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STATE-OF-THE-ART IN AGRICULTURAL AND FOREST CROP STRESS AND DAMAGE DETECTION BY THE USE OF REMOTE SENSING TECHNIQUES - A CRITICAL REVIEW

Abstract

Basic principles and the results of research work concerning the use of remote sensing techniques for detecting stress or damage in agriculture and forestry are given. In most cases, aerial IRC photography was used, because, in general, both changes in spectral reflectance as well as in texture have to be taken into account in data evaluation. In forestry, practical application of research results has been established in a large variety of cases, whereas in agriculture only a few research findings could be transferred to practical use yet. The reasons for these facts are discussed, and proposals are made to close the existing gaps between science and application.

I Introduction

The shortage of food on a world-wide level is - apart from technical reasons, like inadequate soil, water, and planting management as well as international exchange and transportation difficulties - mainly a result of damage caused by biotic (pests, diseases, weeds) and abiotic (floods, draughts, etc.) agents in food and forage crops. Biotic agents are responsible for about 35 per cent crop losses between planting and harvest (see table 1), while losses caused by abiotic agents are very difficult to estimate on a global scale, as they usually occur irregularly in different confined areas, where they often cause up to 100 per cent damage to the crops.

Similar aspects apply for wood production. Apart from uncontrolled cutting which endangers considerable parts of the world's natural forests, wood resources are endangered and diminished by pests, diseases, unfavourable meteorological impacts, and fires. As compared to agriculture, however, there are no global loss data available. Yet an estimated yield loss rate of at least 20 per cent per annum seems realistic, with about an equal share of biotic and abiotic stress or damage causes.

TABLE 1 Losses from pests, diseases, and weeds in world's major crops

CROP	PERCENT LOSS BY			1974 PRODUCTION (MIO METRIC TONS)		
	Diseases	Pests	Weeds	Potential	Actual	Loss
Wheat	9,1	5,0	9,8	396	301	95
Paddy Rice	8,9	26,7		354	190	164
Potatoes	21,8	6,5	4,9	376	255	121
Maize	9,4	12,4	13,0	323	211	112
Millet/ Sorghum	10,6	9,6	17,8	104	65	39
Cassava	16,6	9,0	12,0	125	78	47

Nota: Loss percentages are from CRAMER (1974); production figures from FAO Yearbook (1974)

From the aforesaid it is evident that in agriculture as well as in forestry prevention, control and inventory of stresses and damage is a task of primary importance. In order to optimize the respective actions to be taken, it is necessary to localize, recognize, and quantify the damage. Remote sensing techniques can be of considerable value by furnishing the required informations.

In the following paragraphs a short review of the basics, the state-of-the-art, and proposals for the improvement of the applications of remote sensing in agriculture and forest stress detection is given and discussed.

II Basics of the detection of agricultural and forest stresses by remote sensing

Plant leaves generally provide the largest information content with respect to plant species and vitality. Therefore, the optical properties of leaves shall be described briefly. They are determined by the following characteristics:

