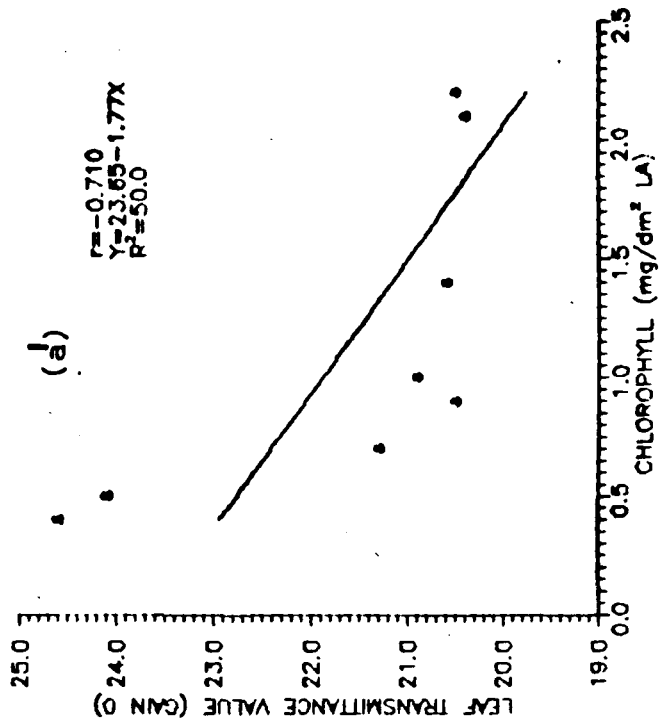
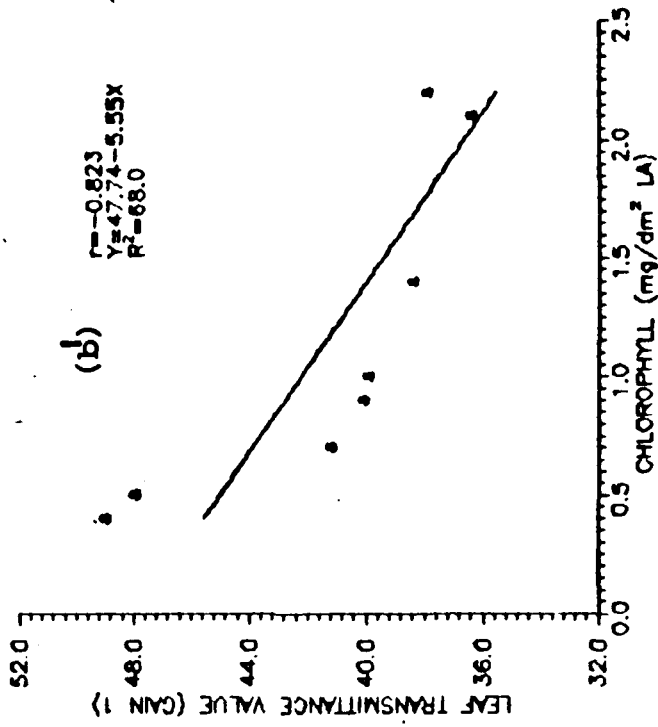
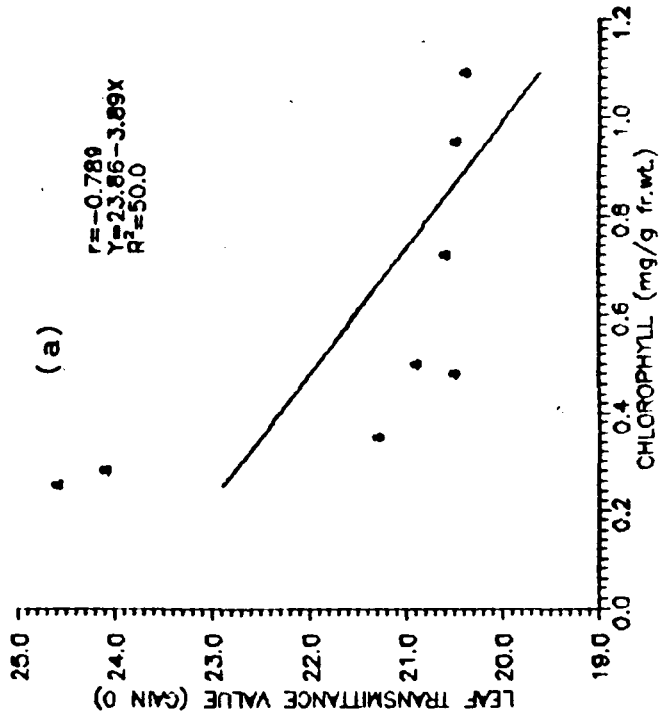
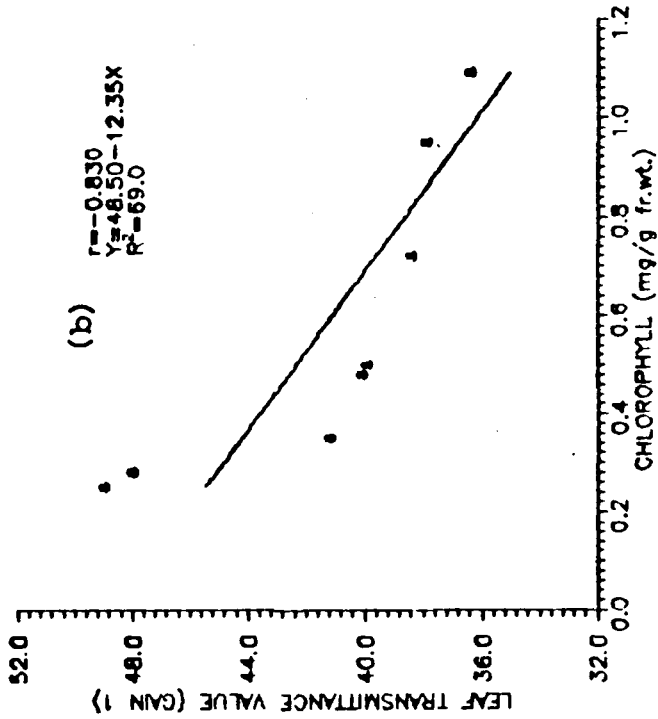


Fig. 15

chlorophyll status of such leaves can be determined in situ merely by assessing the transmittance characters. Based on these results, it can be concluded that leaf transmittance characters at photographic red region can be used to determine the chlorophyll status.

TOBACCO

Experiment-1: Tobacco seedlings were transplanted into the pots filled with soil and they were grown by providing normal recommended fertilizer levels. Seventy five days after transplanting, the lower leaves started showing senescence and were chlorotic. The leaves in the middle and upper whorls were showing different degrees of yellowing. However, the top most leaves were still green in colour.

The objective of this experiment was to assess the relationship between the chlorophyll content and leaf transmittance characters amongst the leaves on the same plant. Therefore, at the time of sampling (75th day after transplanting) two leaves each from bottom, middle and top whorls and also just fully expanded youngest leaves from the top were selected. Depending on the intensity of green colour of leaves by visual observation, they were categorised into eight groups. Increasing in colour intensity from T_1 to T_8 . T_1 showed minimum chlorophyll content and T_8 maximum chlorophyll content.

In these leaves as described earlier the chlorophyll content and leaf transmittance were determined. While taking leaf transmittance values, the blank meter reading was adjusted to meter full scale with or without filters. Thus, the leaf transmittance values were determined at gain of 0, 1 and 2 of the instrument.

The chlorophyll content showed distinct variations from 0.07 to 3.14. Similarly, the range in leaf transmittance value was from 15.8 to 25.6, 28.9 to 51.0 and 54.9 to 99.1 for gains 0, 1 and 2 respectively (Table 12). Though the leaves were taken from different positions of the plant, the differences in leaf thickness was only from 25 to 30 μ . In general, top leaves showed less thickness than of the bottom leaves. But the observed differences in chlorophyll content amongst the leaves was mainly due to differences in chlorophyll content rather than the differences in leaf thickness. In this experiment also there was negative significant relationship between chlorophyll content and leaf transmittance characters. One interesting observation of this experiment was when gain was increased, the regression values between chlorophyll content and transmittance values were increased. For example, the regression values between chlorophyll content (per unit LA) and leaf transmittance values at

Table 12. Leaf transmittance characters at red region (660 nm) and chlorophyll content and leaf thickness in aged (75 DAP) pot grown tobacco plants (Leaf transmittance characters were measured at three different gains of the instrument).

Treat- ments	Chlorophyll content		Leaf thickness (μ)	Leaf transmittance values		
	mg g^{-1} of leaf	fr.wt. mg dm^{-2} LA		Without filter	With thin filter	With thick filter
T ₁	0.03	0.07	30	25.2	49.9	96.8
	0.04	0.08	30	25.3	50.5	99.1
	0.04	0.07	30	25.6	51.0	98.2
	0.05	0.10	29	25.4	50.0	98.9
T ₂	0.06	0.13	29	20.3	41.0	80.0
	0.07	0.17	29	20.3	40.1	79.8
	0.08	0.17	29	20.2	39.8	78.9
	0.09	0.19	28	20.4	40.0	78.9
T ₃	0.16	0.33	25	18.8	37.6	72.3
	0.18	0.36	28	18.9	37.0	71.8
	0.19	0.36	28	18.7	37.0	71.9
	0.21	0.42	27	19.0	37.8	72.3
T ₄	0.21	0.41	27	18.7	37.0	71.8
	0.22	0.44	26	18.4	36.2	70.9
	0.29	0.58	26	18.6	36.6	71.3
	0.32	0.56	27	18.5	36.4	71.8
T ₅	0.30	0.53	27	18.2	35.6	71.2
	0.30	0.54	27	18.0	36.0	69.9
	0.34	0.62	26	18.1	35.8	70.3
	0.35	0.59	26	17.9	35.9	70.4
T ₆	0.70	1.41	26	17.0	34.6	68.1
	0.71	1.35	27	17.5	34.9	68.4
	0.76	1.44	28	17.9	35.0	17.0
	0.79	1.51	28	18.0	35.9	69.9
T ₇	1.15	2.39	25	16.3	32.1	61.8
	1.21	2.17	27	16.6	32.4	61.6
	1.28	2.57	25	16.4	31.9	59.9
	1.30	2.44	26	16.5	32.1	60.1

Contd. . .

T ₈	1.38	2.81	25	15.8	28.9	54.9
	1.47	2.81	26	16.0	31.0	59.0
	1.48	3.21	27	15.9	30.0	58.9
	1.58	3.14	26	16.0	32.0	59.4

Mean:

T ₁	0.08	0.08	25.8	25.38	50.35	98.25
T ₂	0.17	0.17	26.3	20.30	40.25	79.40
T ₃	0.37	0.37	27.3	18.85	37.35	72.08
T ₄	0.50	0.50	26.5	18.55	36.55	71.45
T ₅	0.65	0.65	26.5	18.05	35.83	70.55
T ₆	1.43	1.43	27.5	17.80	35.10	69.10
T ₇	2.39	2.39	28.8	16.45	32.13	60.85
T ₈	2.99	2.99	29.8	16.18	30.48	38.05

CD 5%	0.04	1.17	NS	0.34	0.78	1.44
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T₁ to T₈ is the leaf position from bottom to fully just expanded youngest leaf.

gain 0 was -0.708, where as at gain 1 and gain 2 it was -0.749 and -0.778 respectively (Fig.16).

The results of this experiment also confirmed that the differences in chlorophyll content amongst the leaves can be determined in situ by determining leaf transmittance values.

Experiment-2

The results obtained in the prveious experiments indicated that the relationship between chlorophyll content and leaf transmittance characters were more pronounced when blank meter reading was adjusted to meter full scale with thick yellow gelatin paper filter. Therefore a specific ground glass filter which approximately reduces light transmittance by 50 per cent was used for further studies. The extent of reduction in leaf transmittance values by this ground glass filter is similar to thick yellow gelatin paper filter. Using this ground glass filter the leaf transmittance characters were determined in this experiment.

In this experiment also, the pot grown tobacco plants were used . Seventy five days after transplanting leaves from different whorls were brought to the laboratory in turgid condition and leaf transmittance characters were determined. Depending on

Fig.16: Relationship between chlorophyll content and leaf transmittance characteristics at red region (660 nm) in tobacco. Chlorophyll content per unit fresh weight at gain 0(a), 1(b) and 2(c). Chlorophyll content per unit LA at gain 0(a¹), 1(b¹) and 2(c¹).

