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Alan S. Belward

**The use of AVHRR data for
large area vegetation studies**

Supervisor:

J. C. Taylor

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the Degree of Doctor of Philosophy**

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Abstract

This thesis compares the attributes and limitations of the various Advanced Very High Resolution Radiometer (AVHRR) data types for large area vegetation studies in the context of global change research.

In chapter 1, some of the major scientific issues customarily associated with the Global Change concept are outlined, and the specific role of vegetation dynamics in the earth's energy, hydrological and biogeochemical cycles is discussed. Deficiencies in currently available global vegetation data sets and the role of remote sensing as a new source of information are reviewed. This review is supplemented by detailed discussion of the spectral properties of vegetation, soil and water in chapter 2.

In chapter 3 the Normalised Difference Vegetation Index (NDVI) and the Perpendicular Vegetation Index (PVI) from 1 km resolution AVHRR High Resolution Picture Transmission (HRPT) data are compared as a means of providing biomass estimates for large geographical areas. The PVI provides better measures of biomass than NDVI, particularly where cover is sparse. Caution in the use of NDVI is recommended. Problems of accurate ground location because of the AVHRR's coarse resolution are highlighted. High resolution (80 m) satellite imagery from the Landsat Multi Spectral Scanner (MSS) is shown to be an effective intermediate step. Comparison with MSS also shows the effect of landscape structure on areal estimates of vegetation cover from the AVHRR HRPT.

In chapter 4, MSS and HRPT comparisons show that sensor-induced spatial autocorrelation in AVHRR HRPT data can limit the use of these data for the identification of spatial structure and pattern at full resolution. The same limitation on the use of full resolution data is also found to apply to the spatially sampled AVHRR Global Area Coverage (GAC) archives. In this case local variance induced by sampling in GAC data generation is thought to be the cause.

In chapter 5 the structural analysis is extended across a range of resolutions. Sampling artefacts are found for all West African ecosystems at full GAC resolution (4 km), though at coarse resolutions spatial patterns observed with the GAC and the unsampled AVHRR HRPT are very similar. Differences between the two are most pronounced where landscape features are either points or lines. A resolution of 12 km is found to suppress the negative effects of the sampling for all West African ecosystems. At resolutions coarser than 12 km, the GAC data are just as good a measure of landscape structure as the unsampled data. The relevance of these coarse measurement scales to global change research is discussed.

Chapter 6 shows that transitions across major ecological zones can be detected at resolutions coarser than 12 km, though the agreement between the sampled and unsampled AVHRR changes both with geographical location and time. This is particularly so for ecosystems affected by fire.

Fire is increasingly recognised as a key factor in both the study of global vegetation dynamics directly, and for global change research. This is the focus of chapter 7. Problems relating to the poor sensitivity of the AVHRR's middle-infrared and thermal channels are identified and resolved. The GAC sampling method is shown to affect the sensitivity of these data for fire detection in relation to ecosystem and season. Regional stratification is highlighted as a means of improving fire analysis over large areas, improving land cover classification, and helping in the definition of new cover classes (particularly at continental and global scales)

Finally, the results of the previous chapters are discussed with reference to the existing and planned processed AVHRR data archives. The importance of the 12 km limit with reference to the GAC archives is stressed, the need for circumspection in the use of NDVI reiterated, particularly with reference to the derivation of physical measurements from AVHRR, and the requirement for new synergistic approaches to the use of AVHRR with other data emphasised.

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Chapter 1. Introduction

The use of AVHRR data for large area vegetation studies

1. Scientific requirements for large area vegetation studies

This work is concerned with the study of vegetation dynamics in the context of global change research. This implies observations over large areas, that is on regional, sub-continental and continental scales. The key vegetation attributes required by global change research programmes relate to plant phenology, plant distribution and the effects of fire in vegetation (IGBP 1992a).

From the time the first land plants evolved, some 350 million years ago, fire has been a natural feature of many ecosystems. Around 1.5 to 2 million years ago, hominids began to use fire intentionally, drastically increasing fire frequency and forcing considerable ecosystem change (Schüle 1990). Changes in phenology and distribution (ecosystem composition) can thus be in response to human actions, hence changes in vegetation dynamics can act directly as an indicator of ecosystem change. However, changes in vegetation over extensive areas can itself cause such ecosystem changes.

1.1. Vegetation and global change

Direct measurements have shown that the concentration of atmospheric carbon dioxide (CO₂) and other greenhouse gases is rising (Keeling *et al.* 1982). Deforestation, conversion of natural vegetation to agricultural land and biomass burning are firmly implicated in this process (Crutzen and Andreae 1990, Houghton and Skole 1990, Houghton *et al.* 1991).

In addition to CO₂, biomass burning also releases nitrogen oxides to the atmosphere, which form nitric acid, thus contributing directly to acid rain (Dignon and Penner 1991). Biomass burning can effectively alter the spatial boundaries of ecosystems, forcing transition from one to another (Menaut 1983). As a result of fires, rainfall interception by plant canopies is reduced, causing increased runoff, accelerated soil erosion and loss of soil nutrients (Morgan 1980).

Biomass burning is also one of the major agents of deforestation, which is itself linked to climate change by altering surface-atmosphere energy exchanges (Nobre *et al.* 1991). Deforestation is also linked with unparalleled losses in the biodiversity of the earth (Wilson 1988). Furthermore, because vegetation cover is important in determining both fluxes and storage within the hydrological cycle, changes in forest cover affect local or even regional hydrological regimes (Salati 1987).

These examples illustrate why large area vegetation studies are important in international global change research strategies, such as the International Geosphere-Biosphere Programme (IGBP; IGBP 1989) and NASA's Earth Observing System (EOS; NASA 1987), and why, in particular, the study of biomass burning is considered as fundamental to understanding the full role of vegetation in global change *e.g.*, the IGBP's International Global Atmospheric Chemistry project (IGBP 1990) and the 1991 Dahlem Workshop on global change in the perspectives of the past (Malingreau *et al.* 1993).

1.2. Data requirements

Mapping, monitoring or modelling global vegetation processes requires extensive, spatially (or geographically) referenced data sets. The scale on which a process operates dictates the characteristics of the data required. Thus biomass burning studies require observations at resolutions in the order of hundreds of metres, whilst data sets for use in climate models will be at resolutions in the order of hundreds of kilometres (Mathews 1983). A common requirement is that all data sets must be capable of providing consistent, long-term measurements or observations (Rasool 1987).

Current data sets describing global vegetation characteristics are extremely limited. They tend to be derived from cartographic sources and are, without exception, on very coarse scales (resolution varies from a best of 50 km to over 100 km). The most widely available examples include Udvardy's Biogeographical Provinces of the World (Udvardy 1975), Bailey's World Ecoregions (Bailey and Hogg 1986), Major World Ecosystems ranked by carbon in live vegetation (Olson *et al.* 1985) and Mathews' Vegetation, Land use and seasonal Albedo datasets (Mathews 1983).

Townshend *et al.* (1991) and IGBP (1992a) identify a number of problems with such data sets; variations in estimates of the area of land cover from one data set to another, nomenclature which varies from data set to data set, disparate primary sources for each dataset, interpretation and generalisation involved in classification, coarse resolution, and perhaps most significantly, the fact that these data are static in time.

2. The role of satellite remote sensing

A number of key policy statements have stressed the unique role of satellite remote sensing as the provider of information for large area vegetation studies (e.g., IGBP 1992a, NAS 1990, NASA 1987). The first space remote sensing data came from the United States' Mercury, Gemini and Apollo manned space missions in the 1960s. By the end of the decade the United States had a series of meteorological satellites in operation and the program specifications for the world's first earth resources satellite finalised. The early 1970s saw this system become operational, with further advanced systems coming into operation in the early 1980s. The second half of the 1980s saw the launch of new earth resource satellites by France, India, Japan, China and the former USSR. In April 1992, the Committee on Earth Observation Satellites identified 14 fully operational earth observation satellite programmes, seven of which are listed as significant data sources for global and regional scale land applications (CEOS 1992); the same report identifies an additional 40 or so systems that could fly by the end of the century.

2.1. Suitability of satellite data sets

Out of this wealth of data, three programmes have dominated land applications of remote sensing over the last twenty years, these are the USA's Landsat and TIROS-N/NOAA programmes and the primarily French SPOT programme. Of these three it is the Advanced Very High Resolution Radiometer (AVHRR) datasets from the TIROS-N/NOAA programme are deemed most suited to large area vegetation studies (IGBP 1992a). The AVHRR data (called High Resolution Picture Transmission; HRPT, when transmitted direct to earth, and Local Area Coverage; LAC, when recorded on board the satellite before transmission) are, in principle, available globally every day with a nominal resolution of 1.1 km by 1.1 km. These data are multi-spectral covering, visible, near-infrared, middle-infrared and two thermal-infrared wavelengths.

The visible and near-infrared spectral reflectance of vegetation can vary from species to species. Furthermore, for any given species, the reflectance at these wavelengths changes during plant growth and development. The spectral properties of vegetation are described in chapter 2 (Belward 1991). The chapter also introduces the idea of vegetation indices. These are a single spectral variable created by combining red and near-infrared spectral measurements.

The use of AVHRR visible and near-infrared data for vegetation studies was first proposed in 1981 (Schneider *et al.* 1981, Townshend and Tucker 1981). Since this time these data have been used in various ways. For example, as a measure of primary production (e.g., Tucker and Sellers 1986, Prince and Justice 1991), for crop yield estimation (e.g., Taylor 1991, Bartholomé 1991), to study the dynamics of major biomes (e.g., Malingreau 1986, Viovy *et al.* 1992), and for land cover classification (Tucker *et al.* 1985, Townshend *et al.* 1991, Arino *et al.* 1992). The rationale behind this type of application is explained in chapter 3 (Taylor *et al.* 1986). The focus of the chapter is the use of vegetation indices from AVHRR data for estimating grassland biomass.

The middle-infrared and thermal-infrared AVHRR channels provide complementary information for vegetation studies. Thermal data have been used successfully in evapotranspiration models (e.g., Seguin 1987, Sogaard 1988), though surface temperature estimates are still hampered by uncertainties concerning the emissivity of vegetation. The middle-infrared data have been used to separate land cover classes (Kerber and Schutt 1986, Malingreau *et al.* 1989), to detect disturbance in forest ecosystems (Malingreau 1991), and for the detection of fires (biomass burning) in many biomes; tropical forests (Malingreau *et al.* 1985, Tucker 1986), woodland savannahs (Grégoire 1990), grassland savannahs (Langaas 1992), boreal forests (Levine 1991) and temperate agricultural regions (Muirhead and Cracknell 1985). Fire detection is the second criterion on which this assessment of the use of AVHRR for large area vegetation studies is made. The theme is developed from chapter 4 on.

3. The AVHRR data sets

3.1. Data availability and sampling

Though the potential of the AVHRR for large area vegetation studies has been demonstrated, global, long term, daily, full resolution AVHRR data sets do not exist. The long term, global cover data sets are sampled, either spatially in the case of a nominally 4 km resolution product, Global Area

Coverage (GAC) data (Kidwell 1991), or spatially and temporally in the case of a 19.5 km resolution product, Global Vegetation Index (GVI) data (NOAA 1990).

Complete HRPT archives do exist for parts of the world (e.g., the European archive maintained at the University of Dundee) though systematic daily global HRPT/LAC archives only began in April 1992, under the auspices of the IGBP Data and Information System (IGBP 1992b). The program is currently guaranteed until September 1993. Preliminary findings of the IGBP-DIS initiative highlight why there are no suitably processed long term, large area HRPT/LAC data sets; processing data to create a single global 10 day composite image is estimated to require 22.55 CPU days (J. Eidenschink, EROS Data Center, personal communication).

The most complete data set is the GAC. This is global, daily and all channels are available at full radiometric resolution. Time-series of these data have been used for large area vegetation studies (e.g., the special editions of *International Journal of Remote Sensing*; volume 7, 1986 and volume 12, 1991). These data are sampled spatially such that for a given scan line the first four pixels out of every five are averaged, and only every third scan line is processed. This gives a spatial resolution, at nadir, of approximately 1.1 km by 4 km, with a gap of around 3 km between pixels across the scan lines, although the data are generally treated as 4 km resolution (Kidwell 1991).

3.2. Effects of AVHRR data sampling strategies

If an ecosystem has a uniform surface, extending over many square kilometres, then imagery from the sampled GAC data would provide exactly the same information as HRPT. On the basis of this assumption, calibration coefficients derived from GAC data over deserts are applied to the HRPT and LAC data sets (e.g., Holben *et al.* 1990). Unfortunately such conditions of uniformity do not apply to vegetated surfaces. If the GAC archives are to be more profitably used for large area vegetation studies, it is important that the effects of the sampling are determined.

The effects of the sampling used to create the GAC data were first documented by Justice *et al.* (1989). In this paper a number of different sampling strategies were compared, and the conclusion was that the GAC sampling strategy gave a relatively poor representation of the HRPT. Malingreau and Belward (1989) working with imagery from West Africa show that in fact the degree to which the GAC are representative of the HRPT changes as a function of ecosystem. In some cases the GAC and HRPT agree extremely well, in others not. Variations in image structure were thought to be the primary influence over the level of agreement between the two data types.

Image texture has been proposed as a measurement of image structure (Woodcock and Strahler 1987). Belward and Lambin (1990) used this to quantify the differences between GAC and HRPT images, again of West Africa. Their paper showed that the structure of GAC vegetation index and middle-infrared images was affected by artificial spatial contrast caused by the sampling. The paper suggested that this may compromise the use of GAC data for studies at the full GAC resolution, but may not be relevant at coarser scales. Belward (1992) extended the analysis to other scales and showed that at resolutions coarser than 12 km the detrimental effects of the GAC sampling were suppressed.

3.3. Implications for large area vegetation studies

Twelve kilometres is considerably coarser than the resolutions suggested as optimum for large area vegetation studies by Townshend and Justice (1988, 1989). However, Malingreau and Belward (1992) show that transitions across major ecological zones can be detected at resolutions even coarser than this, and Justice *et al.* (1991) report considerable spatial variability of vegetation activity at resolutions of up to 256 km. Indeed, coarse resolution measurements of vegetation characteristics are a requirement for improving current global climate models (Prentice 1990, Verstraete *et al.* 1991).

Malingreau and Belward (1992) also showed that the degree to which the GAC are representative of the HRPT varies not just with ecosystem, but also with time. This is particularly so where ecosystems are affected by fire. The averaging involved in degrading the GAC to a 12 km resolution effectively smoothes out any fire signal (Belward 1992). Thus, if the GAC are to be used for large area biomass burning studies, the fire detection capabilities of the GAC at full resolution have to be established. This is most easily achieved by comparing the GAC with the HRPT data.

Comparing the GAC and HRPT as a data source for fire detection is only relevant if the accuracy of the HRPT is first established. Robinson (1991) and Kennedy (1993) provide very complete reviews of fire detection methods using AVHRR HRPT. However, no universally applicable method exists.

Grégoire *et al.* (1993) show that many ecosystems of the West African sub-continental area can give a spectral response identical to that of fire, even though they are not actually burning. Whilst this was shown to be an important new indicator of vegetation condition, it restricted the use of AVHRR for fire detection over the region. A solution was eventually found by Kennedy *et al.* (1993). Applying this technique to HRPT and GAC data for the whole West African region, Belward *et al.* (1993) were finally able to quantify the effects of the GAC sampling on fire detection.

Many of the papers referred to above are presented in this thesis. Together they document the potential and the limitations of the AVHRR for large area vegetation studies. Realising the full potential of the AVHRR will require improved access to suitably processed data. The Commission of the European Communities' (CEC) Joint Research Centre (JRC), through a research agreement with NASA has obtained a copy of the GAC archives for Africa and Asia. As described in the concluding chapter, these data-sets are currently being processed for use in just such vegetation studies.

4. Thesis structure

The research presented here has either been published or has been submitted for publication as reports, in books and in the *International Journal of Remote Sensing*. The thesis is made up of the following papers.

Chapter 2. BELWARD A. S., 1991, Spectral characteristics of vegetation, soil and water in the visible, near-infrared and middle-infrared wavelengths, in *Remote Sensing and Geographical Information Systems for Resource Management in Developing Countries* eds A.S. Belward and C.R. Valenzuela (Dordrecht: Kluwer Academic) pp31-54.

Chapter 3. TAYLOR, J.C., BELWARD, A.S., HEWETT, D.G., and WYATT, B.K., 1986, Mapping of vegetation and soils and estimation of biomass in the Sahel. Final report to the Commission of the European Communities on: Monitoring of pastureland ecosystems in the Sahel and Mapping of Cloud cover and rainfall.

Chapter 4. MALINGREAU J-P., and BELWARD A. S., 1989, Vegetation monitoring using AVHRR data at different resolutions. Presented at 4th AVHRR data users' conference, Reichsstadthalle, Rothenburg ob der Tauber, Federal Republic of Germany, 5th - 8th September 1989. pp 141-144.

BELWARD, A. S., and LAMBIN, E., 1990, Limitations to the identification of spatial structures from AVHRR data. *International Journal of Remote Sensing* 11, 921-927.

Chapter 5. BELWARD, A. S., 1992, Spatial attributes of AVHRR imagery for environmental monitoring. *International Journal of Remote Sensing* 13, 193-208.

Chapter 6. MALINGREAU J-P., and BELWARD A. S., 1992, Scale considerations in vegetation monitoring using AVHRR data. *International Journal of Remote Sensing* 13, 2289-2307.

Chapter 7. GREGOIRE, J-M, BELWARD, A. S., and KENNEDY, P. J., 1993, Saturation du signal dans la bande 3 du senseur AVHRR: Handicap majeur ou source d'information pour la surveillance de l'environnement en milieu soudano-guinéen d'Afrique de l'Ouest? *International Journal of Remote Sensing* (in press).

KENNEDY, P. J., BELWARD, A. S. and GREGOIRE, J-M., 1993, An improved approach to fire monitoring in West Africa using AVHRR data *International Journal of Remote Sensing*, (submitted).

BELWARD, A. S., KENNEDY, P. J., and GREGOIRE, J-M, 1993, The limitations and potential of AVHRR GAC data for continental scale fire studies. *International Journal of Remote Sensing* (submitted).

Appendix 2. BELWARD, A. S., VOGT, J. V., FALK-LANGEMANN, A., SARADETH, S. and CAMBRIDGE, H., 1992, Preparation of AVHRR GAC data sets for global change studies, in *proceedings of the Central Symposium of the 'International Space Year' conference held in Munich, Germany 30th March to 4th April, 1992* (ESA SP341, July 1992) pp19 - 23

5. Disclosure

The publications are from work started while I was on the staff of the department of Rural Land Use at Silsoe College, and later developed while working for the Institute for Remote Sensing Applications, CEC Joint Research Centre (JRC).

Where I am the only author then responsibility for data collection, analysis and conclusions rests wholly with myself. Where I am senior author the responsibility for the structure of the paper is mine, though parts of the data collection, analysis and results are the work of my co-authors. In all other papers I am second author. In each case I was solely responsible for specific aspects of the work. With the exception of the papers by Taylor *et al.* (1986) and Grégoire *et al.* (1993), I was actively involved in structuring and writing the papers, rather than providing only an editorial or supporting role.

Chapter 2 is from a book edited by myself and Carlos Valenzuela of ITC, Netherlands. Chapter 3 (Taylor *et al.* 1986) is from a final report to the CEC's DGVIII study on desertification processes. My involvement concerned image processing with John Taylor (Silsoe College) and Barry Wyatt (Institute of Terrestrial Ecology; ITE), plus ground data collection, conducted during three field visits to West Africa, two with David Hewett (ITE). In the paper Vegetation monitoring using AVHRR data at different resolutions (Malingreau and Belward 1989), the sections concerning GVI GAC comparisons and aggregation of GVI time series are the work of Jean Paul Malingreau (JRC), whilst the GAC HRPT comparisons and use of image texture to measure structure, are my contribution. In our paper 'Scale considerations using AVHRR for vegetation monitoring' (Malingreau and Belward 1992) my contribution is again the GAC HRPT comparisons, though here I also provided the African examples used in the GAC GVI comparisons. In the paper by Belward and Lambin (1990), Eric Lambin (JRC visiting scientist) contributed the HRPT Landsat comparisons, and I the GAC HRPT. The three papers making up chapter 7 are the result of research with Jean-Marie Grégoire (JRC) and Pam Kennedy (JRC). Throughout the research we worked closely together though each of us took the lead in a particular aspect. Jean-Marie Grégoire led the work concerning the middle-infrared saturation problem (Grégoire *et al.* 1993). My contribution was the section dealing with regional saturation patterns. Pam Kennedy took the lead concerning the development of a suitable fire detection method for West Africa (Kennedy *et al.* 1993). I helped with image processing, testing, evaluation and analysis. I co-ordinated the work concerning the use of GAC data for fire detection (Belward *et al.* 1993). For this paper Pam Kennedy provided the fire detection methodology and the ecosystem framework used in the analysis. Jean-Marie Grégoire was responsible for the data and analysis used in the section dealing with continental scale fire patterns. Appendix 2 (Belward *et al.* 1992) describes an AVHRR processing chain, resulting from three years of design and tests. Without the particular efforts of Jürgen Vogt (JRC), Antonia Falk-Langemman (Gesellschaft für Angewandte Fernerkundung mbH; GAF), Stefan Saradeth (GAF) and Howard Cambridge (Serco space), suitably processed, daily, multi-channel, continental scale GAC data sets would still be a requirement, rather than reality.

Chapter 2. Spectral characteristics of vegetation, soil and water

SPECTRAL CHARACTERISTICS OF VEGETATION, SOIL AND WATER IN THE VISIBLE, NEAR-INFRARED AND MIDDLE-INFRARED WAVELENGTHS

A. S. BELWARD

*Commission of the European Communities,
Joint Research Centre,
Institute for Remote Sensing Applications,
21020 Ispra (Varese) Italy.*

1. Introduction

In the previous chapter the concept of identifying and characterizing earth surface features on the basis of spectral behaviour was introduced. It was shown that electromagnetic radiation (EMR) incident with an object is either reflected, absorbed or transmitted. Furthermore, the relative proportion of each of these was shown to vary with the wavelength of the incident EMR and with the nature of the material making up the object. Spectral reflectance curves were presented as a means of describing the spectral properties of objects, and example curves of vegetation, soil and water were given. This chapter describes in more detail the basic mechanisms which influence the spectral properties of these major earth surface features in the visible, near and middle infrared wavelengths; data recorded through these parts of the electromagnetic spectrum are most frequently available to the user of remote sensing, and if the controlling mechanisms are properly understood then we can begin to make inferences regarding the physical and physiological nature of earth objects from measured spectral response.

2. Spectral properties of vegetation

The spectral properties of vegetation are quite distinctive, as Gates (1970) observed "A plant leaf reflects and transmits incident radiation in manner that is uniquely characteristic of pigmented cells containing water solutions". Figure 1 shows a generalized spectral reflectance curve for a green plant over the wavelength range 0.4 μm - 2.6 μm . Spectral reflectance is low in the visible and middle-infrared wavelengths, which are dominated by absorption, whilst the near-infrared is characterized by high levels of reflectance and transmission, with minimal absorption. These features can be explained in terms of the physical and physiological characteristics of vegetation.

2.1 VISIBLE LIGHT

Plants use light energy from the visible part of the spectrum to synthesize the organic compounds necessary for maintenance and growth. This is brought about by the process of photosynthesis.

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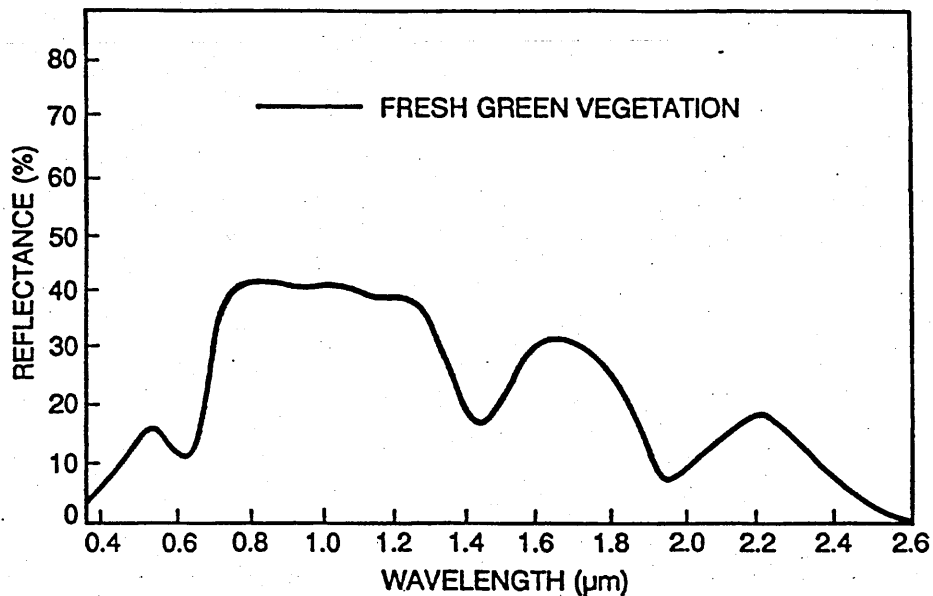


Figure 1. Spectral reflectance curve of fresh green vegetation

Cell organelles, called chloroplasts, contain pigments capable of absorbing light energy and using this to convert energy-poor carbon dioxide (CO_2) and water (H_2O) into energy-rich carbohydrates (CH_2O) and oxygen (O_2). This is shown in equation (1)



(1)

Leaf structure is such that the raw materials needed for this process are brought into contact with the chloroplasts; carbon dioxide, present in air, enters the leaf through the leaf openings (stomata) and moves through the leaf in inter-cellular air spaces; water is present in all hydrated leaf cells; and leaf optical properties are such that most light penetrates the leaf surface rather than being reflected (Knippling 1970, Woolley 1971).

As light enters the leaf it is scattered by refraction and Rayleigh / Mie scattering (see Bird, chapter 2). Many cell organelles, lysosomes for example, are smaller than $1 \mu\text{m}$ in size and are therefore capable of causing Rayleigh scatter. However since early this century refraction has been identified as the main cause of scattering of light within leaves (Willstätter and Stoll 1918, Allen *et al.* 1973). This occurs because of refractive index differences between hydrated plant cells - refractive index of 1.47, and inter cellular air - refractive index of 1.0, (Gausman 1985).

The light, being scattered and refracted throughout the leaf, comes into contact with the chloroplasts. The pigments in the chloroplasts, such as the chlorophylls and carotenes absorb light

Type of pigment	Characteristic absorption maxima (μm) - in organic solvents
Chlorophyll a	4.20, 6.60
Chlorophyll b	4.35, 6.43
β -Carotene	4.25, 4.50, 4.80
α -Carotene	4.20, 4.40, 4.70
Violaxanthol	4.25, 4.50, 4.75

Table 1. Absorption maxima of the main photosynthetic pigments found in higher plants.

of specific energy, causing electron transitions within the pigment molecular structure, and the resulting transfer of energy is used to drive the photochemical reactions of the photosynthetic cycle.

As a result of the quantum requirements for energy absorption (discussed in chapter 1) the plant pigments absorb light strongly at some wavelengths and not at all at others. The main pigments found in higher plants and their absorption maxima are listed in table 1.

All the pigments show strong absorption of blue light, with the chlorophylls also showing strong absorption of red light. Absorption, by individual leaves, at these wavelengths is between 70 and 90% (Gausman 1985). As there is usually 5 to 10 times as much chlorophyll as carotenoid pigments in higher plants, chlorophyll tends to dominate spectral response.

At the wavelengths shown in table 1 each photon has the precise energy needed to cause the electron transitions in the photosynthetic pigments. The energy of green light does not cause these electron transitions and so tends to be reflected and transmitted, rather than absorbed. Hence maximum reflectance from plants in the visible wavelengths occurs in the green part of the spectrum, and so we see plants as green.

Towards the end of the functional life of leaves and other plant organs there is a stage where the tissues deteriorate. This is called senescence. During senescence the chlorophyll breaks down, which leads to a marked increase in reflectance at red wavelengths as absorption by this pigment is reduced. Other pigments such as the orange carotenes and yellow xanthophylls (violaxanthol is a xanthophyll), plus non-photosynthetic pigments such as red anthocyanins and yellow flavones are often still present. No longer masked by the presence of the chlorophylls, these pigments are clearly seen in the brown and yellow colours of senescent vegetation, for example ripe cereal crops such as Sorghum (*Sorghum vulgare*), Millet (*Pennisetum typhoides*) and Wheat (*Triticum sativum*).

2.2 NEAR-INFRARED LIGHT

As we saw in the first chapter, the longer the wavelength of EMR, the lower the energy value of each photon. In contrast to visible wavelength EMR, the energy levels of near-infrared light (0.8-1.1 μm) are not great enough to drive the photochemical reactions within the photosynthetic cycle, thus the pigment containing chloroplasts are transparent to near-infrared light.

With absorption typically around 5%, the spectral response of plants in the near-infrared is dominated by transmission, about 40% and reflection, 55% (Figures for a single citrus leaf, *Citrus sinensis*, Gausman 1985). The proportion of each of these varies with plant species; Gates *et al.* (1965) and Sinclair *et al.* (1971), among other early workers, observed that internal leaf structure is dominant in controlling the spectral response of plants in the near-infrared.

Variations in the internal structure of leaves causes differences in the amount of internal scattering, and thus differences in transmission and reflection. This can be seen in figure 2a which is an image of an area of woodland recorded through the near-infrared waveband (0.91 - 1.05 μm). Figure 2b is the corresponding forest stand map identifying tree species. The coniferous trees (with needle leaves), mainly Scots pine (*Pinus sylvestris*) and Corsican pine (*Pinus nigra*) appear as dark areas on the image, (ie they have low reflectance), the broad leaved trees, mainly Beech (*Fagus sylvatica*) appear much brighter, (ie they have much higher levels of reflectance), note, in particular, the striking contrast between the high reflectance from the Beech trees along the curving road which runs through the wood, and the low reflectance from the surrounding conifers.

During senescence, near-infrared reflectance also changes. Sinclair *et al.* (1971) note that reflectance increases marginally in the early stages. This may occur because the leaf internal cells become dehydrated, and the cell walls pull apart and change in orientation. This leads to increase in cell / air interfaces (Daughtry and Biel 1985) and, as stated above, liquid (cell) / air discontinuities largely control the internal scattering of light, and thus reflectance.

In the advanced stages of senescence near-infrared reflectance falls; the internal tissues completely collapse, forming a series of horizontal layers of cell walls with the resulting reduction in air spaces being the probable cause of decreased reflectance (Knipling 1967).

Because much of the incident radiation at near-infrared wavelengths passes through a single leaf the multiple leaf layers of a developing vegetation canopy have an additive effect on near-infrared reflectance. If a figure of 50% near-infrared transmission for a single leaf is taken then a simple diagram, shown in figure 3 can be used to illustrate this (Hoffer 1978). Of the total incident near-infrared EMR at the first leaf layer 50% is reflected and 50% transmitted. The transmitted component is then incident upon the second leaf layer where again 50% is transmitted and 50% reflected. The reflected component from the second layer is passed back to the first where again 50% is reflected and 50% transmitted. Thus, in this simple model if one leaf layer returns 50% of the incident near-infrared EMR, two leaf layers will return 62.5%. Myers (1970) working with cotton plant leaves recorded increases in near-infrared reflectance from 50% with one leaf up to 84% with six leaves. There comes a point when further increases in the number of leaf layers no longer affects reflectance. This point is referred to as the near-infrared infinite reflectance ρ^∞ ; in the example cited from Myers (1970) ρ^∞ is 84%.

2.3 MIDDLE-INFRARED LIGHT

In the middle-infrared the internally scattered light is absorbed by water in the plant. Liquid water, like pigments, absorbs EMR with specific energy levels. Unlike pigments the water absorptions are caused by transitions in the vibrational and rotational states of the water molecules, not electron transitions which require much higher energy levels. It is primarily the longer wavelength, lower energy, middle-infrared light which is absorbed by water, and the shorter wavelength, high energy, visible light absorbed by the plant pigments.

Fundamental moisture absorption bands occur at 2.66, 2.73 and 6.27 μm . Objects containing appreciable amounts of water will have extremely low reflectance levels at these wavelengths. Progressively weaker "overtone" bands are found at 1.9, 1.4, 1.1 and 0.96 μm .

Water absorption is, of course, most pronounced at these specific wavelengths, and can reach more than 90%. However, the absorption bands are strong enough to exert a carry over effect, such that reflectance at wavelengths between the bands is also influenced. In other words, when reflectance is low (or high) in the moisture absorption bands it is also low (or high) between them.