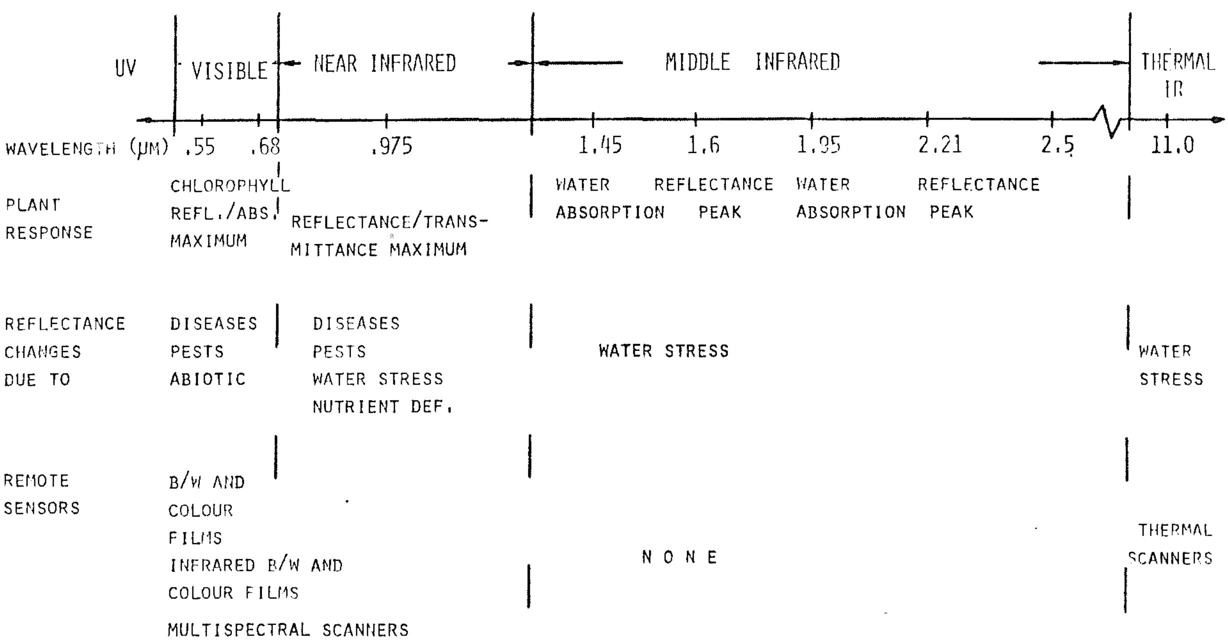
- leaf surface properties (cuticular wax, roughness, epidermal hairs) are responsible for the spectral reflectance at the surface of the leaves, especially in the ultraviolet and blue wavelength bands (WOOLLEY 1971, GAUSMAN et al. 1978)
- composition, concentration, and distribution of leaf pigments which largely govern absorption in the ultraviolet and visible spectral range, with characteristic absorptance maxima of the chlorophylls a and b, a reflectance maximum in the green, and, for ripening plants or in some stress situations, reflectance maxima in the yellow to red spectral bands, following the decomposition of chlorophyll and the appearance of carotinoids (ALLEN et al. 1969, WOOLLEY 1971)

- anatomical structure of the mesophyll tissue, and total cell wall thickness as summed up across the leaf, which influences the relation between reflected and transmitted energy in the near infrared wavelengths, where absorption is at a minimum and for green, healthy leaves reflectance and transmittance equally amount to nearly 50 per cent each (WILLSTAETTER & STOLL, 1918, SINCLAIR et al. 1973, TUCKER & GARRAT 1977)
- water content and distribution, which is related to absoption in the infrared water absorption bands between 1300 and 2500 nanometers, and as well influences canopy temperature (GATES 1970, WOOLLEY 1971).

Now plant canopies are complex, three-dimensional structures, and so leaf reflectance can not be considered per se as being characteristic of the canopy´s reflectance properties. Leaf angular position, stems, branches, shadow spaces, underlying soil and buds or inflorescences act jointly with single leaf reflectance forming an integrated reflectance system. Moreover, on its way to the sensor the reflected radiation is influenced by atmospheric constituents, whereby the visible shortwave ranges are attenuated by scattering, the middle infrared band by water vapour, and the thermal range by surface properties and meteorological factors. In general, however, the spectral response pattern of a plant canopy as recorded by a groundbased or airborne spectroradiometer or any other passive sensor is in its shape approximately the same as that of a single leaf, and the differences found are of a quantitative manner only (COLWELL 1974).

In the following graph (figure 1), a general idea of spectral reflectance of plants as well as the response of remote sensors is given.

Figure 1 Plant spectral reflectance properties and remote sensor response



In the case of crop stress or damage situations, two groups of symptoms may be distinguished with respect to their detection by remote sensing techniques (biological details cannot be entered within the scope of this paper):
(a) changes in the leaves themselves, and
(b) changes in the plant canopy.