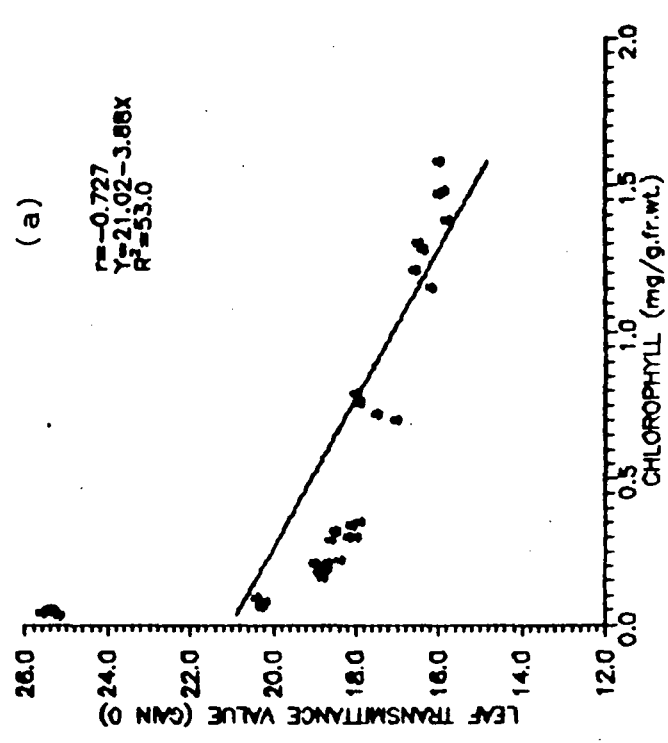
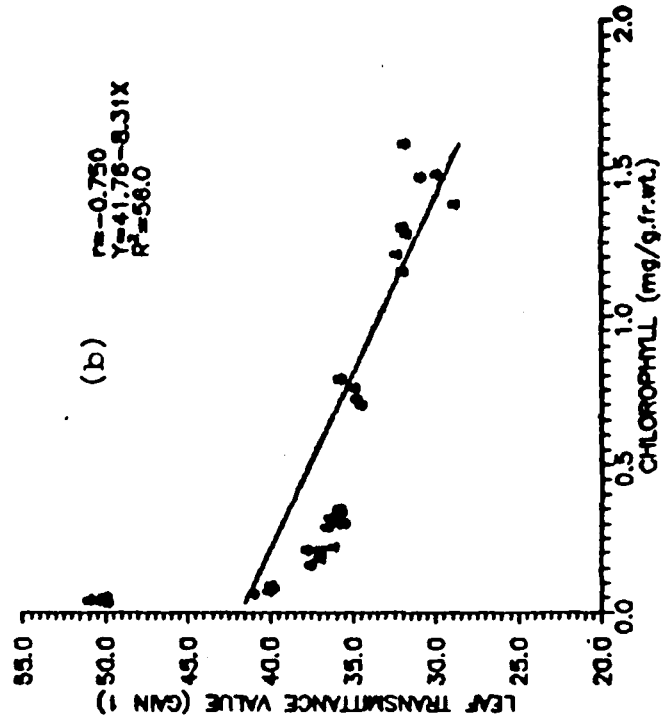
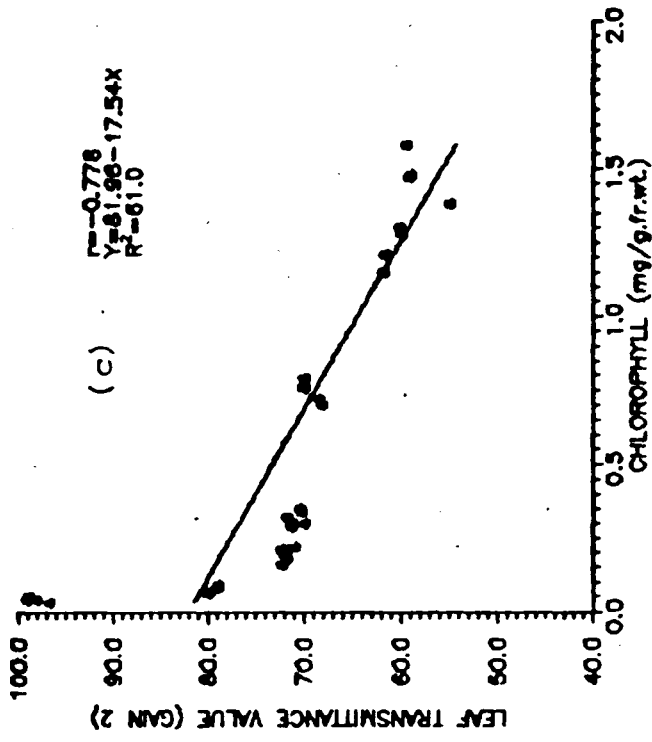
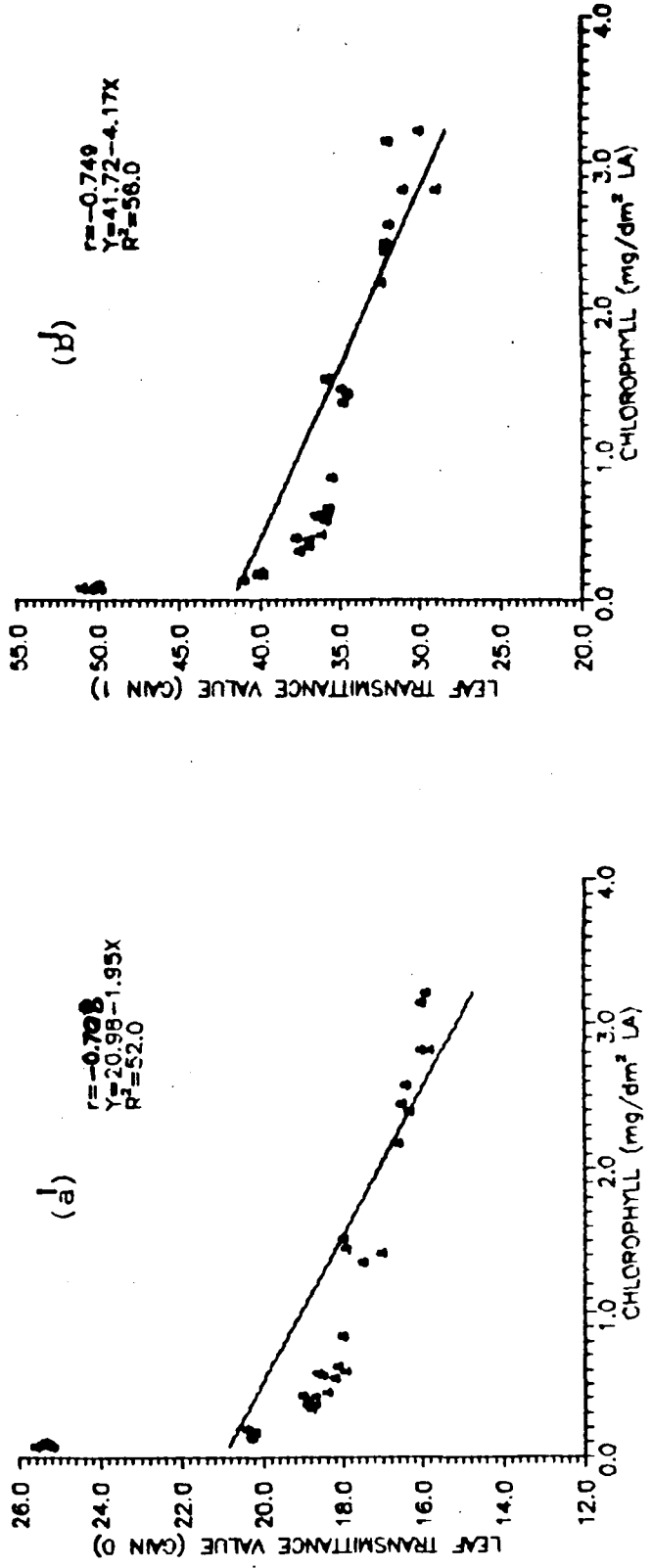
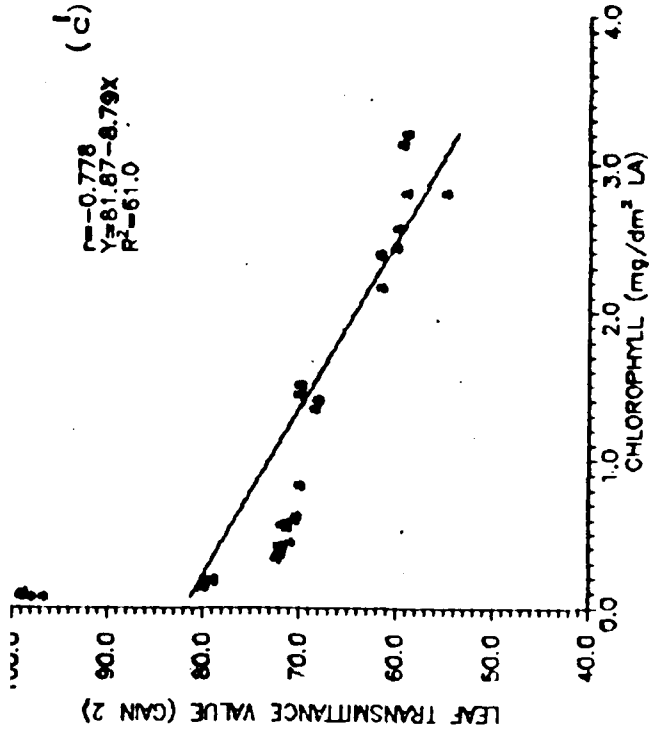


FIG. 16

Fig. 16 contd.



the intensity of green colour of leaves by visual observation, they were categorized into four groups. Increasing colour intensity T_1 to T_4 .

The T_1 contained minimum chlorophyll content and T_4 maximum chlorophyll content. The leaf transmittance characters were also determined by using ground glass filter (Table 13).

The results showed a significant negative relationship between chlorophyll content and leaf transmittance characters. The regression values between chlorophyll content per unit fresh weight and leaf transmittance values at gain 0 and gain 2 (ground glass filter) were -0.814 and -0.828 respectively. Similarly regression values between chlorophyll content per unit leaf area and leaf transmittance values were -0.697 and -0.723 at gain 0 and gain 2 respectively (Fig.17).

Experiment-3

In another set of pot grown tobacco plants, the relationship between chlorophyll content and leaf transmittance characters was assessed amongst leaves of the same plant. As in the previous experiments leaves from top, middle and bottom whorals and also from just fully expanded youngst leaves were collected and chlorophyll content and leaf transmittance characters

Table 13. Leaf transmittance characters at red region (660 nm) and chlorophyll content and leaf thickness in aged (75 DAP) pot grown tobacco plants (Leaf transmittance characters were measured at two different gain of the instrument).

Treat- ments	Chlorophyll content		Leaf thickness (μ)	Leaf transmittance values	
	mg g^{-1} of leaf	fr.wt. mg dm^{-2} leaf area		Without filter	With ground glass filter
T ₁	0.02	0.00	25	22.8	61.6
	0.02	0.00	25	24.2	64.7
	0.02	0.27	25	24.2	64.7
	0.03	0.00	26	23.5	61.8
T ₂	0.14	0.29	26	17.6	47.1
	0.16	0.29	26	17.4	50.1
	0.16	0.29	26	17.4	48.8
	0.18	0.28	25	16.7	50.0
T ₃	0.55	1.31	26	14.8	45.0
	0.56	1.24	26	15.4	44.0
	0.61	1.23	26	15.0	45.4
	0.64	1.25	26	15.0	44.3
T ₄	1.00	2.38	26	13.8	40.6
	1.04	2.31	28	14.8	42.8
	1.06	2.57	25	13.8	40.6
	1.07	2.61	26	14.1	42.6
Mean:					
T ₁	0.022	0.068	25.50	23.675	63.200
T ₂	0.160	0.287	25.75	17.500	49.000
T ₃	0.590	1.257	26.00	15.050	44.675
T ₄	1.042	2.467	25.50	14.125	41.550
CD at 5%	0.05	0.160	NS	0.860	2.310

T₁ Leaves from bottom whorl of the plant
T₂ Leaves from middle whorl of the plant
T₃ Leaves from top whorl of the plant
T₄ Leaves from top whorl (just fully expanded youngest leaf) of the plant.

Fig.17: Relationship between chlorophyll content and leaf transmittance characteristics at red region (660 nm) in tobacco. Chlorophyll content per unit fresh weight at gain 0(a) and ground glass filter(b). Chlorophyll content per unit LA at gain 0(a¹) and ground glass filter(b¹).

