

Spectral reflectance characteristics of vegetation and their use in estimating productive potential

P S ROY

Forestry and Ecology Division, Indian Institute of Remote Sensing, (National Remote Sensing Agency), 4 Kalidas Road, Dehra Dun 248 001, India

MS received 27 July 1987; revised 10 January 1989

Abstract. Spectral properties of plants have been utilized in the context of their usefulness in studying vegetation from remote sensing platforms. A synthesis of data on spectral properties, vegetation types, growth and energy conditions provides valuable information about biomass and productivity. A comparison of capabilities and methodologies to quantify vegetation from remote sensing platforms is presented. An approach has also been made to estimate biomass production of various ecosystems.

Keywords. Electromagnetic radiation; spectroradiometer; energy sources; vegetation reflectance; phenological changes; satellite platforms.

1. Introduction

Interaction of radiation with plant leaves is extremely complex. General features of this interaction have been studied but many spectral features are yet unexplained. Gates *et al* (1965) studied the spectral characteristics of leaf reflection, transmission and absorption. Optical properties of plants have been studied further by Allen *et al* (1970), Wooley (1971) and Gausman and Alien (1973). In India, Kamat *et al* (1982) and Ajai *et al* (1983) observed in crops that spectral data were highly correlated to leaf area index (LAI), leaf dry biomass and chlorophyll content. Patel *et al* (1985) studied spectral and temporal characteristics of paddy and obtained important parameters to monitor crop growth. Roy *et al* (1986, 1987) studied grassland spectral properties and their relationship with biomass. The relationship varied among parameters like composition, leaf orientation and soil background.

A study of vegetation reflectance involves the study of (i) reflection from plant parts, (ii) reflection from plant canopies, (iii) nature and state of plant canopies, and (iv) structure and texture of plant canopies.

A synthesis of these data will be required to fully understand the remote sensing data collected by space-based and aerial platforms. It has been attempted for crop canopies through the development of models but has not yet been fully achieved. This review will initially discuss the electromagnetic spectrum and its interaction with vegetation canopies. Factors affecting the spectral reflectance of plant canopies with its possible applications in remote sensing technology will be discussed next.

1.1 *Electromagnetic radiation*

Various ranges of wavelength of electromagnetic radiation (EMR) make up the electromagnetic spectrum. Important regions of the spectrum are (i) ultraviolet, (ii) visible (VIBGYOR—violet, indigo, blue, green, yellow, orange and red), (iii)

infrared (near-, medium, thermal and far-) and (iv) Hertzian (microwave, UHF, VHF, high-frequency, etc.).

1.1a *Interaction of EMR with matter*: When EMR strikes matter the following phenomena take place. (i) A part of the incoming energy returns to the space containing the source; this is known as reflection ρ . (ii) A second part enters the matter and the process is known as absorption α . (iii) A third part, having passed through the matter, is transmitted beyond it; this is known as transmission τ .

If I is the value of the incident radiation, the budget of this interaction between EMR and matter may be written as

$$\rho + \alpha + \tau = I.$$

This equation conveys the conservative property of the energy. The present study will deal with only the first of the above phenomena.

1.2 Reflection

Reflection from natural surfaces is a complex phenomenon. There are basically two main types of reflection:

- (i) The specular reflection which occurs with perfectly smooth (polished) surfaces. This type of reflection is described through the laws of Descartes.
- (ii) The diffuse reflection occurring with rough surfaces (known as diffusing surfaces). The perfect case (that from a Lambertian surface) is described by the Lambert's law.

In most real situations, the actual reflection is always between these two cases. The reflection from the surface is given by the so called 'indicatrix' (figure 1), which gives

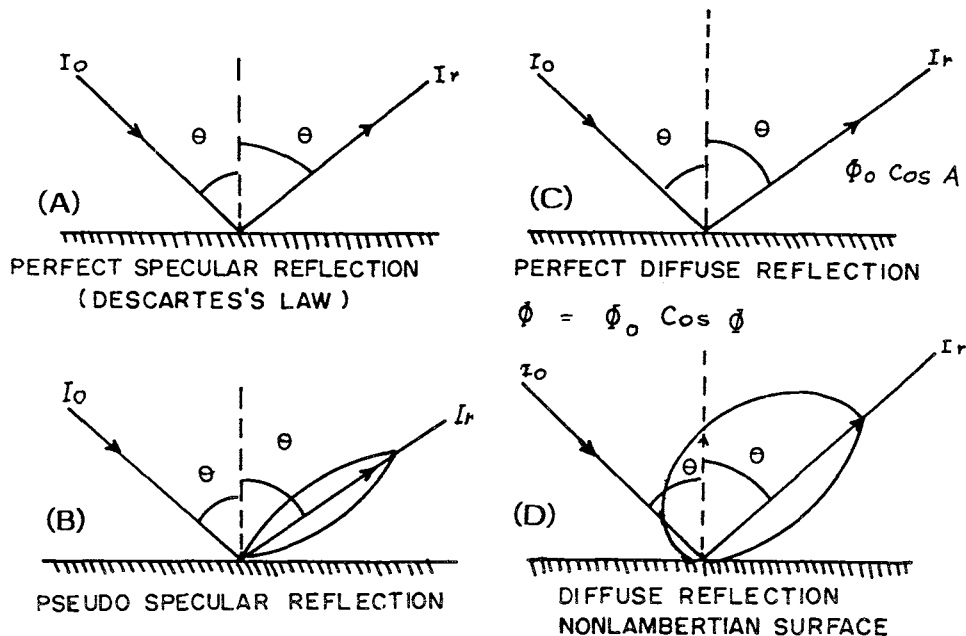


Figure 1. Types of reflection.

the value of the energy measured in each direction θ reflected by surface when lighted by an incident flux I_0 .

Reflection is usually considered as a surface property of matter. Diffraction also occurs when the surface has a periodical structure (such as in a grating). However, analysis reveals that radiation penetrates matter and the interaction of EMR with the material medium takes place in a layer, the thickness of which mainly depends on the wavelength of the radiation and the electrical properties of the medium. The spontaneous afterglow of some substances, which occurs even after the exciting radiation has been removed, is the result of such an interaction.

The interaction of EMR with matter finds expression in alteration of the incident radiation in direction, intensity (depending on the absorption or extinction coefficient of the medium), spectral composition (depending on the colour or spectral 'signature' of the medium) and polarization.

Two classes of variables are used to describe reflection:

- (i) Relative variables, also called coefficients (albedo and reflectance).
- (ii) Absolute variables, defined in energy units (radiance).

A relative variable is expressed as the dimensionless ratio (often in per cent terms) of two variables of the same nature. For example, the albedo or whiteness coefficient is defined as

$$\frac{\text{All the light reflected by the surface}}{\text{All the light incident on the surface}}$$

It must be noted here that this variable is improperly used to characterize spectral reflection because of the angular dependence of reflection phenomenon.

The evaluation of such a coefficient implies that the sensor is able to measure, first, the whole spectrum of the incident radiation with even sensitivity and, second, the whole radiation reflection in all directions by the irradiated surface. The latter condition is not met in either aerial or space-based remote sensing.

The reflectance coefficient ρ_θ is the ratio of the reflected radiation in specified direction θ to the incident radiation. As reflection is a function of wavelength the spectral reflectance coefficient $\rho(O\lambda)$ is the value of this ratio at a given wavelength λ . The value of this ratio is often given for a small interval $\Delta\lambda$ with $\Delta\lambda = 1 \mu\text{m}$. Unless a specification is made the reflectance coefficient will be understood to include both specular and diffuse components in the measured reflected energy. When the values of specular reflectance coefficient and diffuse reflectance coefficient are known separately, the hemispherical (spectral) reflectance coefficient is given by

$$\int^{2\pi \text{ Ster}} \rho(\lambda\theta) d\theta.$$

When the reflected radiation is considered in all directions, θ of the source space (2π Steradian), it is obvious that integrating over λ (which gives the spectrum of the source) leads to the albedo value.