Both groups include symptoms of biotic as well as abiotic stress or damage factors.
The effects of stresses on leaves appear as a result of changes in their physiological, morphological, and anatomical properties. This includes (1) changes in qualitative and quantitative pigment configuration (i.e., discolouration), which may be caused by nutrient or water deficiency, insects, viruses, or pollutants; (2) discolourations following internal or external attacks of e.g. fungi, bacteria, or viruses; (3) changes in leaf shape, like folding, bending, or slacking as a result of insect, fungal or viral attack, or deficient water or nutrient supply; and (4) changes in cell structure, especially in the mesophyll, which occur consequently to a large variety of stress influences.
While discolourations manifest themselves largely in the visible spectral range, changes in cell structure appear in the near infrared, and morphological changes may be perceived in either of them. Stresses impairing the water supply and thereby reducing leaf water content and evapotranspiration are detectable in the middle and thermal infrared.

Changes in the plant canopy may coincide with or follow stress effects on the leaves, like, for instance, when leaf angular positions are altered, leaf area is diminished, or defoliation occurs. Other aspects are abnormal bending or twisting of stems, branches, or twigs, uncontrolled emergence of sprouts (witch brooms), etc. Meteorological influences may greatly alter canopy structures, e.g. by causing lodging, disrooting, flooding, and burning. All these features change the canopy's spectral reflectance properties mainly in the visible and near infrared wavelangth bands. They originate from different angular reflectance characteristics, enhanced contribution of radiation reflected by petioles, branches, stems, and soil or ground cover as well as from changes in shadow spaces and different leaf area indices.

Different spectral response characteristics of stressed as compared to non-stressed agricultural and forest crops which express themselves on remotely sensed data are in a variety of cases accompanied by textural (i.e.,two-dimensional) changes in the otherwise homogeneous canopy. As these patterns indicate the distribution of the stress or damage within the field or forest, they can furnish valuable clues as to the origin and nature of the stress factor(s), especially if they are evaluated in combination with the spectral properties.

III Literature review

The work done hitherto in the field of remote sensing of agricultural and forest crop stresses has been summarized in table 2 and 3, respectively. They were collected from comprehensive studies on the literature dealing with this subject complex HENNINGER et al. 1979, REICHERT et al.1980). Table 2 gives an account of the kinds of sensors as well as of the techniques applied for each of the cases described. A variety of published results in other crops, like sugar beets, citrus, cotton, and others, are not included in this table as only the most important food crops are mentioned. Due to the large variety of published results in forestry, the different stress or damage factors were listed in detail, and because aerial photography is most commonly used, sensor types were not mentioned separately.

TABLE 2 Remote sensing of stresses and damage in the most important agricultural crops

		REMOTELY SENSED BY					TECHNIQUES APPLIED			
CROP	STRESS/ DAMAGE FACTORS	Photography IR3/W	IRC	Airb. MSS	Spaceb. MSS	Thermal Sensors	Multi-spectral	Multi-temporal	Texture analysis	Meteo-data
Wheat	leaf rust	X	X				X		X	X
	drought		X			X				
	stem rust				X		X	X		X
	take-all	X	X				X		X	
	frost				X					X
	lodging	X	X				X			
Rice	tungro	X	X				X	X	X	
	bact.blight		X				X	X	X	
	virus yellowing					X				
	weeds	X	X				X			
	nutrient def.		X				X		X	
Potatoes	phytophthora	X	X	X			X	X	X	X
	nematodes		X				X		X	
	verticillium-wilt	X	X				X			
	water/nutrient deficiency	X	X				X			
Maize	leaf blight		X	X	X		X	X		X
	mites		X				X			
	army worms, locusts	X					X			
	nematodes		X	X			X		X	
Millet/ Sorghum	nutrient def.		X	X	X		X	X		
Beans	bact.blight		X				X	X	X	
	nematodes	X	X				X			

While in forestry remote sensing for stress or damage detection can be regarded as being firmly established and accepted from the scientist's as well as from the user's point of view, and most of the different results have been transferred to practical application, it is just the opposite with the field of agricultural stress detection. Here, only very few of the research findings could successfully be transferred to use in practice, like within the framework of the lacie experiment for wheat (Mac DONALD 1978), the Corn Blight Watch Experiment (NASA 1973), or for nematode detection in sugar beets (SANWALD 1979).