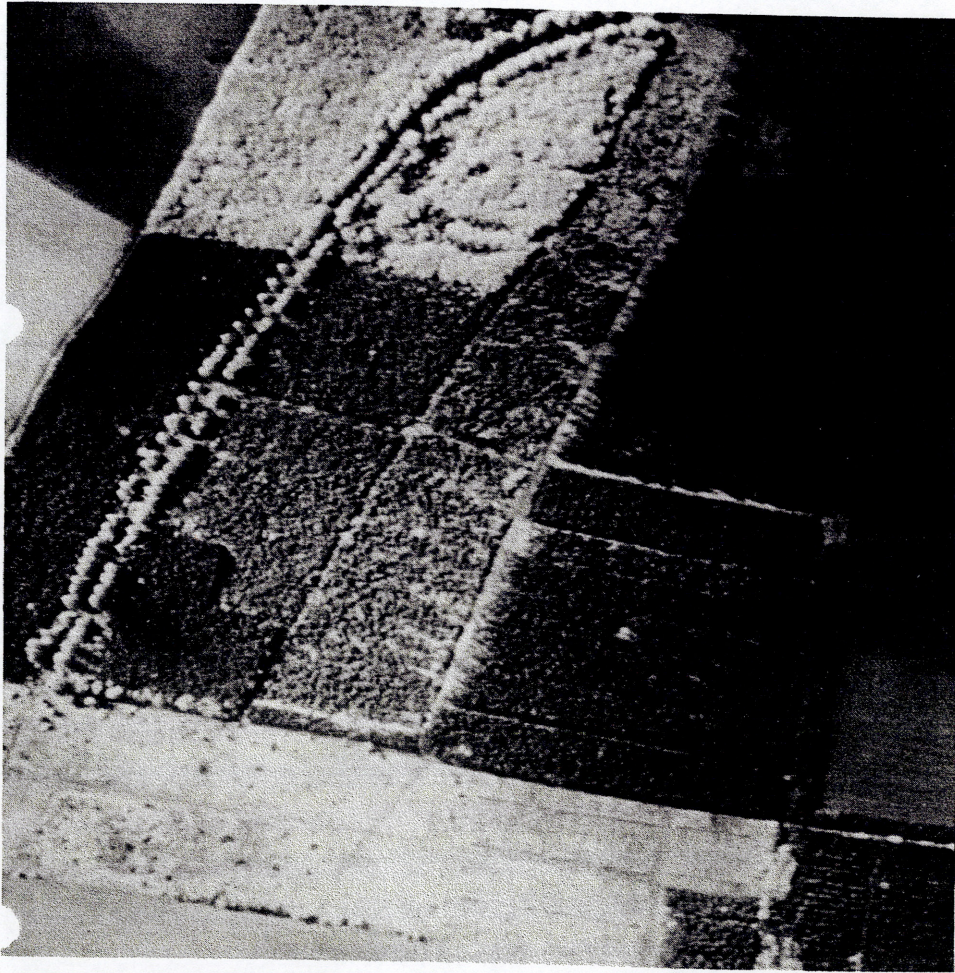


Figure 2a Near-infrared ($0.91 - 1.05 \mu\text{m}$) data from an airborne multi spectral scanner. The image is not a photograph but a digital image which has been displayed using computer image processing methods (see Wilkinson, chapter 5). The image shows the sharply defined contrast between the high NIR reflectance from the beech trees and the much lower reflectance from the conifers. The area covered by the image is about 1 km^2 . The "resolution" of the scanner (ie the smallest ground area viewed) is around 2 m. This provides images with sufficiently high resolution for individual tree crowns to be seen.

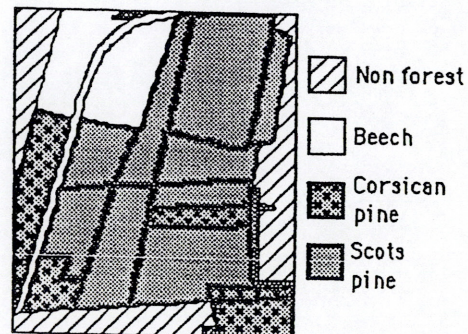


Figure 2b Forest stand map

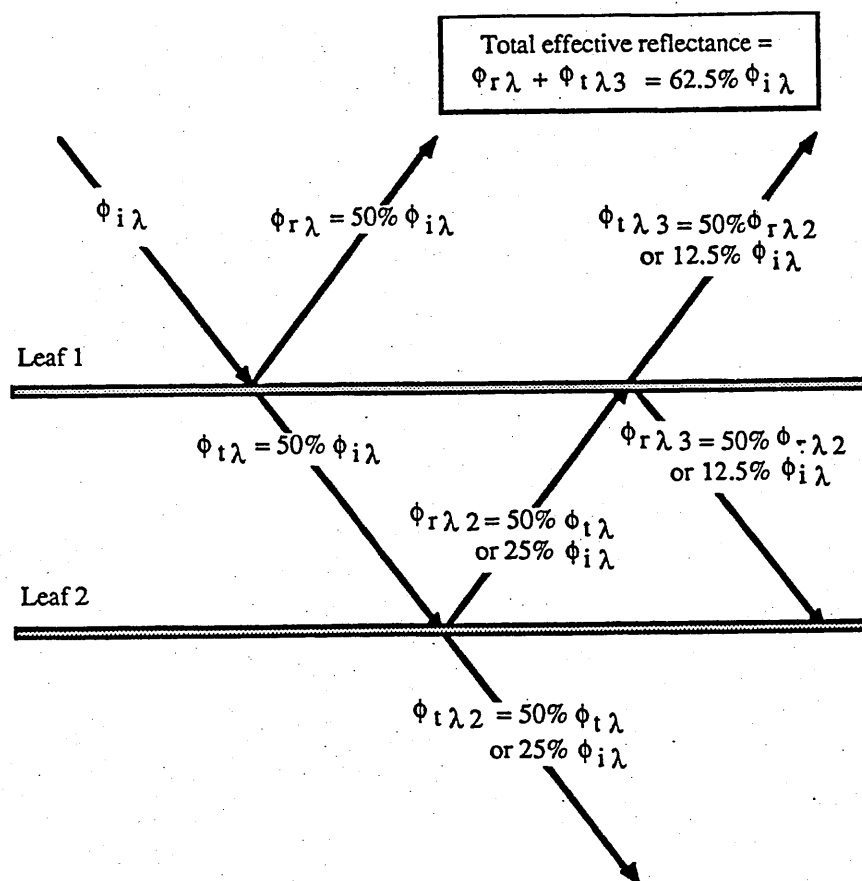


Figure 3. The effect of multiple leaf layers on the effective reflectance from vegetation. $\phi_{i\lambda}$ = the incident flux, $\phi_{r\lambda}$ = the reflected flux, $\phi_{t\lambda}$ = the transmitted flux, (after Hoffer 1978)

This is important when we consider spectral measurement from space platforms; with the exception of the very weak overtone bands, at 1.1 and 0.96 μm , all the moisture absorption bands fall outside the atmospheric windows used in remote sensing (see Bird, chapter 2, §3.) thus it is only the carry over effects which can be detected from satellite sensors.

In general, the lower the water content of a plant the higher the reflectance will be in the middle-infrared, with reflectance peaks occurring between the moisture absorption bands at around 1.6 and 2.2 μm . The water content of a plant will depend upon a) the percent moisture content, and b) the thickness of the leaves. The effects of water absorption are so strong that changes in middle-infrared reflectance are most obvious where water content is very low.

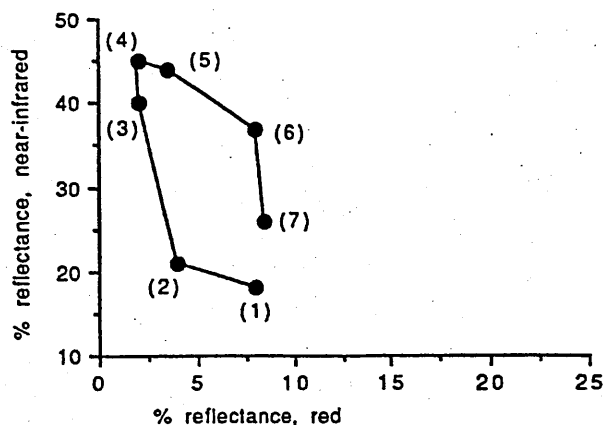


Figure 4. Changes in red near-infrared reflectance for an annual cereal crop through a single growing season. Figures in brackets identify specific stages, see text for explanation

Hoffer and Johannsen (1969) working with Maize (*Zea mays*) found that pronounced increases in middle-infrared reflectance were most evident where moisture content fell below around 54%.

2.4 TEMPORAL AND SPATIAL CONSIDERATIONS

All plants undergo two processes of change, those of growth and differentiation. Growth is applied to quantitative changes (ie changes in volume, not form or function), differentiation is applied to qualitative changes such as the changes from vegetative to reproductive phase in a plant growth cycle.

The term phenology is often used to describe the seasonal changes in vegetation. Different plant species in the same geographical location can have contrasting phenologies; in temperate regions, for example, Barley (*Hordeum vulgare*) reaches maturity two to three weeks before Wheat. The yellow / brown barley fields contrast sharply with the still green wheat fields. Earlier in the season the phenological contrast between the two is less well defined, with both crops appearing lush green. Similarly, the phenology of the same plants in different locations can contrast; for example Maize (*Zea mays*) can reach maturity 4 months after sowing at low altitudes in Kenya, yet can take over a year to mature at higher altitudes.

We have seen from the preceding subsections that the spectral reflectance properties of vegetation change during growth and development. Multi spectral measurements taken at different times can, therefore, be used to track the phenology of different vegetation types.

Figure 4 shows spectral changes in red and near-infrared wavelengths for an annual crop such as wheat. Reflectance is shown in the feature space defined by axis representing these two spectral regions. The numbers in brackets relate to points on the figure. Soon after emergence crop cover is very low and the resulting reflectance is strongly dominated by soil (1). The precise position in the red near-infrared space will depend on the reflectance characteristics of the soil (see §3.4, below). As the vegetative cover develops, the increase in chlorophyll content causes spectral response in the

red wavelengths to drop because of the increased effects of pigment absorption, and near-infrared reflectance to increase because more highly reflective vegetation, and less soil is seen (2). As cover continues to develop red reflectance usually reaches a minimum value; so much red light is absorbed by the upper canopy (§ 2.1) that additional leaf layers, appearing with canopy development, have little influence, i.e. red infinite reflectance is soon reached (3 & 4). Usually, near-infrared reflectance continues to increase with increasing number of leaf layers, even after red ρ^∞ has been reached (3 & 4), this continues until near-infrared ρ^∞ too is reached (4). During senescence the breakdown of chlorophyll leads to a marked increase in the levels of red reflectance, and the re-orientation of the leaf cells also causes a drop in near-infrared (5). Note that in the early stages of senescence a slight increase may be apparent in near-infrared reflectance. Red reflectance continues to increase as senescence progresses and chlorophyll breaks down, further changes in leaf structure cause further reduction in near-infrared reflectance (6). Finally harvest returns us to bare soil and post-harvest crop residue (7).

Graphs, such as this, are thus a temporal spectral representation of the plant's phenology. Because different plants have different phenologies they will have different temporal spectral profiles. Characterization of temporal spectral profile can be used for example, as an aid to crop mapping by identifying periods of maximum spectral separation between crop types.

Figure 5 shows false colour infrared satellite images from an arable area of the United Kingdom near the beginning (February), in the middle (April and May) and towards the end (August) of a growing season. The intensity of the red tones is related to the level of near-infrared reflectance. Field (W) was planted with winter wheat. In February the wheat has emerged, cover is not complete and the pale pink tones indicate the low levels of near-infrared reflectance. During April and May the crop cover develops, and we can see how the red tones deepen as NIR reflectance increases. In August the crop has been harvested, we are left with bare soil and stubble, NIR reflectance is correspondingly low. Field (R) was planted with winter oilseed rape (*Brassica napus*). This follows a similar growth pattern to the wheat, with the obvious exception of the May image. Winter oilseed rape flowers in May; fields of brilliant yellow rape flowers stand out dramatically against the more uniform green of other crops in the United Kingdom at this time. The flowers have very high reflectance in visible and near-infrared wavelengths, and the fields appear almost white on satellite images. By August the rape too has been harvested and the fields have the same appearance as the wheat. Field (B) was planted with sugar beet (*Beta vulgaris* var. *altissima*). This crop is sown far later than the other two crops and throughout February, April and May the fields of beet appear as bare soil on the images. In August however, the beet is well developed and the fields now take on the spectral response of vegetation.

Although spectral temporal profiles are variable, all green plants follow the general pattern of decreasing red reflectance, and increasing near-infrared reflectance, with an increase in plant cover and phytomass. Various ratios and combinations of red and near-infrared reflectance (collectively known as vegetation indices) have been used to quantify the relative changes in reflectance that occur at these wavelengths during plant development. Vegetation indices are widely used as surrogate measurements of vegetation production and as a means of studying vegetation phenology; these subjects are discussed in later chapters.

The highly variable nature of plant reflectance is not just due to the processes of growth and differentiation but also due to spatial variations such as background soil type (Huete *et al.* 1984) and, in the case of crops, managerial difference such as nutrient inputs and planting density (Christ 1984). In addition, because leaves are not diffuse, Lambertian reflectors (Grant 1987), variations in sun-target-sensor geometry are known to influence the reflectance characteristics of vegetation. This point is discussed in more depth by Baret in a later chapter.

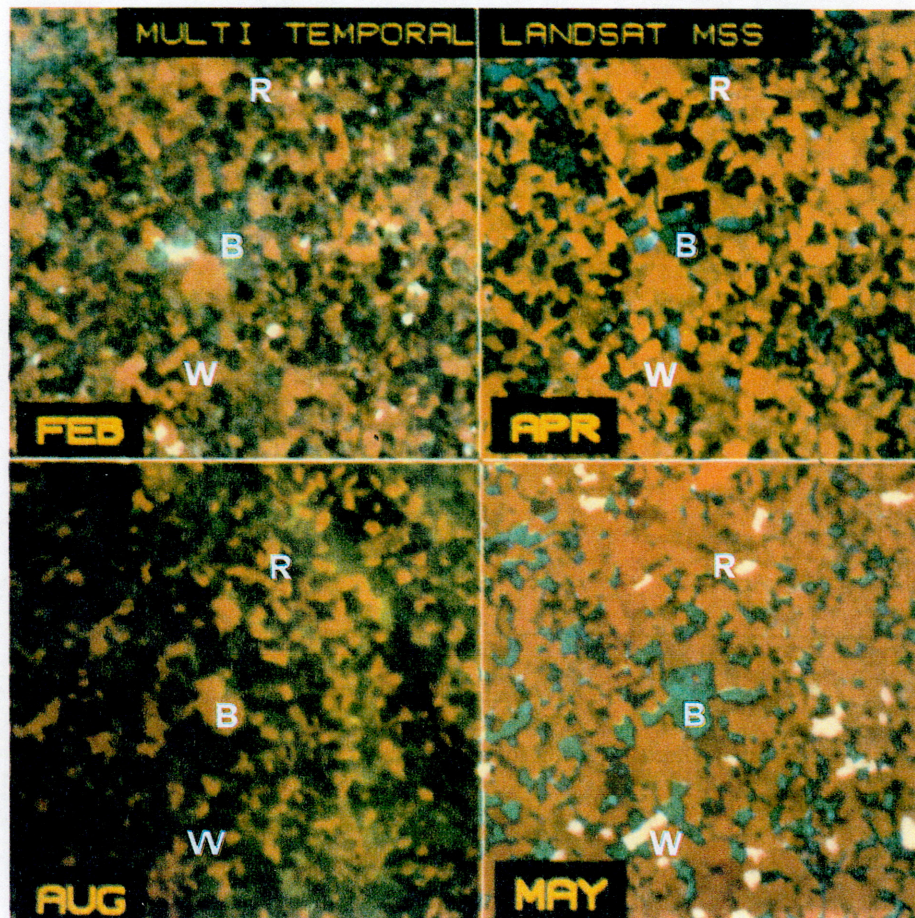


Figure 5. Four Landsat Multi Spectral Scanner (MSS) false colour composite (FCC), 12 km² images of an agricultural area of UK, from 1980. Hill, chapter 4, describes the MSS. FEB = 18th February, APR = 12th April, MAY = 18th May, AUG = 16 August. FCCs are created by displaying data from the green (0.5 - 0.6 μm), red (0.6 - 0.7 μm) and NIR (0.8 - 1.1 μm) wavelengths through the blue, green and red channels of a colour monitor. Green vegetation always appears bright red on FCC images because the high reflectance from vegetation in the NIR is displayed in red. Soils never appear bright red on FCCs. Here the soils appear blue / grey. The white patches in the February image are clouds; note the dark cloud shadows on the ground (above, and slightly to the left of each cloud). The images show how reflectance changes of an agricultural area can be captured by satellite sensors. The increasing NIR reflectance of the developing winter wheat (W) can be seen in the increasing intensities of red, until August when the wheat is harvested and we are left with bare soil plus stubble. The rape (R) follows the same pattern, except in May the rape comes into flower. The flowering rape has quite distinct reflectance characteristics and appears white on the May image (confusion with clouds is avoided; a) there are no shadows, b) the fields have a more regular shape). The August image is the "inverse" of the earlier scenes, the winter sown crops have been harvested and appear as bare soil, all the later sown crops, such as beet (B) have emerged, and no longer appear as bare soil. Multi temporal analysis requires careful image preparation: images must have the same geometry, sensors must be calibrated, and if possible, atmospheric effects (Bird, chapter 2), must be accounted for - these operations are discussed in chapters 5 and 6.

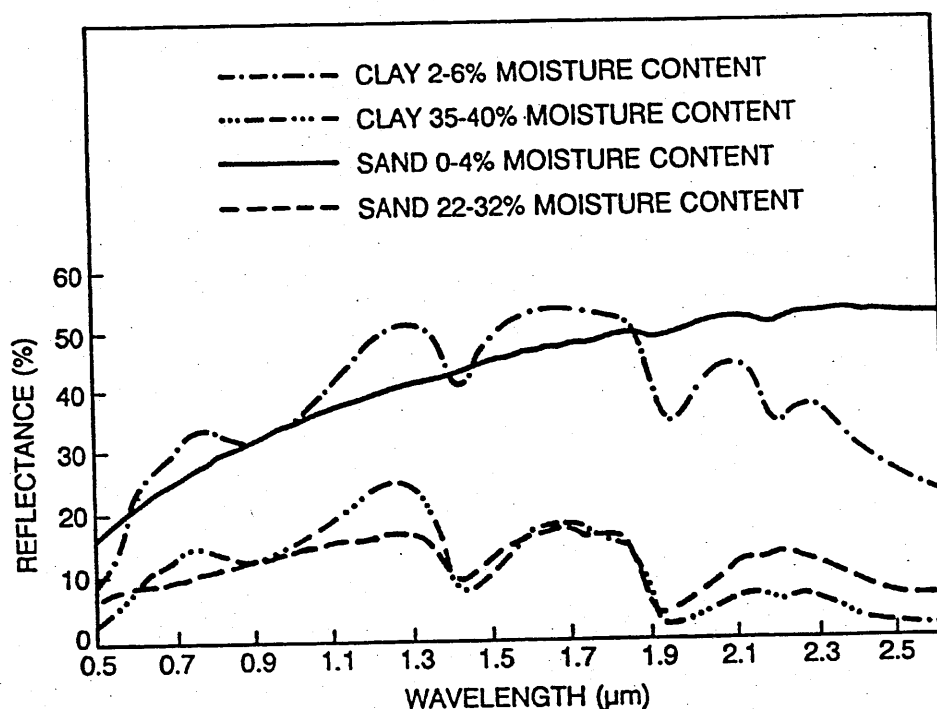


Figure 6. Spectral reflectance curves for bare soil (after Hoffer and Johannsen 1969)

3. Spectral properties of soil.

The spectral properties of soils are much simpler than those of vegetation; transmission of EMR in the optical wavelengths is non-existent and all incident energy is either absorbed or reflected. Figure 6 shows spectral reflectance curves for clay and sandy soils. There is an increase in reflectance with increasing wavelength for both soils, though the effect of variations in water holding capacity upsets this trend in the moisture-sensitive middle-infrared. The basic form of the curves holds for many soils (Condit 1970), though the magnitude varies. This variation is due to the physical properties of any particular soil. The main soil variables found to influence spectral properties are texture, moisture content, organic matter content and iron oxide content.

3.1 SOIL TEXTURE AND MOISTURE CONTENT

The main criterion used in classifying soils is texture. The term soil texture is used to describe the size and distribution of soil particles. There are a number of different classifications in current use, all of which identify three major groupings; sand, silt and clay. Table 2 shows name and size range of constituent particles for two widely used systems.

Name	Size range (mm)	
	International system	MIT * system
Clay	< 0.002	<0.002
Silt	0.002 - 0.02	0.002 - 0.006 0.006 - 0.02 0.02 - 0.06
Fine sand	0.02 - 0.2	0.06 - 0.2
Medium sand		0.2 - 0.6
Coarse sand	0.2 - 2.0	0.6 - 2.0
Gravel	>2.0	2.0 - 60.0

* Massachusetts Institute of Technology

Table 2. Particle size range and name according to two widely used soil classification schemes.

Early laboratory analysis of soil reflectance properties showed that increasing particle diameter was related to decreasing reflectivity (Bowers and Hanks 1965). However, laboratory analysis is concerned with dispersed soils, not the aggregates found in natural conditions; it has been observed that decreasing particle size increases reflectance from sandy soils, however the opposite is true for fine textured soils. Outside the laboratory, factors such as moisture content cannot be easily controlled and there are very strong relationships between soil texture and water holding properties.

The relative proportions of sand, silt and clay affect the movement of air and water through a soil. If moisture is present in a soil then each particle is covered by a thin film of water. Thus soils with a small particle size, and therefore a large total surface area per unit volume, will hold a large amount of water. In addition some of the air spaces in the soil will be occupied by water. The ease with which water drains or evaporates from a soil is very much influenced by the size of the pores. Sands for example, with large particles and large pores dry out easily whilst clays do not. Marshal and Holmes (1979) provide a good review of this process.

The effect of this on soil reflectance is particularly marked when the spectral reflectance curves of air dry and moist soils are compared. The spectral reflectance curves in Figure 6 are for air dry and moist sand and clay. The large particle size of the sand allows more complete drying than the clay, consequently an air dry sand contains less water than an air dry clay (in this case 0 - 4% for the sand, compared with 2 - 6% for the clay); the sand shows little in the way of moisture absorption in the water absorption bands at 1.4 and 1.9 μm . In comparison the air dry clay still retains sufficient moisture for pronounced dips in reflectance to occur at these points. On wetting the sand too displays these dips.

The changes in soil reflectance on wetting are most pronounced in the moisture absorption wavebands, but note that reflectance at all wavelengths is lower for the wet soils; we are all familiar with the way in which soil goes darker after rain.

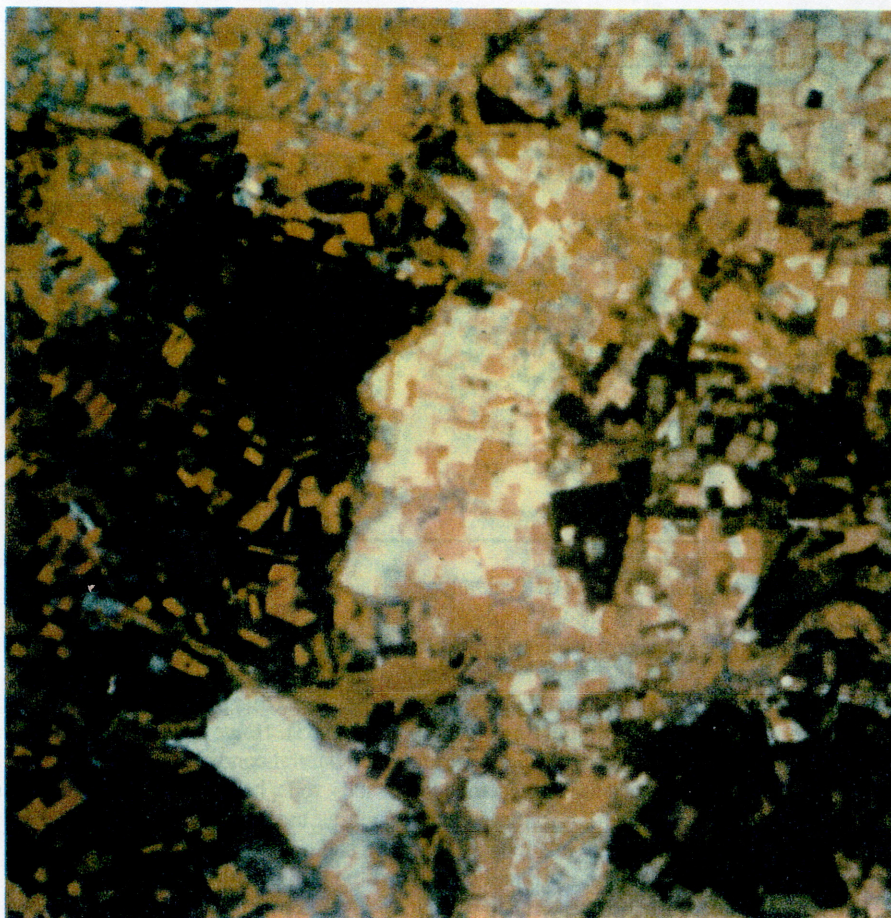


Figure 7. Landsat Multi Spectral Scanner (MSS) false colour composite (FCC), 50 km² image of part of the United Kingdom, April 1982. As with the FCCs shown in figure 5, vegetation, with the exception of the extensive coniferous woodland, appears red. Here the red areas are grassland and winter cereal crops, *eg* wheat. Coniferous woodland, as shown in figure 2, has relatively low levels of NIR reflectance and appears as dark red / brown on the FCC shown here. The bare soils, again largely supporting late sown crops like beet, appear almost black where the organic content is high (humified peat), and almost white where organic content is very low (brown earth). Note how the concrete runways of the airfield can easily be confused with the brown earth soils. Spectral confusion between bare soil and man made features such as roads, or urban areas in general, is common with these images.

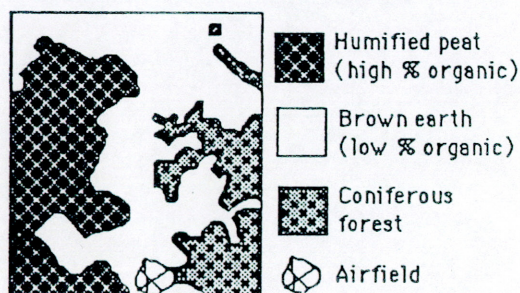


Figure 7. Soil distribution

In addition to the moisture absorption bands, the spectral reflectance curves for the clay dip at $2.2\ \mu\text{m}$. This wavelength corresponds to a hydroxyl absorption band (Hunt and Salisbury 1970). The other hydroxyl absorption band at $1.4\ \mu\text{m}$ is confused with moisture absorption. The hydroxyl absorption bands tend to give soils with a high clay content quite distinctive spectral curves.

Apart from its effect on air and water movement through a soil, texture also has an effect on surface roughness. In theory small particle size leads to a smooth soil surface, which in turn leads to higher levels of reflectance. However, in practice, clay soils form aggregates more easily than sandy soils. Thus natural processes and cultivation operations tend to mask the simple effect of texture by introducing soil surface roughness on a macro scale. A rough surface, with a high incidence of interaggregate cracks and pores, will trap more of the incoming light and reflectance will be correspondingly reduced.

3.2 ORGANIC MATTER CONTENT

Soils containing a high percentage of organic matter generally have low levels of reflectance, and appear quite dark in colour, usually dark brown or black. Soils with little or no organic material tend to reflect more light and are often light brown or grey in colour. In general, the higher the percentage of organic material, the darker the soil will be. The colour will also be influenced by the degree of decomposition of the organic material; well decomposed material gives a black soil colour, whilst less well decomposed material generally imparts a brown colour to the soil. Figure 7 shows a false colour infrared image from a satellite sensor of an area of contrasting soils. The very dark grey / black areas on the left hand side of the image are soils from the Adventurers series of humified peat soils group (these are soils with a high organic matter content). The almost white areas on the right hand side of the image are soils from the Freckenham and Worlington series of the brown earth group (these are soils containing very little organic matter). The red areas are cereal crops and grassland, the brown areas on the extreme right are extensive conifer plantations.

The above observations on the relationship between colour and organic matter content are mainly based on work done on soils which have developed in temperate climates (Page 1974 for example). As such they may not hold true for all climatic conditions in which soils may develop. Care should be taken in applying these observations to the interpretation of spectral reflectance data for soils from other climatic regions.

3.3 IRON OXIDE CONTENT

Many of the red soils of the world owe their colour to a high iron content. In general, the higher the iron oxide content the lower the reflectance, particularly in the visible wavelengths. Figure 8 shows a false colour infrared image from a satellite sensor of an area of contrasting soils in the West African Sahel. The dark grey / black areas are Laterite crust, the grey areas are clay outwash and the pale yellow tones are sands. Vegetation again appears bright red. The laterite has much lower reflectance than the sands or clays in all the wavelengths used to make this image, hence the almost black appearance. The low reflectance of the laterite areas may be due to the specific absorption characteristics of the metallic ions in the soil.

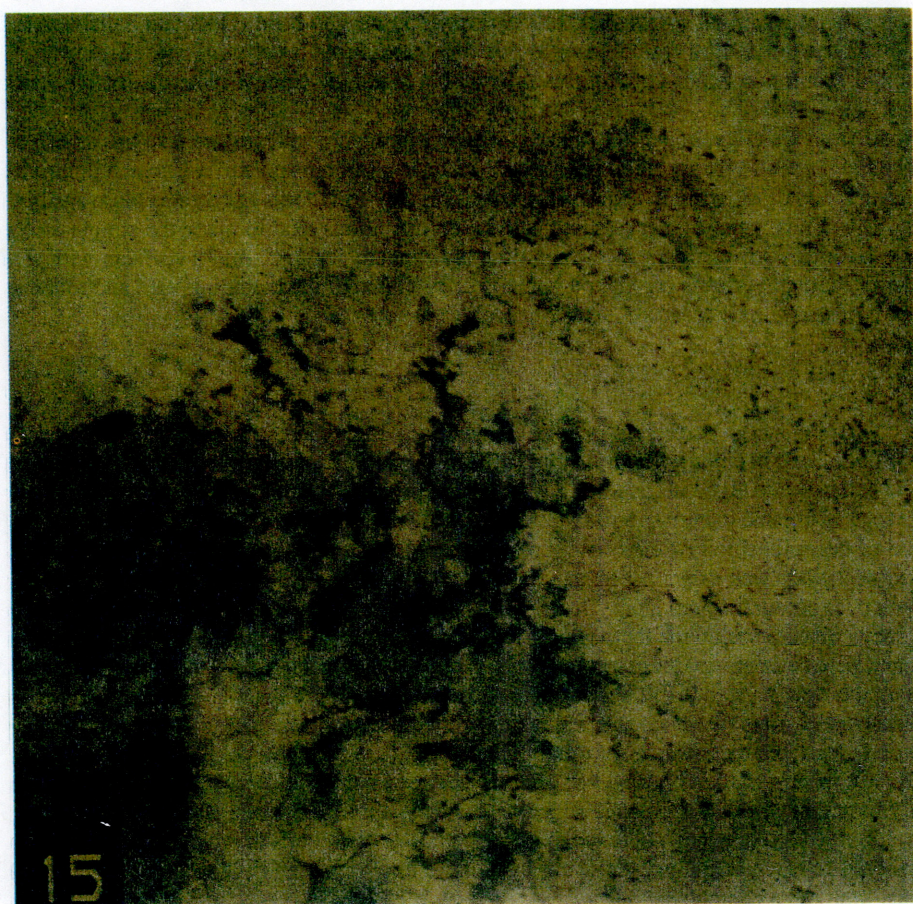


Figure 8. Landsat Multi Spectral Scanner (MSS) false colour composite (FCC), 50 km² image of the Sahel rangelands of Niger, October 1984. The faint pink blush over much of the image is from a sparse grass cover after the poor rains of '84. Denser vegetation occurs where soil moisture is greater; along the rivers and in the inter-dunal depressions (the latter are marked by the scatter of red dots across the image). The sands show through the poor vegetation cover as yellow tones. The almost black laterite crust has a high % iron oxide (Fe_2O_3) and correspondingly low reflectance. These soils largely follow escarpments of low lying hills. The clays, appearing as grey, are an "outwash" from the edges of these hills. The limited crop production in this area (appearing as the brightest reds) is mainly confined to growing Sorghum at the edges of the clay outwash fans.

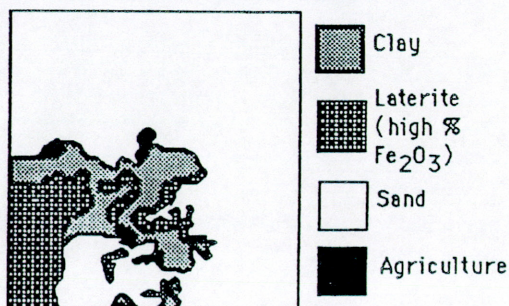


Figure 8. Soil distribution

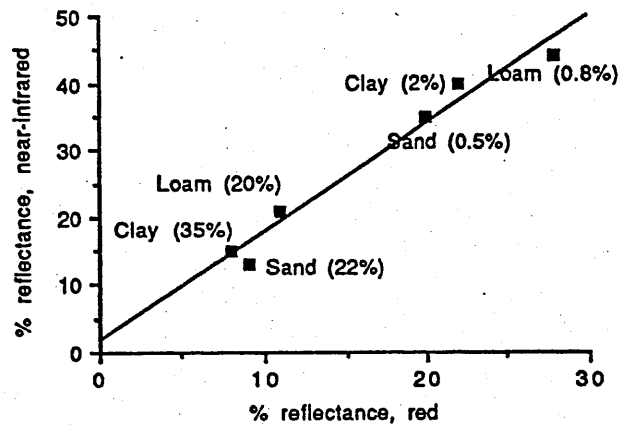


Figure 9. Red near-infrared reflectance for Loam, Sand and Clay soils at different moisture contents. The numbers in brackets are % moisture content

3.4 TEMPORAL AND SPATIAL CONSIDERATIONS

Soils develop over many years, Myers (1984) estimates that the formation of 2.5 cm of top soil can take anything from 100 to 2500 years depending on the soil type and climate. Thus within the framework of most natural resource surveys, factors such as organic matter content and iron oxide content may be considered as stable. However, there are considerable variations in soil moisture content, and, as Baret discusses in a later chapter, sun-target-sensor geometry has to be considered for soils as well as vegetation.