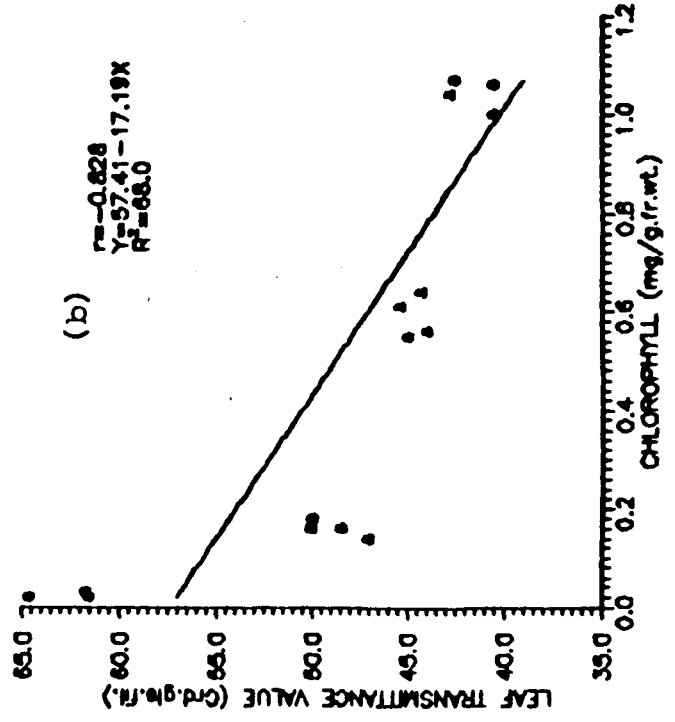
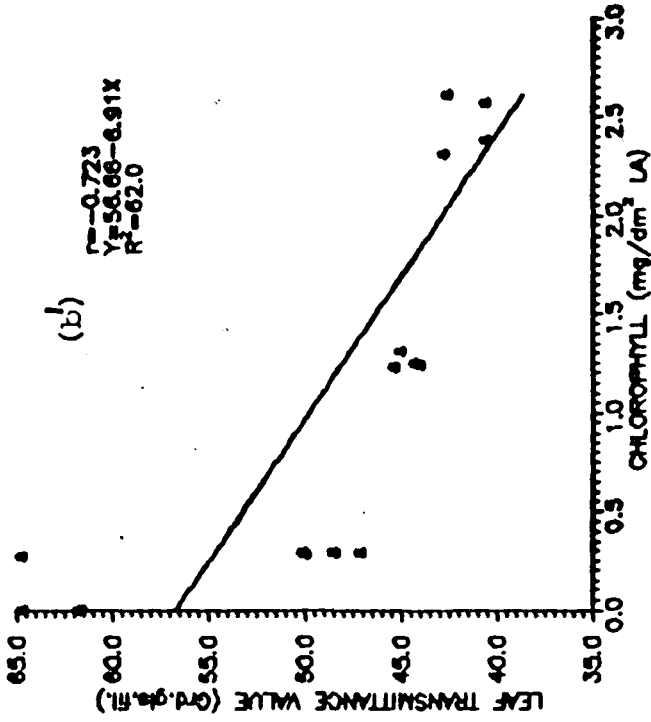
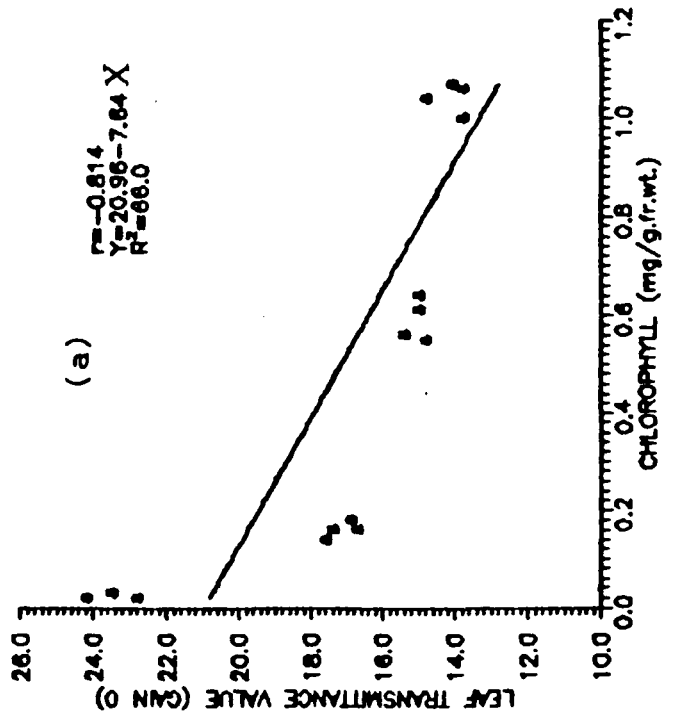
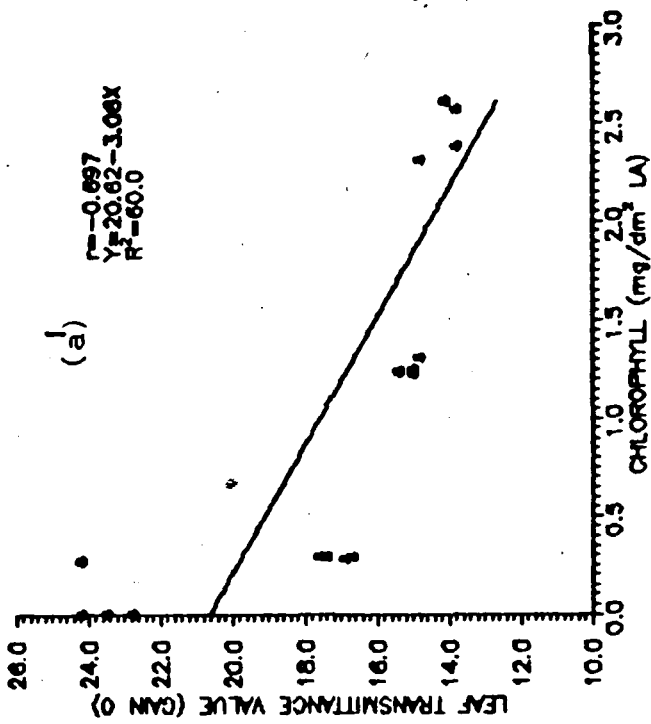


Fig. 17

were determined. Leaf transmittance characters were also determined both at gain 0 (without filter) and gain 2 (with ground glass filter).

In this experiment also chlorophyll content decreased progressively from top leaves to bottom leaves and leaf transmittance values increased correspondingly (Table 14). A significant negative relationship was seen between chlorophyll content and leaf transmittance values. The regression values between chlorophyll content per unit fresh weight of leaf and leaf transmittance values were -0.737 and -0.859 at gain 0 and gain 2 respectively. Similarly regression values between chlorophyll content per unit leaf area and leaf transmittance values at gain 0 and gain 2 were -0.764 and -0.874 respectively (Fig.18).

The results obtained in these experiments using the different species clearly indicates that a significant negative relationship exists between chlorophyll content and the leaf transmittance values.

Several methods were adopted to obtain leaves differing in chlorophyll content. In one of the approaches the leaf material with different chlorophyll content was developed by manipulating the nitrogen levels supplied in the nutrient media. The other approach was selecting plants which differ in degree of

Table 14. Leaf transmittance characters at red region (660 nm) and chlorophyll content and leaf thickness in aged (75 DAP) pot grown tobacco plants (Leaf transmittance characters were measured at two different gain of the instrument).

Treat- ments	Chlorophyll content		Leaf thickness (μ)	Leaf transmittance values	
	mg g ⁻¹ of leaf	fr.wt. mg dm ⁻² leaf area		Without filter	With ground glass filter
T ₁	0.05	0.07	29	24.7	56.3
	0.05	0.08	29	24.5	56.0
	0.05	0.09	30	24.2	55.9
	0.05	0.10	28	24.1	55.3
T ₂	0.23	0.47	28	29.1	41.2
	0.23	0.46	27	17.3	42.2
	0.23	0.46	28	17.4	42.9
	0.25	0.54	27	17.0	42.0
T ₃	0.41	1.04	27	15.9	41.2
	0.41	1.03	27	15.9	41.0
	0.41	1.00	26	16.0	40.0
	0.42	1.02	28	16.0	40.2
T ₄	1.50	3.13	26	14.3	33.8
	1.54	3.14	27	13.9	31.0
	1.58	3.16	27	14.0	30.0
	1.58	3.31	26	13.2	29.0
Mean:					
T ₁	0.05	0.09	29.0	24.38	55.88
T ₂	0.24	0.48	27.5	17.28	42.30
T ₃	0.41	1.02	27.0	15.95	40.63
T ₄	1.55	3.19	26.5	13.85	30.95
CD at 5%	0.1	0.07	NS	0.37	1.92

T₁ - Leaves from bottom whorl of the plant
T₂ - Leaves from middle whorl of the plant
T₃ - Leaves from top whorl of the plant
T₄ - Leaves from top whorl (just fully expanded youngest leaf) of the plant.

Fig.18: Relationship between chlorophyll content and leaf transmittance characteristics at red region (660 nm) in tobacco. Chlorophyll content per unit fresh weight at gain 0(a) and ground glass filter(b). Chlorophyll content per unit LA at gain 0(a¹) and ground glass filter(b¹).

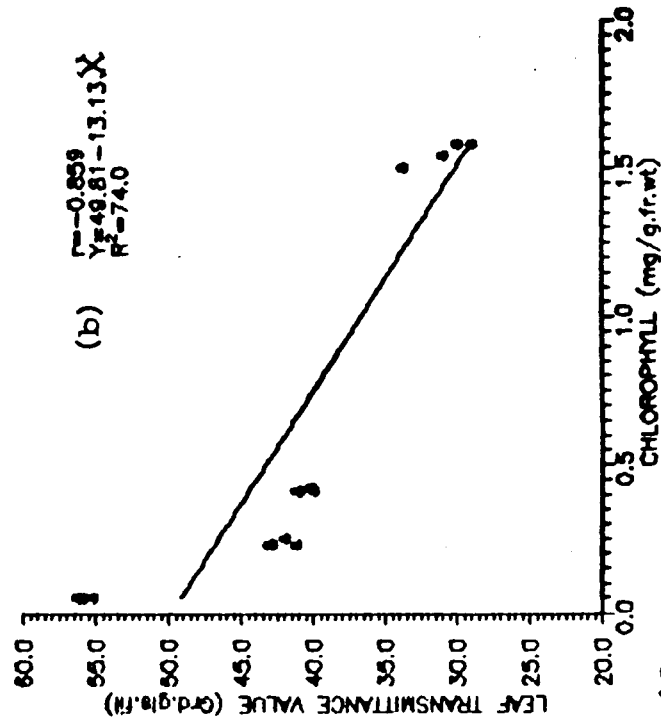
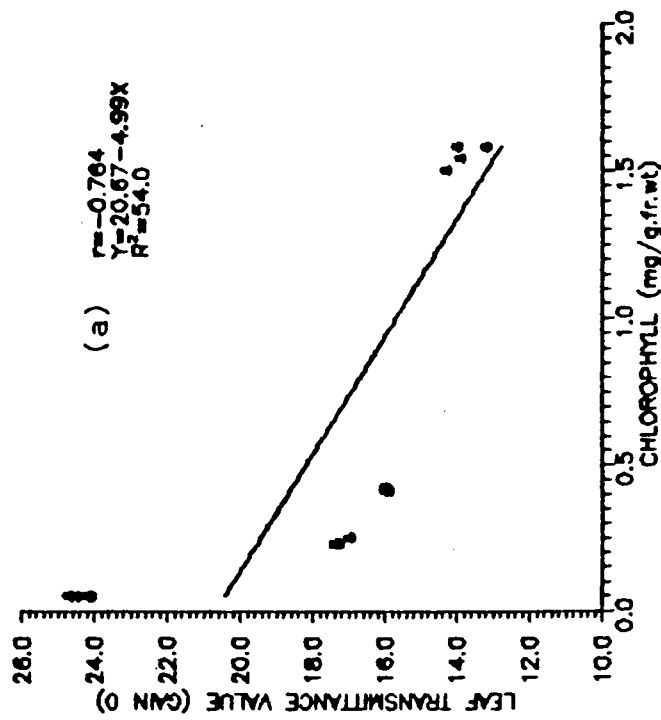
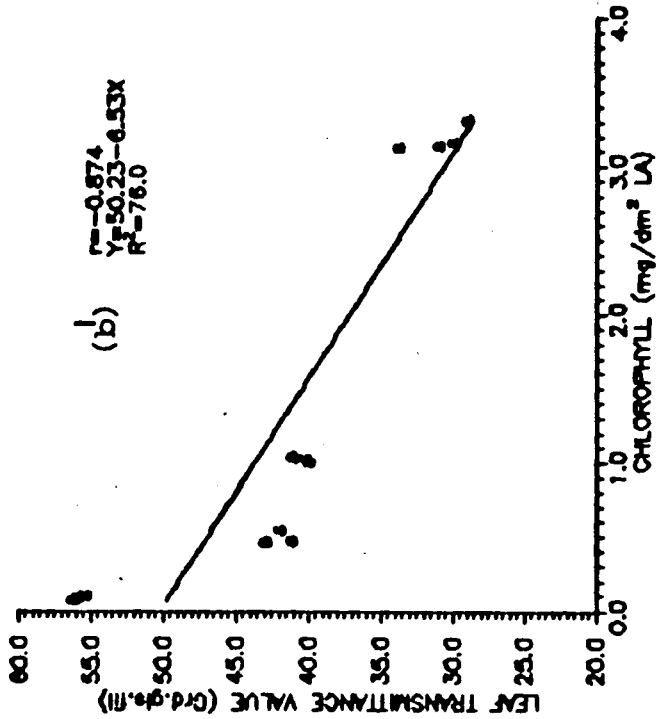
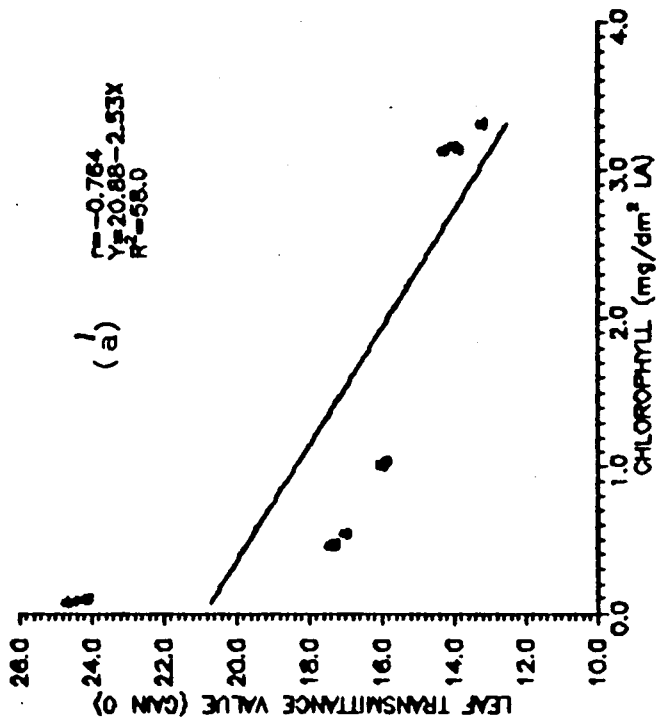