1.2a *Absolute variables*: For the sake of comparison of the measured values of same feature in different times it is imperative to calculate absolute variables. In remote sensing the spectral radiance $N(\lambda)$ is measured for such comparisons. It is worth noting that while absolute values are scarcely referred to in the studies on reflectance—apart from special work on the instrument technology—they are

fundamental for studies involving the emittance of the surface (thermal infrared) (figure 2).

$$N = \frac{\delta[\delta\Phi(\lambda)]}{\delta A \cdot \cos \theta \cdot \delta\Omega \delta\lambda} \quad (\omega\text{Sr}^{-1} \text{m}^{-2} \mu\text{m}^{-1}) \text{ per unit of spectral band } \delta\lambda,$$

where $\delta\Phi$ = total power (or radiation flux w) radiated by the surface element δA in the elementary solid cone angle $\delta\Omega$ of direction θ and ρ .

For a Lambertian surface N is θ and ρ is independent, thus the distribution of radiant flux from the surface is found to be spherical.

2. Reflectance measurement methods

2.1 Photography

A photograph may be considered as an image of the scene reflectance. The colour at each point is due to the spectral alteration of the incident solar radiation by each surface element of the targets in the scene. The optical density of the film is treated as the intensity of the reflected radiation.

However, the photographic sensor is unstandardisable in actual practice and thus unsuitable for quantitative radiance measurements. Nevertheless, it provides useful information, the exploitation of which is inexpensive as long as no machine processing is involved (i.e. if confined to photointerpretation techniques).

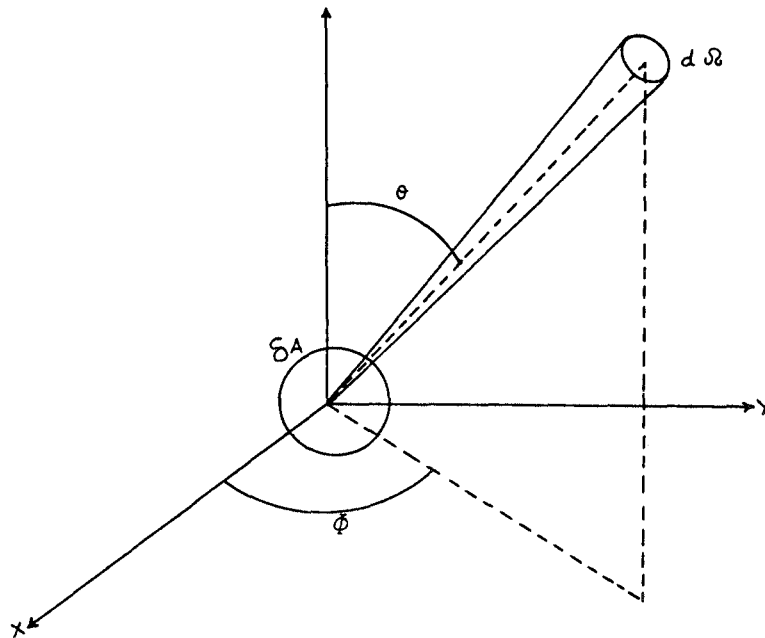


Figure 2. Measurement of spectral radiance.

2.2 *Photoelectric elements*

2.2a *Reflectance spectrophotometers*: These instruments measure the hemispherical reflectance of sample stick on a window of a sphere and lighted by an artificial source of radiation. The set-up of these instruments makes them unsuitable for field measurements. They have been broadly used to determine the specific spectral reflectance of a wide variety of natural surfaces and to study the variation of this reflectance in radiation to the state of the sample. The measurements can be used to determine (i) the sensitive spectral bands and (ii) the amplitude of reflectance variations which can be expected.

2.3 *Spectroradiometers*

There are two types of spectroradiometers: (i) with fixed spectral bands scanners (aerial or space-based and handheld radiometers compatible with such scanners belong to this category), (ii) with shifting spectral bands.

3. **Energy sources in reflectance remote sensing**

3.1 *Natural*

- (i) Sun: Punctual and localised source (by clear sky the spectral emission of which stretches from 300–3500 nm).
- (ii) Atmosphere (eventual clouds included): It is a stretched and diffused source.
- (iii) Surrounding of the considered point in the scene: The reflective and emissive properties of surrounding structures such as trees and hedges contribute to the irradiance of the elements in the scene.

3.2 *Artificial*

- (i) Radar (using microwaves).
- (ii) Laser-Lidar (visible in the broad sense).

The above basic considerations of physics are essential to understand how remote sensing makes use of reflectance phenomena of vegetation and also explains why discrepancies may arise when various measuring methods are implemented.

As a general rule, the reflectance value of a surface at a given wavelength depends on (i) the geometry of the set (source, surface and sensor) and (ii) the spatial composition and incident flux polarisation (irradiance) on the target surface.

4. **Vegetation reflectance**

The vegetation reflectance is influenced by the reflectance characteristics of individual plant organs, canopy organisation, type and growth stage of plants and structure and texture of the canopies. A synthesis of these aspects provides true reflectance characteristic. However, effects of individual parameters have been

studied by various authors without fully achieving models to determine vegetation reflectance characteristics.

4.1 Nature of the plant

Numerous measurements have been performed to evaluate the spectral response of various categories of plants with a spectrophotometer (figure 3). The studies have led to the following general conclusions. For a plant in its normal state, i.e. typical and healthy, the spectral reflectance is specific of the group, the species and even of the variety at a given stage in its phenological evolution.

The general aspects of spectral reflectance of a healthy plant in the range 400–2600 nm is shown in figure 4. Figure 4 shows five striking features concerning the absorbance.

- (i) High in the ultraviolet and the blue.
- (ii) Reduced in the green.
- (iii) High in the red.
- (iv) Very low in the near infrared ($700 < \lambda \text{ nm} < 1500$) along with high reflectance and transmittance. The very abrupt increase in reflectance near 700 nm and the fairly abrupt decrease near 1500 nm are present for all mature healthy green leaves.
- (v) Very high further in the far infrared ($\lambda > 3000 \text{ nm}$).

Thus the typical spectral curve of plant is divided into three prominent zones correlated with morphological characteristics of the leaves.

4.1a *Pigment absorption zone*: The important pigments, viz. chlorophylls, xanthophylls and carotenoids, absorb energy strongly in ultraviolet, blue and red regions. The reflectance and transmittance are weak. The absorbed energy of this part of the spectrum is utilized for photosynthetic activity.

4.1b *Multidioptric reflectance zone*: In this zone the reflectance is high while the

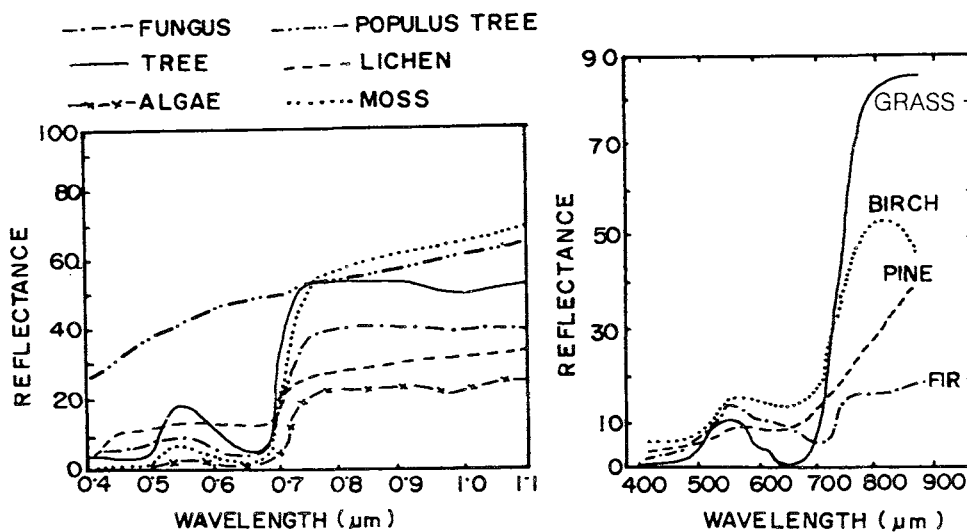


Figure 3. Spectral reflectance of species of plants belonging to various groups.