Because soils are a mixture of complex and varied materials, reflectance from an area of unknown soil could be attributed to a range of physical factors. Is an area of dark soil seen on a satellite image high in organic matter content, high in iron oxide content, or just wetter than surrounding areas?

The use of imagery from different times can help to resolve such confusion; tonal characteristics which are constant with time are likely to be due to soil physical properties such as texture or organic matter content. In contrast, variations in tone for a given area are likely to indicate changes in soil moisture status. An alternative is the use of thermal measurements, as wet soils usually have a lower surface temperature than dry soils due to the cooling effect of evapotranspiration.

Even though the spectral curves of soil change with texture, moisture content, organic matter content and iron oxide content it has been shown that there is a linear relationship between reflectance at any two wavelengths for soil, and that by and large, this feature of soil reflectance is spatially and temporally constant. Thus, if a soil has relatively high reflectance in the visible wavelengths, then reflectance in the near-infrared will also be high, and vice versa, if visible reflectance is low, then near-infrared reflectance is low.

This can be seen in figure 9 which plots the reflectance of a number of soils in red near-infrared feature space. Note how the position varies not just as a function of soil type but also the moisture

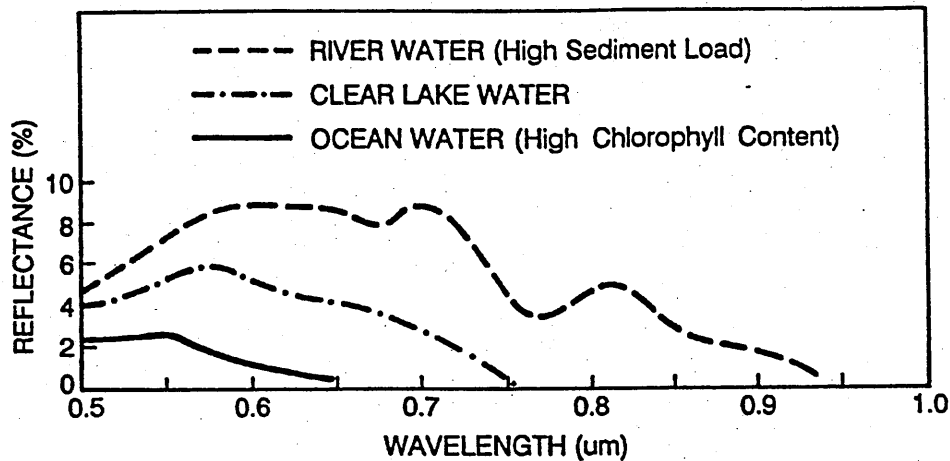


Figure 10. Spectral reflectance curves for water. River and lake water after Bartolucci *et al.* 1977, ocean water after Clarke *et al.* 1970.

content of any given soil. As moisture content increases, regardless of soil type, then the soils move down closer to the origin.

The nature of the soil background will, of course, influence the reflectance characteristic of any vegetated area at low percentage vegetation cover. Thus position (1) in figure 4 (§2.4) could be anywhere along the linear distribution for soils seen in figure 9. Some authors have even suggested that for crops growing on very bright soils reflectance from the developing canopy can fall in the early stages due to shadowing effects; there is considerable reduction in the reflectance from a shaded bright soil, compared with non-shaded, see Kauth and Thomas (1976), for example. The linear properties of soil reflectance have important implications concerning the use of remotely sensed data for the quantitative estimation of plant biophysical parameters such as % canopy cover and leaf area index, and are discussed by Baret later in the book.

4. Spectral properties of water

As with vegetation and soil the spectral characteristics of water change with wavelength. Changes in spectral response also occur with changes in physical, chemical and biological state; just as dry soil and wet soil, green vegetation and senescent vegetation have contrasting spectral properties, so too do clear rivers and turbid rivers, shallow lakes and deep oceans.

The spectral properties of pure water, as measured in the laboratory, have been known for many years. Clear water is known to have excellent transmission properties and weak absorption characteristics in the visible wavelengths, and weak transmission, strong absorption characteristics in the infrared. This can be seen from the spectral reflectance curve for clear lake water shown in figure 10. Reflectance peaks in the green wavelengths, and tails off to almost zero in the infrared.

Water bodies are three dimensional, therefore any measure of reflectance may include a component from the bottom, from the surface and from the water column itself. Water can behave as a specular reflector. Specular reflection, from the surface, is usually perceived as sun glint from

air or space platforms, and has the effect of obscuring all sub-surface features. Variations in the bottom material and the depth and quality of the water column are associated with changes in the spectral properties of water. These changes are only apparent to any great extent in the visible wavelengths. In the infrared, relationships between reflectance and water quality parameters tend to be random because of the effect of the fundamental and overtone water absorption bands noted in § 2.3 (Lathrop and Lillesand 1986).

4.1 CLEAR WATER

The depth to which light will penetrate water varies with wavelength. Lepley *et al.* (1975) estimate the depth of penetration for clear water to be 10 m in the 0.5 - 0.6 μm waveband, falling to only 10 cm in the 0.8 - 1.1 μm range. Values approach zero at longer wavelengths.

As depth of water increases then reflectance for any wavelength decreases, because there is a greater path length through the water column over which absorption and scatter can occur. As a result it is possible to use remote sensing measurements to update the bathymetric information on navigation charts. Because of the greater depth of penetration of blue and green wavelength EMR it is data recorded through these parts of the spectrum which are used for such work. For example, Hammack (1977) working with satellite sensor data recorded through the 0.5 - 0.6 μm waveband reports the accurate measurement of depths to 22 m, and even the effective mapping of shoals as deep as 40 m in the clear waters off Berry Island in the Bahamas, in less clear water, off the Florida coast, shoals only as deep as 10 m could be detected.

From clear water the signal will not only depend on the depth of water but also on the nature of the bottom material; a light sandy bottom will give stronger reflectance than a bottom composed of decaying organic matter. The reflectance detected from clear water can therefore be difficult to separate from the reflectance from bare soil. However, water absorbs almost all EMR at infrared wavelengths, and, in contrast to bare soil, reflectance is very low. Because of this, coastal and lacustrine boundaries and even small rivers and water bodies can be reliably identified from infrared remotely sensed data, (Work and Gilmer 1976 for example).

4.2 TURBID WATER

Water bodies under natural conditions usually contain a range of organic and inorganic materials, some dissolved, others in suspension. Turbid waters can be divided into those containing phytoplankton and their derivative products, and those containing organic and inorganic sediments (Aranuvachapun and Robertson 1985).

4.2.1 Phytoplankton and their derivative products have a profound influence on the spectral properties of water, particularly in the blue and green wavelengths. The ability to identify and map plankton rich waters is important for commercial reasons because phytoplankton support large zooplankton and fish populations, and for environmental reasons, as evidenced by the concern with algal pollution in the Adriatic in summer 1989. Algal blooms are often associated with upwelling events. These occur where nutrient rich cold bottom water is brought to the surface. At the surface the water receives more sunlight, which leads to the development of the blooms. These sites are commercially important for the fishing industry, and can be mapped using satellite images, such work is almost impossible from *in situ* measurements as the blooms soon decay and are dispersed.

As with higher plants, chlorophyll, and other photosynthetic pigments, in phytoplankton absorb blue light for photosynthesis, and as with higher plants increase in chlorophyll concentration also

leads to increased levels of green reflectance. These effects can be directly seen on the reflectance from water with high phytoplankton, and therefore high chlorophyll concentrations. Reflectance in blue wavelengths is reduced and green enhanced. Note how the reflectance in the red wavelengths drops sharply for the ocean water with high chlorophyll content shown in figure 10. Many empirical equations have been developed which use changes in reflectance at these wavelengths for the quantitative estimation of the pigment concentration of water (Verdin 1985, Lathrop and Lillesand 1986 for example).

4.2.2 organic and inorganic sediments in water tend to affect reflectance in the green and red wavelengths. Monitoring and mapping of sediment loads in water is also of commercial and environmental importance. For example, sediment transport studies provide information on rates of upstream soil erosion, on silting rates in irrigation storage ponds, on harbour silting patterns, on estuary sediment distributions, they provide information for maintenance of shipping lanes and data needed in planning causeway or bridge construction.

Water with high inorganic sediment loads usually has higher reflectance than clear water, and peak reflectance usually occurs at the longer red wavelengths, rather than green. This shift can be seen in the spectral reflectance curve for river water with a high sediment load shown in figure 10. Many investigators have found that reliable quantitative estimates of suspended sediment concentration can be made from measurements of reflected solar radiation in the visible wavelengths, particularly in the red wavelengths (Scarpace *et al.* 1979 for example). These are usually derived from linear multiple regression techniques between some measure of radiance and water quality measurements such as turbidity (Whitlock *et al.* 1982).

4.2.3 Other factors influencing water quality such as chemical variations are, in themselves, nearly impossible to detect with current optical remote sensing systems. For example, Scherez (1971) showed that no spectral reflectance differences in the optical wavelengths were apparent when gases such as oxygen and carbon dioxide, or inorganic salts such as sodium chloride were dissolved in distilled water. Detection of chemicals such as nitrogen or phosphorous may, however, be possible, if variations in their concentration correlate well with some measurable factor such as turbidity.

Salinity has been identified by Johnson and Munday (1983) as being a chemical variable in water which can be measured by remote sensing, though from passive microwave radiometry, not from EMR in the optical part of the spectrum. Microwave remote sensing, both active and passive, has also been successfully used for the detection of oil films on water (Gruner *et al.* 1986). Though, unlike salinity, oil films on water can also be detected using satellite sensor measurements of EMR from the visible and near-infrared wavelengths (Deutsch and Estes 1980).

4.3. ICE AND SNOW

The detection and mapping of ice and snow is of great importance to hydrologists interested in estimating runoff from snow melt. Monitoring iceberg production and movement is important to oil companies concerned with location and protection of expensive rigs, and to the protection of shipping in general.

The spectral properties of water in a frozen state are quite distinct from those of liquid water, with reflectance levels being generally very high. Indeed in the visible and near-infrared wavelengths the reflectance from snow can be so high that the detectors on some satellite sensors reach saturation (Bartolucci *et al.* 1975).

The high levels of reflectance can lead to spectral confusion with clouds which also reflect strongly across the wavelength range 0.4 - 3.0 μm . This spectral overlap also exists in the thermal-infrared as both cloud tops and snow are cold.

However, O'Brien and Munis (1975) showed that snow exhibits a unique transition in spectral response from around 100% at wavelengths less than 0.8 μm to nearly 0% at wavelengths above 1.4 μm ; at these wavelengths clouds still reflect strongly, thus middle-infrared wavelengths can be used to separate the two.

The condition of snowpacks varies in terms of wetness and density / grain size. In general older wetter snow is characterized by a slight decrease in reflectance at wavelengths less than 0.8 μm and a more pronounced drop in the near-infrared (O'Brien and Munis 1975). The difference between visible and near-infrared reflectance also increases as the density of snow changes from fresh powdery snow through to more compact snowpacks.

Bimie (1986) suggests that the changes in reflectance may be due to discontinuities in cover as the snow ages and melts. Thus, when viewed from space platforms, a sensor would see a mixture of snow free and snow covered ground, rather than continuous snow cover.

4.4. TEMPORAL AND SPATIAL CONSIDERATIONS

The monitoring of many water quality variables, such as sediment load, chlorophyll content, bathymetry and snowcover and ice mapping is relevant on local scales; the references cited throughout the section are nearly all concerned with local situations. However, more than seventy percent of the planet surface is covered with water; oceans, snow, ice, lakes and rivers, which along with ground water, aquifers, clouds and atmospheric water vapour make up the the global hydrologic cycle. The water component of our planet effectively forms a continuous ecosystem, in a state of flux, which has a profound influence on the functioning of the earth system. The need for coherent monitoring of the "blue planet" ecosystems is now keenly felt (NASA undated). The spatial scale is global, which introduces problems of data acquisition and processing, the temporal scales to be considered present other difficulties. Snowfields melt, form rivers which flow into lakes and oceans, evaporation returns the water to the atmosphere where it forms clouds and falls as rain or snow; on average water can be resident for around 10 days in the atmosphere and a similar period in rivers, tens of years in lakes, centuries in deep aquifers or glaciers and anything from 10 to more than 1,000 years in the oceans. The monitoring of a global ecosystem on a temporal scale ranging from days to years represents an immense challenge.

The oceanography and hydrology communities have, over the years, amassed an impressive range of remote sensing capabilities to meet this challenge, a full discussion of which is beyond the scope of this book. Johnson and Munday (1983), and Maul (1985) provide good introductions to this subject.

5. Summary

Reflectance from a vegetation canopy varies both with wavelength and with the growth and development of the plants. Absorption by pigments controls plant reflectance in the visible wavelengths; leaf structure, controlling the scattering of light in the leaf, is the dominant factor in the near-infrared; and in the middle-infrared absorption by water in the leaf is most important.

Soil reflectance is less variable. All soils generally show an increase in reflectance with increasing wavelength, particularly at visible and near-infrared wavelengths. Increasing moisture

content, iron oxide content and organic matter content reduce soil reflectance in all wavelengths considered in this chapter, with water absorption having a particularly pronounced effect in the middle-infrared. There is a positive correlation between soil reflectance in one wavelength and another, and this is, by and large, spatially and temporally constant.

Most spectral information concerning water characteristics is gleaned from the visible wavelengths, though the land / water boundary is most obvious in the infrared. The blue / green wavelengths are best for bathymetric studies in clear water, and for the mapping of phytoplankton rich waters. The green / red wavelengths are best for detecting inorganic sediments.

Snow and cloud both have very high visible and near-infrared reflectance, though they can be separated in the middle-infrared where reflectance from snow is minimal. The near-infrared wavelengths contain information relating to snow aging and condition.

6. Conclusions

This chapter has introduced the basic concepts needed for the interpretation and analysis of remotely sensed data recorded through visible, near and middle-infrared wavelengths. Subsequent chapters develop these ideas and show how such data can be applied to aspects of natural resource management such as agricultural production monitoring, estimation of tropical deforestation rates, and for hydrological studies.

Such use of spectral information is only possible if it is captured in some permanent form such as a spectral curve. The spectral curves, used above to describe the spectral characteristics of earth surface features, are from non imaging electronic sensors. Much of remote sensing relies on the use of multi spectral images. Currently the sensors used to produce such images only record data through a few wavelengths. However, if the waveband is known, then the spectral characteristics described above can be used in the interpretation process. The following chapters describe the sensors and platforms from which these images are derived, and introduce some of the data processing techniques in current use.

As Bird points out in the first chapter the technology for recording longer wavelength, lower energy EMR is complex, and so has a shorter history than that of the wavelengths discussed here. After all, the photographic process has been known since 1839. This situation is changing, thermal data are becoming far more widely used and sensors operating in the microwave regions of the electromagnetic spectrum will provide much of the data for remote sensing by the mid 1990's. The use of thermal data in rainfall estimation and in crop yield forecasting are presented in later chapters, whilst elsewhere, energy matter interactions in the microwave region are combined with a review of present and future Radar remote sensing systems.

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Chapter 3. Large area vegetation mapping and biomass estimation using AVHRR data

MAPPING OF VEGETATION AND SOILS AND ESTIMATION OF BIOMASS IN THE SAHEL

J. C. Taylor, A. S. Belward,
D. G. Hewett and B. K. Wyatt

ABSTRACT

In semi-arid grasslands, rainfall is often the most important of the environmental variables which determine ecological productivity. Nevertheless, other factors are also significant, and measurements of rainfall alone give an inadequate guide to optimal rangeland management strategies.

This part of the study describes the development of operational procedures for mapping the distribution and quantity of rangeland vegetation using remote sensing. Such maps of the distribution of green biomass are of immediate use in monitoring the condition of pasturelands. Subsequently, it is intended to apply them in calibrating remotely-sensed estimates of rainfall with green biomass as a basis for the development of predictive aids for rangeland management in the Sahelian zone of Africa at national and regional scales.

Herbaceous biomass was determined in a range of arid grasslands in the Republic of Niger. Two indices of green vegetative cover derived from digital multispectral data, the Normalized Difference Vegetation Index (NDVI) and the Perpendicular Vegetation Index (PVI) were evaluated. A method is described for calibrating AVHRR imagery using Landsat-MSS as an intermediate step. Correlation curves, relating biomass with NDVI and with PVI were constructed. These correlations were tested using biomass values measured independently. A Soil Brightness Index (SBI), replicable between different images, is also described. Large-area maps of biomass and soil type were generated from the NDVI, PVI and SBI images.

An operational system is proposed, based on the use of AVHRR imagery for quantifying and monitoring biomass and its spatial distribution in Sahelian rangelands to assist livestock management.

1 INTRODUCTION

Multispectral remote sensing is becoming increasingly important for assessing and managing rangeland in many parts of the world. In the Sahelian zone of Africa, particular interest is being shown in the use of satellite imagery as an operational management tool for monitoring the condition of grassland in order to ameliorate the effects of drought by means of improved livestock management. For this aim to be realised, accurate identification and mapping of vegetation communities is an essential first step. In order to calculate grazing capacity, it is then necessary to have the means of making accurate estimates of available biomass in each of the main vegetation types. These estimates must be responsive in real-time (or near real-time) to changes in the distribution of biomass. The types and spatial distribution of soils are also of interest because of their influence on land capability.

Because of the need for rapid response to changing environmental conditions, an operational rangeland monitoring system therefore requires data at high temporal frequencies. For applications at national and regional scales, spatial resolution is less critical. Recently, there has been considerable interest in the potential of the NOAA Advanced Very High Resolution Radiometer (AVHRR) for multi-temporal observation of vegetation patterns, amongst other reasons because of the high repeat frequency of the imagery (Hock, 1985). For example, AVHRR-NDVI images have been used to illustrate spatial and temporal changes in vegetation at regional (eg Tucker, Gatlin and Schneider, 1984, Duggin and Piwinski, 1984) and at continental scales (Justice *et al*, 1985).

However, calibration of imagery from sensors with low spatial resolution presents formidable sampling problems for the collection

of ground data. It is extremely difficult to measure biomass over sample areas large enough to correlate with the coarse spatial resolution of the imagery (1.1km Instantaneous Field of View in the case of AVHRR Local Area Cover (LAC) imagery). Consequently, there are few published examples in which AVHRR imagery has been calibrated to give biomass estimations. This Report describes the use of Landsat-MSS imagery to solve this problem and calibrate AVHRR data against type and amount of vegetation.

Previous studies have adopted a variety of approaches to the use of multispectral satellite imagery for vegetation mapping in arid zones. These include supervised and unsupervised classification methods (e.g. Tucker, Townshend and Goff, 1985) and the use of indices of green vegetation. A variety of indices have been proposed for the quantitative estimation of green biomass from remotely-sensed multispectral data (Jordan, 1969, Pearson and Miller, 1972, Tucker, 1979, Kumar and Monteith, 1982, Curran, 1983). These indices are all highly correlated with the interception by vegetation of photosynthetically-active radiation, and thus, indirectly, with primary production (Perry and Lautenschlager, 1984).

Of the various indices proposed, the Normalized Difference Vegetation Index (equation (1)) is perhaps the one most frequently cited in the literature (eg Tucker *et al*, 1983, Tucker *et al*, 1985 and Justice *et al*, 1985).

$$NDVI = (NIR - R) / (NIR + R) \quad (1)$$

(NIR - Near Infrared,
R - Red)

One of the main attractions of the NDVI is that it is possible to compute the index from multispectral data alone, without the need for any prior knowledge of the vegetation that produced the image. A second factor that has contributed to its popular use is the availability as a standard product from the US National

Oceanographic and Atmospheric Administration (NOAA) of NDVI imagery, in the form of the Global Vegetation Index (GVI).

However, use of the NDVI in conditions of sparse vegetation cover and variable soil background reflectance has disadvantages, since the NDVI is not independent of the substrate, and confusion between thin vegetation and some bare soils can result. This problem is discussed in greater detail later in the context of our own results.

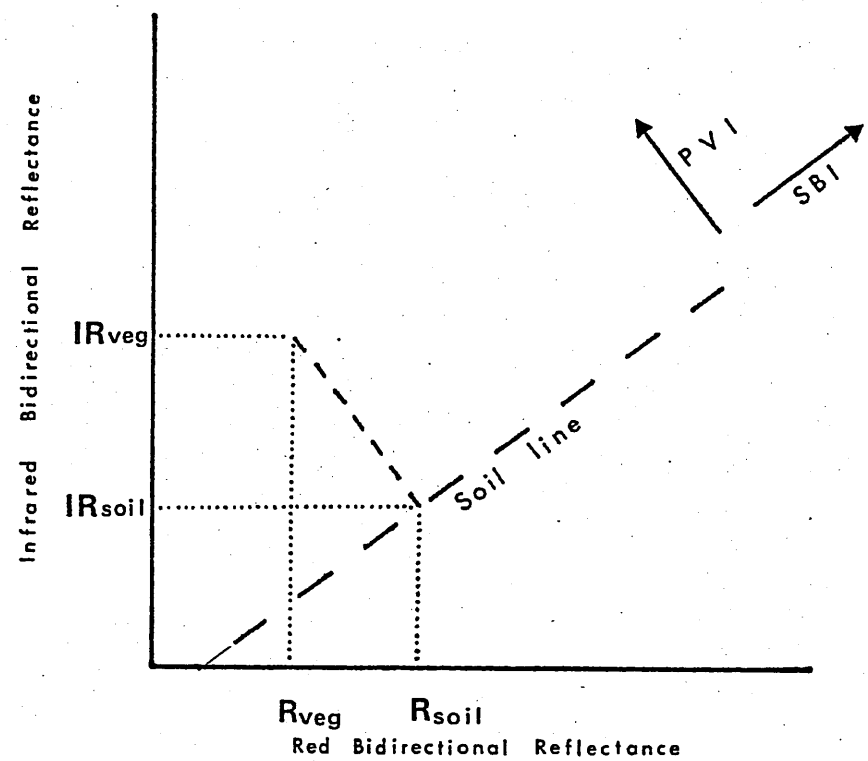
An alternative approach, described in this Report, makes use of the Perpendicular Vegetation Index (PVI), (Richardson and Wiegand, 1977). The PVI depends upon the existence of a strongly linear relationship between the reflectance of bare soils at near infra-red and red wavelengths (the 'Soil Line', Figure 1). The presence of vegetation causes increased absorption of red wavelengths and increased reflection of infra-red radiation. This causes displacement of reflectance values of vegetated surfaces relative to the soil line. The magnitude of this displacement in a direction perpendicular to the soil line has been shown to be correlated to the green leaf area index of the observed vegetation canopy, and can therefore be used as an indirect index of biomass.

In fact, the PVI represents one axis of a transform of the red and near infra-red spectral data (equation (2)).

$$PVI = \frac{(R_{soil} - R_{veg})^2 + (IR_{soil} - IR_{veg})^2}{2} \quad (2)$$

PVI has the advantage over NDVI that it is independent of soil background (soil variation is concentrated in the transform parallel to the soil line), so that it can be used over wide areas and suffers less from confusion in conditions of sparse vegetation. It has the disadvantage of requiring sufficient knowledge of the terrain to be able to identify unvegetated areas in order to compute a soil line.

Figure 1 The 'Soil line' and the Perpendicular Vegetation Index



2 OBJECTIVES

2.1 General Objectives

The overall objectives of this part of the study were twofold:

i) to develop and test methods for the use of multispectral imagery from satellites to estimate the type, extent and condition of rangeland vegetation in the semi-arid regions of West Africa and to monitor changes in these variables.

ii) to apply these methods to map vegetation type and biomass over large areas.

These vegetation maps are intended eventually to form one input into models linking rainfall with rangeland productivity (and thus with carrying capacity). Until these models have been developed and validated, vegetation maps derived from remotely sensed data have considerable potential as a direct means of observing and monitoring arid-zone rangeland.

2.2 Specific Objectives

In realizing these general objectives, the following specific objectives were identified:

i) to develop methods for calibrating remotely-sensed data against ground-based measurements of soil type, vegetation type and biomass.

ii) to investigate alternative methods for estimating biomass from remotely-sensed imagery: in particular, to compare the relative merits of the Normalised Difference Vegetation Index and the Perpendicular Vegetation Index for estimating low levels of green herbaceous biomass.

iii) to carry out a controlled evaluation of the remotely-sensed estimates of soil and vegetation types and of biomass.

iv) to compare the effects of different source imagery upon the performance of these procedures: in particular, to consider the effects of spatial resolution upon areal estimates of soil and vegetation types.

v) to suggest ways in which these procedures could be incorporated into an operational system for routine monitoring of biomass in arid rangeland at national or regional scales, based on the use of remotely-sensed imagery.

3 METHODS

3.1 The Experimental Area

The study was carried out on sites located in semi-arid pastoral regions of the Republic of Niger in West Africa. The precise location of test sites was determined by:

(i) the geographical location within Niger of rangelands threatened by drought;

(ii) the location of meteorological stations within the TAMSAT network established jointly by the Department of Meteorology of Reading University and the Agrhymet Centre in Niamey (see Appendix I of this Report).

(iii) the availability of Landsat MSS imagery of suitable quality;

(iv) considerations of logistics and ease of communication when planning field visits.

Observations were made along six traverses (Figure 2):

Birni-Nkonni - Tahoua	140km
Tahoua - Keita	70km
Tahoua - Tilemses	110km
Tahoua - Kao	109km
Kao - Tchir Tabaraden - Tassara	166km
Tahoua - Abalak - Agadez	260km

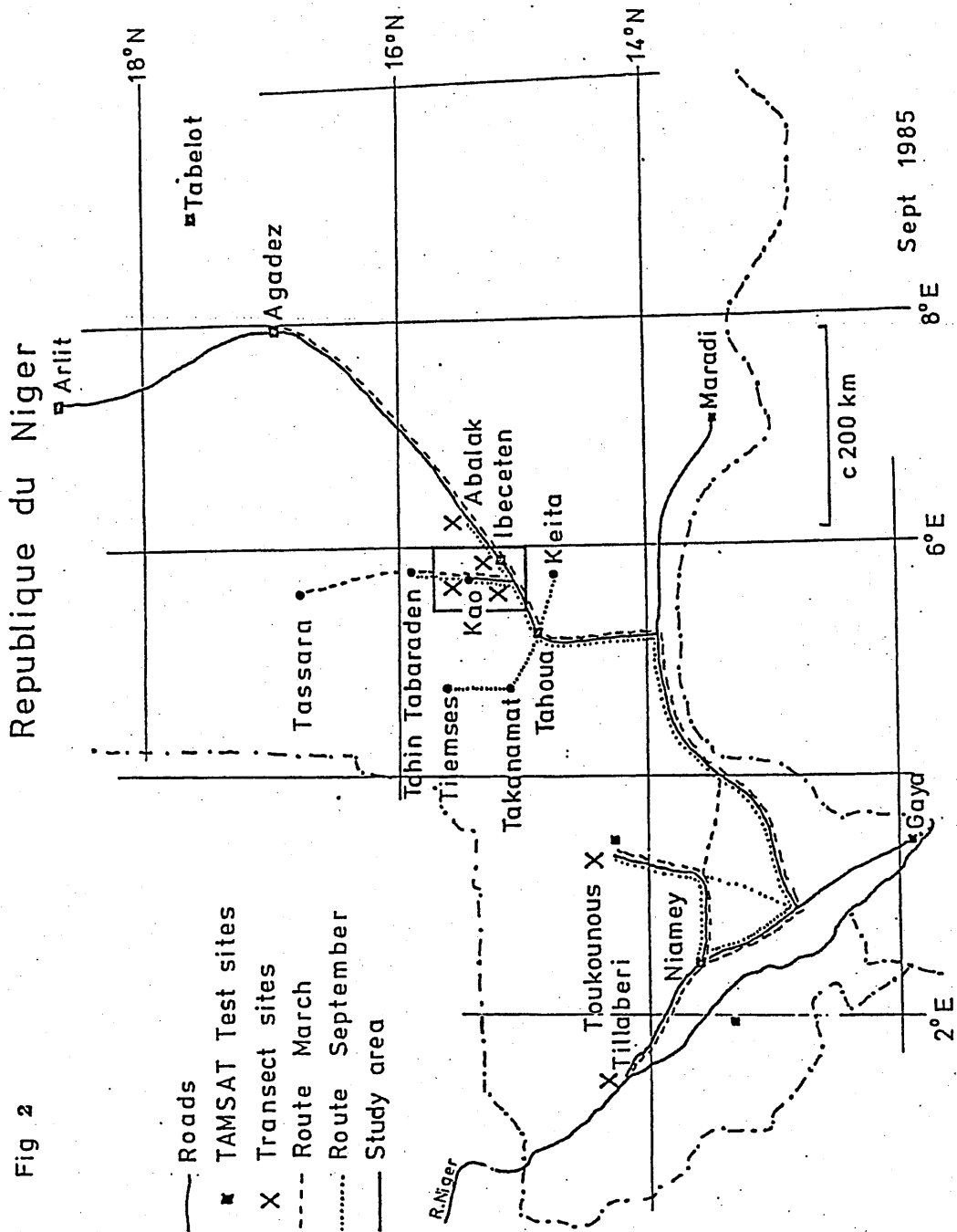
The greatest range of cover types was observed near Kao and a site approximately 25km x 25km, corresponding to a 512x512 pixel Landsat MSS subscene was chosen for detailed study (see Figure 2). This area included part of the State ranch at Ibecetene, where a high-density network of rain gauges and soil moisture probes had been located by the TAMSAT team in order to investigate spatial variability in rainfall distribution. The locality therefore offered scope for detailed study of the relationships between rainfall, soil, vegetation and remotely-sensed radiance.

3.2 Ground Survey

An exploratory visit was made to the area in October, 1984 at the end of the wet season. Subsequently, further field visits were made in March-April and August-September, 1985 to collect ground data during the dry and wet seasons respectively. The ground survey programme comprised four phases.

Firstly, a synoptic survey was undertaken along the above traverses to determine the predominant ground cover types throughout the region and to select a representative study area for more detailed investigation.

Secondly, within the Kao study area (Figure 2), measurement sites were established which could be located on Landsat MSS imagery. At these sites, transects were established and



surveyed in detail to establish the composition and amount of vegetation present and to characterise soil-vegetation spectral relationships.

Thirdly, a stratified ground sampling framework was designed on the basis of a preliminary classification of Landsat-MSS imagery and guided by the results of the first field visit. A further set of transects was chosen, representative of each of the main cover types identified in the images and encountered on the ground and a further survey of soils and vegetation was carried out along each of the new transects.

The main purposes of this second transect survey were:

- i) to evaluate the results of the initial image classification;
- ii) to provide detailed ground data (biomass measurements and records of ground cover) in each of the main land cover classes for use in the subsequent image analysis and interpretation..
- iii) to ensure that, in subsequent studies of the correlation of measured biomass with vegetation indices, vegetation samples were adequately stratified and the widest possible range of vegetation densities were considered.

Finally, a grid of experimental plots was established for the purpose of sampling biomass. This grid was set up adjacent to the TAMSAT network of rain gauges at Ibecetene. This sampling grid was primarily intended to provide a database common to the botanical and meteorological components of the collaborative programme but also formed a useful additional source of field data against which to evaluate our estimates of biomass.

Colour composite prints of geometrically-corrected Landsat MSS images were used in the field for purposes of orientation during the synoptic survey and to assist in the selection of relocatable sites for detailed study. A photographic record was made of the main land cover types encountered, using 35mm colour film.

Measurements of soil and canopy reflectance, soil and vegetation type and biomass were taken along the linear sampling transects. As indicated above, these transects were chosen to provide a stratified sampling framework, representative of each of the main land cover classes identified in a supervised classification of a Landsat MSS image and confirmed during the first (dry season) field visit. The location of the transects is indicated in Figure 2.

Transects were 1km long and measurements were taken at 100m intervals. The following observations and measurements were taken:

- (i) records of the herbaceous vegetation within a 2m x 2m quadrat;
- (ii) a physical sample of vegetation clipped from an area 50cm x 50cm in the centre of this quadrat for estimation of biomass; these samples were later oven-dried to constant weight;
- (iii) soil smears, taken from each 4 sq m quadrat;
- (iv) a visual estimate of the proportion of the surface of the quadrat in a number of soil particle size classes;

(v) a visual count of the number and size of trees and shrubs in 100m x 100m quadrats along the transect;

(vi) measurements of stem diameter for a representative subsample of trees and shrubs in each quadrat, as a means of interpolating the biomass of trees and shrubs from correlations between stem diameter and green biomass (Cisse, 1980).