Fig. 18

yellowing in field grown plants (bulk crops) and third approach was to obtain leaves which differ in the leaf chlorophyll content by collecting leaves from different position of the aged pot grown plants. Irrespective of the methods adopted to obtain leaves with different chlorophyll content, in all the experiments a significant negative relationship was seen between chlorophyll content and leaf transmittance values.

In general, the relationship between chlorophyll content and leaf transmittance characters (r values) were marginally high when gain was increased by adjusting the blank meter reading to meter full scale using a filter. However, at all gains there was significant negative relationship between chlorophyll content and leaf transmittance characters. These results emphasised the possibility of in situ measurement of chlorophyll content by determining the leaf transmittance characters using agrophotometer.

III. Leaf transmittance characters as influenced by moisture stress

Moisture status of leaf also influences the transmittance characters of leaf. This aspect was investigated by taking leaf transmittance characters at near infra-red region using Agrophotometer in leaves differing in RWC. Ultimately the objective of these

studies was to determine leaf water status by using transmittance characters of leaf.

Several experiments were conducted to arrive at the relationship between these two characteristics. Experiments were broadly divided into two categories

- (1) Live wilting experiments with excised leaves
- (2) Pot culture experiments imposing different stress levels.

III(1) Live wilting experiments

In these experiments, the leaf material was brought from well watered pot or field grown plants. The leaves in turgid condition were brought to the laboratory. They were floated in water for a period of six hours to attain the maximum turgidity. These turgid leaves were live wilted for different periods under laboratory conditions to achieve leaf material with different moisture status. In these leaves the leaf water content, relative water content (RWC) and leaf transmittance characters using water channel (NIR) of the instrument were determined.

COWPEA

Leaves from 40 day old pot grown cowpea plants were brought to the laboratory. After bringing them to full turgidity, the fresh weight of the leaves was

recorded and using these leaves, the Agrophotometer reading in water channel was adjusted to 100. Then these leaves were subjected to live wilting under laboratory conditions (temperature $26^{\circ} \pm 2^{\circ}$ C, RH $50\% \pm 10\%$ and light intensity $100 \mu\text{Ei m}^{-2} \text{ sec}^{-1}$). At regular intervals, leaf fresh weight, thickness and leaf transmittance values were recorded. The leaves were live wilted until the fresh weight loss was 50 to 60 per cent of turgid weight. By adopting this method the RWC was altered from 74.57 to 51.53 per cent.

The results obtained in this experiment suggest that though the RWC decreased considerably, there was marginal decrease in the leaf transmittance values (meter reading at water channel). For instance, the leaf transmittance values were 95.1 at RWC of 74.57 per cent, whereas at RWC 67.21 and 51.53 the transmittance values were 93.3 and 91.3 respectively (Table 15). This indicated that there was no relationship between water content of leaf as expressed in RWC and leaf transmittance characters. The regression value between RWC and leaf transmittance values was 0.322.

The leaf thickness was recorded in turgid leaf and also at the end of experiment (when RWC brought down to around 50 per cent). There was marginal decrease in leaf thickness, when leaves were subjected to live

Table 15. Leaf transmittance characters at infra-red (water channel) region and leaf water status and leaf thickness in live wilted leaves of *Compa* under laboratory conditions.

Water content (%)	After 1 hour			After 2 hours			After 3 hours			After 4 hours			
	RMC (%)	Leaf thickness (μ)	Leaf transmittance values	Water content (%)	RMC (%)	Leaf transmittance values	Water content (%)	RMC (%)	Leaf transmittance values	Water content (%)	RMC (%)	Leaf thickness (mm)	Leaf transmittance values
75.32	72.20	17	98.8	69.26	65.37	96.7	58.87	53.66	97.8	55.41	49.76	17	96.0
73.57	71.47	15	91.3	67.57	65.00	90.3	59.13	55.88	90.0	55.89	52.06	14	89.8
72.65	68.83	15	94.5	67.81	63.31	93.4	57.84	51.95	92.8	51.28	44.48	14	92.6
73.63	70.63	16	94.9	67.22	63.49	90.8	56.06	51.06	90.0	51.07	45.07	15	89.2
79.12	76.31	15	97.4	71.65	67.84	95.6	60.32	55.56	94.0	55.15	49.71	15	93.0
79.58	76.83	15	96.8	74.15	70.66	95.3	63.77	58.50	94.2	59.86	55.20	14	92.3
83.24	81.00	16	93.8	76.47	73.33	92.0	68.24	64.00	90.0	64.71	60.00	14	89.0
79.58	76.95	15	93.7	71.62	67.96	93.0	62.33	57.49	92.0	58.62	53.29	14	90.0
79.74	76.95	15	94.8	71.05	67.96	92.8	62.33	57.19	92.1	59.74	54.19	14	90.0
77.38*	74.57*	15.5*	95.1*	70.69*	67.21*	93.3*	60.93*	56.12*	92.3*	56.86*	51.53*	14.6*	91.3*

mean

wilting. This suggest that lack of relationship between water content and leaf transmittance was not due to differences in leaf thickness.

DALBERGIA

To findout the relationship between leaf transmittance characters and the leaf water status, leaves from field grown dalbergia trees were used. Leaves of uniform size and age (3rd or 4th leaves from top of the tertiary branches) were brought to the laboratory. After bringing them to full turgidity leaves were subjected to live wilting as described in the previous experiment. At different water status of the same leaf transmittance characters and leaf thickness were determined. The range in RWC in this experiment was 83.24 to 68.23 (Table 16). However, in this experiment also there was no consistent trend in the leaf transmittance characters with decrease in RWC. There was no relationship between leaf transmittance values and RWC ($r = 0.191$). Water content of leaf also did not show any relationship with leaf transmittance characters.

One of the main objectives of using tree species (Dalbergia) was that the difference in leaf thickness may not be significant when the tissue water content was reduced by live wilting. As expected there was no

Table 16. Leaf transmittance characters at infra-red (water channel) region and leaf water status and leaf thickness in live wilted leaves of *Salbergia* under laboratory conditions.

After 1 hour				After 2 hours			After 3 hours			
Water content (%)	RWC(%)	Leaf thickness(μ)	Leaf transmittance values	Water content (%)	RWC(%)	Leaf transmittance values	Water content (%)	RWC(%)	Leaf thickness(μ)	Leaf transmittance values
89.9	85.57	26	98.3	78.0	73.88	93.5	75.1	70.45	25	89.1
89.0	86.71	25	99.3	79.5	75.08	95.6	77.3	72.43	25	93.0
88.9	86.15	25	99.0	81.0	76.31	99.0	76.0	70.15	24	98.0
83.3	80.18	25	95.5	72.4	67.16	94.0	70.9	65.38	25	93.0
82.2	78.80	25	98.5	73.8	68.03	97.0	73.0	67.80	25	96.0
88.7	76.86	26	92.5	71.1	65.29	91.0	69.5	63.36	26	89.4
84.1	80.85	26	91.4	71.3	70.15	87.1	73.4	67.66	26	86.5
87.6	84.67	26	88.7	76.1	70.38	85.5	74.9	68.99	25	83.5
84.5	80.90	27	89.4	73.5	67.36	87.8	72.7	66.32	26	85.7
93.3	91.67	25	92.4	79.0	73.96	91.7	75.0	69.79	25	89.8
87.0*	83.24*	25.6*	94.5*	76.0*	70.76*	92.2*	73.8*	68.23*	25.2*	90.4*

*Mean

significant differences in leaf thickness when RWC was reduced from 85 to 65 per cent in this tree species.

MAHOGANI

In this species also, the relationship between leaf transmittance and water content were assessed. As described in the previous experiments, live wilting method was adopted to achieve leaves with different water status. The procedures followed was same as described for dalbergia.

The results indicated that there was no relationship between leaf transmittance characters and RWC (or water content) of the leaves. The differences in leaf thickness was also marginal between turgid and stressed leaves (Table 17).

SANDAL WOOD

Method followed for this species was same as in the previous experiments. In this species leaf water content did not show any relationship with leaf transmittance characters (Table 18).

PONGAMIA

The method adopted was same as described in the previous experiments. Even in this species also there was no significant differences between leaf water

Table 17. Leaf transmittance characters at infra-red (water channel) region and leaf water status and leaf thickness in live wilted leaves of ashogani under laboratory conditions.

After 1 hour				After 2 hours			After 3 hours			
Water content (Z)	RMC(Z)	Leaf thickness(μ)	Leaf transmittance values	Water content (Z)	RMC(Z)	Leaf transmittance values	Water content (Z)	RMC(Z)	Leaf thickness(μ)	Leaf transmittance values
90.1	83.7	19	93.0	75.0	51.1	92.0	57.1	44.8	18	92.0
93.3	89.0	18	92.8	80.0	66.9	90.4	66.7	44.8	17	87.9
92.8	88.0	18	94.1	80.6	67.9	90.5	62.3	37.8	17	90.0
93.1	88.0	18	90.5	77.8	61.1	89.1	69.8	33.0	17	89.0
91.1	88.5	18	96.0	88.4	63.2	95.2	67.2	50.2	17	94.2
94.6	85.3	19	97.0	76.3	80.6	95.0	64.1	46.1	18	90.2
96.2	90.9	18	95.5	78.8	60.4	86.0	53.0	40.1	17	86.0
91.5	93.6	19	92.0	78.8	64.5	84.5	50.8	41.3	18	81.6
93.5	86.0	18	93.6	76.6	65.0	90.8	54.4	38.9	18	79.9
91.2	89.3	80	96.0	79.2	61.3	89.9	56.0	44.7	18	89.6
93.2	85.5	19	97.0	78.9	65.8	91.2	64.9	47.6	18	81.7
95.8	88.7	17	91.2	80.9	65.1	90.8	64.1	44.9	17	86.4
93.0*	88.0*	18.1*	94.1*	79.3*	65.1*	19.5*	60.9*	42.9*	17.5*	87.4*

*Mean

Table 18. Leaf transmittance characters at infra-red (water channel) region and leaf water status and leaf thickness in live wilted leaves of sandal wood under laboratory conditions.

Water content (%)	After 1 hour				After 2 hours				After 3 hours				After 4 hours			
	RMC (%)	Leaf thickness (μ)	Leaf transmittance values	Water content (%)	RMC (%)	Leaf transmittance values	Water content (%)	RMC (%)	Leaf transmittance values	Water content (%)	RMC (%)	Leaf transmittance values	Water content (%)	RMC (%)	Leaf thickness (μ)	Leaf transmittance values
75.6	66.15	18	80.2	74.2	58.85	72.2	70.3	50.0	69.1	63.9	45.6	16	66.5			
80.6	72.40	18	77.5	76.6	63.79	67.8	74.6	50.77	67.3	60.5	46.7	15	67.2			
88.3	84.25	17	90.0	75.1	66.54	73.6	75.1	53.54	72.0	65.5	46.5	15	70.6			
77.0	68.61	16	83.2	75.1	70.18	72.6	74.4	48.88	71.2	62.6	40.9	14	70.0			
79.3	71.92	16	81.0	79.3	69.95	70.9	77.8	56.73	70.2	63.6	50.4	15	69.0			
87.4	82.11	16	79.4	79.9	71.54	67.6	64.9	58.73	66.8	70.4	42.8	15	66.8			
85.4	73.15	16	89.8	87.4	66.35	66.2	76.5	54.03	66.0	67.9	44.6	16	64.0			
98.7	95.29	17	90.8	84.4	79.06	64.5	81.8	64.10	63.5	73.2	51.9	16	62.7			
84.0*	69.24*	16.8*	84.0*	79.0*	68.30*	69.5*	74.3*	54.60*	68.5*	66.0*	46.2*	16.0*	67.2*			

Mean

status and leaf transmittance characters (Table 19).