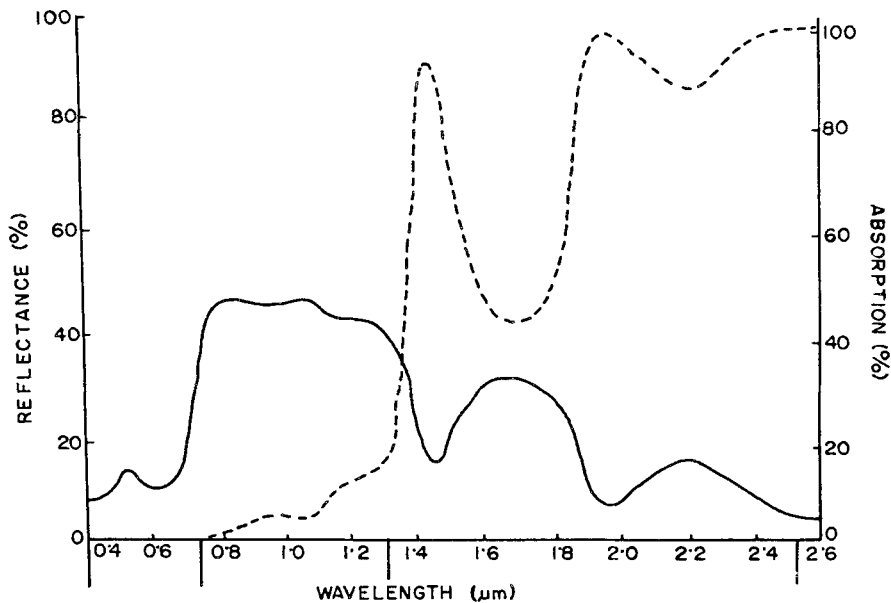


Figure 4. Spectral response of typical vegetation.

absorbance remains weak. All the unabsorbed energy (30–70% according to the type of plant) is transmitted. The reflectance is essentially due to the internal structure of the leaf which the radiation is able to penetrate. The reflectance from internal structure is of physical nature. Apart from the contribution of the waxy cuticle, the magnitude of the reflectance depends primarily upon the amount of spongy mesophyll.

4.1c *Hydric zone*: Amount of water inside the leaf bring on the pattern of spectral reflectance with water-specific absorption bands at 1450, 1950 and 2660 nm. Liquid water in a leaf is largely the cause of the strong absorption throughout middle infrared. Beyond 2500 nm the reflectance becomes less than 5% due to atmospheric absorption.

4.2 *Factors affecting spectral reflectance of vegetation*

There are numerous factors, either internal or external (environmental), which have an influence on the specific spectral reflectance. The above descriptions exposed so far are true only for a normal, mature and healthy vegetation. The factors which affect the spectral reflectance of leaves are leaf structure, maturity, pigmentation, sun exposition, phyllotaxis, pubescence, turgidity (water content), nutritional status, disease, etc. Primarily most important factors are pigmentation, nutritional status, anatomy of leaves and water content. While sun exposition and phyllotaxy affect the canopy reflectance, phenological state and disease are linked to the primary factors affecting the spectral reflectance.

4.2a *Pigmentation*: Low content of pigmentation results in higher reflectance and

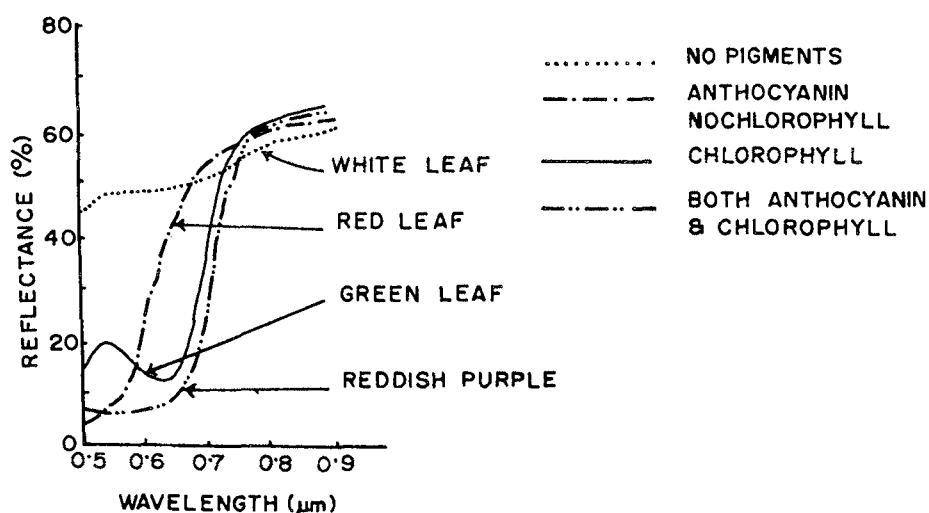


Figure 5. Spectral response of different pigments in leaf of *Coleus*.

vice versa. Moreover different pigments show different spectral response (figure 5). In yellowing of leaf, which is a stage in the phenological cycle or in certain diseases, breaking down of chlorophylls take place thus letting the presence of carotenes and xanthophylls more evident. During this stage leaf shows sharp increase in reflectance starting at $0.50 \mu\text{m}$.

4.2b *Nutritional status*: With increases in nitrogen deficiency reflectance increases from 0.5 to 0.7 and 0.7 to $1.3 \mu\text{m}$ but decreases from 1.3 to $2.5 \mu\text{m}$. The increase of reflectance from 0.5 to $0.7 \mu\text{m}$ is due to the fact that absorption in this spectral region is greatly affected by pigment concentration, which in turn depends on the nitrogen concentration. By lowering the nitrogen content, a decrease in the chlorophylls and consequently a reduced absorption of radiation (hence an increase of reflectance) are expected.

Increase of reflectance from 0.7 to $1.3 \mu\text{m}$ might be related to an increase in the intercellular spaces. Reflectance decreases from 1.3 to $2.5 \mu\text{m}$ might be directly related to a greater water content of leaves (Thomas *et al* 1966).

Al Abbas *et al* (1974) studied chlorophyll concentration of leaves of maize in normal and nutrient-deficiency treatments resulting in low absorbance in the range 0.53 – $0.75 \mu\text{m}$. Potassium-deficient leaves have lowest leaf thickness and leaf moisture content resulting in highest reflectance in infrared region from 0.75 to $1.3 \mu\text{m}$. Sulphur, magnesium and nitrogen-deficient plants have higher moisture content and also showed increased absorbance in the wavelength interval 1.3 – $2.5 \mu\text{m}$.

4.2c *Leaf anatomy*: The influence of internal structure of leaf is very significant. Prominent anatomical features which affect the spectral reflectance are cell walls, intercellular spaces, epidermis, palisade and mesophyll cells.

When radiation falls on the leaf surface, a part of the energy is reflected back from the leaf surface; the reflection depends on cuticle thickness. The rest of the

energy passes through the leaf, interacting with the internal cellular structures, and strikes the lower leaves. The internal structure transmits the energy after cell wall and cell sap interaction. A similar phenomenon takes place in the lower leaves also. However, studies indicate that there is no effect on the spectral reflectance if stacking of leaves is more than 3 or 4 (figures 6 and 7).