Soil and canopy reflectance was measured using a Spectrascan MPS1000 portable seven-band radiometer, measuring in the range 0.4 - 2.35 μ m. Subsequent analysis of field radiometer data concentrated on the four wavebands of Landsat MSS.

3.3 Imagery

The Landsat-5 scene covering our experimental area is Path 191, Row 049. We chose three largely cloud-free scenes, imaged on 7th October, 1984, 11th May, 1985 and 31st August, 1985 (Plate 1). The October and August images followed the wet season and show the widespread presence of healthy vegetation. (This is particularly true in the case of the August, 1985 image). The May image follows the dry season and, apart from the absence of green vegetation, there is evidence of considerable atmospheric turbidity, probably because of recent dust storms.

Landsat MSS, Landsat TM and SPOT imagery are inappropriate for routine operational use for rangeland monitoring in the Sahel because of:

- (i) the high cost of the imagery;
- (ii) the volume of data needed to cover the large geographical units concerned and the consequent difficulties and expense of data processing;
- (iii) the inadequate frequency of cloud-free imagery; (this restriction is most serious in the case of the 16-day return cycle of Landsats-4 and 5).

AVHRR imagery, from the NOAA series of satellites, has many attractions for vegetation monitoring applications at regional scales. Because of the daily overpass of AVHRR, it is possible to generate frequent (ca. monthly) cloud-free imagery of most regions from a mosaic of cloud-free pixels taken from successive images.

Global Area Cover (GAC) data at 5km x 3km resolution have been used in this way to monitor vegetation at continental scales (eg Justice *et al*, 1985); Local Area Cover (LAC) data at 1.1km resolution have also been considered, although their use is less widely reported in the literature. LAC data appear particularly suited to applications at national and regional scales since a two-band 512x512 pixel LAC image covering an area ca. 500km square could be readily processed using low-cost image-analysis systems. However, the design of ground sampling programmes to calibrate imagery at LAC resolution (eg for biomass estimation) presents intractable problems because of the high variability of vegetation cover within an area covered by a single LAC pixel.

Our approach to these difficulties has been to simulate AVHRR radiometrically from Landsat MSS imagery, while retaining the geometric properties of the MSS imagery. We were able to use this simulated 'high resolution' AVHRR imagery for calibration purposes since, at MSS resolution the experimental transects could be reliably identified in the images. Having used the 'high resolution' AVHRR data to establish basic correlations, for example between biomass and computed vegetation indices, it is proposed to further degrade the imagery to LAC resolution and to use the simulated LAC image as a template for geometric registration of 'real' LAC data in order to identify precisely the LAC pixels corresponding to ground sites and thus to calibrate the AVHRR imagery directly.

Table 1 records the key spectral characteristics of MSS and AVHRR. AVHRR channels 1 and 2 are the most significant bands for vegetation discrimination. MSS bands 3 and 4 straddle the spectral range of the AVHRR infrared channel (band 2). AVHRR band 1 has a spectral range which is similar (but not identical) to MSS band 2. We chose to simulate AVHRR spectral bands from MSS by taking MSS band 2 unchanged and adding a composite channel computed by taking the pixelwise mean of MSS bands 3 and 4.

LAC imagery was simulated by creating a new image with pixel values equal to the mean values of blocks of MSS data 18 pixels by 14 lines in each of the two simulated 'AVHRR' spectral channels.

Table 1 Spectral characteristics of the Landsats 4 and 5 MSS and the AVHRR of NOAA-7.

<u>Spectral Band</u>	<u>NOAA-7/AVHRR</u>	<u>Landsat 4 and 5 MSS</u>
Green	-	Band 1 - 0.50-0.60 μ m
Red	Band 1 - 0.58-0.68 μ m	Band 2 - 0.60-0.70 μ m
Near Infra-red	-	Band 3 - 0.70-0.80 μ m
	Band 2 - 0.725-1.1 μ m	-
Mid Infra-red	-	Band 4 - 0.80-1.10 μ m
	Band 3 - 3.55-3.93 μ m	-
	Band 4 - 10.3-11.3 μ m	-
Thermal Infra-red	Band 5 - 11.5-12.5 μ m	-

3.4 Image Analysis

Image analysis was carried out on the GEMS Image Processing System of the UK National Remote Sensing Centre (NRSC) Regional Centre in Silsoe College and on an I²S Model 75 Image Analysis System at the Natural Environment Research Council (NERC) Remote Sensing Applications Centre in the Institute of Terrestrial Ecology (ITE).

MSS imagery was registered with maps at a scale of 1:200 000 using a nearest-neighbour interpolation to generate an image with 50m x 50m pixels. All imagery was radiometrically adjusted to a uniform sun azimuth of 40° using a simple cosine transformation in order to minimise the effects of different levels of irradiance.

Supervised classifications were performed by applying maximum-likelihood algorithms to all 4 MSS channels after implementing the above geometric and radiometric corrections.

In our analyses, both NDVI and PVI were computed from 'AVHRR' data simulated from MSS imagery as follows:

$$R = \text{MSS-2} \quad (3)$$

$$\text{NIR} = (\text{MSS-3} + \text{MSS-4})/2 \quad (4)$$

In computing PVI, bare soil radiance was measured by sampling individual pixels in a colour composite image and the results were plotted in NIR/Red feature space (Figure 4). The equation of the resultant 'soil line' was determined by linear regression (Equation 5).

PVI images were generated by rotation of the axes in NIR/Red feature space, given by equation 6.

The transform parallel to the soil line is called the Soil Brightness Index (equation 7) and is indicative of the nature of the substrate (soil type and moisture)

4 RESULTS

4.1 Identification of Broad Land Cover Classes

Following the first (dry season) field visit, the eleven broad land cover classes listed in Table 2 were distinguished. The main soil types consist of laterite in easily identifiable outcrops with associated outwash deposits which vary in composition from laterite gravels near these outcrops, progressing through various mixtures of clay outwash with laterite gravels to clay outwash furthest from the outcrop. Clay deposits also occur elsewhere in depressions and in intermittent stream channels. This leads us to suspect the presence of clay underlying most of the sandy soils which cover by far the greatest area and seem to have their origin in dunes formed in earlier periods when the boundary of the Sahara was further south.

Table 2 Land cover classes identified in the Republic of Niger, 1984-1985.

<u>RARE SOIL</u>	<u>VEGETATED SURFACES</u>	<u>OTHER</u>
1 Laterite	5 Dense thorn bush, Interdunal and depressional vegetation.	10 Surface water
2 Clay pan, surficial laterite gravels	6 Thorn bush on lateritic sand	
3 Clay outwash	7 Bush (1) - medium density	
4 Sand	8 Bush (2) - low density	Pasture- land classes
	9 Bush (3) - very low density	

The difference in elevation between crests and valleys is generally between 30 to 70 m. Observable increases in the density of vegetation adjacent to streambeds, in depressions and along scarp edges point to the importance of increased moisture supply from concentration of surface and subsurface water flow. These vegetation communities, which consisted of a mixture of thorn species with some *Calotropis procera*, were clearly identifiable on the Landsat MSS imagery. At exceptional locations, such as at Kao itself, surface water was present often covered by considerable quantities of aquatic vegetation.

When the bush occurred on sand containing some lateritic gravel, it had a different appearance on the image and was considered a separate class.

The preceding vegetation communities all occurred in localized areas, as described, and cover a low percentage of the total study area. Much more ubiquitous are the areas of open bush on sandy substrates that form the basic resource for stock rearing in Niger, whether by traditional nomadic methods or in more intensively-managed ranches. The ground cover in these rangeland areas is a mosaic of low and variable density scrub in which grasses (mainly *Cenchrus biflorus*) appear during the wet season.

Scrub density appears to vary with relief, and some basins can support quite thick bush. Three scrub classes were tentatively identified in the field with the help of photographic copies of Landsat colour composite images. The main differences between these scrub classes appeared to be caused by variation in the underlying soil or in the density of the scrub canopy.

A supervised classification was performed on the Landsat MSS image from October, 1984 using a maximum likelihood classifier followed by median filtration to remove noise. The resulting classified image is reproduced as Plate 2. The main purpose in carrying out this classification was to assist in the stratification of subsequent field sampling.

The confusion matrix for the classification of the training areas is shown in Table 3. The values are percentages of the training area classified and magnitudes less than or equal to two percent are not included.

The training areas were more than 70% correctly classified with the exception of class 7 ('Thin Bush') which was highly confused with class 6 ('Bush on Sand/Laterite'). Most sources of confusion could be explained as resulting from subtle transitions between related classes. Aquatic vegetation was the cause of confusion of open water with dense bush. The confusion of laterite and water is an exception, having no obvious explanation other than chance similarity of spectral properties. Only classes 4 ('Sand') and 5 ('Dense Bush') had significant numbers of unclassified pixels.

Time in the field was severely restricted and it was not possible to undertake a rigorous quantitative evaluation of the results of the classification. Nevertheless, while driving the traverses in the course of the synoptic programme of surveillance, it was possible to make a subjective assessment of the overall performance of the classification. Furthermore, biomass sampling transects were established in each of the land cover classes, giving opportunity for detailed assessment of the composition and homogeneity of each class on the ground (see, for example, Plate 3).

TABLE 3 - CONFUSION MATRIX SHOWING CLASSIFICATION PERFORMANCE IN THE TRAINING AREAS

Spectral Cover class		1	2	3	4	5	6	7	8	9	10	U
Lat	1	89									7	
Cl/lat	2				3							
Cl/o.w.	3			88					10			
Sand	4				85						4	8
D. bush	5					79					12	5
Bu/lat.sa.	6		4			4	81 6 41 53					
Scrub 1	7								4			
Scrub 2	8			10				79 7 16 73				
Scrub 3	9						10					
Water	10	5				14					77	
% Area		2.3	2.7	3.5	16.1	4.1	19.2	7.2	19.5	16.1	0.1	8.4

Pastureland
Classes

On a synoptic scale, the classification appears to be very good and location of specific ground sites from photographic prints of the classification was possible. The Open Water, Clay, Clay/Laterite, Bush on Sand/Laterite, and the Medium to Thin Bush categories all appear to show unique characteristics and good class uniformity.

In the case of the remaining classes (Laterite, Bare sand and Dense Bush), the results reported in Table 3 were largely confirmed. In most cases, problems of confusion resulted from high levels of spatial variability in the ground cover which presented difficulties when selecting sites for the experimental transects.

Laterite areas are irregularly cut by gullies, where the underlying clay is exposed and alternates with the laterite surface. Thin patches of vegetation are often associated with these gullies. The high-frequency variability in surface cover within this class is apparent in the classified image.

After the 1985 rains, areas classified as 'Bare Sand' in the October, 1984 wet season image were found to support variable amounts of grass, though there are also large expanses of bare sand, particularly on the dune tops. This evidence suggests that these differences are almost certainly not the result of mis-classification of the 1984 image, but rather reflect a real increase in green vegetation between the very dry 1984 growing season and 1985, when the rainfall was closer to the long-term average for the region.

Although the 'Dense Bush' category is, in general, well-defined and homogeneous, there is confusion with aquatic vegetation growing on the surface of standing water. This is a localized problem which may affect biomass estimates in certain areas.

4.2 Vegetation Indices

Two vegetation indices have been investigated as a means of estimating biomass from remotely-sensed data. The Normalized Difference Vegetation Index (NDVI) - Equation (1) has been shown to be highly correlated with green-leaf area and thus (at least in situations of low vegetation cover) with green-leaf biomass. The Perpendicular Vegetation Index (PVI) - Equation (2) is similarly correlated, but has received less attention, perhaps because of the need for ground data in order to derive the PVI.

In both cases, the vegetation indices were computed from the 2-channel AVHRR imagery produced by radiometrically degrading MSS imagery as described in paragraph 3.3. The NDVI can be calculated directly by pixelwise application of equation (1) to the source image.

In order to apply the PVI, it is first necessary to demonstrate and evaluate the linear correlation between near infrared and red radiance for unvegetated surfaces (the 'soil line'). The results presented in Figure 3 show soil lines for the Kao study area determined (a) from field radiometer measurements and (b) from the simulated AVHRR imagery at MSS spatial resolution, using the values of individual pixels from areas of bare soil. Figure 3 (c) shows a similar soil line computed from simulated LAC-resolution data, where pixels corresponding to bare soil areas were located by reference to the source MSS image. The strength of the linear correlation between NIR and red radiance for bare soils is confirmed in every case. All lines were similar in showing a negative intercept. The reduced spatial resolution of the simulated LAC data compared to MSS had remarkably little effect on the equation of the soil line. Not surprisingly, the equation of the soil line determined from field radiometry differed significantly from those derived from satellite data.

Figure 3. Soil Lines derived from a) Field Radiometer, b) Landsat MSS and c) Simulated AVHRR LAC.

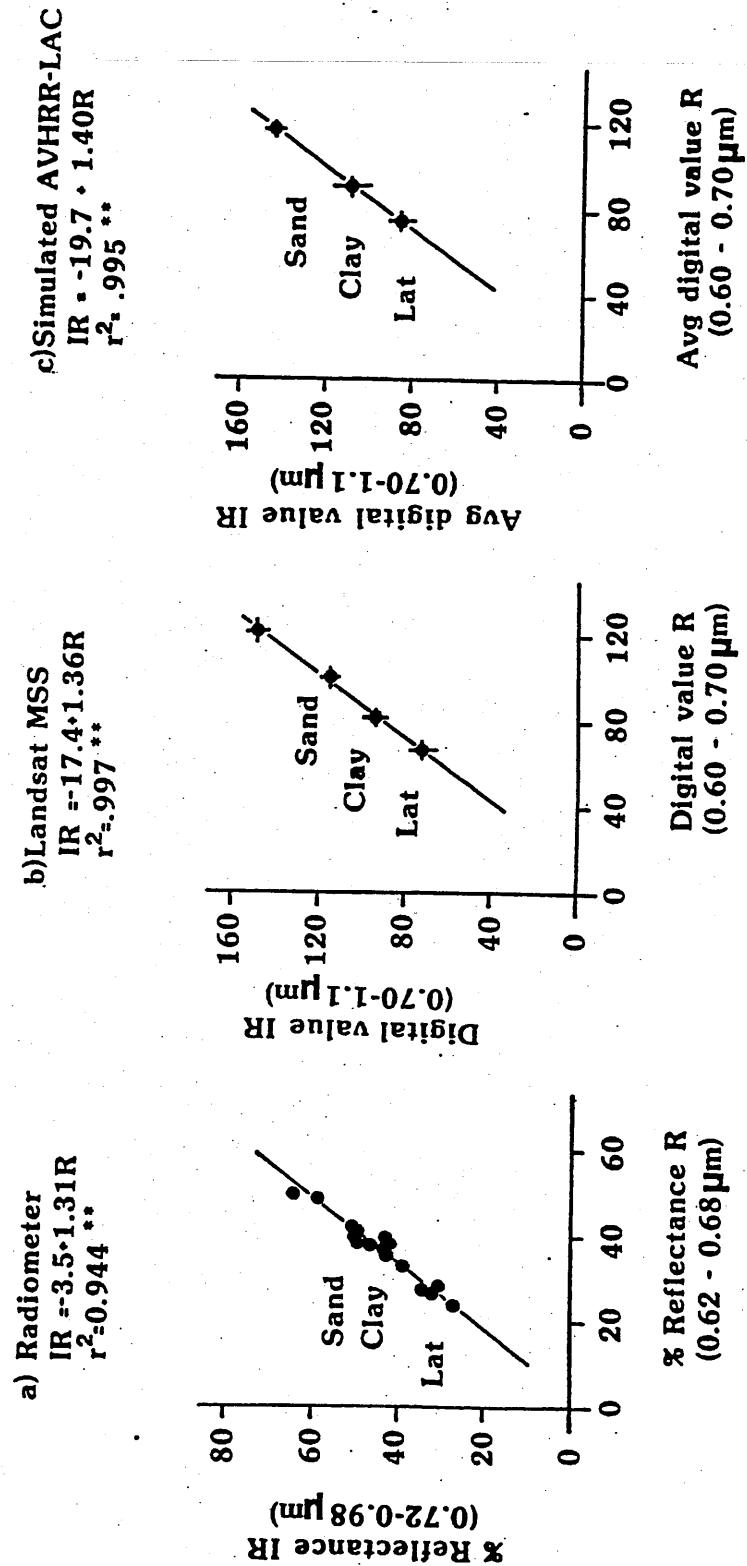


Figure 4 shows the radiance of vegetation in NIR-red feature space in relation to the soil line. Values of the PVI are indicated. Figure 4 (a) records field radiometer radiance values of individual plants and small areas of composite plant canopies. The scattergrams show a consistent pattern, with PVI increasing according to the degree of vegetation cover and the level of photosynthetic activity (inferred from the presence of green leaves). Figure 4 (b) shows digital values for simulated AVHRR NIR and red channels at MSS spatial resolution, extracted from training areas representing the biomass sampling transects in the vegetated land classes in Table 2. Once again, the trend is for an increase in PVI with increasing green vegetation.

Table 4 presents a comparison of mean NDVI and PVI values for the 10 cover classes of Table 2. These results demonstrate the limitations of the NDVI when it is used to characterize sparse vegetation growing on variable substrates. The training set on bare sand has a mean NDVI higher than corresponding values for three of our vegetated categories. The confusion of scrub categories with highly reflective bare soils is avoided when the PVI is used. This confirms the conclusion of Elvidge and Lyon (1985) that the PVI is the most appropriate index for vegetation mapping and biomass estimation in arid and semi-arid regions.

Figure 4. Perpendicular Vegetation Index from a) Field Radiometer readings and b) Landsat MSS.

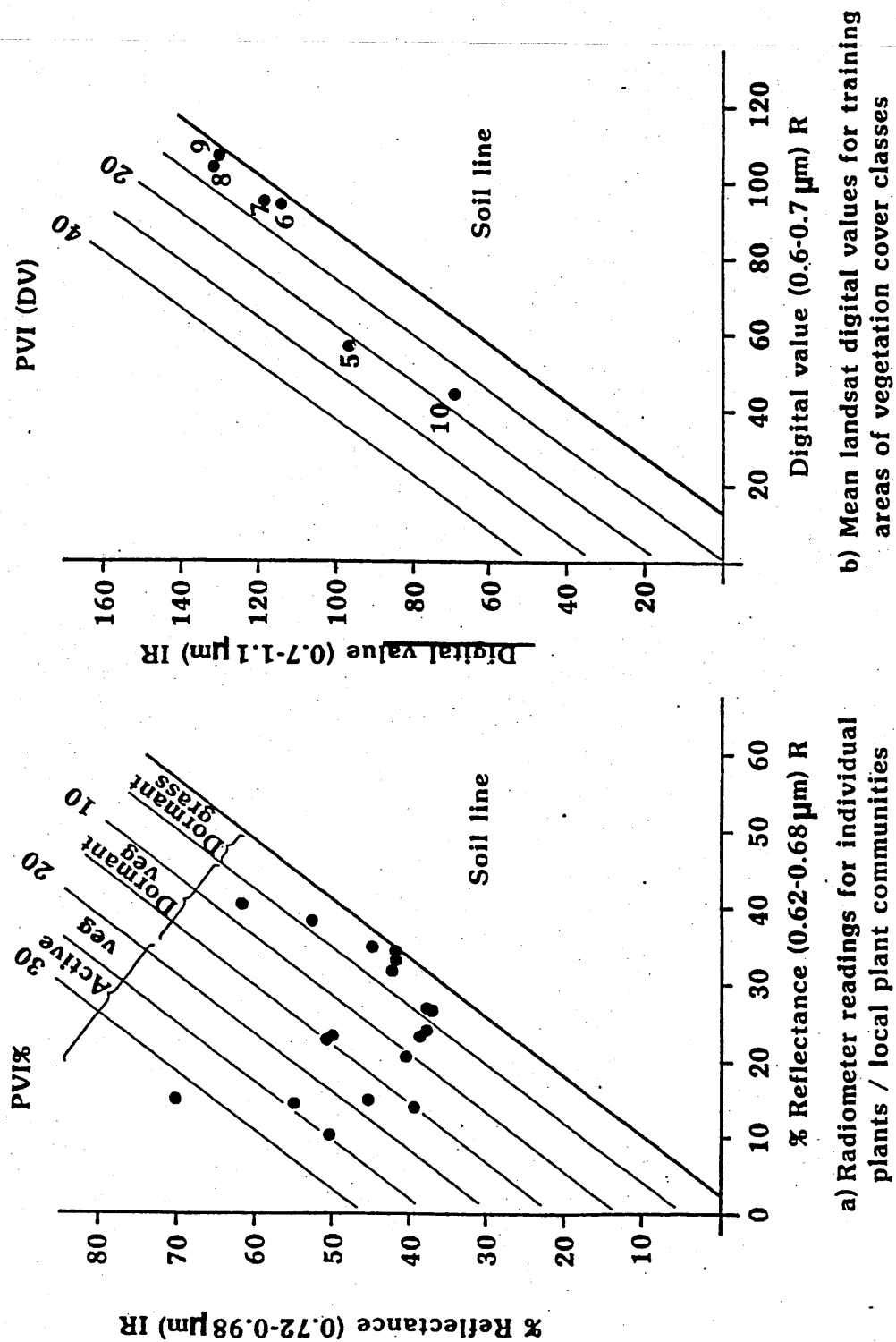


Table 4 Comparison of mean values of Normalized Difference Index (NDVI) and Perpendicular Vegetation Index (PVI) for cover classes identified within the Kao study area.

COVER CLASS	#	NDVI	PVI (Digital Value)
LATERITE	1	0.049	0.2
CLAY/LATERITE	2	0.072	0.4
CLAY OUTWASH	3	0.073	-1.7
SAND	4	0.102	0.7
DENSE BUSH	5	0.260	21.9
BUSH ON LATERITE SAND	6	0.098	2.4
MEDIUM BUSH	7	0.112	4.2
THIN BUSH	8	0.095	1.1
VERY THIN BUSH	9	0.099	1.5
WATER	10	0.228	16.3

4.3 Biomass Estimation

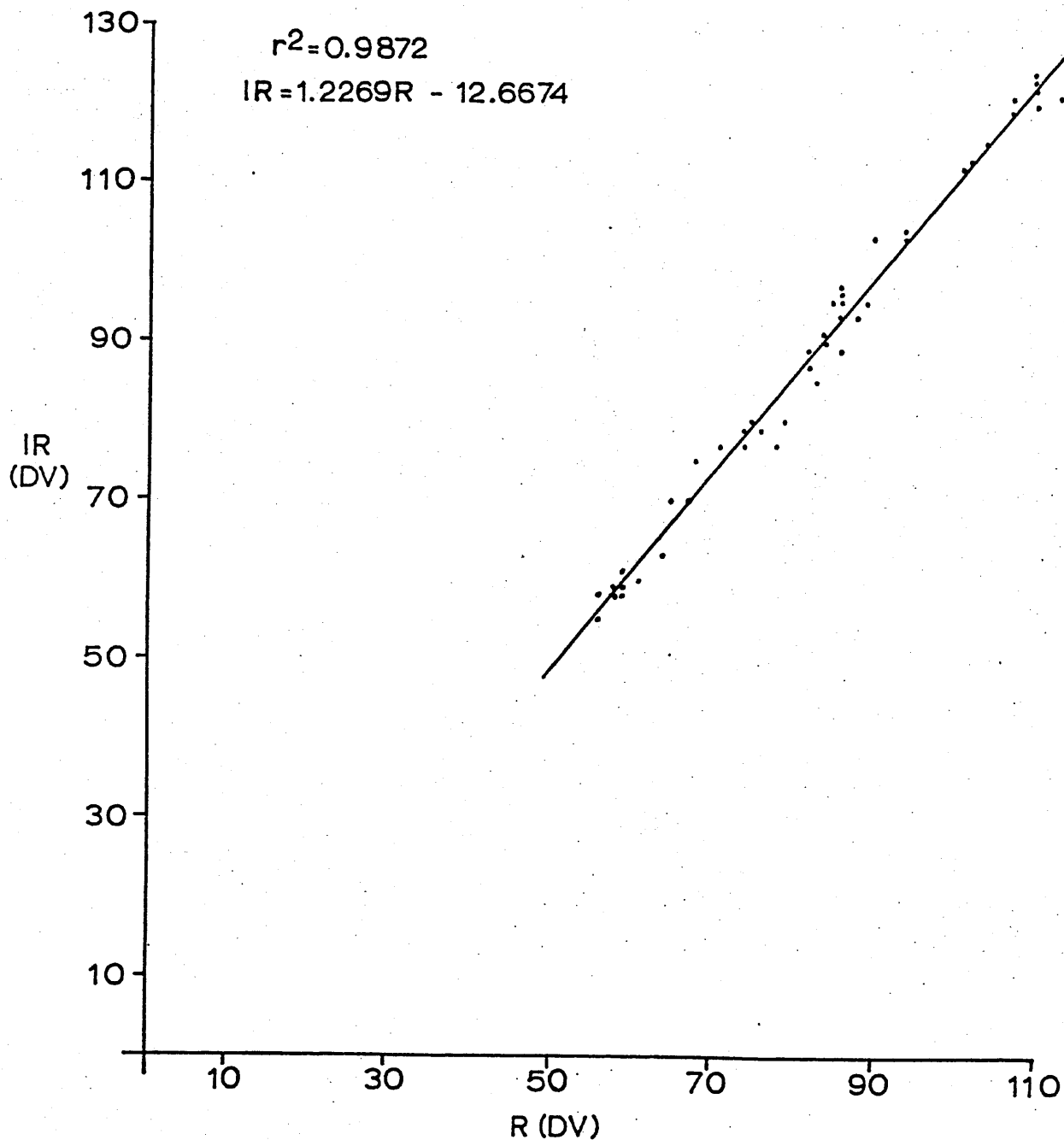
Having demonstrated the validity of the soil line under the field conditions experienced in Niger, using both field radiometry and Landsat-MSS imagery, the next step in developing a procedure for biomass estimation from remotely-sensed imagery was to calibrate the imagery by correlating the chosen vegetation index (NDVI or PVI) against measured biomass.

The procedures adopted for sampling and measuring biomass were described in Section 3.2. We were fortunate in receiving a high-quality Landsat MSS image contemporary with our second programme of field observations at the end of August, 1985. It was therefore possible to calibrate vegetation indices derived from this image directly against our field data.

As before, the source image was first corrected to a standard sun azimuth of 40°. Red and Near-infrared bands equivalent to AVHRR bands 1 and 2 were generated according to the procedures described in Section 3.4. NDVI was computed directly from this image by applying the transform in equation (1). In the case of the PVI, it was necessary to derive a second set of transforms corresponding to a new soil line, consistent with the irradiance conditions and sensor characteristics of the new image.

50 pixels were chosen at random, corresponding to a wide range of bare surfaces, covering the soil categories identified in Table 2. The digital value of each pixel in the two wave bands was extracted and plotted (Figure 5).

Figure 5. Soil Line derived from sun angle corrected simulated AVHRR LAC data, August 1985.



The equation of this line, determined by linear regression, is;

$$IR = 1.2269R - 12.6674 \quad (5)$$

$$r^2 = 0.9872$$

$$n = 50$$

$$\text{Standard error of estimate} = 2.466$$

The PVI and the SBI were derived from the soil line by simple transformations involving rotation of the axes, as follows:

$$PVI = -(R-R_0)\sin \alpha + (IR-IR_0)\cos \alpha \quad (6)$$

$$SBI = (R-R_0)\cos \alpha + (IR-IR_0)\sin \alpha \quad (7)$$

(R_0 is the digital value in the Red band at the Infrared intercept; IR_0 is the digital value in the Infrared band at the Red intercept; α is the slope of the soil line).

Applying values of R_0 , IR_0 and α from the soil line (5), the PVI transform, equation (8), and the SBI transform, equation (9), resulted.

$$PVI = 8.003 - 0.7751R + 0.6318IR \quad (8)$$

$$\text{Standard error} = 1.55$$

$$SBI = -6.523 + 0.6318R + 0.7751IR \quad (9)$$

The standard error in the PVI was estimated by applying the PVI transformation to the standard error computed during the regression of IR_{soil} on R_{soil} .

Using transforms (8) and (9), pixel values in the digital image were re-coded in terms of the PVI (displacement perpendicular to the soil line) and SBI (displacement parallel to the soil line). These transforms were applied to simulated AVHRR visible and near infrared wavebands at both MSS and LAC resolution.

4.3.1 Calibration

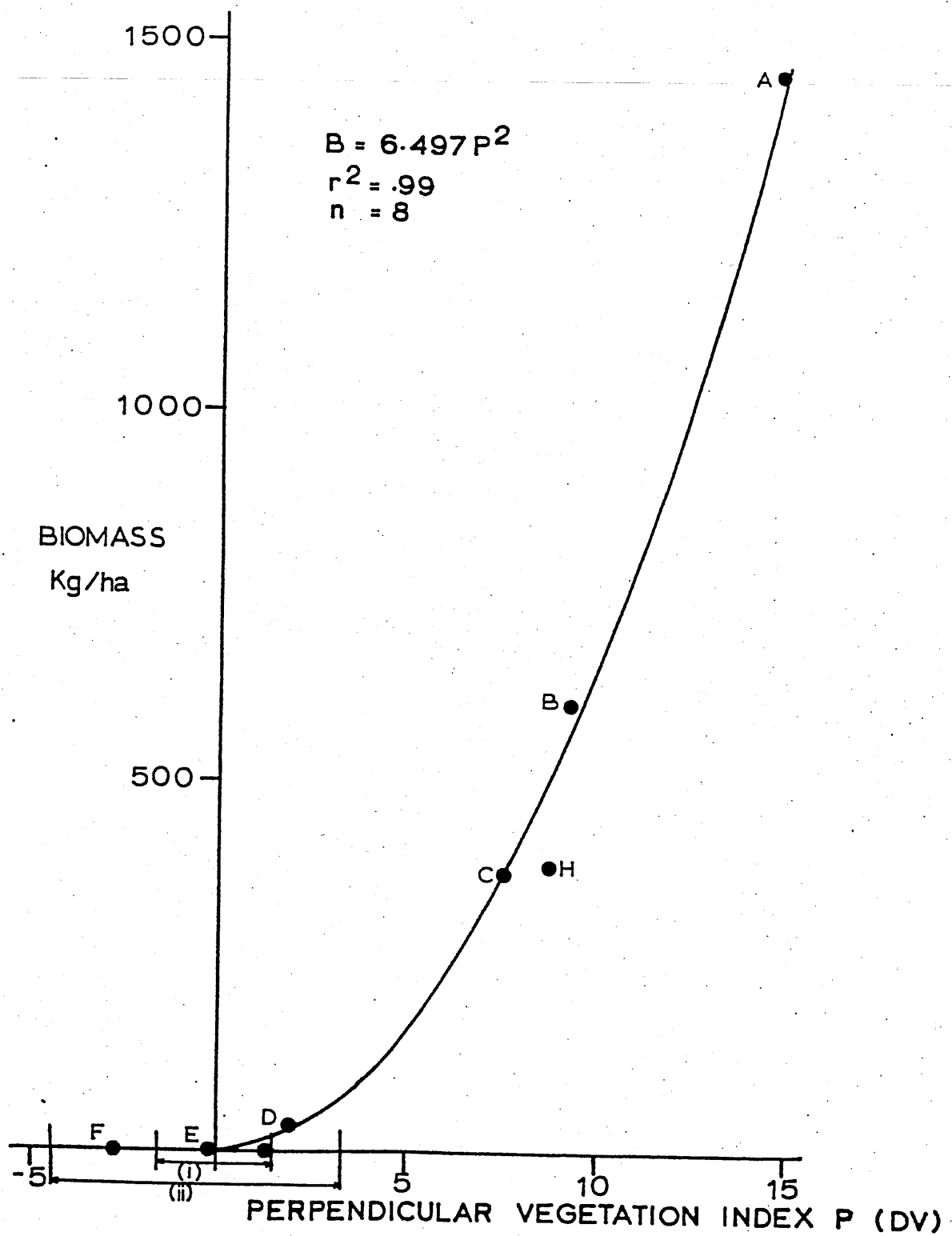
Each of our experimental field transects was located in the MSS imagery and training sets were delineated comprising those pixels which covered the transects. This was possible because the transects had been chosen with ease of location in the image as a major criterion. The task of relocation was simplified with the help of comprehensive colour photography of each transect, which made it possible to identify and locate salient points.

These training sets were then applied to the NDVI and to the PVI transforms of the simulated AVHRR wavebands in order to extract mean values of NDVI and PVI for each transect. Table 5 records mean values of PVI, NDVI and measured biomass for each of the experimental transects. PVI and NDVI are plotted against measured biomass in Figures 6 and 7 respectively.