The data obtained from live wilting experiments in different species clearly indicated that, when water status was altered by live wilting, there was no relationship between RWC and leaf transmittance characters. Therefore it can be concluded that, the leaf transmittance at water channel can not be used to assess the water status of leaf, especially in situations when water content was rapidly depleted in the tissues.

III(2) Pot culture experiments

Experiment-1: Sunflower plants were raised in pots with 8 kg of soil. The plants were manured as per the recommendations and grown in well watered conditions upto 40 days. On 40th day different stress levels were imposed by varying total input of water per pot. The control pots were maintained at field capacity. Whereas, T_1 , T_2 , T_3 and T_4 received 80, 60 and 40 and 20 per cent of water required for field capacity respectively. The plants were irrigated with reduced amounts of water daily for a period of four days. On 5th day leaves were harvested (3rd or 4th leaf from the top) and the relative water content (RWC), leaf thickness and leaf transmittance characters were determined. Before taking leaf transmittance value

Table 19. Leaf transmittance characters at infra-red (water channel) region and leaf water status and leaf thickness in live wilted leaves of pongamia under laboratory conditions.

Water content (%)	After 1 hour			After 2 hours			After 3 hours			
	RWC(%)	Leaf thickness(μ)	Leaf transmittance values	Water content (%)	RWC(%)	Leaf transmittance values	Water content (%)	RWC(%)	Leaf thickness(μ)	Leaf transmittance values
97.50	96.00	15	89.7	80.7	68.8	79.0	65.3	44.0	14	70.0
94.90	92.33	15	93.2	75.6	89.0	88.8	59.8	38.4	14	88.0
93.90	90.26	15	85.5	77.6	64.3	80.6	62.0	39.6	13	79.0
95.70	93.40	15	82.5	75.0	61.9	80.8	67.3	50.3	14	77.0
96.50	94.32	14	81.8	77.3	63.6	77.0	62.8	40.3	13	75.8
95.20	90.23	15	86.4	76.8	62.7	76.0	61.6	39.1	14	74.6
92.90	88.76	14	90.2	75.8	61.5	85.0	61.3	38.5	14	83.6
94.20	90.77	15	90.0	78.2	65.2	88.0	63.6	41.8	14	86.8
92.10	96.32	14	79.4	78.7	66.3	70.4	63.8	42.5	14	69.2
94.20	87.50	15	93.3	81.2	70.0	89.0	65.7	45.4	14	73.6
97.70	90.77	15	88.5	82.7	72.1	78.0	67.3	47.1	14	74.8
92.10	96.32	15	92.4	77.9	65.0	86.0	63.2	41.7	13	84.8
94.70*	92.25*	14.8*	87.7*	78.1*	65.2*	81.6*	63.6*	42.4*	13.7*	78.1*

*Mean

meter reading was adjusted to 100 with turgid leaf with RWC 100 per cent. With decrease in RWC there was a concomitant decrease in leaf transmittance characters. For instance, when the RWC was 75.57 per cent leaf transmittance value was 97.30, where as it reduced to 63.30 when the RWC was 47.22 (Table 20). There was a positive significant relationship between RWC and leaf transmittance ($r = 0.912$). Similarly even the water content of the leaves also showed a positive significant relationship with leaf transmittance characters (Fig.19).

In this experiment, there was significant difference in leaf thickness, with the decrease in leaf water content there was a concomitant decrease in leaf thickness. A positive significant relationship was observed between leaf thickness and leaf transmittance characters ($r = 0.725$).

Experiment-2: In another pot culture experiment stress was imposed in 40 day old sunflower plants by withholding irrigation. In T_1 water was withheld for a period of two days, where as in T_2 , T_3 and T_4 water was withheld for three, four and five days respectively. On day six the leaves (3rd or 4th leaves from top) were harvested and leaf water status, leaf transmittance values and leaf thickness were determined as described in the previous experiment.

Table 20. Leaf transmittance characters at infra-red region (water channel) and leaf water status and leaf thickness in pot grown sunflower plants subjected to moisture stress.

Treatments	Water content	Per cent RWC	Leaf thickness (μ)	Leaf transmittance values
T ₁	78.50	75.57	25	97.3
	77.64	74.40	24	98.5
	79.30	76.14	25	98.1
	82.35	79.31	24	97.7
T ₂	65.63	57.96	21	86.9
	66.78	59.34	20	87.0
	66.77	59.61	21	87.6
	66.96	60.60	92	87.0
T ₃	61.79	54.18	20	82.2
	61.40	47.37	19	80.0
	67.00	54.00	18	80.9
	57.54	50.23	20	79.9
T ₄	51.79	44.21	21	63.6
	58.46	50.18	20	67.0
	54.50	46.92	19	66.2
	54.92	42.22	20	63.3
Mean:				
T ₁	79.45	76.36	24.5	97.9
T ₂	66.54	59.38	21.0	87.1
T ₃	61.93	51.45	19.3	80.8
T ₄	54.87	47.13	20.0	65.0
CD at 1%	6.44	5.91	1.14	2.52

T₁ - Pots received 80% water for 4 days
T₂ - Pots received 60% water for 4 days
T₃ - Pots received 40% water for 4 days
T₄ - Pots received 20% water for 4 days

Fig.19: Relationship between leaf water status and leaf transmittance characteristics at IR region (water channel) in sunflower. Leaf water status(a) and (b) and leaf thickness(c).

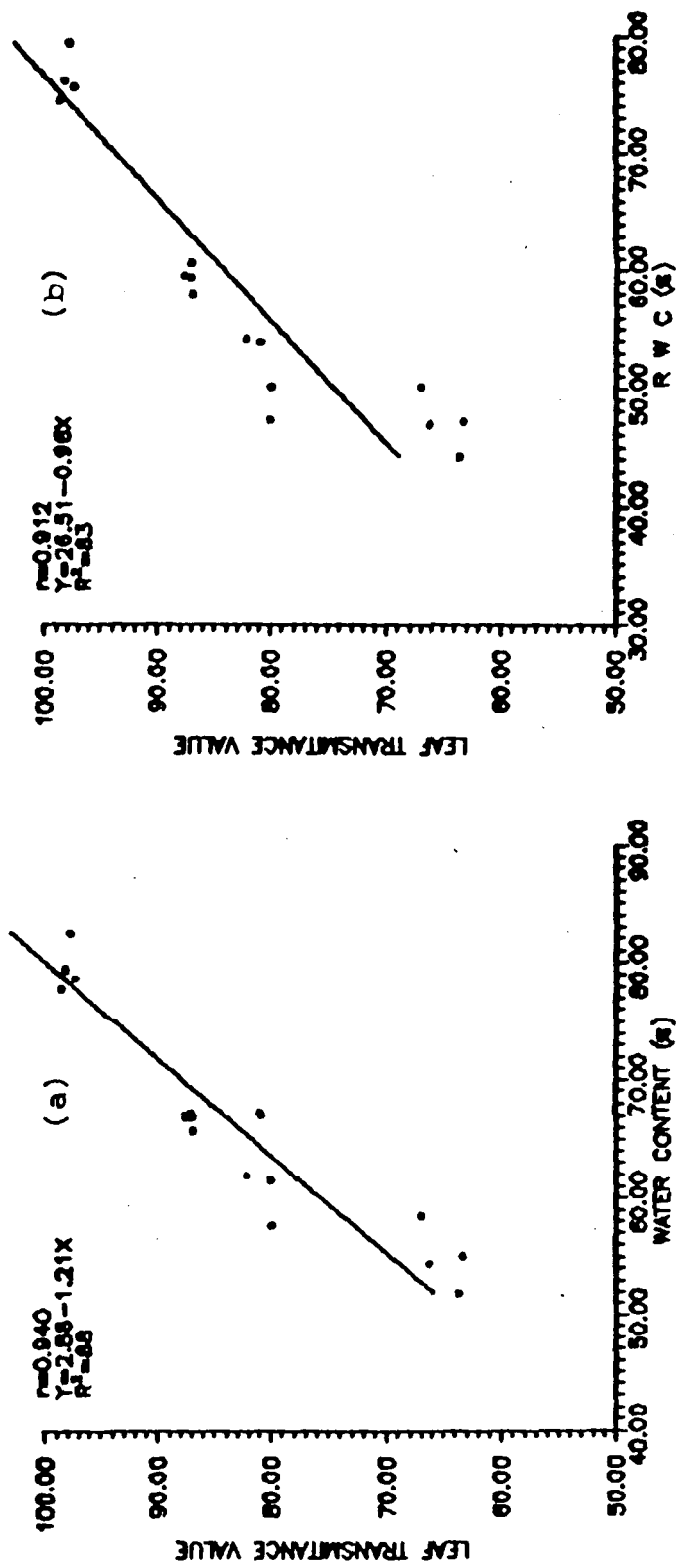
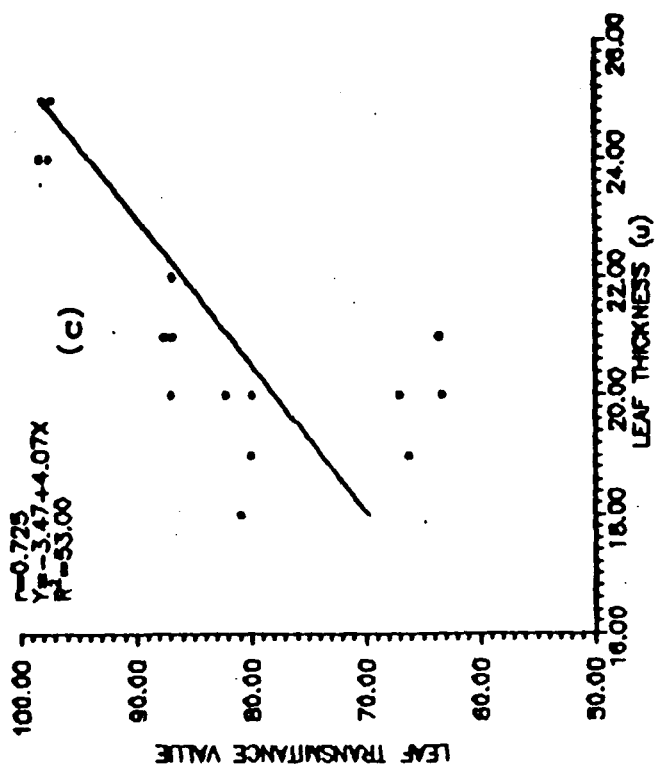


Fig. 19

In this experiment when water was withheld for a period of two days RWC was reduced to 42.3 per cent. In T_4 treatment RWC was 27.35 (Table 21). In this experiment also there was a significant decrease in leaf transmittance values with decrease in RWC. There was a positive significant relationship between leaf transmittance values and RWC ($r = 0.874$) and also with water content ($r = 0.861$) (Fig.20).

The leaf thickness decreased with stress levels especially from T_2 to T_4 . For example the mean leaf thickness in T_2 treatment was 24.0, whereas it was reduced to 18.25 in T_4 treatment. Though the relationship between leaf thickness and transmittance values was positive it was not significant. The results obtained in both the pot culture experiments clearly indicated that, a positive significant relationship existed between leaf transmittance characters and RWC when the leaf moisture status was decreased slowly under pot culture conditions. The leaf moisture status therefore can be assessed by determining leaf transmittance characters using Agrophotometer when stress imposed was gradual.

Table 21. Leaf transmittance characters at infra-red region (water channel) and leaf water status and leaf thickness in pot grown sunflower plants subjected to moisture stress.

Treatments	Water content	Per cent RWC	Leaf thickness (μ)	Leaf transmittance values
T ₁	52.11	42.4	23	79.9
	50.10	41.2	24	78.4
	51.20	43.1	25	85.0
	51.26	42.5	24	81.8
T ₂	49.70	40.4	22	78.0
	47.78	38.6	25	76.4
	48.77	39.8	26	77.6
	46.67	37.6	25	75.0
T ₃	44.99	37.8	18	76.0
	44.13	34.9	18	76.0
	34.39	32.5	20	74.0
	41.74	31.1	20	73.0
T ₄	37.37	25.9	19	65.0
	41.90	28.7	18	65.4
	33.10	29.8	17	66.1
	37.09	25.0	19	44.0
Mean:				
T ₁	51.17	42.3	24.0	81.3
T ₂	48.23	39.1	24.5	76.8
T ₃	44.31	34.1	19.0	74.8
T ₄	39.87	27.4	18.3	60.4
CD at 5%	3.03	3.02	NS	8.17

T₁ - Watering with held for 2 days
T₂ - Watering with held for 3 days
T₃ - Watering with held for 4 days
T₄ - Watering with held for 5 days

Fig.20: Relationship between leaf water status and leaf transmittance characteristics at IR region (water channel) in sunflower. Leaf water status(a) and (b).