Conclusively, multiple leaf layers cause higher reflectance (up to 85%) in the near-infrared region. This is due to additive reflectance: energy transmitted through the first (uppermost) layer of leaves and reflected from the second layer is partially transmitted back through the first layer.

4.2d *Morphological adaptations*: Thorns are reported to have a role in the heat balance of desert plants. Studies on spectral properties of plants with thorns have

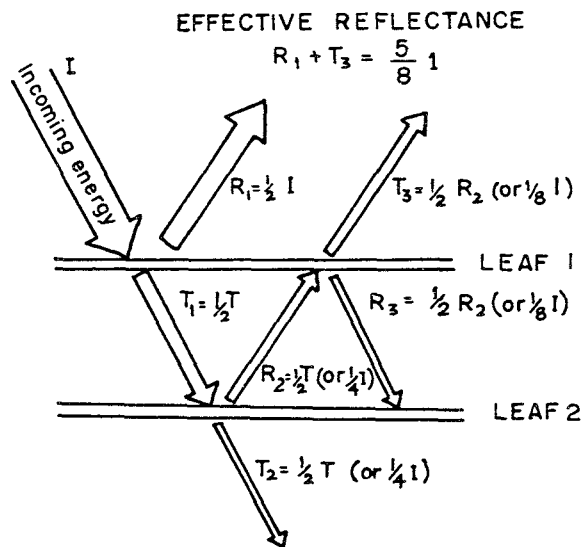


Figure 6. Spectral reflectance from different layers of leaves.

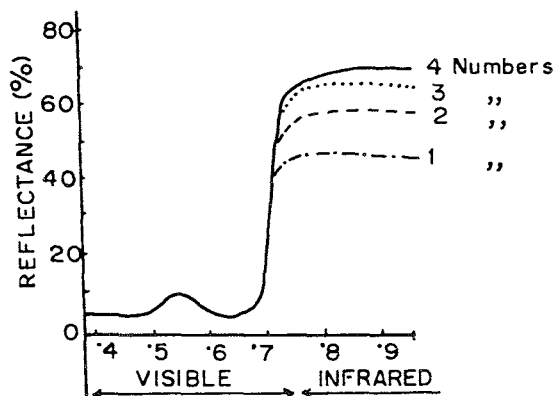


Figure 7. Spectral response of leaves in different stacking states.

indicated that absorption of energy is largely altered by thorns by reducing direct solar radiation at cuticular surface since radiation is absorbed more in the thorn and less in the cuticle and spongy tissue of the plant. Thus, if the incident radiation is absorbed strongly by the thorny mat, heat will be radiated back to the sky and less of it will be transferred by conduction to the underlying cuticle. It is probable that this is an important role for the dense thorn mats, but the function of thorns distributed generally over the surface of a cactus may be different. Thorns, however, also have other functions, serving, for example, as a deterrent to predation. The role of trichomes, including hairs, thorns and bristles on the surface of leaves, is not well understood. Suggested functions include reflection of radiation, reradiation, reflection and absorption of radiation to protect plant pigments and cells against radiation of certain wavelengths, reflection of radiation into the mesophyll in order to provide increased light for photosynthesis, shading of the leaf surface, reducing water loss from leaves, insulation against heat loss and reducing the effect of wind on the leaf boundary layer. Pubescence significantly increases the total diffused reflection in the 750–1000 nm range but decreases it in the 1000–2500 nm range. It has very little effect on the reflectance in the region 500–750 nm.

4.2e *Seasonal reflectance change:* The changes that occur in the spectral properties of plant leaves during the growing season are significant. The very young folded, compact and underdeveloped leaves exhibit lack of chlorophyll. Absorption in the visible range is due to protochlorophyll and anthocyanin. Gradually the leaf becomes more and more green, which decreases red reflectance. Finally, a fully open leaf shows the normal spectral characteristics with the green reflectance strong and the red and blue spectral regions much absorbed. The near-infrared reflectance decreases as the leaf opens. The striking decrease appears to be caused by the unfolding and expansion of the leaf and resultant loss of a multitude of reflecting surfaces which existed in the much-folded, very young leaf.

As the leaf matures the light green colour darkens and chlorophyll absorption becomes well-developed in the red region. However, the near-infrared reflectance increases due to the development of air-spaces in the mesophyll and the presence of many reflecting surfaces within a leaf. Gradually, no change in visible part of the spectrum is noticed but the reflection in near infrared region increases. A stage comes when the reflection characteristics become fairly stable throughout the visible and near-infrared and variation from leaf to leaf is also reduced. After this stage green reflectance increases dramatically as the blue and red absorption weakens. The characteristic progressively takes place and becomes more and more prominent as chlorophyll disappears. This stage is called senescence in phenological staging. With most of the pigmentation gone, the leaf dries out and has collapsed cells throughout most of its structure. At this stage the leaf has a brown dead appearance. It is interesting to note that the near-infrared reflectance over the range 700–900 nm diminishes strongly but the reflectance in the region beyond 900 nm changes very little.

4.2f *External factors affecting spectral reflectance:* The influence of the external factors on the spectral reflectance is due to the alteration they bring about in water content and turgidity, mesophyll structure, evapotranspiration, pigmentation and metabolism. The external factors are connected:

- at ground level
 - to the water availability for the plant
 - to trophic mineral ion availability with specific evidence for nitrogen, iron (chlorophyll), potassium, phosphorus, calcium or magnesium
 - to toxic mineral salts (effect of water salinity)
- from atmosphere
 - climatic factors (wind, air moisture content, temperature, sunshine conditions) on which depend the CO₂ acceptance and evapotranspiration
 - seasonal variations
 - toxic pollutants (especially fluorine, sulphur dioxide)
 - deposition of dust/particulate matter
- biological pathogenic agents
 - parasites
 - predators
- to irradiance incidence angle (sun elevation), which leads to a diurnal variation of the spectral reflectance.

4.2g *Impact of disease on spectral reflectance*: Effect of disease on spectral characteristics of plants can be understood when it is related to the type of disease. Different types of plant diseases are discussed with respect to their impact on spectral reflectance.

4.3 *Trophic diseases*

Diseases under this group are powdery mildew, rusts, downy mildew and cereal smuts. The chlorophyllian or assimilation function of the plants is primarily affected by the pathogens.

The organs affected by the pathogens show a mould layer formed by the pathogen's vegetative reproduction structure. Besides change in the chlorophyllian function, resulting in a decrease of chlorophyll content, the pathological event also leads to other changes concerning the whole plant. In particular, an increase in the respiration and transpiration rates is observed, with evident consequence on the water content. Moreover a greater nutrient demand may result in an increase of dry weight due to the modification of the leaf structure.

As mentioned above, all parameters previously indicated as basic in the determination of the vegetation spectral response, i.e. pigment content, leaf structure and water content, are directly affected by this type of disease.

Due to decrease in pigment content reflectance is increased in the region 0.4–0.7 μm . The spectral response in the far-infrared is expected to change due to the higher metabolism in the affected areas influencing leaf temperature.

Variation in the leaf inner structure should not be important in the case of powdery mildew, as the pathogen lives on the leaf surface, affecting the soil epidermis. The presence of the mould formed by the pathogen on the leaf may cause modification in the response in the visible region.

4.4 *Auxonic diseases*

In this group of diseases the growth capability of the plant or of a part of it is mainly affected. This type of disease can be caused by nutritional stress, chemical

agents (for instance herbicides), bacteria, fungi and viruses. Symptomatology of this kind of diseases present eterogenous characteristics. Hence, it does not seem possible to give any indication on the spectral response.

However, a common characteristic is decrease in chlorophyll content. Hence a variation in the response in the visible region is expected. A similar effect can be expected due to the change in the morphology of the plants.