TABLE 3 Remote sensing of stresses and damage in the most important tree species

TREE SPECIES	STRESS/DAMAGE FACTORS		
	BIOTIC	ABIOTIC	ENVIRONMENTAL
Spruce	bark beetle spruce budworm mistletoe	drought nutrient deficiency (phosphate)	fluoride-emission SO_2-emission
White fir	balsam wooly aphid	epidemic mortality	.
Douglas fir	douglas fir beetle blowdown bark beetle poria root rot tussock moth		
Pine	bark beetle mountain pine beetle pine bark aphid needle miner fomes root rot	copper toxicity nitrogen deficiency drought stagnant groundwater basal canker	SO_2-emission
Oak	oak leafroller	drought	emissions
Beech	beech bark disease	drought	emissions
Eucalypt	crown dieback		
Teak	teak defoliator		
Maple Poplar		drought, salinity	
Elm		dutch elm disease	
Urban trees: Tilia, Aesculus hippoc., Acer sp., Robinia pseudoac.			rocksalt, pollution, emissions

During the course of compiling lists of the scientific literature on these aspects - which may yet be incomplete - it was found that experience in the field of vegetation damage detection by remote sensing is mainly concentrated on forestry: here, 580 publications are dealing with this subject, whereas in agriculture only 255 could be numbered. These facts can hardly be explained from the historical point of view, as the first publication on the detection of forest damage by Spruce budworm appeared in 1920 (CRAIG), and only seven years later NEBLETTE described the detection of Cotton root rot. The reasons for the preponderance of experience and results in forestry and the more efficient research/application rate as compared to agriculture are the following:

- large forest areas which are difficult to suvey from the ground suggest the application of remote sensing techniques rather than intensively managed agricultural production areas

- with wide-spaced forest ownership resp. governmental management of small private property aerial surveys are easier to organize and more economic than with predominating small and scattered agricultural property
- as compared to agricultural crops, the phenological dynamics of forests are lower, whereby the number of surveys required as well as the cost factor and weather risks are smaller
- forest stresses often appear first in the upper parts of the crown which renders their location from the ground difficult. As preventive treatments with pesticides are not carried out in forests, regular surveys of their condition are indispensable
- forest (especially evergreen conifers) and urban trees are very suitable to be used as bioindicators for environmental pollution of the air as well as of the soil
- due to the long-term characteristics of forests, the impacts of stress or damage as well as the success of countermeasures can be monitored sequentially during successive years.

In order to avoid misunderstandings, vegetation 'stress' shall be defined in simple terms as a detrimental impact on the plants whose effects can still be cured wholly or partially by appropriate countermeasures, whereas 'damage' is to be considered as an irreversible condition resulting from stress.
In forestry, the detection of some stress situation generally leads to actions immediately or some time after detection in order to prevent (further) losses in wood yield. After detection of a forest damage, actions are taken as well - in general immediately - in order to get at least some monetary compensation out of the wood.
In agriculture, stress detection is followed by immediate actions, if any possible, in order to save the crop as far as can be done, whilst detection of damage results - depending on its kind - either in economical calculations as to the loss to be expected, or in actions which are taken after harvest for to prevent the same from happening again.

Thus it becomes evident that from biological as well as from economical points of view stress or damage detection or inventory is an important factor in forestry as well as in agriculture.

IV Proposals and recommendations

IV.1 Scientific research aspects

Remote sensing has to be considered as a multidisciplinary science. By its nature, it is no fundamental science like mathematics or physics where research is not necessarily directed at results transferable into practice; but it is an applied science, i.e., research is aimed at application, and therefore should be conducted under pragmatic guidelines.

The term'remote sensing of vegetation stress or damage assessment' implies the aims to which the work in this field is directed. A study of the literature concerned with this subject

complex showed, however, that - to the larger part in agriculture as compared to forestry - pragmatic thoughts are usually neglected. Thus, for instance, results describing a singular case of detection of some kind of stress or the results of some spectral reflectance measurements showing differences between healthy and stressed plant canopies, single plants, or plant organs are published without mentioning thoughts as to their connections to applied remote sensing.
By 'applied remote sensing' we understand that the use of this technology for a certain purpose is serving this purpose satisfactorily in terms of apt and reproducible results as well as in economical terms. The consequences following from this notion are evident: scientists working on the subject of remote sensing for vegetation damage assessment always should consider the aspect of applicability and direct their work accordingly. The publication by MURTHA (1978) is an example for this suggestion.