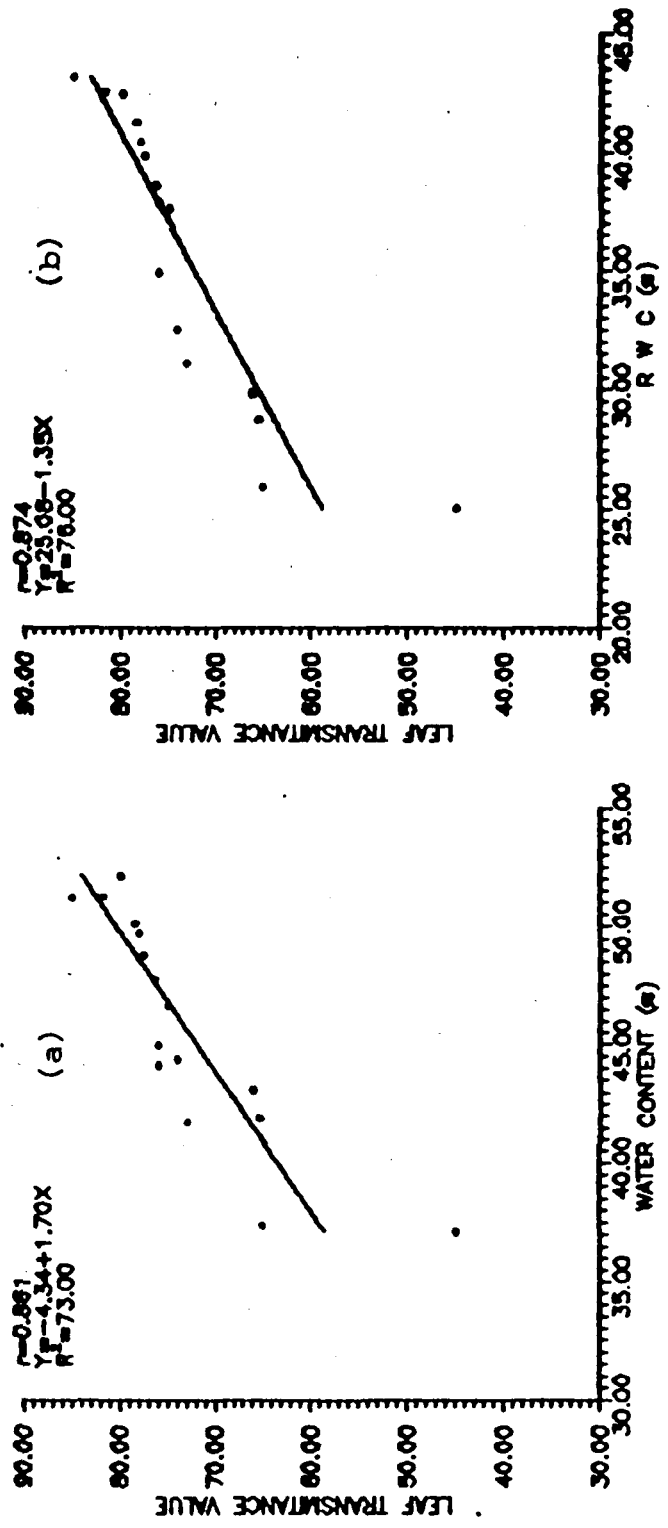


Fig. 20

DISCUSSION

V. DISCUSSION

In many agricultural countries like India, monitoring the crop growth conditions and growth of the forest ecosystems is essential to predict the production potential. Irrespective of the growth conditions the leaf area index (LAI) and evapotranspiration (ET) will give an idea about crop status from which productivity can be predicted. In this context the remote sensing techniques have shown conceptually as powerful technique to rapidly obtain data on certain important crop characteristics.

The main approach in determining the crop characteristics by remote sensing techniques is by measuring canopy optical properties. The canopy reflectance characters (CRCH) in visible, near infra-red (NIR), far infra-red (FIR) and in microwaves have been shown to reflect specifically certain plant characteristics. However, to find the relationship between spectral reflectance and crop canopy status by remote sensing techniques, it is necessary to develop initially the ground truth studies in crop canopies differing in growth characters at a ground level.

The data generated on reflectance properties are not only useful in remote sensing but also can be used

as a quick method for determining canopy cover, canopy temperature, ET etc.

In recent years the optical properties of leaves are also used to determine the leaf physiological status and leaf constituents.

With the discovery of new optical instruments, several plant constituents and certain physiological characteristics are being studied in intact leaves. One specific example of such an approach is determination of leaf fluorescence characters in vivo by using optical instruments.

Due to the recent advances made in optical instrumentation, canopy reflectance characteristics and also transmittance characters of leaves and other plant parts can be studied rapidly with a fair degree of reproducibility.

Keeping this in view, experiments were conducted in present investigation on the following aspects.

1. The inter-relationship between LAI and reflectance characters of the canopy were studied in a series of experiments in several crops. Main objective was to develop a suitable technology for rapid nondestructive determination of LAI by determining the reflectance characters.

2. The leaf transmittance characters were determined in leaves differing in chlorophyll content. The objective of these experiments was to develop a nondestructive technique for measurement of chlorophyll content in situ by using transmittance characters.

3. Leaf transmittance characters were also determined in leaves differing in water status using water channel (near infra-red band) of this optical instrument Agrophotometer. Here also the objective was to develop a method for in situ measurement of water status by using transmittance characters.

To meet these objectives one field experiment, several pot culture and laboratory experiments were conducted.

Canopy reflectance characters in relation to leaf area indices (LAI)

For any crop are stand of natural vegetation four factors determine the net biomass gain (a) the quantity of light received, (b) the proportion of the light intercepted by green plant organ, (c) efficiency of conversion of intercepted light and (d) the respiratory loss of biomass. Therefore one of the important factors associated with the bioproductivity is the

extent of radiation intercepted. Extent of radiation intercepted basically depends on leaf area development and to certain extent the architecture of plant canopy. In many crop species the genotypic differences in crop growth rate (CGR) were considered to be more due to differences in leaf area and to a less degree due to differences in photosynthetic rate.

In view of the importance of the LA selection pressures are always aimed to identify genotypes with high LAI and its rate of development.

Since, the leaf area development pattern is an important contributing factor for crop growth rate (CGR), leaf area estimates and the assessment of amount of radiation absorbed by the canopy are becoming increasingly important. Methods in vogue are cumbersome and precise estimation of leaf area is possible only by destructive sampling techniques. A rapid and a nondestructive sampling techniques for measuring the extent of light intercepted by the crop is very useful.

One of the approaches in recent years has been to make use of the canopy reflectance characters as a measure for assessing the extent of canopy cover (LAI) (Fuchs et al. 1984; Asrar et al., 1984). It has been well documented that, the LAI is directly related to

light intercepted in a given crop species (Kanda, 1975; Devendra and Udaya Kumar, 1980). Until the crop canopy attain an LAI of 3.5 to 4.0, there is a linear relationship between LAI and per cent ASR.

Such an approach to measure LAI and the extent of radiation intercepted based on reflectance properties not only useful for remote sensing but also useful to develop a quick method to measure these parameters.

In view of this, several experiments were carried out in this study to determine LAI and the extent of light intercepted by determining the reflectance characteristics of the canopy using a Spectroradiometer.

Cowpea, soybean, sorghum and amaranthus crops were raised in field conditions during summer. At different stages of the crop growth the LAI, per cent light intercepted and leaf reflectance characters were determined.

The reflectance measurements were taken at an intervals of 20 nm from 500 to 1000 nm using spectroradiometer between 11.00 hrs to 13.00 hours, based on the reflectance values from the reference (barium sulphate coated plate) the per cent reflectance from the canopy was computed. Similarly per cent

reflectance for bare ground was also measured.

Irrespective of the crop species the reflectance properties showed similar trend. The per cent reflectance value was minimum at red region and maximum at 880 to 960 nm (infra-red region). the minimum reflectance at red region is mainly due to absorption by chlorophyllous tissues of this wavelength. One of the absorption peaks of the chlorophyll is at 663 nm. This explains minimum reflectance values of the canopy at this wavelength. With increase in LAI the reflectance at red region decreased and at IR region it showed an increase. Therefore to assess the relationship between spectral reflectance and canopy cover the reflectance characters at red and infra-red regions alone were used.

The results obtained in different crop species clearly indicated that there was an inverse relationship between LAI and reflectance characters at red region and a positive relationship between LAI and reflectance at near infra-red region (900 nm).

The IR/R ratio also showed a positive significant relationship with LAI (Fig.6-9). The IR/R ratio in relation to bare ground also showed a highly positive significant relationship with the LAI.

In different experiments conducted with different crop species a similar relationship was obtained between per cent reflectance of the canopy and the extent of canopy cover. In cowpea crop, the regression value between LAI and per cent reflectance characters at IR region was 0.960 whereas it was 0.950 in sorghum. Similar trend was seen when the relationship was arrived at LAI and other reflectance characters at R and IR/R ratios (Fig.6 and 8). In some of the experiments an attempt was also made to arrive at relationship between per cent reflectance and the canopy cover at narrow range of LAI values. For instance in cowpea range in LAI was 2.20 and 3.23, whereas in sorghum, it was only 2.40 to 2.70 (Tables 1 and 3). In both the experiments there was a significant relationship between LAI and per cent reflectance characters.

From several of these experiments, carried out in present investigation it can be concluded that the extent of canopy cover can be determined by studying the reflectance properties of the canopy.

In recent years, several workers attempted to relate LAI with the reflectance characters of the canopy either at R or at near IR regions. The ratio of near IR to red reflectance was shown to be a useful

parameter to estimate the leaf area (Bunnik, 1978). Asrar et al. (1984) comparing several spectral reflectance transformation confirmed that the LAI of wheat could be estimated just from a ratio of near infrared to red reflectances. In a similar type of experiment by Fuchs et al. (1984), the leaf area values in wheat canopy for several spring and winter wheat cultivars grown under varied conditions and management were calculated based on reflectance characters.

In one of the studies (Singh et al., 1985) on spectral assessment on nutrient and disease stress on paddy crop, similar attempt was made to relate spectral characters with biometric characteristics of the crop. During the crop growth period, the radiance ratio between NIR and red regions was determined in paddy crop grown at different nitrogen levels. At higher nitrogen levels, LAI was more at all growth stages. There was a positive significant relationship between radiance and LAI. The reflectance character, therefore, is reliable method to assess biomass production which was inturn influenced by the leaf area. The integrated radiance for the entire crop growth stage also related with biomass and grain yield (Singh et al., 1982).

Similar relationship between spectral characteristics and also extent of leaf area development have been observed in the present study conducted in several crops (cowpea, soybean, sorghum and amaranthus).

Another objective of the present study was to relate the per cent interception of light with canopy reflectance properties. Since, per cent interception of radiation by crop canopy depends on LA and to a certain extent on the canopy architecture, plant productivity to a large extent depends on the extent of radiation intercepted.

Reliable estimation of canopy cover and per cent radiation intercepted will help in predicting the crop growth rates. The canopy spectral reflectance characters could be measured to assess the extent of radiation intercepted by the canopy

In this study the total radiation intercepted by different crops at different growth stages was assessed by using a pyranometric instrument. In all the crops the extent of radiation intercepted showed a significant relationship with canopy reflectance values. Even in crop canopy with low LAI values and thus low per cent interception of radiation also, the canopy reflectance characteristics were positively

related with light interception (ASR) values. Therefore by measuring reflectance at R and IR, the per cent light interception can be determined at any stage of the crop growth.

However, in none of the experiments conducted the leaf area indices values exceeded the value of 3.5. It has been well demonstrated that the LAI and intercepted values show linear relationship only upto an LAI of 3.5 to 4.0 beyond which the relationship between LAI and per cent reflectance values was not significant. Therefore, it is necessary to see the inter-relationship between spectral reflectance characters, canopy cover and extent of light interception at LAI beyond 4.0.

Similar attempts were made in recent years in different crop species. Daughtry et al. (1983) proposed that spectral reflectance of a canopy could be used to obtain estimates of radiation intercepted by it. Hatfield et al. (1983) and Hipps et al. (1983) have concluded that the absorption of PAR can be estimated from the spectral reflectance. Kumar and Monteith (1982) also showed that the quantity of the absorbed PAR could be estimated from spectral reflectances of crop canopies with horizontal leaves. In another study by Harlan et al. (1978), it was determined that in crop canopy with low LAI due to

disease or pest attack the reflectance properties also altered. An increase at R and a decrease at IR regions were noticed. Therefore, this study also suggests that reflectance characters can be related to LAI.