4.5 *Necrotic diseases*

Diseases under this group are rice blast, leaf blight and scabs. Pathogens attack all the living tissues of the plant, feeding on them after altering them, and causing death of cells. The symptomatology is characterised by necrotic spots on leaves and fruits and cankers on the lignified organs. Chemical compounds and gaseous pollutants of urban and industrial wastes may cause similar effects.

The pathogen's presence results in alterations in pigment content, leaf structure and water balance. Variation in the leaf spectral response in the entire wavelength interval 0.4–2.6 μm can be expected. Reflectance of infected areas is always higher than that of healthy areas and differences are more evident in the chlorophyll absorption bands (0.5–0.7 μm) and water absorption bands (1.45–1.95 μm). These differences have been related to a decrease of chlorophyll and water in diseased tissue.

4.6 *Vascular diseases*

These diseases are characterized by the location of the pathogens along the vascular elements, thus interfering with the plant water supply. There is a disease spectrum of showing various levels of chlorosis (partial or total). The agents of this group of diseases are mainly fungi and bacteria. Obviously, as water stress becomes prominent, the spectral response in the middle-infrared region (1.3–2.5 μm) shows clear indication. The variations will be more evident at the three peaks of highest water absorption, i.e. 1.45, 1.95 and 2.6 μm . Water stress will cause change in the inner leaf structure also which will lead to change in the spectral response in the wavelength interval 0.5–0.7 μm .

4.7 *Lytic diseases*

The main characteristic of this group of diseases from the symptomatological point of view is the formation of 'rots' as an effect of tissue disintegration. The water balance of the plant and the inner structure of leaf are mainly affected. Consequently, the pigment content of the affected areas is modified. It causes variation in the spectral response in the whole wavelength interval 0.5–2.5 μm . Most prominent effect is expected in the form of higher reflectance in the visible portion of the spectrum due to lowering of pigment concentration.

4.8 *Epiphytic diseases*

Here disease is caused by the so-called epiphytic plants which utilise the host as

support. The host plant suffers from an indirect damage due to interference with the photosynthetic activity and gas exchange.

No conclusions can be drawn with respect to variation in the spectral response due to epiphytic plants. The alterations caused by the deposition of dust or particulate matter from industrial sources are also grouped in this category. The dust or particulate matter acts as a screen affecting photosynthesis, and spectral response is expected to change in the range 0.5–0.7 μm due to the presence of extraneous substances (figure 8).

5. Reflectance of vegetation canopies

The spectral reflectance as measured on separate organs by spectrophotometry may present fundamental spectral characteristics but they do not necessarily allow a straightforward interpretation of the information obtained by remote sensing on a scene.

The spectral response of vegetation canopies needs to be studied keeping in view the following points:

- (i) Vegetation coverage on the soil may vary, which gives rise to composite reflectance of soil and vegetation. The ratio describing the actual rate of cover may be related to the LAI. LAI is also reported to be correlated with height.
- (ii) Phyllotaxy of plants combined with canopy architecture. Depending on this parameter the incoming radiation penetrates inside the vegetation cover by multiple reflections and transmissions, acting more specifically on the infrared part of the

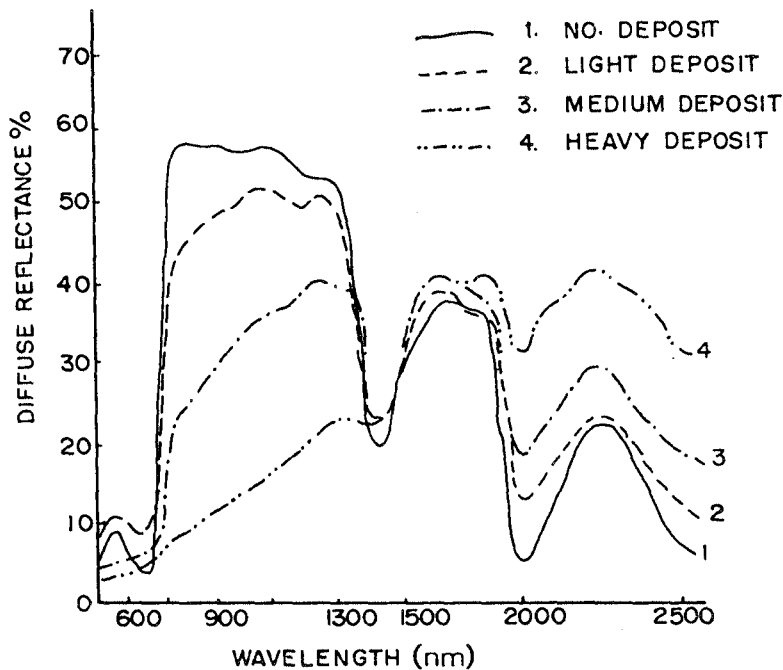


Figure 8. Spectral response of leaves of citrus affected by fungus (*Capnodium citri*).

spectrum (figure 6). The resultant canopy reflectance is consequently less than the one featured by single leaves and rarely exceeds 30%. The rate of diffusion increases with leaf irregularities and sun elevation. Borner (1962) found an exponential drop of the radiation versus thickness of the cover (Lambert's law concerning the attenuation of a beam).

(iii) The irradiance declination is controlled by the time and the season. Generally, the more vertical to the canopy the more intensely the radiance penetrates the cover. A strong angular dependence features the reflectance as a function of wavelength (Allen and Richardson 1968) and according to the structure of the canopy and phenological state. In order to set up the canopy reflectance from the spectral properties of single organs, reflectance models have to be built up.

5.1 Composite reflectance

In natural conditions the elementary area on ground as resolved by the IFOV of a sensor (the pixel in the image) is most of the time composed of mixed elements (vegetation + underlying soil) and this leads to spectral reflectance curves without the clear maximum and minimum values otherwise typical of vegetation. This mixing occurs when the density of the plant or of the cover as a whole is too low or at the transition between two vegetation types. The resulting reflectance of the heterogeneous area appears as being in between the typical reflectances of the constitutive elements. It shows a composite reflectance $\rho(\lambda)$ which can be derived from the proper reflectances $\rho\alpha(\lambda)$ of each of the elements.

The reflectance of a soil area A which is partially covered with vegetation may be expressed as a composite reflectance

$$\rho = \frac{A_v P_v + A_s P_s}{A}, \quad \text{with } A = A_v + A_s,$$

P_v and P_s being the specific reflectances of the vegetation and soil respectively.

In the visible region of EMR, usually $P_s > P_v$.

In the near-infrared, conversely, $P_s < P_v$.

A composite reflectance is all the more difficult to interpret when the spatial variability and area resolved are both greater.

It can be seen from the various phenomena outlined above how a remote sensing technology can be benefitted by study of spectral signatures of vegetation: (i) choice of spectral bands, (ii) choice of spectral bandwidth according to information content, (iii) optimal irradiance conditions (day of the year and time) and (iv) sensitive periods in the vegetative cycles of the plants.

When satellite data are given for interpretation one has to consider how the data have been acquired. It will be required to process the data for useful information extraction.

6. Remote sensing for the assessment of biomass and productive potential

Remotely sensed data present information pertaining to land surface features. The interpreter extracts as much information as precisely as possible for his interest

and objective. Photographs and multispectral scanner image/digital data are the two broad categories of remote sensing data products. Aerial photographs are capable of providing a stereoscopic view of the landscape. They have been used widely for forest classification based upon the gregarious species, stand height and crown density, ultimately producing this stratification in the form of thematic maps. These maps have also been used for estimating timber volume/growing stock by integrating the area of each stratum obtained from the map and data collected on growing stock from representative sample plots of each stratum on the ground employing some efficient statistical design. The utility of photographic products are limited in scope for estimating total vegetation amount as the stereomodel generated through the photographic images provides access only to the emergent trees and top forest canopy. Decreasing production of conventional utilizable components but increasing human needs have necessitated estimation of total vegetation amount and productive potential for possible utilization of all components of vegetation. Quantification of reflectance/emittance from the landscape in discrete spectral regions, a technology commonly known as multispectral remote sensing, carries information of the total vegetation canopy and provides an alternative conceptual basis for estimating vegetation amount. The different satellite platforms providing multispectral remote sensing data for vegetation amount study are given in tables 1 and 2.