Table 5 Measured Biomass, PVI and NDVI at Kao, 2-6 September, 1985

Site	Herbaceous Biomass (kg ha ⁻¹)	PVI (DV)	NDVI	Description
A	1452	14.84	0.1577	On sand with thin bush South of Kao turn
B	604	9.26	0.1113	On sand with medium-thin bush
C	374	7.55	0.0985	On sand at Ibecetene Ranch
D	38	1.88	0.0546	On laterite-sand with bush
E	0	-0.20	0.0074	On laterite North of Kao village
F	0	-2.73	0.0075	On clay South of Kao village. (Possibly wet at time of satellite overpass)
G	0	1.28	0.0387	On clay/laterite South of Kao village.
H	383	8.73	0.1070	On sand South of Kao village

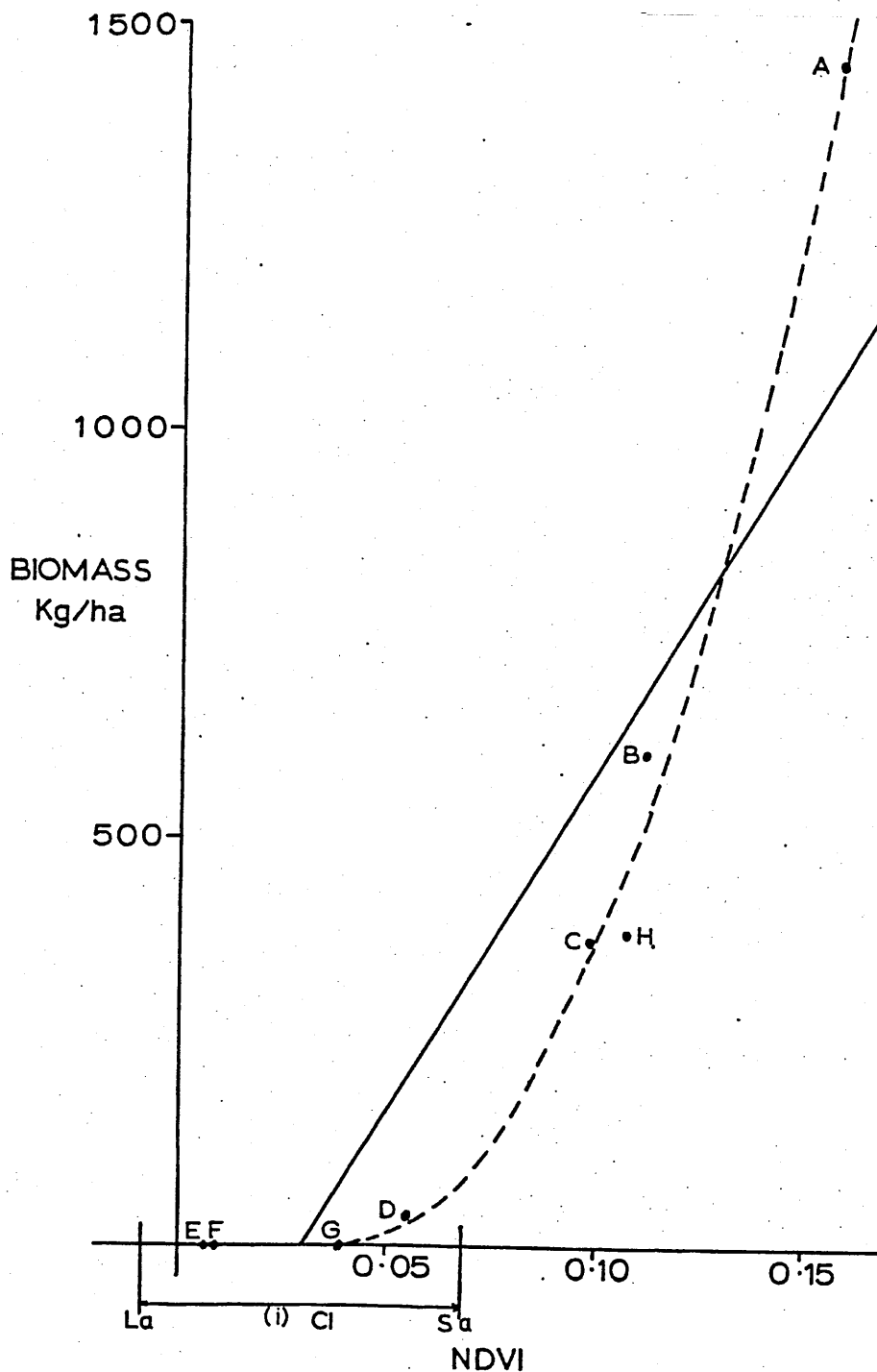
Figure 6. Calibration curve for prediction of dry grass biomass from the Perpendicular Vegetation Index.



(i) = One standard error either side of the mean PVI for soil.

(ii) = Observed range of PVI values for bare soil pixels.

Figure 7. Calibration curve for prediction of dry grass biomass from the Normalised Difference Vegetation Index.



(i) = Range of NDVI values observed in 50 bare soil pixels. There is no central tendency to this range and the position is related to the soil types as shown. (La = Laterite, Cl = Clay and Sa = Sands).

In the case of the PVI calibration, the most satisfactory correlation was obtained from a second order regression:

$$\text{Biomass} = 6.497 \text{ PVI}^2 \quad (10)$$

$$r^2 = 0.994$$

$$n = 8$$

Unvegetated transects (measured biomass = 0) exhibit values of PVI which range across approximately ± 1.5 standard deviations from the mean PVI for soil (see Figure 6). Indeed, PVI values computed for the bare soil areas used to generate the soil line ranged from -4.4 to +3.3, a spread of >4 standard deviations. However, by definition, the PVI at zero biomass is also zero, so, in the case of PVI, the regression line must pass through the origin.

Bare soil NDVI values exhibit a similar spread. NDVI values for the 50 training pixels used to compute the soil line ranged from -0.009 to + 0.067. (NB the total range of NDVI is smaller than the range in observed values of PVI by a factor of 10). NDVI is not independent of soil type, so that there is uncertainty concerning the value of the zero-biomass intercept. In fact, at low biomass values, there should probably be a family of curves corresponding to the range of observed soil types. At high values of biomass, these would converge as the soil background plays a decreasing role in determining spectral response. Since we had inadequate data to permit separate biomass correlations on the different substrates, we were forced to adopt an empirical approach.

Figure 7 records two calibration curves. The first (the solid line) was derived from a linear regression, using all the available data points (equation 11).

$$\text{Biomass} = -240.48 + 8194.36 \text{ NDVI} \quad (11)$$

$$r^2 = 0.791$$

$$n = 8$$

The majority of data points with measurable biomass occurred on lighter soils (sands and clays). It is therefore probable that the bare laterite (point E) is anomalous so far as this calibration is concerned. Similarly, point F, on a clay surface may well have been wet at the time of imaging; this would account for the exceptionally low values observed in both PVI and NDVI for this point.

A second regression of biomass on NDVI was therefore performed, omitting these two anomalous values (see Figure 7, broken line). In this case, as with the PVI correlation, a second-order fit gave the best results (equation 12).

$$\text{Biomass} = 180.15 - 8568.84 \text{ NDVI}^2 \quad (12)$$

$$r^2 = 0.991$$

$$n = 6$$

$$\text{Valid for } 0.04 < \text{NDVI} < 0.16$$

4.3.2 PVI and Soil Images

Transform (8) can be applied on a pixel-by-pixel basis across the entire image. (It may be necessary to increment every pixel by an arbitrary constant in order to avoid negative digital values). The resulting single-band image then records the spatial distribution of values of PVI.

Since we have calibrated PVI against measured biomass, it is possible to use the technique of 'density slicing' to

generate a map of biomass from the PVI image by specifying the slice limits in PVI to correspond with the required class intervals in terms of biomass. Plate 4 is such a map of biomass, derived from the August, 1985 image and covering the Kao study area. A similar map could, of course, be generated via the NDVI.

In Section 3.4, it was pointed out that a transform of red-infrared feature space parallel to the soil line has the effect of concentrating spectral variation due to soil background. This transform, the Soil Brightness Index, is thus indicative of substrate type, independent of vegetative cover.

If transform (9) is applied to the 2-channel (red, near infrared) source image on a pixel-by-pixel basis, a single-band image results with digital values indicative of soil type. Highly reflective soils such as sands exhibit large values of SBI; darker soils, such as clays and lateritic soils take much lower values of SBI.

This image can be processed in a similar way to the PVI image in order to generate a map of soil type (see Plate 5). However, unlike the vegetation map, there is no simple means of calibrating SBI against soil type, so that the slice limits must be arbitrary. Our knowledge of the Kao test area enabled us to assign slice limits interactively in such a way that known soil boundaries were reproduced.

For the technique to be widely useful, it must be possible to define slice limits on the basis of a known test area and to subsequently apply the same slice limits to other areas and to imagery acquired on other occasions.

An investigation of the stability of these slice limits was carried out by computing SBI for the same Kao test area using the October, 1984 and the August, 1985 images.

Initially, it appeared that there was little stability and that slice limits chosen from one image gave very different results when applied to the second image.

Histogram normalization was applied to both SBI images, so as to ensure that the distribution of pixels across the range of values of SBI in the two images was comparable. When these normalized SBI images were density sliced and compared, it was apparent that a single set of slice limits could be applied to both images and that the results were virtually indistinguishable.

4.3.3 Evaluation of Biomass Calibration

Concurrently with our programme of field measurements in August - September, 1985, a much more extensive campaign was being carried out in the Republic of Niger by the International Livestock Commission for Africa (ILCA) as part of the Integrated Livestock Project (ILP). The ILCA programme consisted of an airborne radiometer campaign, with complementary aerial photography and counts of animal numbers. Simultaneously, ILP teams were carrying out a series of field measurements, including estimates of biomass, using methods similar to those used by us and described earlier in this Report (Section 3.2). These field measurements were repeated by the ILP teams on three occasions from early August to late September. The second programme of measurements, carried out from 26th August to 3rd September closely matched the period of our own observations and the acquisition date (31st August, 1985) of the Landsat image used in our study. Eight of the ILP test sites fell within the area covered by this MSS image.

ILCA very kindly agreed to make available to us not only the location of their ground sampling sites and the results of their biomass measurements, but also a set of oblique aerial photographs as 35mm colour transparencies covering

each of these sites. We were thus in a unique position to test our calibrations of biomass with vegetation indices against a comparable data set collected independently.

Table 6 records, for each of the 8 ILCA test sites covered by our MSS image, measured biomass values measured during the three field programmes. It should be noted that the measurement periods concerned do not exactly coincide with the dates of our own field observations and that there are rapid changes in biomass recorded during the span of these three programmes. These changes reflect rapid growth of the grass canopy and, in many cases, a similarly rapid decline, perhaps because of senescence or perhaps due to the effects of grazing.

Each of the 8 sites was located on the Landsat-MSS image and estimates of biomass were made from values of vegetation indices derived from the remotely-sensed data using the calibration curves described in the previous Section. These estimated biomass values were compared with the measured values reported in Table 6.

Procedures for estimating biomass were broadly similar to the methods already described for the generation of the calibration data. The calibration was performed on a small sub-scene. This was the so-called 'Kao test area', 512x512 pixels in extent, corresponding to a ground area of about 25km x 25km. The ILCA sites were scattered over a much larger area than this, so it was necessary to use the full Landsat scene (covering approximately 185km x 185km) to extract the necessary radiance values for computation of Vegetation Indices.

The full Landsat scene was processed in the same way as the Kao sub-scene. It was radiometrically corrected to a standard sun elevation and AVHRR bands 1 and 2 were simulated over the entire image.

Table 6 Dry herbaceous biomass ($\text{kg}\cdot\text{ha}^{-1}$) measured at ILCA test sites during August-September, 1985

ILCA Site No	Measurement Period		
	a	b	c
2	0.2	5.5	96.0
3	320.5	744.2	666.2
4	32.7	387.9	792.4
5	7.1	342.5	85.8
6	10.5	12.5	332.5
7	23.1	488.4	437.6
17	106.8	877.5	339.7
18	21.8	459.9	201.9

a) 3rd-10th August;

b) 26th August - 3rd September;

c) 16th-26th September

To assist in location of the ILCA test sites, the image was geometrically corrected to a pixel size of 50m x 50m, using control points extracted from a 1:200 000 map of the area and applying a nearest-neighbour transform. Geographical coordinates of each site were available from the aircraft inertial navigation system and these could be used to indicate an approximate pixel address within the image. The 35mm colour aerial photography was then used to identify the precise location of the test sites on the image. In general it was possible to recognise vegetation patterns and other terrain features common to the aerial photography and the satellite image. This gave a surprisingly accurate indication of the location of the sites. ILCA sites covered an area 2km x 0.5km - equivalent to 400 50m pixels. In practice, for each ILCA site a training set rather smaller than 400 pixels was designated, because the error in location of the sites was probably of the order of +/- 1-2 pixels.

Because the predicted relationship between biomass and the vegetation indices is second order (see Section 4.3.1), use of a mean value for PVI or NDVI for the site as a whole would introduce unacceptable errors into the biomass estimation. It was therefore necessary to compute vegetation indices on a pixel-by-pixel basis, to estimate biomass for each pixel, to calculate a mean site biomass and to repeat this procedure for each of the 8 sites.

Table 7 lists the predicted values of herbaceous biomass, computed from PVI and from NDVI using the alternative calibrations described in Section 4.3.1. Biomass measured during the period from 26th August to 3rd September (close to the time of the Landsat overpass) is also listed for purposes of comparison. Table 8 lists the percentage error in each prediction compared with the measured biomass values in Table 7.

Table 7 Dry herbaceous biomass (kg ha^{-1}) at ILCA test sites predicted from MSS imagery using PVI and NDVI calibrated against measured biomass

ILCA Site No	PVI	NDVI (a)	NDVI (b)	Measured Biomass (c)
2	6.6	101.2	6.3	5.5
3*	521.2	687.1	562.2	744.2
4**	-	-	-	387.9
5	6.0	135.6	9.1	342.5
6	12.2	184.0	19.4	12.5
7	510.8	508.5	278.4	488.4
17	940.0	830.5	862.7	877.5
18	219.0	482.3	245.2	459.9

(a) Linear regression using all points

(b) Second order regression, 6 points only

(c) Measured between 26th August-3rd September (see Table 6)

* Partial cloud cover; ** Total cloud cover

Table 8 Errors in predicted levels of dry herbaceous biomass at ILCA test sites compared with biomass measured from 26th August - 3rd September

ILCA Site No	Biomass (kg ha ⁻¹)			% error	
	Measured	PVI	NDVI (a)	PVI	NDVI (a)
2	5.5	6.6	6.3	20.0	14.5
3*	744.2	521.2	562.2	30.0	24.5
4**	387.9	-	-	-	-
5	342.5	6.0	9.1	98.2	97.3
6	12.5	12.2	19.4	2.4	55.2
7	488.4	510.8	278.4	4.6	43.0
17	877.5	940.0	862.7	7.1	1.7
18	459.9	219.0	245.2	52.4	46.7

(a) Second order regression, 6 points only

* Partial cloud cover; ** Total cloud cover

In general, errors were in the range 5% - 30%, which is probably acceptable for use as a management aid for estimating herbage distribution over large areas for strategic planning purposes.

Overall, there was little to choose between the performance of the second-order calibrations, whether these were based upon the PVI or the NDVI. The PVI approach gave excellent predictions of biomass in the case of Sites 2, 6, 7 and 17. Second-order regression of biomass on NDVI seemed to give marginally less satisfactory results. Given the uncertainty in the origin of the NDVI calibration, discussed in Section 4.3.1, it is likely that the PVI approach would, in the long term give more reproducible results when applied to a succession of images covering a wide geographic area over an extended period of time.

The first-order regression of NDVI gave results that were far less satisfactory. In particular, this method seriously overestimated vegetation in areas of low biomass. We therefore reject this approach as a means of relating measured biomass to NDVI.

There are also a number of specific conclusions to be drawn from these results:

- i) Site 4 was completely cloud-covered on the Landsat image, and it was not possible to use the measured biomass from this site in evaluating the calibrations.
- ii) Site 3 was partially cloud-covered on the image. Vegetation indices were extracted from an area immediately adjacent to the test site. The justification for this was that visual inspection of the image suggested that the vegetation cover in this area was reasonably homogeneous. However, we

can have less confidence in the results from this site than in those from elsewhere. Indeed, it is noticeable that errors in both the PVI and the NDVI biomass estimates are above average for this site.

iii) The apparent errors in both estimates for Site 5 are abnormally large. Table 6 reveals a correspondingly large variation in measured biomass for this site over the three measurement periods. The data from the earlier and later measurement periods suggest that the vegetation cover on Site 5 is comparable with that on Site 2, and visual inspection of the imagery supports this view. This suggests either an error in the measured biomass for this site or an unusually rapid change in vegetation during the period of interest. In either case, comparison of measured and estimated values of biomass for this site are probably invalid.

iv) The estimates of biomass for Site 18 matched rather poorly with the measured value and there is no obvious explanation for this.

4.4 Effects of Spatial Resolution on Areal Estimates of Biomass

Most of the work reported in the previous Sections was carried out using Landsat-MSS imagery at relatively high spatial resolutions offered by 80m pixels. The intention is that operational systems should be based upon high-frequency low-resolution data such as NOAA-AVHRR LAC imagery with a pixel size of 1.1km. It is therefore important to consider what effect this reduction in spatial resolution may have upon the estimation of areal cover of different biomass levels.

As an initial exploration of this problem, imagery with the spatial and radiometric properties of AVHRR was simulated from Landsat-MSS data using the procedures described in Section 3.3 (see Plates 6a, 6b). PVI images of the Kao study area were generated at MSS and at LAC resolutions, as described in previous Sections. A density slice was applied to the two images to generate six classes of vegetation cover. The areal extent of these six classes was measured in each image by counting pixels, and the results are compared in Table 9.

Table 9 Effects of Spatial Resolution on Areal Estimates of Vegetation Cover in the Kao Study Area
(Based on analysis of Landsat imagery from October, 1984)

PVI	Biomass kg ha ⁻¹	% Area		Cover
		MSS	AVHRR	
< 1	0	37	45	Bare soil
2 - 3	0-70	31	38	Very thin bush
4 - 7	71-200	27	17	Thin bush
8 - 15	201-1500	3	1	Dense bush
16 - 31	> 1500	1	<1	Vegetation of
> 32		<1	<1	depressions and watercourses

Loss of spatial resolution considerably influenced the areas computed for each class. This was particularly evident in the case of areas of dense vegetation which typically occurs in areas much smaller than LAC pixel size. However, the overall pattern of classes was surprisingly well maintained and future work should investigate the possibility of bias-correcting area estimates.

5

CONCLUSIONS

- i) Vegetation indices derived from multispectral remotely-sensed imagery can be calibrated against ground measurements of biomass.
- ii) Remotely-sensed vegetation indices, calibrated in this way, can be used as an estimate of herbaceous biomass with acceptable precision to aid range management policy at national or regional scales.
- iii) Classified multispectral images are an effective aid to the design of ground sampling programmes, particularly in areas where maps are inadequate or unobtainable.
- iv) Calibration of remotely-sensed data against ground measurements requires imagery at moderate spatial resolution. Landsat-MSS was demonstrated to be effective for this purpose; data from meteorological satellites could not be processed in the same way.
- v) Data for an operational range-management system is required with a temporal frequency higher than can be guaranteed from low-altitude polar-orbiting satellites such as Landsat. We suggest the use of Landsat-MSS data as an intermediate step in the calibration of AVHRR LAC imagery.
- vi) The use of NDVI as a vegetation index in conditions of sparse vegetation and variable soil background can be

misleading, owing to the influence of soil variability on NDVI which can result in spectral confusion between vegetated and non-vegetated surfaces.

vii) the PVI produces more consistent results and is recommended in preference to NDVI.

viii) The Soil Brightness Index can be used to generate maps of the distribution of soils by type. Ground data are required to define meaningful class intervals, but the results from test sites can be applied to other areas, provided the histograms of the SBI images are normalized.

ix) Changes in spatial resolution (for example from MSS to LAC) have a major impact on areal estimates of land cover, particularly in the case of cover classes which occur in parcels which are small in relation to the resolution of the imagery. This problem requires further study.

x) An operational system for rangeland mapping and monitoring can be envisaged, based on the procedures developed in this Report. Because the data requirements are modest (2-channel low-resolution imagery), a suitable system could be readily implemented using a modern micro-computer. Such a system should be installed locally to facilitate access to ground data for calibration purposes and to encourage use of the information by range management authorities.

xi) A necessary preliminary to the installation of such systems is an adequate programme for training local personnel in their use.

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Chapter 4. Influence of resolution and sampling on the use of AVHRR data for vegetation studies

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Vegetation monitoring using AVHRR data at different resolutions

J. P. MALINGREAU and A. S. BELWARD

Commission of the European Communities, Joint Research Centre
Institute for Remote Sensing Applications, 21020 Ispra (Varese) ITALY.

Abstract. NDVI temporal curves over an agricultural area from GVI and GAC data are compared. The length of growing season and major breaks of slope associated with key crop development events are equally well shown by both data sets. Detailed examination of the curves reveals some differences, these are thought to result from temporal changes in landscape structure. GVI pixels averaged at different levels again show that the spatial organization of both agricultural and "natural" landscapes, tropical forest in this case, changes throughout a single season. These observations highlight the need for different scales of observation (both in temporal and spatial terms) at different times of the year. A comparison of contemporaneous GAC and HRPT data shows that the transitions across ecological zones are detected with both data, though the undersampling in the LAC to GAC conversion limits the use of GAC data for detection of point phenomena such as fires.

1. Introduction

Vegetation monitoring is now important at spatial scales ranging from the study of localized phenomena to the analysis of processes at the global level. A frequency of observation of days or years may be required. Time series, at a given frequency, may be needed over many years for the study of specific environmental phenomena. Selection of appropriate scales, both spatial and temporal, is becoming increasingly important (Strahler *et al* 1986). It is also known that the spatial resolution of satellite sensors are dependent upon the interaction between system factors and terrain characteristics (Forshaw *et. al.* 1983); whilst the system factors are relatively constant the surface characteristics are not. AVHRR data are available at different spatial scales (in terms of geographical extent of cover, and of resolution) and a range of temporal scales (in terms of frequency of cover and extent of archive). This paper considers both spatial and temporal characteristics of different types of AVHRR data with reference to vegetation monitoring.

2. GAC - GVI time series

This study is based on an agricultural area of the Ganges Plain where winter wheat and summer rice are the two successive crops. Sample points of one GVI pixel and one GAC pixel, located over the same coordinates are used. The temporal frequencies of the two time series are somewhat different, with regular tri-weekly maxima for the GVI and irregular 15 day maxima for the GAC. NDVI temporal curves for one season are shown in figure 1.

Figure 1. NDVI development curves from GVI and GAC

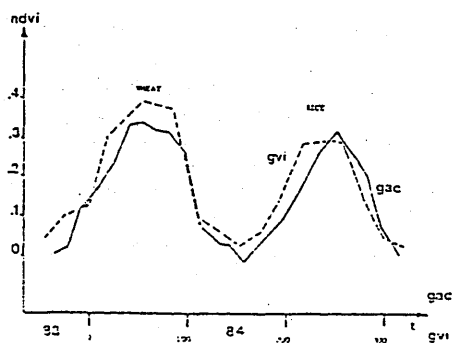
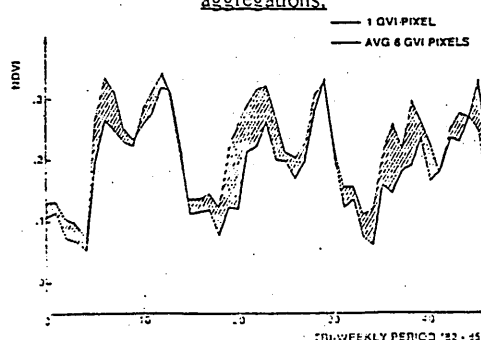


Figure 2. NDVI development curves at different GVI pixel aggregations.



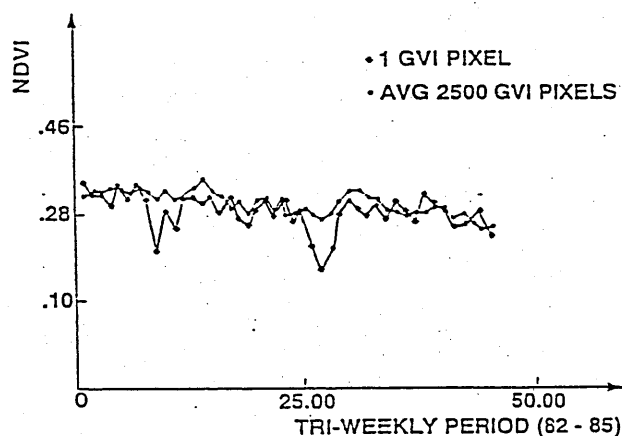
Maxima and minima for both data types occur at similar periods, and the determination of the length of the growing season - the period during which the NDVI is higher than .05, or the period between two definite breaks in slope - can be done equally well using either format. The wheat crop when observed with the GVI has a higher maxima than from the GAC observations. This may reflect landscape heterogeneity combined with the positioning of the GAC pixel in a portion of the ground trace which has less green vegetation than the portion used to produce the GVI. For the rice crop, the GVI curve departs from the GAC curve during the greening-up period. Once again this may be due to a spatial sampling artifact. As a whole the two curves depict the same general pattern of vegetation dynamics, though specific differences are seen. The differences appear to be linked to the distribution of spatial features with respect to time; the relationship between the spatio-temporal behaviour of GAC NDVI and GVI cannot, of course, be fully understood without an exhaustive description of the landscape characteristics.

3. GVI time series at various aggregation levels

To further investigate how the spatial scale of observation influences the temporal information of AVHRR data, we have progressively increased the pixel size by averaging GVI pixels. The first case presented here is from an agricultural ecosystem of east Asia (double rice cropping). The size of the sample was progressively increased from one pixel to a square of 6 by 6 pixels. Figure 2 shows the points for April 1982 to March 1985. Going from one pixel to the average of 36 pixels did not uniformly smooth out the temporal curve. First note that the determination of the agricultural growing season can be done equally well with either the single pixel, or the average of 36 pixels. Second note that in all years the first rice crop has a higher mean for the 36 pixel sample than the individual pixel sample, and the difference between the two samples is always greater for the first crop. This may be specific to the location of the single pixel sample; yet the second rice crop shows similar vegetation index development at both levels of spatial aggregation. We believe that this changing relationship between vegetation index values of samples obtained at various spatial levels contains information regarding the heterogeneity of the landscape. A completely homogeneous landscape (i.e. continuous rice crop canopy) would give similar values at decreasing measurement scales within the confines of the ecosystem. In this case it is clear that the second rice crop is more uniform than the first.

A similar approach was adopted over a non agricultural landscape, the Amazon tropical forest. NDVI time series were established for a series of samples ranging from one GVI pixel to the average of 2500 pixels. It can thus be considered the sampling covers a range of scales from the ecosystem to the biome level. While the one pixel sample was in a "pure" evergreen rain forest area, the largest sample obviously includes a mix of tropical forest vegetation including the flooded varzeas, evergreen and semi seasonal forest. NDVI development curves for the two extremes of the sampling range are shown in figure 3.

Figure 3. NDVI development curves at different GVI pixel aggregations.



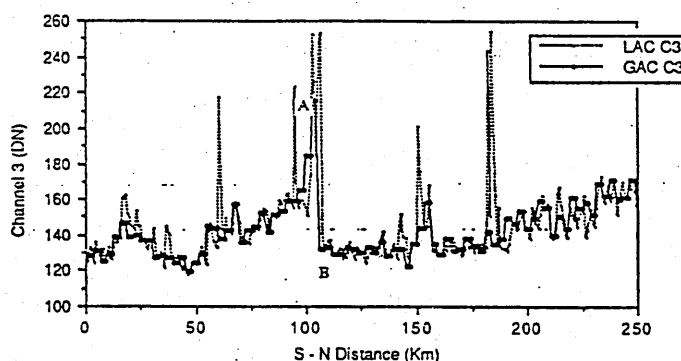
The smoothing of the time series as one goes from 1 to 2500 pixels is evident in this case. With a single pixel seasonal variation is clearly marked by periods of low NDVI values. Even at the 2500 pixel level of spatial averaging a seasonal signal is still seen, but it is more related to the appearance of periods of high NDVI values after the rainy season than to the presence of troughs. The negative slope of the 1982-85 time series is present at all sampling levels. If anything, the slope of the 2500 pixel sample regression line is slightly steeper than for the one pixel sample. The full significance of this feature is discussed by Malingreau, 1989.

4. GAC - HRPT and the detection of fire events

The detection of the occurrence of specific events in the vegetation canopy is important in observation systems geared toward the study of global change. The occurrence of fire, a growing disturbance factor in tropical ecosystems is a good example of such an event. A better understanding of the role of fire in the shaping of tropical vegetation (let alone its influence on atmospheric chemistry) must be based upon an observation system which is truly global in nature. Questions of scale immediately appear in trying to design such a system since the area to be covered is large (inter tropical belt), fires are episodic events and burned areas can range from farmers fields to whole savanna landscapes.

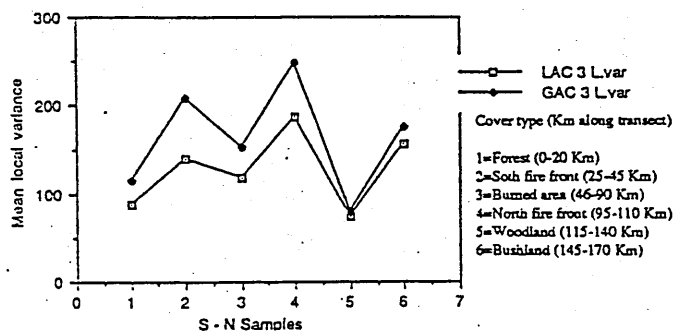
Recent work has shown that AVHRR channel 3 can be used for the detection of active or recent fire sites (Langaas and Muirhead, 1988, Malingreau *et al.* 1989). In order to better assess the information content of AVHRR data with respect to fire detection we have studied contemporary GAC and HRPT data over the savanna - forest transition area of West Africa. To identify the columns and lines from which the LAC to GAC conversion originated, and thus superimpose the two data sets, each GAC pixel was replicated into 5 by 3 pixel/line array.

Figure 4. Channel 3 S - N transect.



A channel 3 south - north transect is shown in figure 4. This clearly shows the main ecological zones: The transect runs from forest in the south (0 - 20 Km) to the boundary of a recent fire (25 - 45 Km), through the burned area (46 - 90 Km) to the northern active burning front (95 - 110 Km), then through open woodland (115 - 140 Km) and into bushland savanna (141 - 250 Km). The forest / fire boundary is clearly seen as a sharp rise in channel 3, the burned area is characterized by relatively high but variable channel 3 values. The northern woodland / fire boundary is again clearly seen in near to saturated channel 3 values. Note that the same basic trends for each graph appear in both the GAC and HRPT data, in each case with the HRPT values scattered around the GAC values.

Figure 5. Mean Local Variance for different cover types.



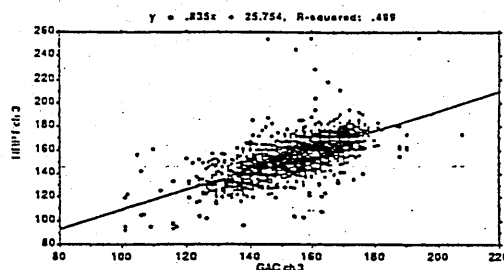
A transect, however, is a one dimensional representation of spectral variance in a two dimensional image. Given the nature of the LAC to GAC sampling, it is important to examine the differences between the HRPT and GAC with some reference to variation in both dimensions. To this end local variance was calculated for GAC (at original 4 km scale) and HRPT, for channel 3, over the whole scene. Local variance was measured as the standard deviation of a moving 3 X 3 window (after Woodcock and Strahler, 1987). Figure 5 shows mean local variance for different cover types along the transect. Those regions where mean local variance is high (associated with high spatial variation in ground cover) correspond to the regions of the transect where the deviation of the HRPT from the GAC is most pronounced.

Table 1 (descriptive statistics obtained from a 5% random sample of forest and savanna domains of Sierra Leone and Guinea) shows how the agreement between the two data formats changes as a function of location.

Cover type	n	r ²
Forest	4089	0.739
Savanna	2545	0.499

For relatively homogeneous regions, such as the forest area, the GAC and HRPT data sets are reasonably well matched. However, the correlation between the two is less good for the more heterogeneous savanna environment. This sharp fall is largely due to the presence of bush fires. Depending on the spatial characteristics of the fires, the technique used to undersample the LAC data may miss some potential fire sites, whilst over emphasizing the importance of more minor sites indeed, a scatter of high value HRPT channel 3 pixels are found on the transect samples corresponding to this region (points A and B, figure 4). This effect of missed fires and over estimates of fires caused by the undersampling can also be seen in figure 6, a scattergram from the 5% random sample, of GAC vs HRPT for the savanna area. Note how it is mainly the high values (associated with probable fire sites) which deviate from an otherwise reasonable correlation.

Figure 6. Correlation between HRPT and GAC (Channel 3).



5. Conclusions

The combination of time series and spatial scale appears to indicate that not only is there a level of information associated with a particular scale, but the passage of scale itself is carrying useful information. The results show that interpolation across scales is time controlled, and that at certain periods in landscape evolution more intermediate scales of measurements are needed.