However, in all the reports the relationship between LAI and to spectral reflectance characters was worked out only in a specific crop.

Even in this study the spectral reflectance properties were related with LAI only within a species. But the objective was ultimately to develop a method to quickly determine the canopy cover and per cent light interception based on reflectance characters irrespective of crop species. However, when comparison was made over the species none of the reflectance values except IR/R ratios were related with LAI or per cent light intercepted. The reflectances at R and IR, though showed a relationship, the regression value was low. For instance relationship between LAI and IR/R across the species was 0.653 whereas for individual species cowpea, soybean sorghum and amaranthus values were 0.977, 0.839, 0.944 and 0.970 respectively. Therefore for precise measurements of LAI and per cent ASR by the canopy initial ground truth studies, standard curves for individual crop species has to be developed at IR and R by using spectroradiometer.

In situ measurement of leaf constituents based on transmittance characteristics

In recent years attempts are being made to develop the instruments for in situ measurements of leaf chemical constituents and also to study certain physiological processes. In situ (non-destructive) measurements, no doubt have specific advantage for repeated measurements and to study over time the effect of environmental variables. With this objective in view an optical instrument, Agrophotometer, has been developed by Indian Space Research Organization (ISRO) in collaboration with Crop Physiology Department, University of Agricultural Sciences, Bangalore. The instrument is designed to determine in situ chlorophyll content and water status. The commercial model (CL-375) of this instrument, developed by ELICO Pvt. Ltd., Hyderabad was used in this present investigation with an objective to confirm the relationship between leaf transmittance characters, chlorophyll content and water status of the leaves.

The leaf chlorophyll content is conventionally determined by adopting colorimetric procedure after extracting with acetone or with other suitable solvents. Though the chlorophyll determination techniques improved considerably the complete extraction of the chlorophyll content is laborious,

slow and inconvenient in some plant species (Umedi Yadava, 1986). Further colorimetric method is a destructive sampling technique.

The principle involved in chlorophyll estimation is still largely based on light absorption properties at a specific wavelength the absorption maxima of chlorophyll is at 340 and 660 nm. Based on this principle some optical instruments have been developed for in situ measurement of chlorophyll content, by assessing the leaf transmittance characters at photographic red region (Umedi Yadava, 1986).

In the present investigation series of experiments were conducted to relate the leaf chlorophyll content and leaf transmittance characters at 663 nm.

The main approach in these experiments was to develop plant material with different chlorophyll content, and in such leaves relate the leaf transmittance values at 663 nm with chlorophyll content.

Maize and amaranthus crops were grown in a sand culture with different nitrogen levels and thus plants with different chlorophyll status were developed. In these experiments in both the crop species an inverse significant relationship was seen between chlorophyll

content and leaf transmittance characters (Table 7, 9 and Fig.11,13). Such a relationship was seen when chlorophyll content expressed both per unit fresh weight of leaf and also per unit leaf area.

It can be inferred that the variability in chlorophyll content due to chlorosis induced by nitrogen deficiency can be determined in situ efficiently by this instrument.

In another approach in field grown sunflower leaves showing some visual chlorotic symptoms were used to relate leaf transmittance characters and chlorophyll content. In this study also there was an inverse relationship between leaf transmittance values and chlorophyll content (Table 11 and Fig 15). This emphasises that even in field grown bulk crops also the extent of chlorosis can be assessed in situ by studying the leaf transmittance characteristics by using this instrument.

In the third approach in tobacco differences in chlorophyll content between top, middle and bottom leaves were compared with leaf transmittance characters. Aged pot grown tobacco plants were used in these experiments. In these experiments also a negative significant relationship was seen between chlorophyll content and the leaf transmittance values

obtained in chlorophyll channel (Table 12, 13 and Fig.16, 18).

In addition to chlorophyll content a number of structural components of leaf may affect the leaf transmittance characteristics. It could be difficult to pin point the structural components which affects the leaf transmittance characteristics. However, the cell number and size, cell wall components and the vascular bundles determines the leaf thickness which inturn will affect the leaf transmittance characteristics. However, though the leaf thickness differed significantly and ranged from 18 to 23 μ in maize and 18 to 21 μ in amaranthus it did not affect the leaf transmittance characters. There was no relationship between leaf thickness and the leaf transmittance characteristics ($r = 0.564$).

When the leaf transmittance characters were measured in leaves differing in thickness, but with approximately similar chlorophyll content, there was no significant relationship between leaf transmittance and leaf thickness values. Such an analysis was made only with in a species, where difference in leaf thickness ranged from 25 to 30 μ .

The results of the several experiments, therefore emphasises that within a range of 5 μ thickness the

leaf transmittance characters were more related to chlorophyll content but not leaf thickness.

In all these experiments chlorophyll content was related with leaf transmittance characters from the data obtained within a species. Therefore though there were differences in leaf thickness the other structural components of leaf which affects leaf transmittance may not significantly differ from leaf to leaf. As a result in all the experiments an inverse significant relationship was observed between chlorophyll content and the leaf transmittance characteristics. But when pooled data from different crop species were analysed to arrive at the relationship between leaf transmittance values and chlorophyll content, the regression values were negative, but not significant ($r = -0.375$). This suggested that in addition to chlorophyll content the other structural characteristics of the leaf also altered leaf transmittance values. For instance at a similar leaf transmittance values 49.0 and 48.0 in sunflower and amaranthus the leaf chlorophyll content was 0.25 and 0.10 mg/g fresh weight, respectively. This emphasises, that it is necessary to develop a standard curve between actual chlorophyll content of the leaf and the leaf transmittance values for different species.

The results obtained in this investigation indicated the possibility of using Agrophotometer for in situ estimation of chlorophyll content.

There is a provision to enhance the resolution of the instrument by enhancing the gain using a filter which cuts off 50 per cent of light transmission. In some of the experiments the regression values between chlorophyll content and leaf transmittance values were more when gain was increased by using filters (Table 14 and Fig.18).

Important role of leaf water status in cell metabolic activity necessitates its estimation, especially in plants subjected to moisture stress. Drought is an important abiotic stress and a major constraint for crop growth and productivity. In any research programme either to identify genotypes for relative drought resistance or to develop methods to ameliorate drought effects an important parameter to be studied is tissue moisture status. Even for scheduling of irrigation it is necessary to know the moisture status of the crop. This aspect is more important in perennial fruit crops. It is evident that excess or delay in irrigation affects the productivity. Therefore a quick reliable method has to be developed to assess leaf water status.

The amount of water in a plant material can be expressed in a number of ways. All are based on the measurement of fresh weight at the time of sampling, dry weight and turgid weight. Generally the water status is expressed either as relative water content (RWC) or as turgid weight to dry weight ratio. In addition to this the water status is measured in terms of water potential, which reflects the free energy status of water. This is a better reflection of water status of the plant.

All the methods described above are destructive sampling techniques. In recent years several new instruments have been developed to determine the water status of leaf in situ.

Infra-red (IR) thermometer is one such instrument which is used to measure canopy water status. This instrument measures the relative water status of the canopy by determining the changes in the canopy temperature.

In this study the leaf transmittance characteristics were determined in leaves differing in water status with an objective to relate the water status and leaf transmittance characters.

In one set of experiments the field grown turgid leaves were subjected to live wilting under laboratory conditions. At different leaf tissue water status the transmittance characters were determined. In all these experiments where rapid wilting techniques were adopted to obtain leaves differing in leaf water status, leaf transmittance characters measured by using Agrophotometer did not show any relationship either with leaf moisture percentage or with RWC.

Even in perennial plant species Dalbergia, Mahogani, Sandalwood and pongamia in which the leaf rigidity is maintained when subjected for live wilting the leaf transmittance characters were not related with RWC (Tables 15-19).

In pot culture experiments with sunflower, moisture stress was imposed by withholding irrigation or by altering input of water to the pots. In these experiments there was significant variation in RWC amongst the stress treatments. The leaf transmittance values showed a positive significant relationship with RWC (Tables 20,21 and Fig.19,20).

From the results obtained in these experiments it can be inferred that the leaf transmittance characters relate to water status only when the plants were

subjected to slow wilting, but not under rapid wilting conditions.

The lack of relationship between leaf transmittance characteristics and water status, especially in rapid wilting conditions indicates that factors other than moisture content the changes in surface properties of leaves, cell volume and other structural properties of leaf are significantly affecting the leaf transmittance characters. The positive significant relationship between leaf thickness and leaf transmittance characters at water channel in pot culture experiment also confirms the facts that other than water status other leaf characters affected under stress were altering leaf transmittance characters.

Water has specific absorption maxima only at an infra-red band. Further it is having a strong absorption maxima in microwave radiation also. Therefore water status of the leaf tissues can be determined precisely only using an instrument with specific water absorption bands.

However, some more experiments need to be conducted in field grown crops to relate leaf transmittance characters with water status by using this instrument.

SUMMARY

VI. SUMMARY

In recent years remote sensing in agriculture has been mainly concerned with developing fundamental relationships for assessing plant condition based on emitted and reflected radiation from crop canopies. Further, with the advent of discovery of new optical instruments it is being attempted to quantify leaf chemical constituents based on transmittance or reflectance properties of leaves. Keeping this in view in this present investigation experiments were conducted with the following objectives.

- i) To study the relationship between spectral reflectance of the canopy and the extent of canopy cover.
- ii) To study the relationship between leaf transmittance characteristics and chlorophyll content.
- iii) To study the relationship between leaf transmittance characteristics and leaf water status.

To meet these objectives one field and several laboratory and pot culture experiments were conducted.

1. Canopy reflectance characters in relation to LAI

In field grown crops of cowpea, soybean, sorghum and amaranthus at different stages of growth the LAI, per cent light interception and canopy reflectance characters were determined.

The reflectance measurements were taken at an interval of 20 nm from 500 to 1000 nm on a cloudfree day using a portable spectroradiometer developed by ISRO Scientists. Based on the reflectance values from reference (Barium sulphate coated plate), the per cent reflectance values from the canopy were computed. Similarly the per cent reflectance for bare ground were also measured, from the reflectance values at IR (900 nm) and red (640 nm), the reflectance ratio of IR to R were computed. An attempt was also made to arrive at IR/R ratio of the canopy in relation to IR/R ratio of bare ground. This ratio is termed as IR/R in relation to bare ground.

From the results obtained in this experiment it can be summarised.

- (a) In all crop species, the per cent reflectance values were minimum at red (640 nm) region and maximum at NIR (800 to 960 nm) region.

- (b) The bare ground reflectance values were relatively more in red and significantly less in IR region compared to the cropped area.
- (c) In view of significant difference in reflectance properties at R and IR, only reflectances at IR and R regions alone were used to assess the relationship between spectral reflectance and canopy cover.
- (d) In all the crop species there was inverse significant relationship between LAI and reflectance characters at R region and positive significant relationship between LAI and reflectance at NIR region (Figs.6-9).

The IR/R ratio also showed a positive significant relationship with LAI (Fig.Figs.6-9).

The IR/R ratio in relation to bare ground also showed a highly positive significant relationship with LAI.

Irrespective of the range in LAI values there was significant relationship between LAI and canopy reflectance values.

- (e) In all the crop species LAI showed a positive significant relationship with the extent of light intercepted by the canopy.

- (f) The canopy reflectances at R, IR and IR/R were also related to the per cent light interception to the crop canopies.
- (g) However, across the species though the canopy reflectances were related to LAI and per cent light intercepted, the relationship was weak and nonsignificant.

CONCLUSION:

It can be concluded that the extent of canopy cover and per cent light intercepted by crop canopy can be determined by studying reflectance properties of the canopy.

2. In situ measurement of leaf chlorophyll content and water status based on leaf transmittance characteristics

Chlorophyll

By using an optical instrument - Agrophotometer developed by Indian Space Research Organization (ISRO), Bangalore in collaboration with Department of Crop Physiology, University of Agricultural Sciences, Bangalore, in situ chlorophyll content and water status of the leaves were measured by determining leaf transmittance characteristics at chlorophyll channel and at water channel.

To study the relationship between chlorophyll content and leaf transmittance characters the plant material with different chlorophyll content was developed either by growing the plants with different nitrogen levels or by identifying the plants differing in the extent of chlorosis under field conditions or by using leaves of different ages varying in chlorophyll content. For these experiments a range of crops - maize, amaranthus, sunflower and tobacco were studied.

The results obtained can be summarised as followed

- (a) In all the crop species an inverse significant relationship was seen between chlorophyll content and leaf transmittance characters measured at chlorophyll channel of the instrument (photographic red region; Fig.10-18, range in 'r' value -0.697 to -0.959.
- (b) Such a relationship was seen when chlorophyll content was expressed per unit fresh weight of leaf or per unit leaf area.
- (c) When the leaf transmittance characters measured in leaves differing in thickness, but with approximately similar chlorophyll content there was no significant relationship between leaf transmittance and leaf thickness values. Such an

analysis was made only with in a species, where difference in leaf thickness ranged from 25 to 30 μ .