The biomass/primary production is a function of physiological activity of leaves forming the canopy while multispectral reflectance is a function of physical and physiological property of the canopy or green biomass. Thus success of estimating biomass production through remote sensing depends upon the ability to derive (i) relationship between canopy parameters and total biomass production, (ii) relationship between canopy parameters and multispectral remote sensing data and (iii) replacing the conventional canopy parameters with multispectral data in the form of a model for non-destructive estimation of biomass production.

6.1 Canopy parameters and biomass production

The structural, physiological and biochemical attributes are micro-level parameters determining the photosynthetic efficiency of individual leaves. Due to variation in these attributes species may differ with respect to their production capacity (Black 1971). However, variations in the micro-level parameters get attenuated when plant growth is compared at the whole plant/crop level in terms of net primary production. Net primary production, which is an area average quantification, has been found to be more crucially related to the amount of foliage, placement and orientation of leaves in the canopy, age structure, flux and pattern of leaf production in relation to the effective interception of photosynthetically active radiation. The studies indicate the existence of dependence of total biomass production on the canopy parameters (Ramakrishnan *et al* 1982; Mishra and Ramakrishnan 1983). The dependence of biomass production of the canopy properties needs to be analysed for the variety of vegetation types of India. In addition, it has also to be investigated to what extent species-specific variation in biomass production influences the spatial functions of biomass in natural vegetation.

The dependence of biomass production on canopy parameters has been shown in

Table 1. Satellite platforms and their characteristics.

Satellite	Data characteristics
National oceanic and atmospheric administration—Advanced very high resolution radiometer (NOAA-AVHRR)	Spatial resolution: 1.1×1.1 km Spectral resolution: Five bands Red— $0.58-0.68 \mu\text{m}$ Near-infrared— $0.725-1.1 \mu\text{m}$ Middle infrared— $3.55-3.93 \mu\text{m}$ Thermal infrared— $10.5-11.5 \mu\text{m}$ Thermal infrared— $11.5-12.5 \mu\text{m}$ Temporal resolution: Twice a day
Landsat multispectral scanner system (Landsat MSS)	Spatial resolution: 79×79 m Spectral resolution: Four bands Green— $0.5-0.6 \mu\text{m}$ Red— $0.6-0.7 \mu\text{m}$ Near-infrared— $0.7-0.8 \mu\text{m}$ Near-infrared— $0.8-1.1 \mu\text{m}$ Temporal resolution: Every 16–18 days
Landsat thematic mapper (Landsat TM)	Spatial resolution: 30×30 m Spectral resolution: Seven bands Blue-green— $0.45-0.52 \mu\text{m}$ Green— $0.52-0.60 \mu\text{m}$ Red— $0.63-0.69 \mu\text{m}$ Near-infrared— $0.76-0.90 \mu\text{m}$ Near-middle infrared— $1.55-1.75 \mu\text{m}$ Thermal infrared— $10.4-12.5 \mu\text{m}$ Middle infrared— $2.08-2.35 \mu\text{m}$ Temporal resolution: Every 16 days
SPOT multispectral mode	Spatial resolution: 20×20 m Spectral resolution: Three bands Green— $0.50-0.59 \mu\text{m}$ Red— $0.61-0.68 \mu\text{m}$ Near-infrared— $0.79-0.89 \mu\text{m}$ Temporal resolution: Every 26 days
Indian remote sensing satellite (IRS—1A)	Spatial resolution: 73×73 m 36.5×36.5 m Spectral resolution: Four bands Blue— $0.45-0.52 \mu\text{m}$ Green— $0.52-0.59 \mu\text{m}$ Red— $0.62-0.68 \mu\text{m}$ Near-infrared— $0.77-0.86 \mu\text{m}$ Temporal resolution: Every 14 days

broad surveys covering diverse vegetation types in other geographical regions. Webb *et al* (1983) found a strong positive correlation between the maximum foliage amount and biomass production amongst vegetation types represented by coniferous and deciduous forests, grasslands and desert vegetation types in the United States. LAI is often used to quantify and parametrise the canopy in terms of its capacity to intercept light. It is expressed as one side area of leaves in the canopy existing over a unit ground area. Maximum sustainable LAI during the entire growing season has been found to be correlated with the vegetation growth when considered over large spatial areas (De Angelis *et al* 1981; Gholz 1982; Schroeder *et al* 1982). Length of growing season and longevity of leaves in different vegetation types are always accounted for in deriving such relationships. However, green biomass does

Table 2. Comparative capability of different remote sensing platforms to measure vegetation amount.

Sensing platform	Sensor	Spatial	Resolution spectral	Temporal
Satellite				
Landsat-MSS	Scanning radiometer	Low	Low	Low
Landsat-TM	Scanning radiometer	Medium	High	Low
SPOT	Charge couple detectors	Medium	Low	Low
IRS-1A	Charge couple detectors	Medium/low	Low	Low
NOAA	Scanning radiometer	Very low	Low	Very high
Aircraft				
Multispectral scanner	Scanning radiometer	Very high	High	Very low
Multispectral photograph	Camera	Very high	Low	Low
Ground				
Handheld radiometers	Radiometers	Very high	Very high	Very high

have relationship with the multispectral data but is reported to show saturation beyond a value of 8 (Tucker 1977). Vegetation types with similar LAI may have different production values if they differ in phenology which is usually attuned to the climatic condition (Whittaker *et al* 1974; Harris *et al* 1975). Leaf area duration, the product of LAI and length of the effective growing season increases the precision of biomass estimation in diverse vegetation types. The monitoring of canopy parameters and properties may also reflect the regeneration potential of a site/landscape. The maximum possible biological production could be predicted through its dependence primarily upon the climatic variables (Leith 1975).

6.2 Multispectral remote sensing for canopy characterization and biomass production

Canopy parameter characterization from the remotely sensed data is based upon the physical and physiological significance of interaction of light energy with the foliage. The simplest approach to study canopy from the point of radiation balance is to consider it as a stack of horizontally placed leaves, the stacking being quantitatively expressed as LAI. However, the remote sensing data is an area-average quantification of albedo. The size of area is represented as a spatial resolution. The information pertaining to canopy in the remote sensing data is therefore invariably contaminated with the spectral characteristics of other area features like soil, rock, senescent leaves and shadow. The reflectance measurement is further influenced by varying illumination conditions (solar zenith and azimuth positions) and leaf angle distribution (Sellers 1985).

A common approach to quantify canopy through multispectral data is to synthesize the information present in different spectral channels in the form of indices. These indices, with canopy parameters like leaf biomass, LAI, leaf overlap index and photosynthetically active radiation (PAR) absorbed, determine biomass production. The idea behind developing such indices is to compress the huge amount of multispectral data in such a way that spectral properties of canopy get enhanced and interference of other area features or variability due to different illumination conditions is reduced. The indices used for the vegetation quantification, termed as vegetation indices, are given in table 3. They can be divided

Table 3. Spectral vegetation indices.