IV.2 Sensor aspects

In the early beginnings of agricultural and forest stress or damage detection, large-scale aerial black and white photography was used. This shows already that - following from the rather poor spectral sensitivity range that the emulsions then posessed - not only spectral reflectance characteristics but also, at least to the same extent, textural peculiarities indicate stressed areas. Up to now, aerial large- to medium-scale photography employing infrared colour (IRC) film is, and quite probably for the next decades will be, the most common remote sensor with respect to vegetation damage detection. The availability of IRC films from the mid-sixties onwards has spurred research and application activities to a considerable extent, and the potentials of this emulsion are by far not exploited yet. Its spectral sensitivity range covers the spectral bands in which vegetation shows characteristic reflectance properties, and its geometrical resolution is sufficient for reproducing textural features.
Its major drawback is the variability of the emulsion, which renders standardization of e.g. interpretation keys difficult. The exposure of a standard colour step wedge on each frame or on the first and last frame of a film roll would be of great advantage.

Multispectral scanner data, providing better spectral resolution as compared to photographic films, are difficult to evaluate with respect to textural informations. Their geometrical resolution is still poor and, even with the high-resolution systems coming up presently, it will still be problematic, time-consuming and expensive to handle the huge amounts of data.
The results obtained hitherto have shown that spectral information alone is probably not sufficient for vegetation stress detection.

There are no MSS systems sensitive in the middle infrared range available yet. Their potentials for detecting vegetation stress should be taken into consideration.

The usefulness of applying thermal sensors is still not quite clear. Theoretically they can furnish valuable informations in

a variety of agricultural and forest stress situations, especially for water stress. As the published results are not unanimous, further research will hopefully enlighten thermal scanning possibilities, be it negatively or positively.
For one aspect this technique has already proven its applicability: in spotting fires raging in wide, inaccessible forest areas, which cannot be detected by other means due to heavy smoke emissions (HILDEBRANDT 1976).

IV.3 Education and public relation aspects

As - especially among agriculturists - little is known about remote sensing as a technological complex and less still about its application possibilities, it is necessary to spread the knowledge of it among the potential users. This can be done by integrating remote sensing in the schedules of universities and colleges as lectures and practical courses in order to train the coming generations of agriculturists, foresters, and ecologists from the beginning.
For professionals and post-graduate students, special and concentrated short-term courses should be made available. As up to now there are no training courses neither on forest or agricultural stress and damage assessment by remote sensing methods nor on general agricultural applications of remote sensing, training capacities must be established or extended at institutions like ITC, IPI, at central research institutes for forest and agricultural plant protection and crop production, at universities, etc. Remote sensing laboratories containing basic equipment (light tables, stereoscopes, etc.) should be established succeedingly and located according to optimum use of their capacities.

Thus practice-oriented research and remote sensing applications on a sound professional background are made possible.

Another aspect of enhancing the level of information for the potential applicators and users is in public relations. Not only an improved interdisciplinary and international exchange of information is suggested but also the arrangement of workshops, colloquies and symposia for which experts in remote sensing as well as in forestry, forest pathology, plant production, phytopathology etc. are invited. Moreover, research results in the field of remote sensing of crop stress and damage shall be published in forestry and agricultural periodicals, as otherwise the potential users will never come to know about them.

The compilation of a 'Manual of Vegetation Stress and Damage Assessment by Remote Sensing' which contains the physical and technical basics as well as illustrated application examples, interpretation keys, and the like, and its distribution to user agencies will also be a valuable contribution in closing the existing gaps between scientific research and application.

Conclusions

The need for and the advantages of using remote sensing for forest and agricultural stress or damage assessment are indisputed. Especially in agriculture, where these techniques have scarcely been applied yet, application concepts have to be evaluated thoroughly for their accuracy and their potential benefits in order to waken the user's interest and to strengthen their confidence in this technology. Ground truth data collection resp. field checks will always be necessary. A wide variety of challenging tasks on a world-wide scale are yet to be tackled.

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