The specific comparison related to biomass burning features has shown the strong dependency of detection upon spatial organization of the fires. The existing global data sets (GVI and GAC), are both derived by the undersampling of higher resolution data sets. It is clear that such undersampling places limitations on the use of these data for surveys of point phenomena. The point phenomena, typical of burning in the tropics, can be underrepresented in some cases and spatially overrepresented in others. The analysis of the sampling effect will not be complete, however, until time series have been investigated. Once again, it will be important to assess if there is a periodicity in the scaling effect as one goes from fine to coarse resolution over fire scenes.

The spatial distribution of features at the surface of the earth is a key characteristic for classifying, monitoring and discriminating between components of the biosphere. We have shown that the interactions between surface features and the spatio-temporal scales are extensive and complex. Scale experiments of the kind reported here must now be systematically explored.

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Limitations to the identification of spatial structures from AVHRR data

A. S. BELWARD and E. LAMBIN

Joint Research Centre, Ispra Establishment, 21020 Ispra, Varese, Italy

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Abstract. Satellite sensor data with different resolution-cell sizes have been used to show how sensor-induced spatial autocorrelation in High Resolution Picture Transmission (HRPT) data, and local variance induced by sampling in Global Area Coverage (GAC) data, may limit the use of Advanced Very High Resolution Radiometer (AVHRR) data for the identification of spatial structure and pattern.

1. Introduction

Satellite sensor data are available at a range of spatial resolutions. The spatial resolution of a sensor is dependent upon system factors; however, the ability to resolve is dependent upon the interaction between system factors, viewing conditions and terrain characteristics (Forshaw *et al.* 1983). A digital image consists of individual measurements; these are pixels, each of which is associated with a specific ground area, the resolution cell (Strahler *et al.* 1986).

Advanced Very High Resolution Radiometer (AVHRR) data are available as either real-time transmissions to ground receiving stations in line of sight, or as on-board recorded data. The real-time data, High Resolution Picture Transmission (HRPT), have a resolution cell size of 1.1 km. The on-board recorded data come in two forms: Local Area Coverage (LAC), which has a 1.1 km resolution cell size, and Global Area Coverage (GAC), which has a resolution-cell size of about 4 km. This case study assesses the suitability of AVHRR HRPT and GAC digital imagery for spatial distribution analysis by assessing the spatial information content of these data.

Past studies of the spatial information of image data from satellite sensors have shown a strong dependence between observed spatial variation in images and scene spatial variation (Woodcock *et al.* 1988 a, b). The spatial information within image data of any given scene is also dependent on the resolution-cell size of the image data. The relationships between resolution-cell size and factors such as the spatial structure of a scene (Woodcock and Strahler 1987), classification accuracy (Cushnie 1987), global monitoring of land transformations (Townshend and Justice 1988) and vegetation dynamics (Kong and Vidal-Madjar 1988) have all been examined. These studies all simulate low-spatial-resolution data from high-spatial-resolution data, using a range of techniques: pixel averaging (Woodcock and Strahler 1987), weighted filter (Cushnie 1987) and Gaussian low-pass filter (Kong and Vidal-Madjar 1988).

In this study, through the use of simulated and real data with different resolution-cell sizes, we examine not only the relationship between local scene spatial variability and resolution-cell size, but also system factors that determine the way in which the electromagnetic flux is collected, detected and converted into data records. Comparisons are made between Landsat Multi Spectral Scanner (MSS) and AVHRR HRPT and between AVHRR HRPT and GAC data. To measure spatial structure, we

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use texture, which is the local variance measured as the standard deviation of a moving 3×3 window (after Woodcock and Strahler 1987); see Woodcock *et al.* (1988a), Jupp *et al.* (1988), Curran (1988) and Haralick (1979) for other methods of spatial analysis as applied to remotely sensed data.

2. Study-area location

The study area for this work is West Africa, extending from around 7°N to 15°N , 7°W to 14°W . The study area includes major biome boundaries, from tropical rain forest in the south, extending north through woodland savannah to grassland savannah.

3. Comparison of MSS and HRPT data

3.1. Resolution-cell size of the AVHRR sensor

The bandwidths of the visible and near-infrared channels of the MSS and AVHRR are different. This difference is greater for the near-infrared than for the visible (visible: MSS centre wavelength $0.65 \mu\text{m}$, bandwidth $0.091 \mu\text{m}$, AVHRR centre wavelength $0.635 \mu\text{m}$, bandwidth $0.117 \mu\text{m}$; near-infrared: MSS centre wavelength $0.92 \mu\text{m}$, bandwidth $0.221 \mu\text{m}$, AVHRR centre wavelength $0.833 \mu\text{m}$, bandwidth $0.240 \mu\text{m}$). The similar visible channels are used in this study.

One full Landsat MSS scene and an equivalent AVHRR HRPT near-nadir sub-image, covering an area of three square degrees, were collapsed to successively coarser resolution-cell sizes by averaging neighbouring pixels into single pixels with correspondingly larger resolution-cell sizes. Local variance was then calculated for the images at each resolution (after Woodcock and Strahler 1987). Mean local variance of the study area was plotted against resolution-cell size (figure 1). Both curves show only small changes in mean local variance with increasing resolution-cell size. This is because the spatial organization of the region is such that the landscape is heterogeneous at a wide variety of scales. The resolution-cell size never exceeds the size of all objects in the area, and thus there is no sharp fall in mean local variance. Figure 1 indicates that the simple averaging of MSS pixels to simulate HRPT spatial resolution (point A, figure 1) results in very different mean local variance to that of the real HRPT image (point B, figure 1). However, the local-variance measurement is image-

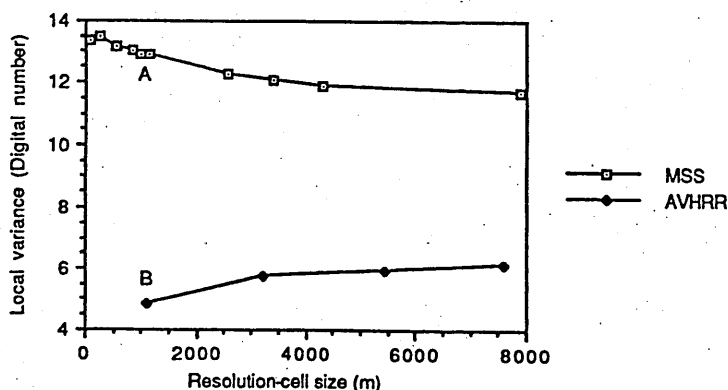


Figure 1. Graph of local variance as a function of resolution-cell size for Landsat MSS and AVHRR HRPT images.

specific, so we have to compare the slopes of the curves of the local-variance/resolution graphs, rather than absolute values (C. E. Woodcock, personal communication). The MSS has a negative slope and HRPT has a positive slope, showing it is not possible to simulate AVHRR HRPT images from Landsat MSS images by the simple aggregation of pixels. Other sensor-specific factors have to be considered.

3.2. Point spread function of the AVHRR sensor

The low values of mean local variance and the flat shape of the curve for the HRPT data shown in figure 1 suggest that high spatial autocorrelation between pixels exists for HRPT images. To test this hypothesis, a low-pass averaging filter of 3×3 pixels was used to spatially smooth the 1 km resolution-cell-size data derived from MSS data. This smoothing process results in the spectral value of each pixel being dependent on that of neighbouring pixels. The smoothed image was then collapsed over the same range of pixel sizes as in §3.1. Local variance was again calculated for the images at each resolution. Figure 2 shows that the shape of the local-variance/resolution curves for this two-step simulation of HRPT data from MSS data is almost identical with that of the HRPT data. Jupp *et al.* (1988, 1989) show that the autocorrelation structure of an image is influenced by spatial averaging as a sensor makes a measurement integrated over a finite ground area. They also point out that the assumption that the sensing device integrates all energy equally within the instantaneous field of view, rejecting all energy outside of it, is probably unrealistic for real sensors. The fact that the spatial averaging of variance, used in our two-step AVHRR simulation, more closely matches the local-variance/resolution behaviour of real AVHRR than the simple aggregation of neighbouring pixels supports the hypothesis that the spatial response function or point spread function specific to the AVHRR sensor results in dependence between neighbouring pixels.

3.3. Practical implications

The dependence between neighbouring pixels has a strong influence on the way we interpret shapes or boundaries of an image. Figure 3 is a spectral profile across a 13 km wide valley from both MSS and HRPT visible channels. The boundaries

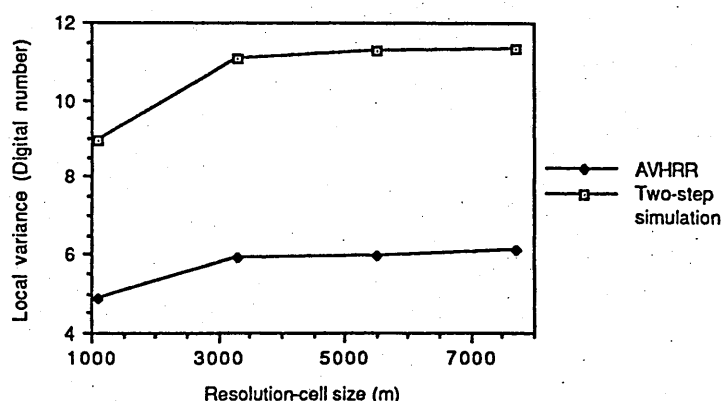


Figure 2. Graph of local variance as a function of resolution-cell size for the two-step simulation from Landsat MSS and for AVHRR HRPT images.

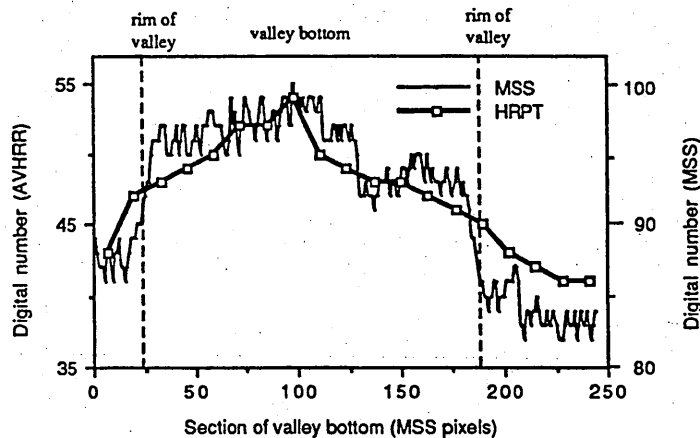


Figure 3. Spectral profile across a valley bottom from Landsat MSS and AVHRR HRPT images.

between the rich grassland of the valley bottom and the surrounding bush savannah are easily detected on the MSS by the sharp changes in digital number, while the profile from the HRPT data is much smoother. More than one mixed-border pixel is created. In other words, the local spatial contrast is low on AVHRR HRPT data.

4. Comparison of AVHRR HRPT and GAC data

4.1. Sampling by the AVHRR system

GAC data are generated by onboard sampling of the full-resolution LAC data. For a given scan line the first four pixels out of every five are averaged, and only every third scan line is processed. This gives a resolution-cell size, at nadir, of $1.1 \text{ km} \times 4 \text{ km}$, with a gap of around 3 km across the scan lines (Kidwell 1986). Since the HRPT and GAC data are derived from the same sensor, this study is not constrained to looking at just the visible channel. Many applications of AVHRR for terrestrial environmental monitoring use the Normalized Difference Vegetation Index (NDVI) and AVHRR channel 3 ($3.55 \mu\text{m}$ – $3.93 \mu\text{m}$) data; consequently this study concentrates on these.

Contemporaneous GAC data (from the United States National Oceanic and Atmospheric Administration) and HRPT data (from the European Space Agency Maspalomas ground receiving station) from 25 January 1988 were used. A $512 \text{ pixel} \times 512 \text{ line}$ extract, over the study area, was taken from the raw HRPT data, and an equivalent area taken from the raw GAC data, both extracts being near-nadir. To identify the columns and lines from which the LAC-to-GAC conversion originated, and thus superimpose the two data sets, each GAC pixel was replicated into a $5 \times 3 \text{ pixel/line}$ array. The resulting image has the same resolution-cell size as HRPT data and the radiometric characteristics of GAC data. The NDVI was calculated from the HRPT and the equivalent GAC data. Local variance was then calculated for GAC (at original 4 km scale) and HRPT for NDVI and channel 3 over the whole scene. It is known that the relationship between resolution-cell size and landscape-unit size influences local variance (see the papers cited in §1). To reduce terrain effects on local variance, polygons were defined over areas where the landscape units are large and individual objects, such as clumps of trees, are very small in relation to

Descriptive statistics (HRPT and GAC AVHRR channel 3 and NDVI data) from polygons over different cover types.

Sample		Channel 3		NDVI	
		HRPT	GAC	HRPT	GAC
Whole scene	MLV	147.4	172.4	49.62	70.22
	MDV	138.2	138.3	64.0	64.5
	SD	20.8	19.4	8.4	8.3
Burned bush savannah <i>n</i> = 313	MLV	84.74	142.85	24.49	64.35
	MDV	144.6	144.7	46.9	47.2
	SD	5.3	5.1	1.6	1.7
Bush savannah <i>n</i> = 355	MLV	73.74	93.07	32.47	41.71
	MDV	130.5	130.5	64.1	64.6
	SD	3.4	2.9	2.1	1.7
Forest <i>n</i> = 1120	MLV	69.04	79.91	36.63	46.99
	MDV	110.0	110.3	77.0	77.7
	SD	3.4	3.1	2.0	1.7

MLV $\equiv$ mean local variance, MDV $\equiv$ mean digital value, SD $\equiv$ standard deviation.

resolution-cell size. Mean local variance was thus calculated within an area of forest, bushland savannah that had been recently burned, and unburned bushland savannah.

The descriptive statistics from each of the polygons are shown in the table. In each case the mean digital value and standard deviation of GAC and HRPT (both for the NDVI and channel 3) are very similar. However, the mean local variance in all the GAC data sets is far greater than for the equivalent HRPT data sets. In this instance absolute values of local variance can be compared, as sensor parameters are identical, and the GAC/HRPT histograms showed the same distributions. Since the effect of landscape-unit size has been limited, this result may be attributed to the GAC sampling. The line skipping involved in the onboard sampling disrupts the dependence between neighbouring pixels. This introduces an artificial local spatial contrast in the GAC data as the autocorrelation between pixels is reduced. The effects of aliasing (a consequence of the sampling interval used in the generation of GAC data) may also contribute to the high local spatial contrasts observed in the GAC data. A Nyquist critical frequency f_c (in Hz) exists for any sampling interval Δ (in s) and is given by

$$f_c \equiv \frac{1}{2\Delta} \quad (1)$$

For digital imagery, the effects of aliasing will only be negligible where the sampling interval is such that the pixel size is less than half the resolution-cell size, i.e. below the Nyquist limit (Forshaw *et al.* 1983); the GAC geometric pixel size is nominally 3 km $\times$ 5 km and the resolution cell associated with each pixel nominally 1 km $\times$ 4 km.

4.2. Practical implications

The undersampling effects influence the way in which the GAC data may be used to identify spatial structures and patterns. A clear, and simple, case is the observation

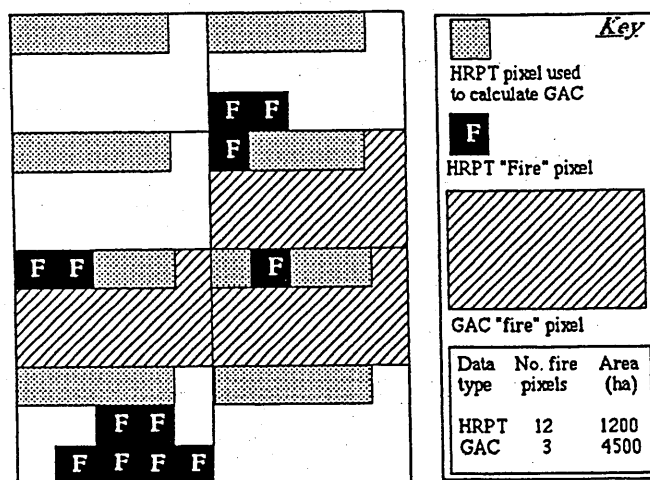


Figure 4. Contemporaneous HRPT and GAC AVHRR channel 3 data showing how the GAC undersampling affects the use of these data for the detection of bush fires.

of point phenomena, for example AVHRR channel 3 data for bush-fire monitoring. Possible recent or active fire sites are indicated by saturated or near-saturated pixels. However, as shown in figure 4, the distribution pattern of saturated pixels, and the equivalent ground area covered, from GAC and HRPT are quite different. The technique used to undersample misses a major potential fire site in the bottom left of figure 4 and expands the importance of the more minor sites in the centre of the figure.

More generally, small structures, features with marked periodicity or linear features may not appear on the image, particularly when their orientation tends to the across-track direction. Thus artificial contiguity or variability may appear on AVHRR GAC images.

5. Conclusions

The use of AVHRR data for identification of spatial structures and pattern recognition is limited by system and sensor effects. We have identified here the high level of spatial autocorrelation for HRPT and the artificially introduced spatial contrast for GAC. These points are of little consequence when studying objects far greater in size than the resolution-cell size of the AVHRR. However, at larger scales these points must be considered. This is true not only for spatial but also for spectral and temporal studies. Spectral and temporal studies require the labelling of pixels in terms of surface features. The spatial limitations of the AVHRR data make the accurate assignment of thematic content to specific groups of pixels difficult, because such classification relies to a great extent on the spatial information of the image.

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Spatial attributes of AVHRR imagery for environmental monitoring

A. S. BELWARD

Joint Research Centre, Institute for Remote Sensing Applications TP 044,
Ispra Establishment, 21020 Ispra (Varese), Italy

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Abstract. Spatial analysis of Advanced Very High Resolution Radiometer (AVHRR) data at Global Area Coverage (GAC) and High Resolution Picture Transmission (HRPT) resolution shows that structural information is detectable across a range of scales and that different biomes exhibit different detectable spatial characteristics. The spatial patterns observed in GAC and HRPT data are similar at coarse resolutions. Differences between the two are observed where point phenomena occur, and where scene objects are generally linear. The undersampling in GAC data generation can cause artificial contiguity and artificial disunity to appear in the image of any scene. The spatial structure observed in GAC image data must therefore be considered unreliable, at least at the scale of the GAC AVHRR resolution-cell size. However, the use of the spatial domain in studies of surface phenomena operating at scales greater than that of the resolution-cell size are unlikely to be limited by the undersampling effects. Indeed, the spatial temporal evolution of structure in AVHRR images may provide important indicators of regional environmental change.

1. Introduction

Our expanding human population is paralleled by depletion of the Earth's elemental resources, by tropical deforestation, by desertification and by the pollution of the oceans and atmosphere. Global environmental issues such as these emphasize the importance of the concept of the Earth as a single self-sustaining biosphere (Myers 1984). It is axiomatic that studies of the Earth as a single system require observation and measurement on a global scale, a task well suited to Earth observation from space platforms; current projects such as the International Council of Scientific Unions' International Geosphere-Biosphere Programme, and NASA's Earth Observing System serve to illustrate the importance of space observation in global studies.

Of the existing satellite-borne Earth observation instruments the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA/TIROS-N platforms is arguably the best for environmental monitoring at regional and global scales. The advantages over the high spatial resolution systems, such as Landsat, are the daily global coverage, which largely overcomes problems of restricted cloud free image availability, and lower data volumes, which make the analysis of long time series over large geographical areas possible (Justice 1986).

Whilst the spectral and temporal characteristics of AVHRR data are well-known with regard to both work at continental scales (Justice *et al.* 1985) and for particular environmental issues such as regional fire monitoring (Langaas and Muirhead 1988, Malingreau *et al.* 1989), tropical deforestation (Malingreau and Tucker 1988) and grassland biomass estimation (Prince and Tucker 1986) limited use has been made, in

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a systematic way, of information from the spatial domain. Of course when we look at a digital image we make a lot of use of spatial information in the image interpretation process; images can be characterized by the shape, size, pattern, texture, tone, site and association of objects. Unfortunately there is considerable difficulty in integrating the pattern recognition process of the human into computer-based image analysis (Woodcock *et al.* 1988 a).

However, recent years have seen the emergence of a number of techniques of spatial analysis suited to computer-aided study of digital images. Two main avenues of study have emerged as particularly relevant to remote sensing; firstly the measurement of image texture, and secondly the measurement of spatial dependence. Measurements of spatial dependence in digital images have largely been based on the use of variograms and semi-variograms to describe the relationship between adjacent pixels. The variogram is a graphic representation of the dependence between pixels at various distances apart. Adjacent points in a scene can be expected to be spectrally more similar than points some distance apart, that is, they can be said to be spatially autocorrelated. In the variogram variance is plotted against distance between pixels. The resulting graphs are related to the spatial structure of the objects in that scene, though they do require careful interpretation. Curran (1988) and Jupp *et al.* (1988 and 1989) provide an introduction to, and guidance on interpretation of the variogram.

The use of image texture as a measure of structure is, in comparison with the variogram, perhaps easier to interpret, if less flexible. Texture is the local variance measured as the standard deviation of a moving 3 by 3 window. The application of this technique to spatial studies is described by Woodcock and Strahler (1987). The procedure is based on the creation of a series of images of a single scene at different resolutions. The original full resolution image is collapsed to successively coarser resolutions by averaging neighbouring pixels into single pixels with associated larger resolution-cell sizes. Mean local variance is then calculated at each resolution and plotted against resolution-cell size; the resulting graphs of local-variance/resolution can be used as a measure of spatial structure in images.

Digital images exhibit spatial structure when the imaged scene contains discrete objects, that is to say, objects which are identifiable because their spectral properties are relatively homogeneous internally whilst contrasting with other elements of the scene (Jupp *et al.* 1988). As such, the structural organization of a digital image from remotely sensed data will vary depending on the part of the electromagnetic spectrum through which the data were recorded. In addition, there is a link between the nature of objects detectable within a scene and the resolution-cell size of the sensing device (Forshaw *et al.* 1983, Woodcock *et al.* 1988 a and b).

Spatial studies using AVHRR data have to take into account the existence of two different resolution-cell sizes; High Resolution Picture Transmission (HRPT) and Local Area Coverage (LAC) with a 1.1 km resolution-cell size, and Global Area Coverage (GAC), with a resolution-cell size of around 4 km. However, given that using AVHRR data at HRPT/LAC resolution already brings data volume for regional studies down to manageable, or in the case of continental studies, more manageable levels, why use GAC data?

The simplest answer to this question is that for much of the world GAC are the only data available, certainly in terms of long time series of 5 channel daily cover. At the same time there is a clear need for regular observation over a number of years in many environmental studies, for example the characterization of the spatial temporal dynamics of fire in vegetation communities. Unfortunately extensive archives of full

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resolution data are far from widely available, the only complete one being the cover of western Europe provided by the ground receiving station at the University of Dundee in Scotland. This lack of full resolution archive material is because first, LAC data availability is limited by the on-board recording capacity and this is insufficient to provide systematic global cover and secondly, HRPT data cover is limited to the area in which the satellite is in direct line of sight of a ground receiving station's antenna. Thus the length of archive available for different parts of the globe will depend on the period of operation of stations offering cover, and this is highly variable. For example the Maspalomas station (Canary Islands) has been archiving daily HRPT data for west Africa since 1986. Cover of west and central Africa has recently been extended with the opening of the Niamey station (Niger) in 1988, however this station's archive of daily 5 channel data only exists from 1990 on, though decadal composites of the Normalized Difference Vegetation Index (NDVI) which is a linear combination of the first two channels (Sellers 1985, among others) are available dating back to 1988. Cover of eastern and southern Africa will only be assured once the Nairobi (Kenya), Harare (Zimbabwe) and Réunion Island (off the east coast of Madagascar) stations are all fully operational; this is expected by the end of 1991. In contrast, the global daily GAC archive dates back to June 1981, and continental scale time series of these data are in regular use for environmental monitoring (see for example Snijders 1989).

So, for regional or continental scale studies (outside Europe) requiring a historical perspective there is really little alternative to using GAC data. Nevertheless, if quantitative use is to be made of these data we need to establish the limitations of the GAC data set. This is equally true whether information from the spectral or spatial domain is considered, and can be achieved by comparing the information content of the GAC with high resolution data sets.

Past work comparing high resolution Landsat Multi-spectral Scanner data with HRPT data, and HRPT with GAC data has shown that spatial contrast in AVHRR imagery is relatively poor, and that this is particularly limiting with respect to detailed studies, but is likely to be less so for smaller scale regional studies (Belward and Lambin 1990). This work examines the spatial attributes of AVHRR images for environmental monitoring at such regional scales. Given the greater global availability of GAC the study specifically focuses on the relationship between image structure at GAC and HRPT/LAC resolutions. Texture is used to measure spatial structure (after Woodcock and Strahler 1987) and the study uses the NDVI and AVHRR channel 3 (3.55 μm –3.93 μm) data because these are widely used in environmental monitoring.

2. AVHRR data at different resolutions

2.1. Methods

The study area is West Africa, from the coast of the Gulf of Guinea (approximately 3° N) to the northern border of Senegal (approximately 17° N) and from the Atlantic coast (approximately 18° W) to the Greenwich meridian. Figure 1 shows the location map.

Dry season imagery from a standard HRPT scene (four minutes of data) covering the study area was obtained from the European Space Agency's Maspalomas station. The HRPT data were from the NOAA-9 ascending orbit of 25 January 1988 with an equatorial crossing longitude of 9° 42' W. Data in GAC format from the same orbit were obtained from the United States' National Oceanic and Atmospheric Administration. GAC is generated by onboard sampling of the full resolution data such that

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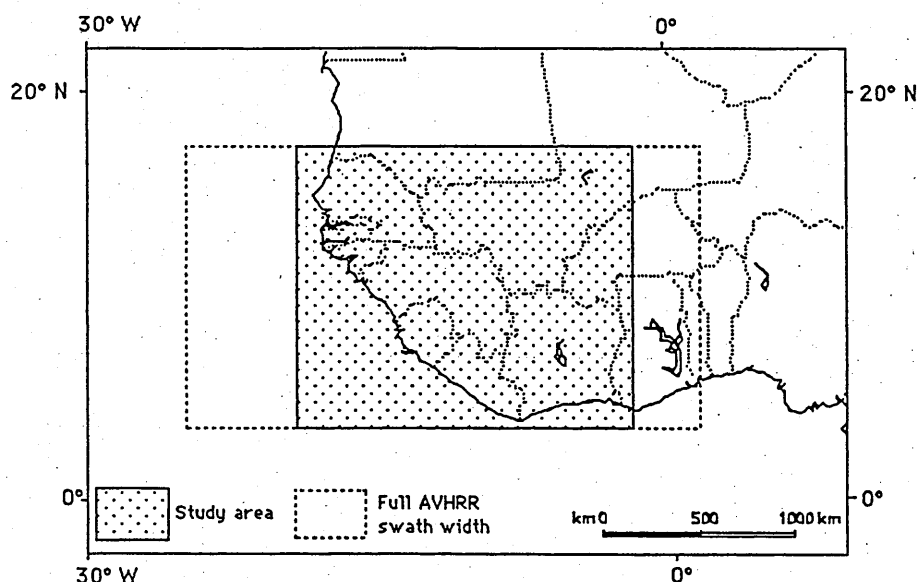


Figure 1. Location map showing the study area and the full extent of the AVHRR swath width.

for a given scan line the first four pixels out of every five are averaged, and only every third scan line is processed (Kidwell 1986). To acquire GAC and HRPT image extracts covering identical scenes the columns and lines from which the GAC conversion originated had to be identified. This was achieved from the raw data by matching the digital values from single pixels in the GAC image to the four source pixels in the HRPT image using well defined control points. Once the offset was established image extracts over precisely the same ground area could be made from each data type. To avoid extreme view angles, and the associated panoramic distortions, only the central section of the swath covering the West African landmass was used. This resulted in a 1350 pixel by 1404 line extract for the HRPT data, and an equivalent 270 pixel by 468 line extract for the GAC data.

The sampling involved in the degradation to GAC resolution can result in artificially high local variance (Belward and Lambin 1990) so a control which simulated the spatial resolution of GAC without the biasing effects of the sampling was constructed. The control (referred to as AVG data) was created by taking the mean of consecutive 5 by 3 pixel blocks of the HRPT data. Justice *et al.* (1989) have shown this to give a better spectral representation of the original data than alternative sampling strategies.

The NDVI was calculated for all three data sets (HRPT, GAC and AVG). The NDVI and channel 3 full resolution images were then collapsed to successively coarser resolution-cell sizes by averaging squares of neighbouring pixels into single pixels with correspondingly larger resolution-cell sizes. As resolution-cell size increases, then for a constant scene, the number of pixels decreases. This limits the number of times that an image can be degraded yet still have sufficient pixels to make calculation of local variance meaningful. Woodcock and Strahler (1987) suggest that as a rule of thumb images with a minimum of around 60 pixels on a side should be

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used. Accepting this limit the data sets were collapsed over a range of resolution-cell sizes from 1 to 6 pixels on a side for GAC and AVG data, and 1 to 24 pixels on a side for HRPT data; in common with general usage GAC pixels are treated as having a 4 kilometre resolution-cell size (Kidwell 1986), likewise the AVG data, and a nominal resolution of 1 km is assumed for the whole HRPT image. Local variance was then calculated for both NDVI and channel 3 for the images at each resolution, and mean local variance plotted against resolution-cell size.

2.2. Comparison of the different resolutions

In the interpretation of the local-variance/resolution graphs it is important to remember that where the spatial resolution of the sensor is finer than the mean size of the scene's dominant objects then proximate pixels are highly correlated and local variance is low. Where resolution-cell size approaches scene object size then proximate pixels are less similar and local variance rises. Where the resolution-cell is larger than the objects in a scene then proximate pixels are, once more, similar and local variance is again low. Thus local variance/resolution graphs will have a positive slope until the scene object size is approximately equal in size to the resolution cell, at which point the curve flattens off, and becomes negative as the resolution-cell size exceeds that of the scene objects. Users must also be aware that graphs of local variance from one image cannot usually be directly compared with another as they are dependent on global variance in each image. However, in this instance as the data all come from the same sensor and orbit and the GAC/HRPT/AVG histograms show the same distributions absolute values of local variance can be compared.

2.2.1. The whole scene

The West African region covered by the imagery is essentially an elevated plain, broken only by the Guinean highlands. The spatial structure of the area is at multiple scales. At one level there is the south-west to north-east succession in vegetation type from tropical forest to grassland savannah. At another level, each of these major biomes exhibits unique structural characteristics. If this multiplicity of scale is recorded by the AVHRR data, then the resulting graphs of local-variance/resolution will be characterized by more than one peak.

The curves in figures 2 and 3 do indeed reflect this multiplicity of scale. All generally have a positive slope across the whole resolution range, thus indicating that the resolution cell size never exceeds the size of all objects in the scene. This is to be expected as each biome represents a structural element many hundreds of kilometres across. The exceptions to this are the curves derived from the GAC data, particularly channel 3. The fall in local variance between 4 and 8 kilometres suggests that at this scale the GAC sampling interval is already larger than the scene object size. For the same scene the HRPT curves rise steeply between 1 and 4 kilometres. The initial steep rise indicates the presence of scene objects around 2 to 4 kilometres in size. At this size it is quite possible for the objects to be missed by the GAC undersampling. The fact that the AVG data follows the HRPT suggests that the shape of the GAC curve is a product of undersampling rather than coarser resolution-cell size, in other words spatial information has been lost.

2.2.2. The savannah zone

The savannah region covered by the imagery used in this study has a Sahelo-Sudanian climate with vegetation types ranging from shrub savannah in the south to

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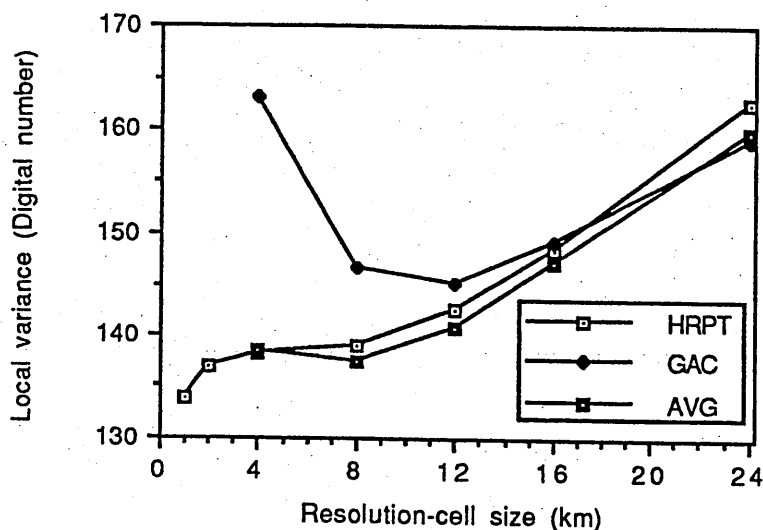
A. S. Belward

Figure 2. Graph of local variance as a function of resolution-cell size for the whole scene. (Channel 3).

grassland savannah in the north, with much of the region used for cereal crop production.