Name	Computation	Reference
Ratio-based indices, Simple division	IR/R	Curran and Milton (1983)
Complex division	IR/R + Other wavelengths	Curran (1980)
Simple multiratio (normalised difference)	IR - R/IR + R	Tomlins and Thompson (1980)
Complex multiratio (transformed vegetation index)	$\sqrt{IR - R/IR + R + 0.5}$	Rouse <i>et al</i> (1973)
<i>n</i> -space indices		
Perpendicular vegetation index	$\frac{\sqrt{(R \text{ soil} - R \text{ veg}) + \sqrt{(IR \text{ soil} - IR \text{ veg})}}}{\sqrt{(IR \text{ soil} - IR \text{ veg})}}$	Richardson and Wiegand (1977)
Green vegetation index	$0.29(G) - 0.56(R) + 0.60(IR) + 0.49(IR)$	Kauth and Thomas (1976)

R, Red reflectance; IR, near-infrared reflectance; G, R, IR, IR, are the green, red and two near-infrared spectral bands of Landsat MSS; Veg, vegetation.

into two groups, ratio-based vegetation indices and *n*-space vegetation indices. Ratio-based indices employ various computations of red and near-infrared data. Their use is common because of simpler computation procedures and limited ground data requirements. It is also presumed that ratioing reduces data variability resulting from differential illumination conditions (Yool *et al* 1986).

A positive linear relationship between red and near-infrared reflectance has been found for a rock-soil type. Kauth and Thomas (1976) reported the multispectral data (green, red and near-infrared reflectance data of Landsat-MSS) to be concentrated along a specific direction for bare soil and they defined it quantitatively in terms of soil brightness index in multivariate feature space constructed by the 4 spectral band data. Vegetation canopy alters the reflectance which would otherwise be obtained from the bare soil in the absence of any vegetation. The quantitative measure of this alteration at a vegetated place would reflect the canopy parameters at that place. The orthogonal distance between the reflectance at a vegetated place and the soil line in a multispectral feature space is called green vegetation index (GVI). Perpendicular vegetation index (PVI) developed by Richardson and Weigand (1977) is similar to the GVI except that it makes use of only two bands, red and near-infrared. The soil line is obtained by plotting red and near-infrared from the bare soil. The orthogonal distance in this cospectral plot from a point to the soil line is PVI, which is subsequently used to predict the canopy parameters. *n*-Space transformations of spectral data are performed using Gram-Schmidt orthogonalisation process (Jackson 1983).

Suitability of specific index for estimating biomass production is initially assessed through pilot studies using ground radiometers and aerial scanner data complementary to the satellite data. Indices have become more efficient estimators of vegetation amount when compared with the performance of different bands independently. Selection of remote sensing data acquisition is based on the required spatial resolution. A balance between spatial, spectral and temporal resolution is usually made depending upon the scale of study.

The typical relationship between multispectral reflectance and herbaceous vegetation is shown in table 4. While these relationships provide good indication for

Table 4. The relationship between multispectral reflectance and vegetation amount.

Ultraviolet/blue	350–500	Strong chlorophyll-carotenoid absorption	Strong negative
Green	500–600	Reduced level of pigment absorption	Weak positive
Orange/red	600–700	Strong chlorophyll absorption	Strong negative
Far-red	700–740	Transition between strong absorbance and strong reflectance	Strong positive
Near-infrared	740–800	High vegetation reflectance	Strong positive

Table 5. The relationship between multispectral reflectance and vegetation amount: the effect of vegetation senescence and soil reflectance (Curran 1980).

Vegetation	Soil colour	Wavelength				Ratio IR/R
		Blue	Green	Red	Infrared	
Live	Light	– ve	0	– ve	+ ve	+ ve
	Dark	– ve	+ ve	– ve	+ ve	+ ve
Live/dead mixture	Light	0	0	0	+ ve	+ ve
	Dark	0	+ ve	0	+ ve	+ ve
Dead	Light	0	0	0	+ ve	+ ve
	Dark	+ ve	+ ve	+ ve	+ ve	0

+ ve, Positive relationship; – ve, negative relationship; 0, no or poor relationship.

a healthy grass on a medium-toned soil, variation can be expected with soil type, the amount of senescent vegetation and the angle of sun with respect to the sensor.

6.3 Factors interfering with multispectral reflectance and vegetation amount relationship

6.3a Soil background: If the reflectance of the soil is similar to the reflectance of vegetation at a particular wavelength then the relationship between reflectance and vegetation amount will be weak in that band. For light-coloured soil with strong infrared reflectance the relationship between infrared reflectance and vegetation amount is less than for dark soil with a low infrared reflectance (table 5).

6.3b Solar elevation: Two interrelated factors contribute to the effect of solar elevation on the reflectance of a vegetation canopy. The first is the degree to which solar radiation can penetrate the canopy and this is negatively related to solar elevation. The second is the amount of canopy shadow and is positively related to solar elevation. As a result most canopies have a negative relationship between near-infrared reflectance and solar elevation and poor relation or no relation between visible reflectance and solar elevation.

6.3c Sensor elevation: The elevation of the sensor determines the amount of substrate and shadow seen. As the elevation moves from the vertical, the area of soil and shadow seen by the sensor decreases and area of vegetation increases.

6.3d *Relative solar and sensor azimuth:* For most remote sensing applications where sensor look angle is nearly vertical the effect of solar azimuth on reflectance increases with decrease in solar angle and increase in vegetation canopy roughness.

6.3e *Presence of senescent vegetation:* As vegetation senesces the near-infrared leaf reflectance does not significantly decrease. However, the breakdown of plant pigments causes rise in red reflectance. Therefore, if the amount of senescent vegetation in a canopy increases, the positive relationship between near-infrared and green LAI will weaken and probably disappear. This is a problem in seminatural vegetation, particularly grassland, where there is some senescent vegetation in the canopy throughout the year.

7. Model approach to quantify vegetation using remote sensing data

Two distinct approaches have been adopted for quantifying vegetation from remote sensing data:

- (i) Integration of greenness indices or vegetation indices over the entire growing season. The integrated product becomes a function of total PAR absorbed by the vegetation during a year/specified period.
- (ii) Relating the maximum greenness index obtained during the growing season with the total biomass production.

The first approach is a modification of Monteith's (1972) model which had widely been implicated for agricultural production. Biomass production during a specific period at a place can be worked out if we know the length of the growing season which may be expressed as number of days (n), total incident radiation (s), proportion of photosynthetically active radiation in the total incident solar radiation (Es), proportion of the photosynthetically active radiation which is absorbed by the vegetation (Ei), photochemical efficiency factor of the vegetation (Ec) and a vegetation stress index (C).

$$\text{Biomass production } (M) = \sum_{i=1}^n Ec, Ei, Es SC \text{ (Monteith 1972).}$$

Total amount of solar radiation reaching the earth's surface (S) is a function of the geographical position of the area under consideration. This variable is more or less constant for a given geographical position. The proportion of photosynthetically active radiation in the total incident radiation has been found to be constantly contributing nearly 50% of the total radiation and is also not affected much by the variation in atmospheric conditions.

Photochemical factor Ei expresses the proportion of the absorbed photosynthetically active radiation which is converted to chemical energy. It is related to the genetical and physiological organisation of the plants and is constant within a limited environmental variability for a species. The derivation of photochemical efficiency factor on an area basis is simple for uniform plant-cover types like agricultural land and plantations consisting of single species. However, it becomes complicated for natural vegetation where a variety of species differing with respect to their photochemical efficiency co-exist.

Factors limiting plant growth are referred to as stress factors. Amongst a large

number of stress factors, temperature and water are considered to be most critical for plant growth. Crop stress index (C) is a measure of the response of a species to these stresses. This index could be obtained by getting a ratio of actual and potential evapotranspiration and can be taken as a constant for a given vegetation type in a bioclimatic region.

The proportion of the photosynthetically active radiation absorbed by the vegetation depends upon the concentration of photosynthetic pigments, amount, area and orientation of leaves in the canopy. This variable changes upon the growth stage of the plant and also the management practices and therefore its frequent quantification is important for estimating biomass production. Multispectral measurements through remote sensing techniques have been found to be correlated with the fraction of PAR absorbed by the vegetation. Remotely sensed data could be an efficient nondestructive substitute of the absorbed photosynthetically active radiation. A cumulative index of the data collected during the entire growing season may be used for estimating biomass production during the year.