Therefore within a range of 5 μ thickness the leaf transmittance characters more related to chlorophyll content, but not leaf thickness.

- (d) Across the species there was no relationship between leaf transmittance characters and chlorophyll content.

CONCLUSION:

In situ chlorophyll measurements can be made by determining leaf transmittance values at chlorophyll channel using Agrophotometer. However, a standard curve separately for each species has to be developed for computation of data.

Leaf water status

By determining leaf transmittance characters at water channel of the instrument an attempt was made to relate transmittance characters with leaf water status. In one set of experiments field grown turgid leaves were subjected to live wilting under laboratory conditions to obtain leaves differing with water status. In other set of experiments moisture stress

was imposed in pot grown plants by with-holding irrigation and thus leaf tissue water status was altered.

From the results obtained it can be summarised

- (a) In leaves subjected to the live wilting (rapid decrease in water status), the leaf transmittance characters measured by using Agrophotometer did not show any relationship either with leaf moisture per cent or with RWC.
- (b) In pot culture experiments when stress imposed was not rapid the leaf transmittance values at water channel showed positive significant relationship with RWC and water content ($r = 0.912, 0.940$)
- (c) In these pot culture experiments leaf thickness also related with leaf transmittance characteristics.

CONCLUSION:

Leaf transmittance characteristics at water channel were related to water status only when the plants were subjected to slow wilting but not under rapid wilting.

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VII. REFERENCES

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*Original not seen

APPENDICES

**Appendix-I: Canopy reflectance measurements at different wave lengths
as influenced by leaf area indices in cowpea**

LAI	2.20	2.27	2.41	2.45	2.50	2.50	3.20	3.21	3.23
nm									
500	17.65	17.65	19.12	17.86	19.60	19.60	15.63	15.63	15.63
520	14.44	13.33	15.56	14.71	17.60	17.60	14.10	12.82	14.10
540	14.00	14.00	15.00	12.22	13.30	13.30	11.00	11.00	11.00
560	13.33	13.33	13.33	12.00	13.00	13.00	10.00	10.00	10.00
580	12.14	12.14	12.86	11.82	12.70	12.70	9.23	8.42	9.23
600	12.50	12.50	12.50	11.54	12.50	12.70	8.23	9.23	8.46
620	13.33	13.33	13.33	12.00	12.00	12.30	8.82	7.65	7.65
640	14.00	14.00	14.00	12.40	12.40	12.94	8.82	8.82	7.65
660	15.45	15.45	15.45	14.21	13.70	12.40	8.82	8.57	7.84
680	16.96	17.39	16.52	14.20	14.30	13.70	10.43	10.00	8.82
700	19.17	19.17	18.33	17.27	15.90	14.30	12.08	12.50	10.00
720	20.80	20.80	22.40	21.74	14.10	15.90	15.20	15.20	12.00
740	23.08	23.68	24.08	24.17	20.80	19.10	17.78	17.78	14.07
760	26.15	25.38	27.70	26.67	23.30	20.80	21.54	21.54	19.23
780	27.70	27.70	30.00	30.40	27.80	23.30	23.70	23.70	25.93
800	30.00	34.00	38.46	36.00	28.00	27.80	28.15	28.89	28.15
820	38.41	34.61	38.41	40.00	31.20	30.00	34.46	34.00	34.00
840	40.00	38.00	40.00	40.00	36.00	36.20	40.00	40.00	40.00
860	40.00	40.00	44.00	41.67	41.67	38.00	48.00	48.00	48.00
880	41.67	41.67	44.17	43.50	43.50	44.50	50.00	50.00	51.00
900	41.67	41.67	43.50	43.50	45.85	47.82	54.17	54.17	54.17
920	43.47	43.47	45.50	45.50	47.83	47.87	56.17	56.52	56.52
940	43.47	43.47	47.83	46.55	50.00	50.00	54.17	54.17	54.17
960	45.45	45.45	47.83	47.00	47.83	47.83	52.17	52.17	52.17
980	42.85	42.85	45.45	45.00	45.45	45.45	50.00	50.00	50.00
1000	40.00	40.00	45.00	45.00	45.00	45.00	50.00	50.00	45.00

**Appendix-II: Canopy reflectance measurements at different wavelengths
as influenced by leaf area indices in soybean**

LAI	2.13	2.23	2.23	3.00	3.10	3.27	3.37	3.37	3.37
mm									
500	20.60	20.40	23.20	23.20	18.75	18.75	21.88	21.88	17.19
520	18.60	20.20	19.10	20.10	15.38	16.67	16.67	16.67	14.10
540	15.01	19.10	15.50	14.40	12.00	13.00	13.00	13.00	9.00
560	13.31	15.40	14.00	14.00	11.82	11.82	10.91	10.91	6.15
580	12.90	14.40	13.60	12.70	10.00	10.77	9.23	8.82	6.67
600	12.50	13.33	12.30	12.30	10.77	10.77	8.82	9.23	8.46
620	13.30	13.30	12.00	12.00	10.77	9.41	10.00	10.00	9.41
640	14.00	13.00	12.40	12.40	12.40	11.00	10.00	10.00	9.41
660	15.50	13.70	13.70	13.70	12.17	12.17	13.04	13.04	13.04
680	17.00	14.80	14.80	14.80	12.86	12.86	15.83	15.83	15.42
700	17.50	16.40	16.40	16.40	15.00	15.00	20.80	20.00	20.00
720	17.60	20.90	21.70	21.70	18.40	18.40	22.22	22.22	20.74
740	21.50	22.80	22.80	22.80	20.74	19.25	27.69	27.69	23.08
760	24.60	22.50	22.50	22.50	26.15	24.92	37.04	37.04	25.12
780	26.20	24.80	24.80	24.80	28.89	26.92	44.00	37.04	28.15
800	30.80	27.20	27.20	27.20	37.04	28.87	52.00	44.00	40.00
820	38.80	34.40	34.40	34.40	44.00	37.04	52.00	48.00	44.00
840	40.00	36.90	36.00	36.00	44.00	44.00	54.17	52.00	52.00
860	40.00	37.50	37.50	37.50	48.00	44.00	56.33	44.17	54.17
880	41.70	43.50	43.50	43.50	48.00	48.00	58.33	58.33	58.33
900	41.70	43.50	43.50	43.50	50.00	53.00	58.33	58.33	58.33
920	43.50	45.50	45.50	43.50	52.00	52.17	60.87	60.87	60.87
940	43.50	45.50	40.90	40.90	48.83	47.83	56.52	56.52	56.52
960	40.91	40.40	40.00	40.00	47.83	47.83	57.14	60.00	57.04
980	40.00	40.00	38.00	38.00	45.50	50.00	56.00	56.52	56.52
1000	38.10	40.00	38.00	38.00	45.00	45.00	50.00	50.00	55.00

Appendix-III: Canopy reflectance measurement at different wavelengths as influenced by leaf area indices in sorghum.

LAI	2.40	2.43	2.45	2.53	2.55	2.60	2.70	2.70
500	21.43	21.43	21.43	17.65	17.65	25.00	21.88	25.00
520	19.12	19.12	19.12	15.00	15.00	19.44	17.95	19.44
540	18.56	18.56	15.56	15.50	15.50	14.00	14.00	14.00
560	18.00	18.00	15.00	15.00	15.00	13.33	13.64	12.72
580	17.55	17.55	13.65	14.29	14.38	12.72	11.54	13.33
600	16.65	16.85	13.65	14.00	14.29	12.50	11.54	12.50
620	16.85	16.00	13.56	14.00	14.00	12.31	9.82	12.31
640	16.00	16.00	13.33	13.33	12.86	10.29	9.41	10.29
660	16.47	16.47	16.00	17.73	17.73	14.78	8.57	14.78
680	16.74	15.26	16.47	20.87	20.87	17.60	11.30	17.60
700	18.10	18.10	16.84	22.50	22.50	19.23	12.38	20.00
720	22.73	22.73	18.14	24.80	24.80	21.43	14.80	21.43
740	22.50	21.74	22.73	26.92	26.92	25.71	18.52	25.71
760	25.00	22.50	22.73	29.23	23.23	26.21	22.31	26.90
780	28.00	25.00	22.50	38.46	38.46	34.48	27.80	34.48
800	29.60	28.80	25.00	38.46	38.46	36.67	29.63	36.67
820	30.40	29.60	28.80	42.31	42.31	40.00	40.00	40.00
840	30.40	30.40	29.60	44.00	44.00	43.33	44.00	43.33
860	32.22	30.40	30.40	44.00	44.00	50.00	44.00	50.00
880	32.22	37.50	37.50	45.83	45.83	51.85	50.00	51.85
900	33.33	37.50	37.50	45.83	45.83	51.85	51.85	51.85
920	37.50	39.13	39.13	45.83	47.83	53.85	54.17	53.85
940	39.13	43.50	43.50	52.17	47.83	53.85	52.17	53.85
960	43.50	43.50	43.50	47.83	45.45	52.00	47.82	52.00
980	43.50	39.00	39.00	45.45	46.61	52.00	47.76	52.00
1000	40.00	39.00	39.00	45.00	45.00	50.00	45.00	50.00

Appendix-IV: Canopy reflectance measurements at different wavelengths as influenced by leaf area indices in amaranthus.

LAI	2.06	2.10	2.10	2.33	2.46	2.50	2.50	2.60	2.70
nm									
500	20.50	20.50	20.50	27.94	29.41	20.60	19.40	19.40	18.40
520	20.60	20.50	20.60	22.22	23.33	15.60	18.50	18.50	18.30
540	19.40	18.00	19.40	20.00	20.00	15.00	15.60	15.60	15.00
560	19.20	19.40	19.00	19.80	18.33	13.30	14.40	14.20	14.30
580	19.00	19.20	19.50	18.43	18.43	12.90	12.70	12.70	12.70
600	19.50	19.50	19.50	18.00	18.00	12.50	12.50	12.50	12.00
620	20.00	20.00	20.00	18.55	17.55	13.30	12.20	12.20	12.20
640	21.20	21.20	21.20	17.00	17.00	14.00	13.33	13.33	13.33
660	22.00	21.00	22.00	17.00	27.27	15.50	14.30	14.30	14.30
680	24.50	24.80	24.80	17.27	21.74	17.00	15.40	15.60	15.60
700	27.30	27.30	27.30	21.74	22.50	17.50	18.50	18.50	18.50
720	27.80	27.30	27.80	22.50	26.40	17.60	20.70	20.70	20.70
740	30.00	30.00	30.00	26.40	29.23	21.50	23.60	23.60	23.60
760	32.50	31.70	31.10	29.23	34.62	24.60	26.20	26.20	26.20
780	40.00	32.50	40.00	34.62	36.46	26.20	28.46	28.46	28.46
800	40.00	40.00	40.00	38.46	38.46	30.80	34.00	36.33	36.33
820	44.00	40.00	40.00	46.13	38.46	38.50	38.20	38.20	38.70
840	44.00	44.00	44.00	48.66	46.13	40.00	41.70	40.70	44.70
860	44.40	44.00	44.00	50.00	52.00	44.00	44.40	44.40	44.40
880	44.40	44.40	44.44	50.17	52.00	48.00	50.17	50.20	50.20
900	44.44	44.44	44.44	50.17	52.20	52.20	52.20	54.17	54.17
920	50.00	52.00	50.00	52.20	54.17	52.20	54.17	54.17	54.17
940	52.20	52.20	52.20	54.17	54.17	54.50	51.21	50.20	50.20
960	52.20	50.00	50.00	56.52	56.52	54.50	48.20	48.20	48.20
980	47.00	47.70	47.70	52.17	52.17	52.40	46.20	46.20	46.20
1000	45.00	45.00	45.00	50.00	50.00	50.00	42.30	42.30	42.30

Appendix-V: Per cent reflectance measurement at different wavelengths of bare ground.

nm	Per cent reflectance		
	I	II	III
500	21.88	16.67	16.18
520	19.23	15.00	14.44
540	23.00	15.45	15.50
560	22.73	18.33	15.83
580	20.00	17.86	15.71
600	21.54	20.00	17.78
620	20.00	20.53	19.00
640	22.35	21.90	21.17
660	22.86	22.60	20.00
680	23.48	23.20	21.74
700	25.00	24.38	22.50
720	26.40	24.79	24.00
740	26.66	24.86	24.62
760	29.23	25.38	25.38
780	26.40	25.71	26.15
800	26.66	27.86	26.92
820	29.33	27.86	26.92
840	26.00	25.38	26.92
860	25.00	27.33	28.00
880	29.33	28.34	28.00
900	33.33	31.30	27.50
920	33.33	30.77	27.83
940	29.33	30.77	27.83
960	29.33	32.00	28.18
980	26.66	32.00	28.57
1000	26.40	30.77	28.00

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ವಿಶ್ವವಿದ್ಯಾನಿಲಯ ಗ್ರಂಥಾಲಯ
ಗ. ಕೃ. ವಿ. ಕೆ., ಬೆಂಗಳೂರು-65.
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