The cultivated areas mainly follow the drainage network, benefiting from the deeper cultivatable soils with higher moisture levels. This pattern can be seen in figure 4, a false colour infrared air photo taken in December 1980 (original scale 1:50 000) over the village of Nteguédo (8° 17' W 13° 08' N) in the Kati region of Mali.

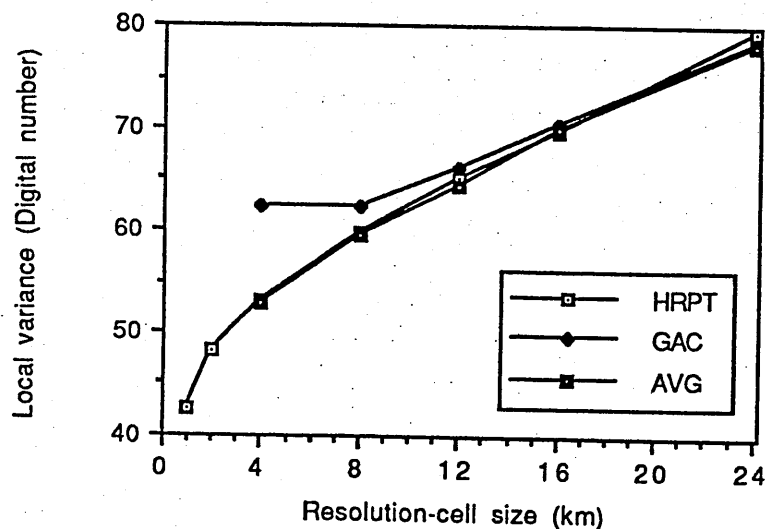


Figure 3. Graph of local variance as a function of resolution-cell size for the whole scene (NDVI).

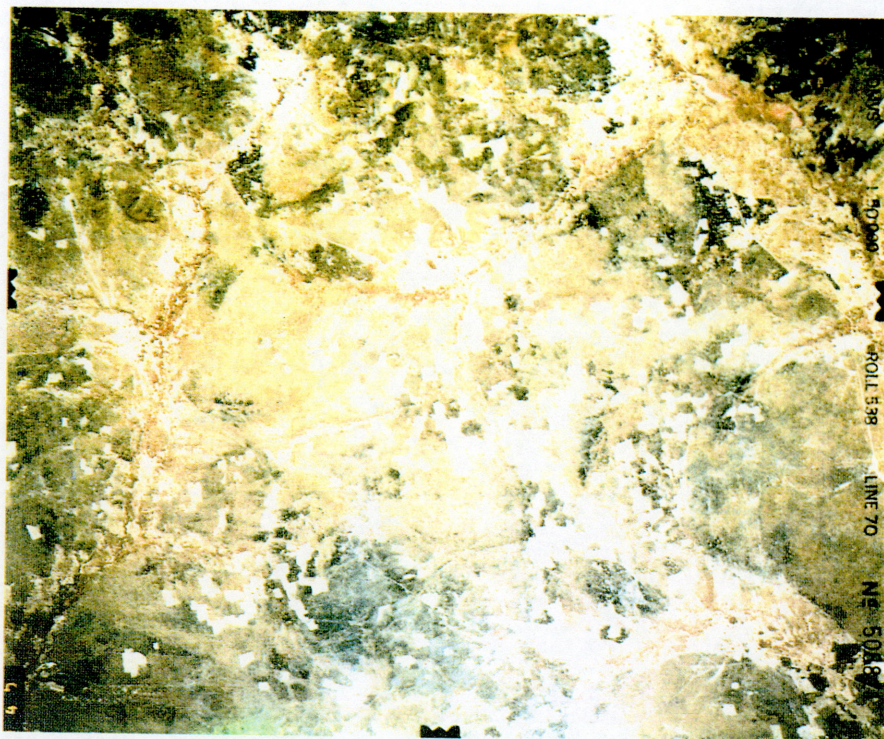


Figure 4. False colour infrared air photo showing cultivation around Nteguédo, Kati, Mali ($8^{\circ}17' W$ $13^{\circ}08' N$), December 1980, scale 1:100 000—original scale 1:50 000.



Figure 5. False colour infrared air photo showing shrub savannah, Manding plateau, Kati, Mali ($8^{\circ}21' W$, $12^{\circ}34' N$), December 1980, scale 1:100 000—original scale 1:50 000.

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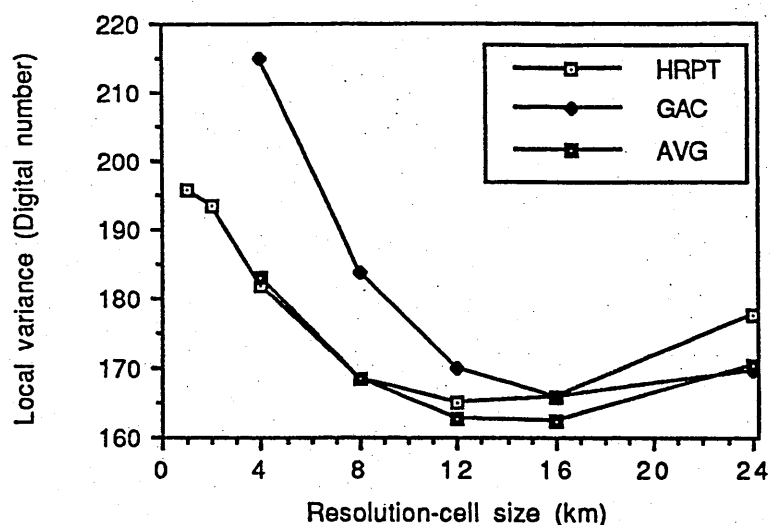


Figure 6. Graph of local variance as a function of resolution-cell size for the Savannah zone (Channel 3).

The shrub density in the savannah zone is highly variable, again largely being controlled by moisture availability, and thus also strongly linked to the drainage network. This can be seen in figure 5, a false colour infrared air photo which shows an area where there is almost no agricultural activity. Note how the shrub density decreases with increasing distance from the drainage channels. The photo was also taken in December 1980 (original scale 1:50 000) over the Gon-Koulou area of the Manding plateau (8° 21' W, 12° 34' N) again in the Kati region.

In terms of structural organization then, this savannah zone can be viewed as a background of open shrub and grassland areas laced by a network of drainage channels, generally around two kilometres across, supporting much higher shrub densities and agricultural production.

Such structural organization is not expected to be apparent in channel 3 dry season imagery as the combination of reflective bare soils and senescent vegetation with high afternoon surface temperatures is enough to saturate channel 3 for large parts of the savannah zone. This in turn leads to a lack of spectral contrast in the imagery and hence a lack of structure. All the curves in figure 6 show a decline in local-variance with increasing resolution-cell size characteristic of imagery with minimal detectable structure.

In contrast with channel 3 the dry season NDVI imagery of the savannah zone does reflect the structural organization of the region. The different soil types, higher tree/shrub density and irrigated crop production associated with the valley bottoms and sides give higher NDVI values than the background open bush and grassland savannah areas. The valleys appear on the HRPT NDVI imagery as a network of bright linear features, two to three pixels across, superimposed on a more uniform dark background. As expected, this is seen in the form of the local-variance/resolution graph, figure 7. As the HRPT resolution-cell size is increased from one to two kilometres the number of adjacent pixels falling within valleys decreases, and thus adjacent pixels are less likely to be similar and thus local variance rises. As resolution-

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cell size increases beyond two kilometres then fewer pixels fall entirely within individual valleys, pixels become a mixture of valley and surrounding background thus pixels are more similar and local variance falls. The resolution-cell size of the full resolution GAC data is already too large to detect structure at the scale of the valley formations.

2.2.3. The transition zone

The transition from shrub savannah in the north to more dense woodland and evergreen forest in the south is clearly defined in the dry season (Malingreau *et al.* 1989). The region has a Sudano-Guinean climate with a natural climax vegetation of moist semi-deciduous forest which has largely been replaced by tree savannah. A high incidence of bush fires is a characteristic of the dry season in the region. These are usually running fires characterized by intense but relatively narrow active fronts, less than 50 metres across (Grégoire 1990). The burned areas can reach many square kilometres in size. Figure 8 is a photograph taken in the transition zone shortly after such a fire started, the scars of a previous burn are visible in the foreground. The photograph in figure 9 more clearly shows the bare soil and dark ash left after a fire, the domed structures are termite mounds. These photographs were taken in the Kérouané region of Guinea (approximately 9° W, 9° 15' N) in January 1989.

The active fire fronts are ordinarily large enough to cause saturated or near saturated channel 3 pixels, usually forming linear patterns around one or two pixels across. In contrast with the more northern savannah zone channel 3 values are not generally saturated. Thus the fire pixels speckle the entire image in this zone, contrasting sharply with the much lower, and more uniform digital values of the surrounding intact tree savannah. Given the above it can be predicted that local-variance/resolution graphs from channel 3 data will show a peak in local variance at a resolution of around two kilometres on a side.

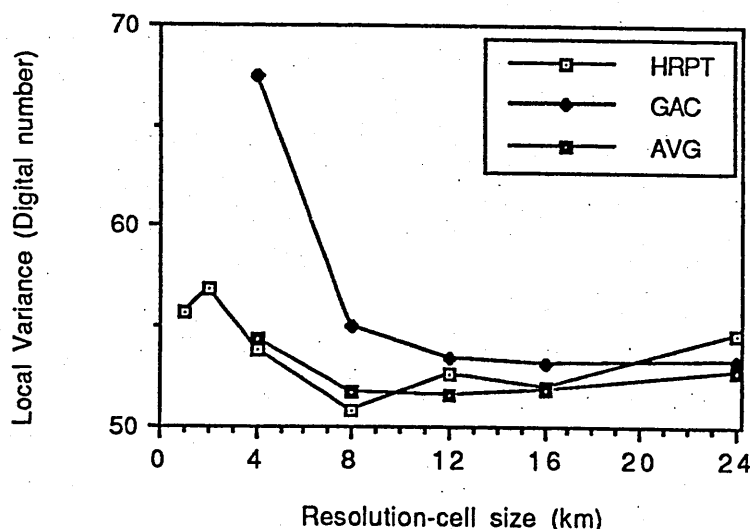


Figure 7. Graph of local variance as a function of resolution-cell size for the Savannah zone (NDVI).

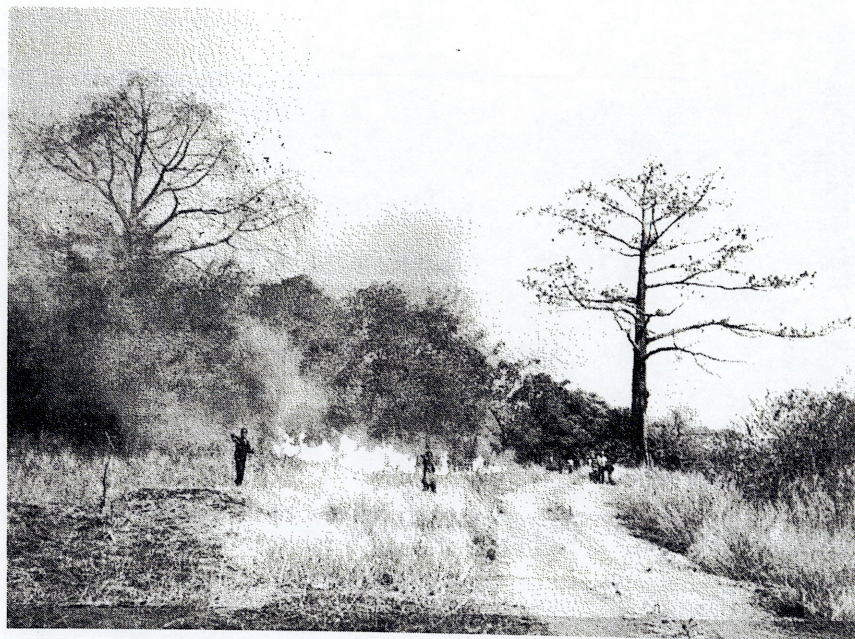


Figure 8. An active bush fire in the Kérouané region of Guinea (approximately 9° W, $9^{\circ}15$ N), January 1989—photo courtesy of J-M Grégoire. Fires, like this one, are started intentionally for many different reasons, for example path clearing, hunting, honey collecting by smoking out bees, insect/snake control, and to kill trees for fuel wood.



Figure 9. The site of a recent bush fire in the Kérouané region of Guinea (approximately 9° W, $9^{\circ}15$ M), January 1989—photo courtesy of J.-M. Grégoire. The large 'mushrooms' are termite mounds.

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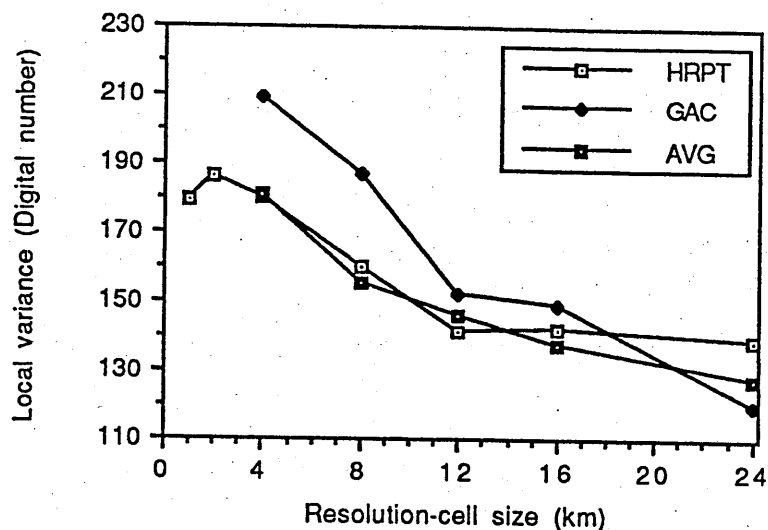


Figure 10. Graph of local variance as a function of resolution-cell size for the Transition zone (Channel 3).

Figure 10 shows how as the HRPT resolution-cell size is increased from one to two kilometres then fewer pixels comprise each fire so there is a greater likelihood of proximate pixels being dissimilar and local variance rises. Above two kilometres then pixels fall across the fires, rather than exclusively within them, neighbouring pixels are more likely to be similar and local variance falls. The line skipping in the GAC undersampling renders the resolution-cell size of the GAC data too coarse for consistent fire detection, at least in the West African context.

Figure 11 shows superimposed HRPT and GAC channel 3 data for an active burning front. Note the uniform image tone away from the fire front, indicating that the spectral information in the GAC and HRPT in this area are closely matched. The active front as detected by the HRPT is shown by the red pixels. The much larger GAC pixels are shown in blue. The near-white pixels appear where saturated GAC pixels are coincident with fire pixels in the full resolution data set. For the most part the fire front is missed by the undersampling used in the GAC generation.

The burning fronts of the bush fires go undetected by the NDVI, hence there is not the 'shot-gun' pattern of small fires superimposed on a more uniform background, instead the contrast between the low NDVI values from the dark ash of the burned areas and the higher values from the surrounding unburned tree savannah give structure of a different scale to the image. As the burns can cover hundreds of square kilometres a resolution-cell of 24 kilometres on a side is small enough for pixels to fall uniquely within either burned or unburned areas and thus have very different values. Thus we can predict that increasing resolution-cell size up to 24 kilometres will lead to increasing values of local variance. This is confirmed in figure 12 where all the curves show a consistent positive slope.

2.2.4. The forest zone

The forest region has a Guinean forest climate with a natural climax vegetation of dense moist evergreen forest. Those areas of evergreen forest still present are found in

blocks surrounded by more open degraded forest and dense woodland savannah. This can be seen in figure 13 which is part of a photo mosaic (original scale 1:50 000) derived from panchromatic air photos taken between 1977 and 1979. The figure shows part of the Diecke forest reserve in the Nzérékore area of Guinea (approximately 9° W, 7° 30' N). The contrast between the homogeneous forest block (in the bottom left quadrant) and the surrounding degraded forest can clearly be seen.

The forest zone shows very little variation in brightness temperature between the evergreen forest and the background of dense woodland savannah during early and mid dry season (Malingreau *et al.* 1989), thus neighbouring pixels are very similar. Increasing the resolution-cell size just increases the level of homogeneity hence the consistent negative slope of the curves in figure 14. Malingreau *et al.* (1989) showed that NDVI, in contrast to channel 3, can serve to separate the evergreen forest and dense woodland savannah. The blocks of evergreen forest are characterized by lower NDVI values than the open forest. The more intact canopy of the evergreen forest is thought to act as a radiation trap at near-infrared wavelengths, thus lowering NDVI values. Even with a resolution-cell of 24 kilometres on a side the stands of evergreen forest still form unique scene elements within the NDVI image. Individual blocks of

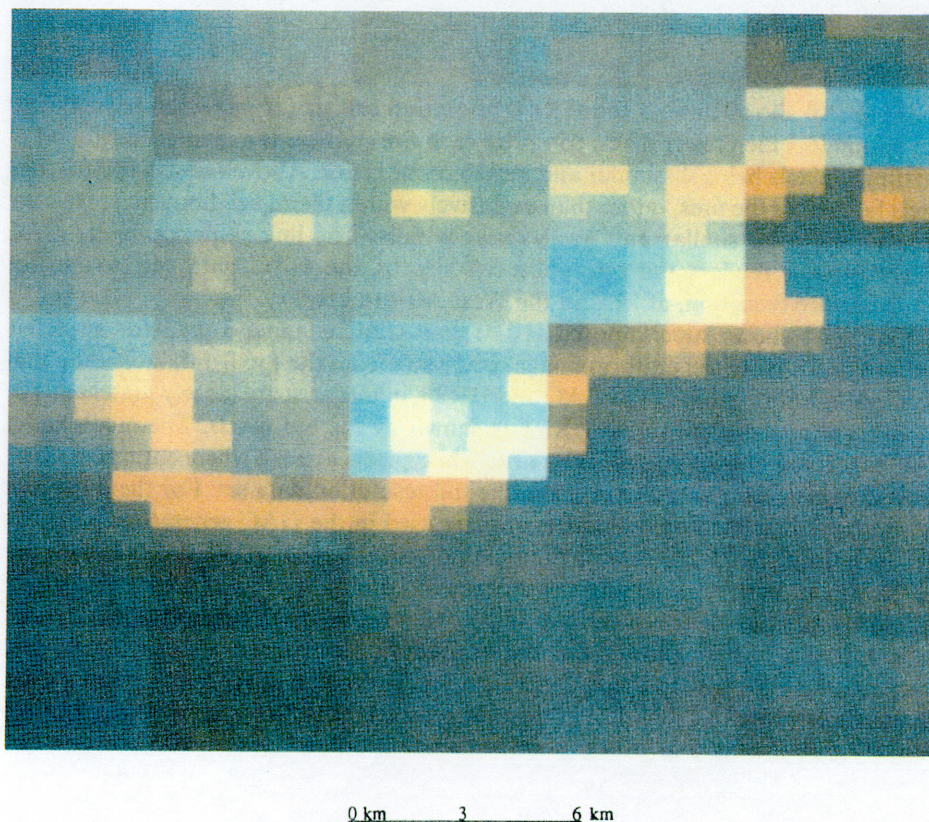


Figure 11. AVHRR GAC channel 3 data from 25 January 1988, superimposed on HRPT channel 3 data from the same date. The image shows how an active fire front, as detected by the HRPT (the red pixels), is largely missed by the GAC sampling process (the GAC fire pixels appear as near-white on the image).

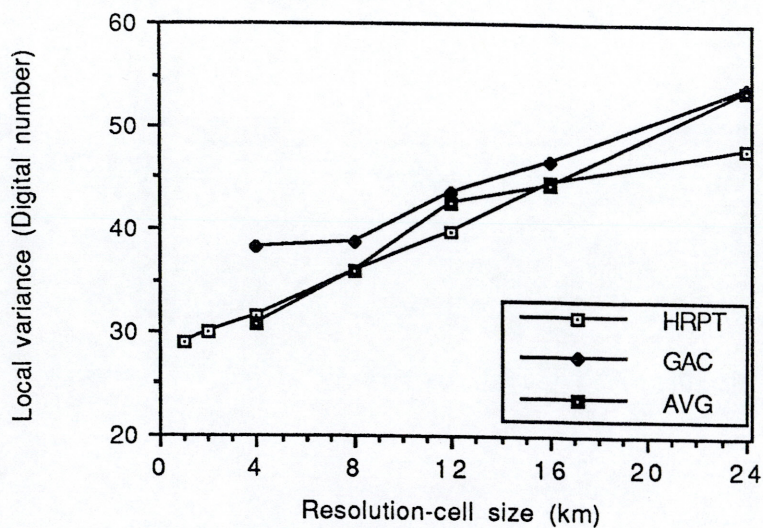


Figure 12. Graph of local variance as a function of resolution-cell size for the Forest zone (NDVI).



Figure 13. Panchromatic air photo mosaic covering part of the Diecke forest reserve in the Nzérékore area of Guinea (approximately 9° W, 7°30' N) scale 1:300 000—original scale 1:50 000.

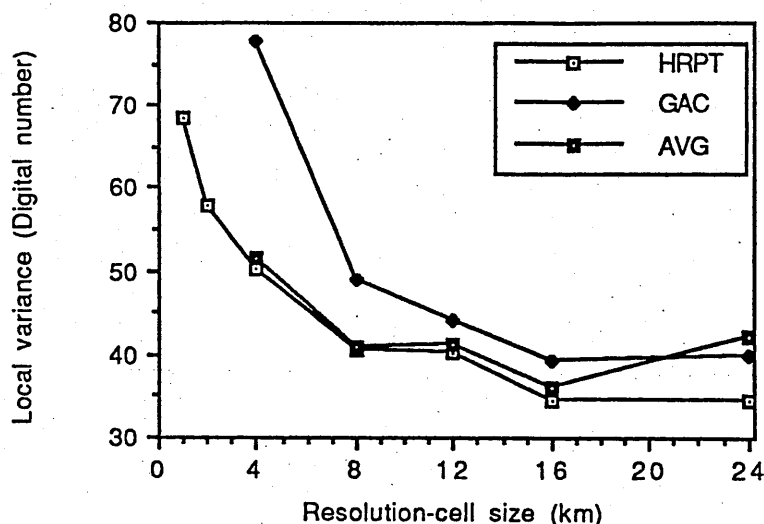


Figure 14. Graph of local variance as a function of resolution-cell size for the Forest zone (Channel 3).

forest can, in places, cover 40 kilometres or more (Centre Technique Forestier Tropical 1989) again leading to a situation where resolution-cell size never exceeds the size of all imaged scene objects, hence, in figure 15, we see a steady rise in local variance as a function of resolution-cell size.

3. Conclusions

There are considerable differences in the behaviour of local-variance/resolution graphs depending on the ecological zone covered by the imagery and on the part of the electromagnetic spectrum through which the data were recorded. The observed forms of the graphs can be predicted on the basis of recognizable physical scene elements. In the savannah zone structure related to land use is detectable (monitoring changes in landuse pattern has important implications for agricultural production forecasting), in the transition zone there is a clear link between structural character and the incidence of bush fires (bush fires are a major agent of change in tropical biomes, besides exerting considerable influence on atmospheric chemistry), and in the forest zone the observed spatial properties may indicate the distribution of remaining blocks of primary forest (deforestation is related to ecological issues ranging from global climate modifications to soil degradation and species extinction). It is thus clear that structural information relevant to environmental monitoring at regional scales is inherent in AVHRR HRPT data.

The results also highlight the effects on local variance of the undersampling in the GAC data generation. Values of mean local variance in the GAC data are much higher than in the HRPT and AVG data sets in both NDVI and channel 3 images for all ecological zones at resolution-cell sizes of less than 12 kilometres on a side. What is interesting to note is that at resolution-cell sizes greater than 12 kilometres on a side the behaviour of the GAC local-variance/resolution graphs more closely parallels those of the HRPT and AVG data. It has been suggested that the line skipping involved in the under-sampling reduces the autocorrelation between neighbouring

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GAC pixels, thus introducing high local variance into the images (Belward and Lambin 1990). The meaning of blocks of 3 by 3 GAC pixels used to create the 12 kilometre resolution-cell size would appear to smooth out this effect, i.e. at coarse scales the GAC provides comparable spatial information to the HRPT.

Furthermore, this study has clearly shown that spatial variability within sampling units of 12 kilometres and upwards does exist; in a number of the examples presented here the maximum resolution-cell size of 24 kilometres on a side was still smaller than scene object size, and recently Townshend and Justice (1989) have shown that detectable spatial information exists where resolution-cell size exceeds 100 kilometres. Scales such as these are relevant to many global studies, for example as input to general circulation models (Verstraete and Dickinson 1986). Indeed for studies carried out at regional to global scales coarser resolutions are desirable because of the reduction in data volume; processing continental scale HRPT resolution archives may be 'more manageable' (§ 1) than high resolution data but, as Sharman (1989) states, 'the processing of such an archive to a high quality in a reasonable time presents some formidable challenges'.

However, it must be stressed that this study is based on imagery from a single date in the dry season. As such it is impossible to establish hard and fast rules concerning the relationship between the spatial information in GAC and HRPT/LAC data. This is dependent on the nature of the scene's objects, and the changes in vegetation cover, in the incidence of bush fires and in the background surface temperature with changing season will be paralleled by transformations in the structural organization of the region. Indeed, observation and measurement of the dynamics of the land cover is crucial for environmental monitoring. If information from the spatial domain is to be fully integrated into such work, then it is important to establish if changes in surface characteristics result in detectable structural changes, and if relevant ecological and environmental information can be drawn from such temporal spatial behaviour. The example presented here shows that at least during the dry season of west Africa (1) structural variability, relevant to environmental studies can be detected at regional scales using AVHRR data; (2) that HRPT data can provide spatial information at full resolution, but that spatial information is unreliable from full resolution GAC data; and (3) at resolutions coarser than 12 kilometres degraded GAC data are as good a source of spatial information as degraded HRPT data.

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Scale considerations in vegetation monitoring using AVHRR data

J. P. MALINGREAU and A. S. BELWARD

Commission of the European Communities, Joint Research Centre, Institute for Remote Sensing Applications, 21020 Ispra (Varese), Italy

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Abstract. The Advanced Very High Resolution Radiometer (AVHRR) is currently the only operational remote sensing system capable of providing global daily data which can be used for vegetation monitoring. These data are available with resolution cell sizes ranging from around one to 20 km on a side, though the temporal and spatial extent of cover at each resolution is variable. In this paper Normalized Difference Vegetation Index temporal curves derived from AVHRR at different resolutions are compared over both agricultural and natural tropical vegetation types. For the agricultural regions the length of growing season and major breaks of slope associated with key crop development events are equally well shown at coarse and fine resolution. Detailed examination of the curves reveals differences thought to result from temporal changes in landscape structure. Temporal curves derived from AVHRR data at different spatial resolutions shows that the spatial organization of both agricultural and natural landscapes, tropical forest in this case, changes throughout a single season. Transitions across major ecological zones are detected across a range of resolutions, though the undersampling employed in the generation of the coarser resolution products is found to exert some limitations on the spatial representivity of these data; this varies both with geographical area and time. These observations highlight the importance of a consideration of scale when using AVHRR data for vegetation monitoring, and emphasize the need for different scales of observation (both in temporal and spatial terms) for different problems and at different times of the year.

1. Introduction

Recent developments in biosphere studies have considerably expanded the range of scales on which ecological problems are investigated. The growing realization that ecological systems are not only affected by physical and biological processes operating at proximate scales, but that they are equally controlled by factors acting over a variety of temporal and spatial scales has been instrumental in bringing about such renewed interest. In the past ecological studies have generally been carried out on scales of manageable dimensions (i.e., the field observation plot) and as a consequence, the emerging generation of global problems have often been met with serious methodological shortcomings (Dyer *et al.* 1988).

A second development pressing the scale issue relates to the availability of computational and observational techniques. Computer models are fairly scale independent and can be operated, albeit at a cost, at various levels of complexity linked to spatial organization or temporal sampling (Avissar and Verstraete 1990). Observations provided by remote sensing techniques can measure ecosystem parameters at repeated intervals and over areas of variable size. The choice of scale for ecological studies, hitherto guided by research objectives but in reality limited by the

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constraints of field measurements, is now increasingly open and bound mainly by the development of the instrumentation. Progress in this sector has been fast and it is realistic to forecast that we will soon be faced with more scales than can be handled, especially considering that ecological concepts for interpreting the spatio-temporal arrangements revealed by satellite data are still in their infancy. Furthermore, computational and observational requirements have changed current perspectives so that rather than viewing heterogeneity and variability as frustrating complications, these can now be considered as intrinsic characteristics of landscapes and ecosystems. One of the current challenges in remote sensing is to determine how well understood processes operating at scales of metres can be integrated upward in larger spatial units. This, in turn, will lead to a better understanding of the ground resolution needed and number of observations required for the monitoring of such processes.

Of course the choice of ground resolution and number of observations needed to build a time series of satellite sensor data should principally depend upon the intended application. With regard to the analysis of vegetation dynamics both these factors can vary. In some circumstances, such as in operational crop monitoring, specific phenological stages of a crop are sought. In others, such as in an early warning system, a continuous watch must be maintained to detect anomalies in plant development, especially during critical stages. The number of observations can thus vary not only according to the type of application but should even be adapted as the season progresses. In natural ecosystems a study of primary productivity (a continuous process) needs to be based upon a fairly frequent series of measurements, while a parameter like the length of growing period can be derived from a few measurements at the beginning and end of the season. There are unfortunately few studies comparing contemporary time series of satellite data obtained with different pixel sizes over a given area, yet it is only through the assemblage of long time series that statements can be made regarding the respective advantages of one spatial scale or another for monitoring. Indeed, the spatial aggregation of features in coarse resolution imagery is likely to vary as the landscape mosaic evolves through time. During periods of uniform cover, coarse resolutions may suffice while during periods of high spatial variability a higher resolution will be needed. Such flexibility in adapting observation instruments and sampling methods to landscape dynamics is not yet possible but will have to be increasingly examined when confronted with the global data bases of future platforms (Salomonson *et al.* 1989).

This paper considers some of these issues with respect to vegetation monitoring through the examination of contemporary sets of satellite sensor data having different ground resolutions. Advanced Very High Resolution Radiometer (AVHRR) data from the U.S. National Oceanic and Atmospheric Administration's (NOAA) NOAA/TIROS-N platforms are used since these satellites are currently the closest to an operational Earth observation system on the global scale. Vegetation monitoring on this scale, at present, relies heavily on coarse resolution sampled data sets, as full resolution data are still only selectively available in terms of space and time. Given the variations in areal and temporal cover there is a need to assess the effect of different spatial resolutions on information content and on the derivation of temporal profiles. The paper focuses on time series of such data for vegetation monitoring over selected tropical and subtropical ecosystems and upon features related to fire, a growing disturbance factor in tropical vegetation. The information content of series of measurements obtained over natural landscapes at different

scales is explored, with particular emphasis placed on the effect of changing the ground resolution upon the evolution of time series of data.

2. Scales

When investigating the problem of scale in remote sensing it is necessary to examine both the temporal and spatial dimensions of any data set. Within the spatial domain we make the following threefold distinction: The intrinsic scale (grain) is a property of the ecological process of interest, for example, tree fall, competition, stomatal control or microclimatic feedbacks. This intrinsic scale is governed in part by the size of individual organisms (or events) and in part by the range of their interactions with the environment. Ideally, this dimension has to be matched by a measurement scale which, in remote sensing terms, is the size of the area on the ground from which measurements are derived. Each individual measurement gives rise to a pixel and the assemblage of pixels forming an image may be visually represented at a certain geographical scale which is the ratio of the distance between any fixed points on the displayed image (or map derived from such an image) and the actual distances between the corresponding points on the ground.

Inconsistencies between these scales can be a source of confusion when interpreting and presenting data. Associated problems are best put as a series of questions. First, can patterns detected at a given measurement scale be linked with specific ecological processes, and how can changes in patterns lead to the prediction of changes in ecological processes? Secondly, when measurement scales are not attuned to the intrinsic scale of a specific ecological process, can inferences be made regarding this process, or do new concepts have to be developed? Thirdly, can the geographical scale of, for example a map derived from an image, be made compatible with the measurement scale of the image used in its preparation?

The temporal domain can also be characterized by three distinct properties. The first characteristic to consider is the natural cycles of the components of the biosphere. These are partly controlled by endogenous rhythms and to a larger extent by the dynamics of external forcing factors. Interactions among the major components of global systems also proceed at a certain pace and response times may vary. Feedbacks, which are deemed so important in the regulation of biosphere-atmosphere interactions, are a case in point. The second characteristic to consider relates to the frequency of observation and measurement. Remote sensing data on any given area are acquired with a certain frequency, dependent upon orbital and instrument parameters. The amount of useful data may be reduced by adverse atmospheric conditions such as clouds, and the frequency of observation is therefore not a well controlled factor. Yet meaningful information can only be obtained if the frequency of observation matches, or samples in a representative manner, the natural cycle of the ecological process of interest. Finally, since many ecological processes have long term dynamics, especially those under the generic heading of global change, it is essential to consider the time-horizon over which data are available. Data accumulation over decades and more are necessary before it becomes feasible to assess trends, normality of seasonal behaviour, effects of continuous forcing functions, frequency of episodic events and surprises (Holling 1986). This raises technical issues such as long-term calibration of sensors and policy issues such as the commitment to consistent measurements over extensive time periods.