The green biomass shows positive relation to infrared bidirectional reflectance and negative reflectance to chlorophyll absorption bands, viz. blue–orange–red. If the soils are excessively light or dark and if the vegetation is more alive than dead, the look angle is vertical and the solar angle constant, then the type of relationship to be expected between multispectral reflectance and vegetation amount is dependent upon the soil covered by the vegetation. The relationship is curvilinear, reaching an asymptote when the soil is completely covered by vegetation. From LAI 0–4, the relationship between multispectral reflectance and vegetation amount can be considered linear.

The model is considered significant and has also been made practically operational for uniform cover-types such as agricultural systems where biomass production is accounted largely by a few species. It is easy to estimate photochemical efficiency factor and crop stress index for agricultural crops. The calculation of these indices seems not to be possible due to spatial variations in species composition and representation in natural vegetation. There is also a possibility that the relationship between vegetation indices and canopy parameters may not be sensitive to the variability in species composition (Tucker *et al* 1983). The reason could be the area average measurements rather than the species-specific measurements from remote sensing platforms. These findings led to the estimation of primary production in the natural and seminatural diverse vegetation types through remote sensing. Quantitative information on the various vegetation types and reduction in the 'noise' (the spectral signals other than that of vegetation) are required to increase the precision of extracting information regarding dense and seasonal forest types. It is significant to note that photochemical efficiency factor and crop stress index have not been incorporated in the models estimating biomass production in natural vegetation from remote sensing data.

Acknowledgements

The author is grateful to Prof. B L Deekshatalu, National Remote Sensing Agency, Hyderabad, and Prof. S K Bhan for their support and encouragement. Thanks are due to Mr K S Bist and Mr B K Payal for assisting in preparation of this paper.

References

- Ajai, Kamat D S, Chaturvedi G S, Singh A K and Sinha S K 1983 Spectral assessment of leaf area index, chlorophyll content and biomass of Chickpea; *Photogramm. Engg. Remote Sensing* **49** 1721-1727
- Allen W A, Gausman H W and Richardson A J 1970 Mean effective optical contents of cotton leaves; *J. Opt. Soc. Am.* **60** 542-547
- Allen W A and Richardson A J 1968 Interaction of light with a plant canopy, *Proc. 5th Int. Symp. remote sensing of Env.*, Ann Arbor, USA 219-232
- Ai Abbas A H, Hall J D, Crane F L and Baumgardner M F 1974 Spectral of normal and nutrient deficient maize leaves; *Agron. J.* **66** 16-20
- Black C C 1971 Ecological implications of dividing plants into groups with distinct photosynthetic production capacities; *Adv. Ecol. Res.* **7** 87-114
- Curran P J 1980 Multispectral remote sensing of vegetation amount; *Prog. Phys. Geogr.* **4** 315-341
- Curran P J and Milton E J 1983 The relationship between the chlorophyll concentration, LAI and reflectance of a simple vegetation canopy; *Int. J. Remote Sensing* **4** 247-256
- De Angelis D L, Gardner R H and Shugart H H 1981 Productivity of forest ecosystems studied during the IBP; the woodland data set; in *Dynamic properties of forest ecosystems*, (ed.) D E Reichle (London: Cambridge Univ. Press) pp 567-572
- Gates D M, Keegan H J, Scheleter J C and Weidner V R 1965 Spectral properties of plants; *Appl. Opt.* **4** 11-20
- Gausman H W and Allen W A 1973 Optical parameters of leaves of 30 plant species; *Plant Physiol.* **52** 57-62
- Gholz H L 1982 Environmental limits of above ground net primary production, leaf area and biomass in vegetation zones of the Pacific Northwest; *Ecology* **63** 469-481
- Harris W F, Sollins P, Edwards N T, Dinger B E and Shugart H T 1975 Analysis of carbon flow and productivity in temperate deciduous forest ecosystems; in *Productivity of World ecosystems* (Washington: Int. Biol. Prog. Natl. Acad. Sci.) pp 116-122
- Jackson R D 1983 Spectral indices in n-space; *Remote Sensing Environ.* **13** 409-421
- Kamat D S, Ajai, Shashi Kumar M N, Sinha S K, Chaturvedi G S and Singh A K 1982 Remote Sensing of Plant Physiological Parameters; *Proc. Int. Symp. Int. Soc. Photogrammetric Engg. and Remote Sensing Commission VII*, Toulouse, pp 1041-1050
- Kauth R J and Thomas G S 1976 The tasseled cap graphical description of spectral-temporal development of agricultural crops as seen by Landsat; *Proc. Symp. Machine Processing of Remotely Sensed Data*, LARS Purdue University, West Lafayette, pp 41-51
- Leith H 1975 Modelling the primary productivity of the world; in *Primary productivity of the biosphere* (eds) H Leith and R H Whittaker (Berlin: Springer Verlag) pp 237-263
- Misra B K and Ramakrishnan P S 1983 Secondary succession subsequent to slash and burn agriculture at higher elevation in north-east India. I Species diversity, biomass and litter production; *Acta Oecologia* **4**
- Monteith J L 1972 Solar radiation and productivity in tropical ecosystems; *J. Appl. Ecol.* **9** 747-766
- Patel N K, Singh T P and Baldev S 1985 Spectral response of rice crop and its relation to yield and yield attributes; *Int. J. Remote Sensing* **6** 657-664
- Ramakrishnan P S, Shukla R P and Boojh R 1982 Growth strategies of trees and their application to forest management; *Curr. Sci.* **51** 448-455
- Richardson A J and Wiegand C L 1977 Distinguishing vegetation from soil background; *Photogramm. Engg. Remote Sensing* **43** 1541-1552
- Rouse J W, Haus R H, Schell J A and Deering D W 1973 Monitoring vegetation systems in the great plains with ERTS; *3rd ERTS Symposium*, NASA. sp-351 I, pp 309-317
- Roy P S, Saxena K G and Kamat D S 1986 Biomass estimation through Remote Sensing; *Technical Report IIRS*, Dehradun, pp 1-78
- Roy P S, Jonna S and Pant D N 1987 Evaluation of grasslands and spectral reflectance relationship to its biomass in Kanha National Park (MP), India; *Geocarto-Int. J. Remote Sensing* (in press)
- Sellers P J 1985 Canopy reflectance, photosynthesis and transpiration; *Int. J. Remote Sensing* **6** 1335-1372
- Schroeder P E, McCandlish B, Waring R H and Perry D H 1982 The relationship of maximum canopy leaf area and forest growth in Eastern Washington; *Northwest Sci.* **56** 121-130
- Thomas J R, Myers V T, Heilman M D and Wiegand C L 1966 Factors affecting light reflectance of cotton; *Proc. 1Vth Int. Symp. on Remote Sensing of Environ.*, Michigan, pp 305-312

- Tucker C J 1977 Use of near infrared/red radiance for estimating vegetation biomass and physiological status; *NASA/GSFC Report X-923-77-183*
- Tucker C J, Vanpraet C, Boerwinkel E and Gaston A 1983 Satellite remote sensing of total dry matter production in the Senegalese Sahel; *Remote Sensing Environ.* **13** 461-474
- Webb W L, Lauenroth W K, Szarek S R and Kinerson R S 1983 Primary production and abiotic controls in forests, grasslands and grasslands and desert ecosystems in the United States; *Ecology* **64** 134-151
- Whittaker R H, Bormann F H, Likens G E and Siccama T G 1974 The Hubbard Brook ecosystem study: forest biomass and production; *Ecol. Monogr.* **44** 233-254
- Wooley J T 1971 Reflectance and transmittance of light by leaves; *Plant Physiol.* **47** 556-662
- Yool R S, Jefrey L S, Estes J E, Botkin D B, Eckhardt D W and Davis F W 1986 Performance analysis of image processing algorithms for classification of natural vegetation in the mountains of south California; *Int. J. Remote Sensing* **7** 683-702