The temporal and spatial aspects of scale are intimately linked at the ecological process scale (Delcourt *et al.* 1983, Dyer *et al.* 1988). Remote sensing data are

characterized by variable temporal scale, being usually composed of short, irregular time series, but the spatial scales are consistent. The space-time arrays of data yielded by satellite observation systems are thus heavily slanted toward the spatial dimension. Discussion in the literature mainly examines spatial resolution alone (Woodcock and Strahler 1987, Belward and Lambin 1990, Belward 1992); so far there appears to have been little attempt to study the time dependency of spatial variations. The availability of appropriate time series of remote sensing data at relevant spatial resolution is indeed controlled by a difficult compromise between frequency of coverage, ground resolution and geographical extent of coverage (Townshend and Justice 1988, Townshend and Justice 1989, Justice *et al.* 1989). When deciding on the right combination of such parameters, rules of thumb are not easy to adopt even if we intuitively know that it is not possible, say, to cover the whole world daily at high spatial resolution. What is in the realm of feasibility both from an interpretation and a data management point of view is still a matter of debate.

3. AVHRR data available for scale comparisons

The AVHRR data used in this study are from the Global Vegetation Index, Global Area Coverage, Local Area Coverage and High Resolution Picture Transmission archives. These are described below in terms of spatio-temporal scales following the distinction proposed in the introduction.

3.1. High Resolution Picture Transmission

The real time High Resolution Picture Transmission (HRPT) from the NOAA platforms includes AVHRR full resolution digital data for all five channels at 10 bit radiometric resolution. The pixel aspect ratio changes from almost 1:1 at nadir (resolution cell size of 1.1 km) to 1:2.9 at extreme view angles (resolution cell size 2.4 km along track by 6.9 km across track). The measurement scale of the raw data is thus not constant. For most applications the raw data are transformed to some specified map projection, both to aid location and analysis of the data, and to facilitate the production of thematic output at specific geographical scales. This process involves resampling of the data, usually to a pixel size equivalent to a ground resolution cell of 1 km². Such a procedure introduces a false sense of scale to the HRPT data. Further complications arise because the spatial resolution of any sensor is dependent on the interaction between system characteristics and terrain characteristics (Forshaw *et al.* 1983), thus the intrinsic scale of objects detectable with HRPT data will depend on the spectral region used to make the observation and the physical characteristics of the objects in the observed scene. For example, discontinuities in the case of the thermal channels arise because of sensor saturation (Kaufman *et al.* 1988); these may be due to intense thermal features much smaller than the nominal spatial resolution, or larger but less intense phenomena. It may thus be difficult to make precise statements regarding the information content of HRPT data at the pixel level. An area this size will usually include a mix of cover classes. Recent work has shown that improvements in the land cover discriminatory capacity of AVHRR can be made by adopting a mixture modelling approach. This relies on the use of high resolution remotely sensed data (Landsat Thematic Mapper) to classify the mosaics which make up individual AVHRR pixels and use this information to weight the pixels' components in subsequent analysis (J. Settle

and N. Drake, personal communication, Achard and Blasco 1989, Iverson *et al.* 1989).

AVHRR HRPT thus provides an integrated view over an area of around one square kilometre at nadir. Such observations, if made on suitable temporal and geographical scales, can provide information relating to the dynamics of ecological parameters such as the structure, composition and phenology of plant communities, to canopy physical parameters, and to their collective response to external forcing functions.

The orbital geometry and swath width of the NOAA AVHRR system are such that one daylight pass per day is obtained, though useful cover is restricted by extreme off nadir viewing. This represents a maximum, as clouds and other forms of atmospheric degradation can corrupt, or block the image. The geographical extent of HRPT cover is limited to the area in which the satellite is in direct line of sight of the station's antenna. This will vary depending on the station's latitude and the antenna elevation used; cover is at least in the order of 18 to 20 million km² surrounding the station. Thus regional, if not continental, cover can be assured by a single station.

Whilst it is clear that certain environmental phenomena have a life span which may be measured in hours or days, changes in evapotranspiration rates or bush fires for example, it is also known that other environmental changes occur over longer periods. The need for an historical perspective and long time series as inputs to environmental modelling processes calls for a time horizon of years. The time horizon of the cover varies from station to station; there is currently no systematic inventory of HRPT archive holdings on a global basis.

3.2. Local Area Coverage

Local Area Coverage (LAC) are again full resolution 1·1 km, 10 bit data, though recorded on-board the satellite, rather than directly transmitted to a receiving station. This offers considerable advantage in terms of geographical scale of cover. Unfortunately for any given day only partial coverage of the Earth's surface can be guaranteed as the capacity of the on-board recording facilities is not enough to allow data acquisition for every orbit. Acquisitions are based on user requests, which always exceed capacity; further, requests are given a priority ranking and scientific investigations come fifth out of the sixth (Kidwell 1986).

Because of the nature of LAC data acquisition the geographical extent of the cover and the temporal characteristics are not consistent. Data may or may not be available for a given region, sequential days data may or may not have been recorded, and the length of the archive will vary from region to region.

3.3. Global Area Coverage

Global Area Coverage (GAC) are reduced spatial resolution 10 bit data again recorded on-board the satellite. The GAC data are generated by on-board sampling of the full resolution data using the following well known method: for a given scan line the first four pixels out of every five are averaged, and only every third scan line is processed. This gives a spatial resolution, at nadir, of 1·1 km by 4 km, with a gap of around 3 km between pixels across the scan lines, although the data are generally treated as 4 km resolution (Kidwell 1986). Such a sampling scheme is far from

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optimum (a simple average of all 15 pixels has been shown by Justice *et al.* (1989) to be more representative of LAC/HRPT data), but it does result in a considerable reduction in the volume of data.

The reduction in data volume has two important implications for environmental monitoring. First, the reduced data volume is such that the on-board recording facilities are able to preserve complete daily global cover. Secondly, the lower data volumes make the processing of long time-series over large geographical areas a more realistic proposition.

The GAC data set offers daily cover for the last decade (the global GAC archive dates back to June 1981). The geographical scale is such that data are available for virtually any terrestrial environment. However, the advantages in terms of data volume, extent and frequency of cover are offset by the reduced measurement scale and associated changes in information content.

3.4. Global Vegetation Index

Global Vegetation Index (GVI) data differ from the preceding data types in that they are only available as mapped 8 bit data, rather than the raw (albeit under-sampled in the case of GAC), 5 channel, 10 bit data of the HRPT/LAC and GAC products. The GVI data set consists of a geophysical product, the Normalized Difference Vegetation Index (NDVI), plus channels 1 and 2, truncated to 8 bit precision (from 1982–1984) and channels 1, 2, 4 and 5, where 4 and 5 are converted to 8 bit GOES counts corresponding to temperature values (from 1985 on). The NDVI is calculated from the day time passes of all 14 daily orbits of GAC data. From May 1982 to March 1985 these are mapped onto a polar stereographic projection with a resolution cell size of 15 km at the equator, and from April 1985 to the present a Plate Carrée projection (16 km at the equator), and a Mercator projection (19.5 km at the equator) are used. Only one GAC pixel is selected for each GVI pixel: depending on the period this single pixel is selected either systematically or randomly as explained in the NOAA Global Vegetation Index Users' Guide (NOAA 1986). The final product is the result of compositing the daily arrays over a seven-day period such that the maximum NDVI value, (and equivalent channel 1, 2, 4 and 5 values) are retained for each location. Thus the GVI is produced by both spatial and temporal sampling of the GAC data.

The GVI data set provides a weekly synthesis of NDVI activity expressed as maximum value composites, over a similar period to that of the GAC data it is derived from, being more than 10 years (the global GVI archive dates back to May 1982). The geographical extent of the data varies between first and second generation products, but is essentially global: first generation Polar Stereographic products give close to complete Earth cover, second generation Plate Carrée arrays (and also the Polar Stereographic and Mercator arrays produced from the Plate Carrée) cover the region between 75° N and 55° S.

The massive undersampling involved in the creation of the GVI products severely limits the use of these data for studies requiring precise location or detailed spatial information. However, the advantages for studies on continental to global scales in terms of the temporal scales of these data and the reduced data volumes cannot be ignored (Justice *et al.* 1985, Townshend and Justice 1986, Malingreau 1986).

4. Combining space and time dimensions in AVHRR analysis

4.1. GVI time series at various aggregation levels

To explore the relationship between the spatial and temporal scales of AVHRR data, we have progressively increased the resolution cell size of the GVI by averaging neighbouring pixels to cover increasingly large areas on the ground while remaining within the confines of a given ecosystem. The first case presented here is from an area of East Asia where double rice cropping is practised (Jiangsu province, People's Republic of China). The resolution cell size selected for the time series was increased from one pixel to a square of 6 by 6 pixels. Figure 1 shows monthly NDVI means for the period April 1982 to December 1984 at each resolution.

As the larger area (the 36 pixel sample) contains the smaller (the single pixel) the two are not statistically independent and one would not expect the curves to differ greatly. However, the curves do behave differently depending on the season. In each of the three years the first rice crop reaches higher NDVI values for the 36 pixel sample mean than for the single pixel sample, while for the second rice crop the NDVI values are much closer. On the basis of this data set we can say that the first crop seems to be more heterogeneous than the second; a homogeneous scene would (within the confines of the rice growing area) give the same NDVI curve at either resolution. The difference in scene homogeneity is likely to be due to variations in the spatial organization of the vegetation, but could also be related to differences in atmospheric uniformity during these two periods; in either case it is only through the examination of time series covering the same ground area at different resolutions that such anomalies can be detected. The scale comparison applied to temporal series thus carries information of interest for a better understanding of vegetation dynamics at the agro-ecosystem level. A systematic investigation of such relationships is however necessary to determine rules of aggregation for different vegetation associations.

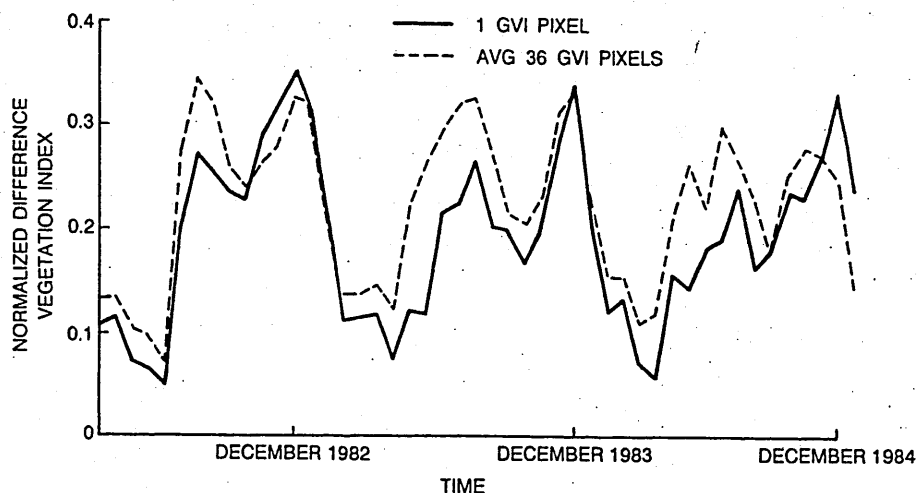


Figure 1. Normalized Difference Vegetation Index curves at two AVHRR GVI pixel aggregations over an area used for double rice cropping in the Jiangsu province of the People's Republic of China.

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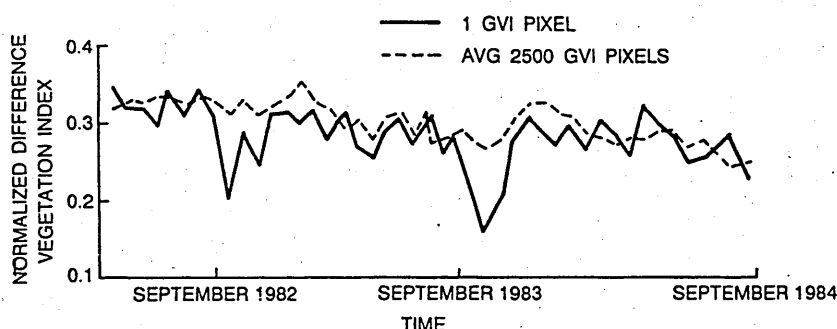


Figure 2. Normalized Difference Vegetation Index curves at two AVHRR GVI pixel aggregations over an area of the Amazon rain forest, Brazil.

To determine the consistency of spatial resolution—temporal spectral response from different vegetation types, the same GVI pixel blocking approach was adopted over a non-agricultural landscape, the Amazon tropical forest. Given the more extensive nature of the forest biome, in comparison with the agricultural production system, a greater range of resolution cell sizes could be examined. In this case NDVI time series were established for a series of samples ranging from one GVI pixel to a 50 by 50 pixel block centred on 60°E, 4°S. It can thus be considered that the sampling covers a range of scales from the ecosystem (the single pixel covered an area of 'pure' evergreen rain forest) to the biome level (the largest sample covers a mix of tropical vegetation including the flooded varzeas, evergreen and semi-seasonal forest, plus a very small percentage of agricultural land). NDVI development curves for the two extremes of the sampling range are shown in figure 2. A smoothing of the time series as one goes from 1 pixel to the average of 2500 pixels is clearly evident. At the resolution of a single pixel seasonal variation is clearly marked by periods of low NDVI related to the dry seasons around September each year, the impact of the 1983 drought is marked by a particularly obvious trough (Malingreau and Setzer 1991, and Malingreau 1990). Even at the 50 by 50 pixel level of spatial averaging a seasonal signal is still seen, but is more marked by the appearance of periods of high pixels values after the rainy season than by the presence of individual troughs.

When the NDVI time series from the single pixel is correlated with the NDVI time series from each of the coarser resolutions created through the pixel blocking we find that all the samples, including the average of 2500 pixels, show significant but decreasing coefficients of determination (r^2). Figure 3 shows the r^2 from each correlation as a function of the sample size used in the blocking (*nb* the sample size has been square rooted to show the trends in figure 3 more clearly). The decrease in the correlation between time series obtained at various levels of spatial resolution is not uniform, being rapid at first, then gradually levelling off. The particularly marked change around the 16 to 25 pixel sample sizes (approximately 90 000 to 140 000 km²) is a limit which may be related to some spatial arrangement of tropical forest formations in the Amazon Basin and should be further investigated. Once again, the nesting of various sample sizes appears capable of yielding information regarding the spatial organization of vegetation formations even at the more generalized levels of aggregation (biome, in this example).

4.2. GVI—GAC time series

The first data set presented here is from an agricultural area of the Ganges Plain where winter wheat and summer rice are grown in succession. One GVI pixel and

one GAC pixel, located as precisely as possible over the same coordinates are used to create the time series. The compositing period of the two time series differ slightly, being three-weekly maximum value composites for the GVI and 15 day maximum value composites for the GAC. Both vegetation index temporal curves, shown in figure 4, are smooth, being relatively free of the usual noise affecting such data sets. The overall form of the curves from each data set match well, with maxima and minima occurring at similar periods. In this region the length of growing season can be determined from NDVI by recording the period of time between two clearly defined breaks in slope (Malingreau 1986). Using this criterion the length of growing period can be determined equally well from either the coarse scale GVI data or the higher resolution GAC data.

Although in a general sense the two curves depict the same pattern of vegetation dynamics, specific differences can be seen. The maximum NDVI value recorded for the wheat crop is higher when observed with the GVI than the GAC, and for the rice crop, the GVI curve departs from the GAC curve during the greening-up period. Once again this difference may be due to sampling; remember that only one GAC pixel is selected as representing the ground area for each GVI pixel, and further, that this pixel can come from any one day out of the 21 day compositing period. Thus it is possible that the GAC and GVI pixels were selected from different locations in the ground area covered by the single GVI pixel (again this would only affect NDVI where the ground cover was not homogeneous) or indeed selected on different days (thus atmospheric conditions may be different).

When a GVI time series is compared with a time series from the average of all GAC pixels from which the GVI could possibly have been derived, rather than a single GAC pixel, we find that the differences in the curves is reduced, i.e. the differences attributed above to the spatial sampling involved in the GVI data generation are no longer so obvious. Figures 5, 6 and 7 show time series of NDVI (monthly averages for GAC and GVI) derived from the mean of four GVI

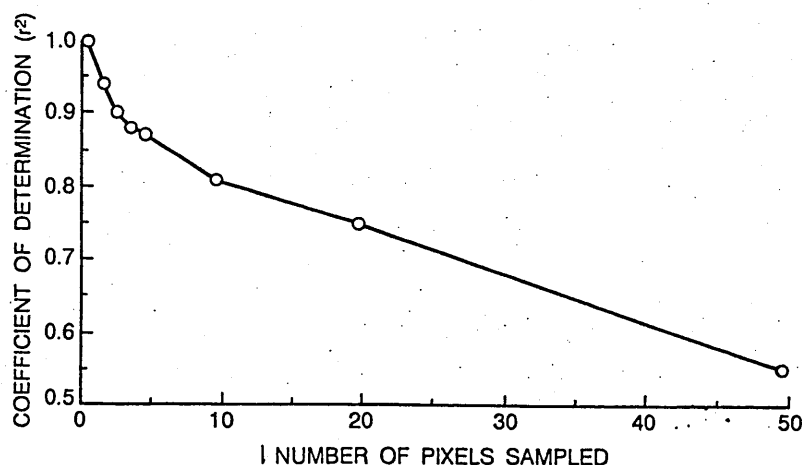


Figure 3. Graph showing the coefficient of determination (r^2) from the correlation of time series of NDVI from a single pixel and the same time series from coarser resolutions produced by averaging increasing numbers of pixels. Number of pixels sampled are shown as square roots for clarity. Time series are from the same data as in figure 2.

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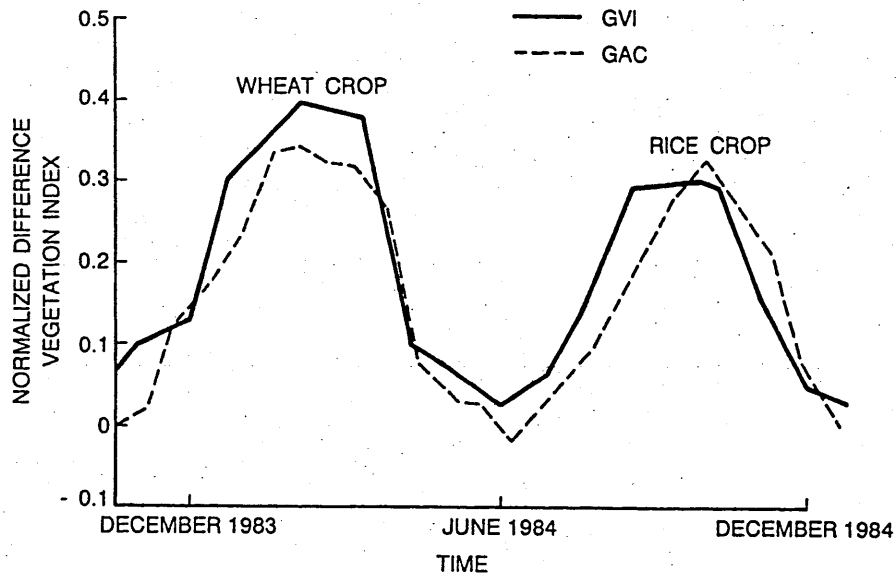
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Figure 4. Normalized Difference Vegetation Index curves at AVHRR GVI and GAC resolutions over an area used for winter wheat and summer rice cropping in the Ganges Plain, Bangladesh.

(Mercator, 19.5 km cell size) pixels, and an equivalent mean of 100 GAC (Mercator, 4 km cell size) pixels. The figures are from West Africa over the Mauritanian Sahara (figure 5), the Sudano-sahelian savannah in Mali (figure 6), and the Liberian tropical rain forest (figure 7). The GVI and GAC time series follow near identical trajectories for all three ecological zones. In other words the GVI can be seen to carry the same spatial temporal information as the GAC at these scales.

4.3. GAC—HRPT and the detection of fire events

The detection of the occurrence of specific events in the vegetation canopy is an important character of an observation system geared toward the study of global change. Such events are indeed often significant in terms of climatic and human

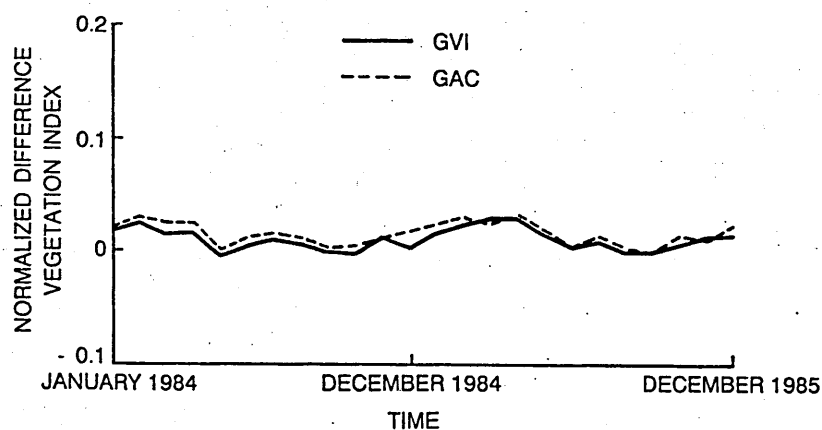


Figure 5. Normalized Difference Vegetation Index curves at AVHRR and GAC resolutions over the Mauritanian Sahara.

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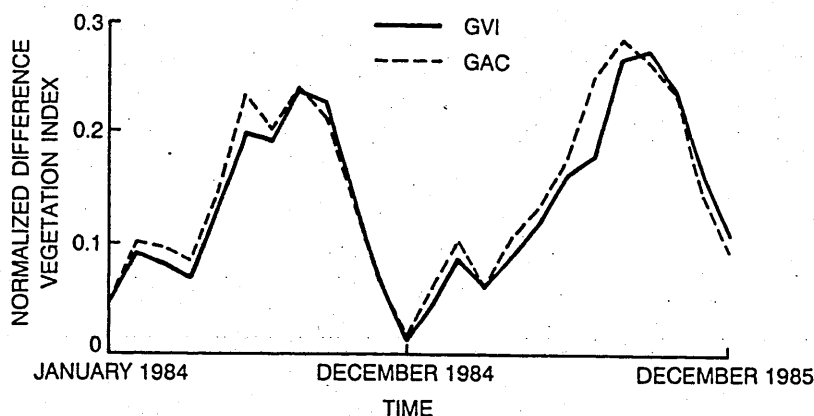


Figure 6. Normalized Difference Vegetation Index curves at AVHRR GVI and GAC resolutions over the Sudano-sahelian savannah of Mali.

impacts or in terms of vegetation adjustment to an evolving environment (IGBP 1988). The detection of drought impacts through the response of vegetation, as measured by satellite derived vegetation index, is a case in point (Malingreau 1987). The occurrence of fire, a growing disturbance factor in tropical ecosystems, is another important phenomenon; a better understanding of the role of fire in the dynamics of tropical vegetation, and of its impact on atmospheric chemistry, must be based upon an observation system which is responsive to the particular nature of these events. The system must be able to detect active fires and measure the burned area, further, both these parameters need to be related to particular ecological units: a fire covering 10 km² of forest will have quite different environmental implications to a 10 km² burn in an area of open bushland savannah (Malingreau 1990).

The consideration of scale is implicit in the design of any such system since the area to be covered is large (the entire tropical belt), fires are episodic events and burned areas range in size from single field plots a few square metres in size to whole landscapes. The AVHRR thermal channels and NDVI have frequently been used in

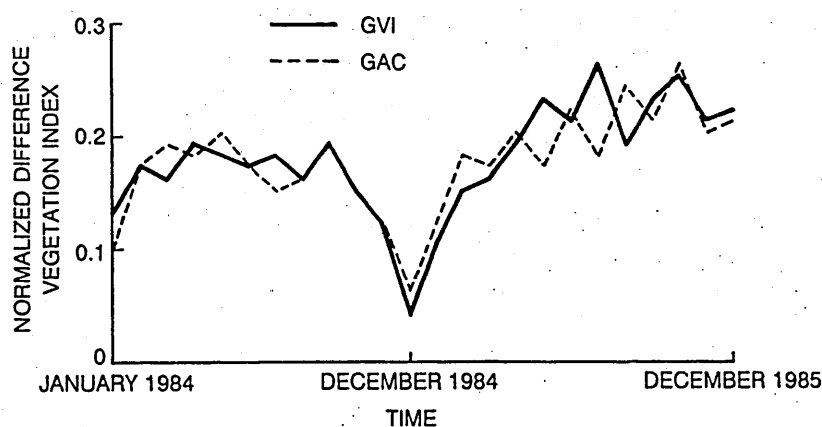


Figure 7. Normalized Difference Vegetation Index curves at AVHRR and GAC resolutions over the Liberian tropical rain forest.

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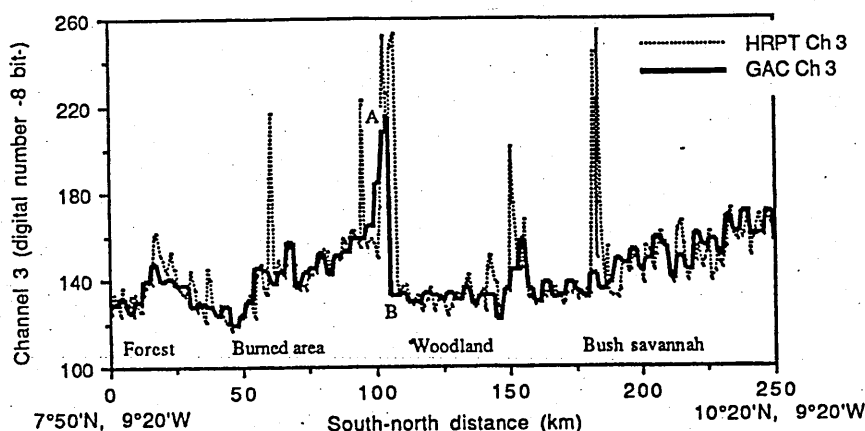
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Figure 8. South to north transect (runs left to right) from contemporaneous AVHRR GAC and HRPT channel 3 data from 25 January 1988. The transect is derived from 249 HRPT pixels and 83 GAC pixels each of which is repeated 3 times. Points A and B are described in the text.

fire studies, in particular channel 3 ($3.55\text{ }\mu\text{m}$ – $3.93\text{ }\mu\text{m}$) has been shown to be reasonably well suited to the detection of elevated heat sources such as bush and forest fires (Malingreau and Tucker 1986, Stephens and Matson 1987, Langaas and Muirhead 1988, Kaufman *et al.* 1989, Malingreau 1990) and NDVI has been successfully used to study fuel moisture content (Paltridge and Barber 1988); these publications show that even though there are spatial and radiometric limitations to the use of HRPT/LAC resolution AVHRR for fire monitoring these 1 km resolution data are potentially a valid basis for a global cover system. Unfortunately, as shown in §3, AVHRR (full resolution) data are not routinely available on a global daily basis, and the time-horizon is limited. At this stage it is difficult to use such data to obtain any consistent historical perspective on the spatial-temporal distribution of burning within the tropics. In order to guarantee global daily fire accounting the lower resolution data, principally GAC, have to be exploited. This immediately raises the question of the suitability of the measurement scale of the GAC data in relation to the intrinsic scale of the fire events and detection of the ecological units affected by the fire.

In order to assess this suitability we have studied HRPT data and contemporary GAC data from three dates during the first half of the 1987–88 dry season. The data are from the transition zone between the savannah and the forest domains of West Africa. Once registered this contemporaneous data set was used to obtain channel 3 and NDVI North–South transects. These run from the area of Nzérékoré to Kankan in Guinée (approximately $7^{\circ}50'N$, $9^{\circ}20'W$ to $10^{\circ}20'N$, $9^{\circ}20'W$). The results for 25 January 1988 are shown in figures 8 and 9 respectively.

The graphs derived from the GAC data and HRPT data are similar, especially for the NDVI. The boundaries between the ecological units are clearly visible at either resolution. The transect runs from forest in the south (0–20 km) to the boundary of a recent fire (25–45 km), through the burned area (46–90 km) to the northern active burning front (95–110 km), then through open woodland (115–140 km) and into bushland savannah (141–250 km).

The forest/fire boundary is obviously seen in the sharp fall in NDVI and a rise in channel 3. The dark ash left on the surface following the burn has very low

reflectance in the near-infrared wavelengths, hence the low NDVI values of the burn. The surrounding semi-deciduous forest and woodland in contrast, have higher NDVI values associated with green vegetation. The fire is marked by a rise in channel 3 value, associated with an increase in brightness temperature. The burned area itself is characterized by variable channel 3 values. The background channel 3 value is not much higher than for the bushland savannah at the extreme north of the transect. However, superimposed on this are the near to saturated pixel values associated with active fire sites. This is particularly evident at the northern woodland/fire boundary where the transect crosses an active fire front.

It is in relation to point phenomena, such as the fires, that the major differences between the GAC and HRPT transects can be seen. Point A in figure 8 is an example of where the HRPT pixels used to create the GAC pixel crossed by the transect were fire pixels, and thus the GAC data successfully identifies the fire at this locale. Point B in the same figure shows the opposite situation where the pixels skipped in the undersampling were the fire pixels. The NDVI is not characterized by the same high spatial frequency variations as channel 3 and in figure 9 one can see that the agreement between the two resolutions is generally much better.

Table 1 (descriptive statistics obtained from a 5 per cent random sample of the pixels covering the forest/savannah transition zone and the savannah of Sierra Leone and Guinea) shows how the agreement between the two data formats changes not only as a function of location, and thus spatial variation in ground cover, but also as a function of time and spectral range. These statistics are also presented in graph form as scattergrams, shown in figures 10 (NDVI data) and 11 (channel 3 data).

The correlation between the GAC and HRPT is generally much stronger in the NDVI than channel 3. Note also that as the dry season advances, from November, to January and February, the NDVI GAC/HRPT correlation improves; during this period vegetation activity slows down and many species begin to senesce. The contrast between the NDVI signal from different senescent vegetation types tends to be less marked than for active vegetation, thus the NDVI images tend to become

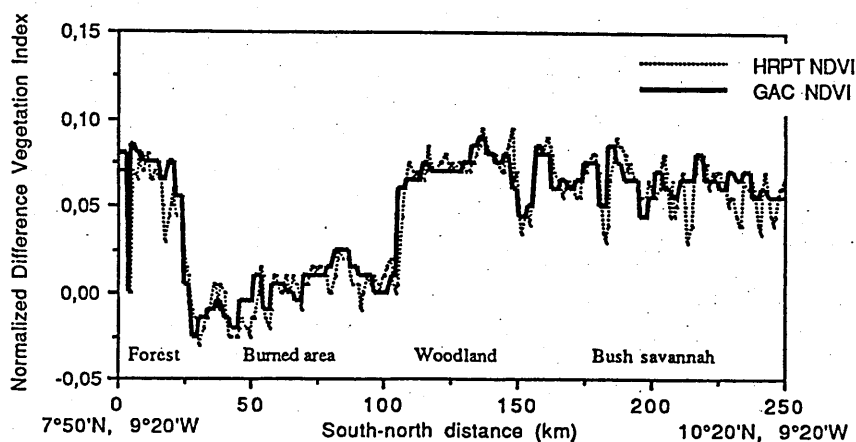


Figure 9. South to north transect (runs left to right) from contemporaneous AVHRR GAC and HRPT NDVI data from 25 January 1988. The transect is the same as for figure 8, again derived from 249 HRPT pixels and 83 GAC pixels each of which is repeated 3 times.

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Table 1. Descriptive statistics obtained from a 5 per cent random sample of all channel 3 and NDVI GAC and HRPT pixels over the savannah and the savannah/forest transition zones of Sierra Leone and Guinea for 22 November 1987, 25 January 1988 and 2 February 1988. The table also shows the correlation between each contemporaneous GAC and HRPT data set.

Ecological Zone	Channel 3						NDVI					
	November 1987		January 1988		February 1988		November 1987		January 1988		February 1988	
	HRPT	GAC	HRPT	GAC	HRPT	GAC	HRPT	GAC	HRPT	GAC	HRPT	GAC
Savannah	MIN	103	107	115	121	128	0-005	0-025	0-015	0-005	-0-01	-0-005
	MAX	250	193	252	201	222	0-22	0-18	0-16	0-15	0-13	0-125
	MEAN	133-88	133-44	159-69	158-84	156-97	0-109	0-106	0-08	0-078	0-041	0-039
	SD	13-44	10-62	15-55	12-90	12-03	5-42	4-62	4-57	4-03	3-55	3-31
	R ²	0-344		0-510		0-600	0-505		0-611		0-699	
Savannah/forest transition	MIN	91	101	80	108	113	0-005	0-07	-0-035	-0-035	-0-04	-0-04
	MAX	229	182	254	235	246	0-26	0-235	0-15	0-145	0-11	0-09
	MEAN	113-88	113-43	133-48	133-12	145-45	0-171	0-168	0-048	0-047	0-066	0-064
	SD	6-03	5-15	15-94	12-45	16-89	4-14	3-76	5-96	5-72	5-22	5-08
	R ²	0-436		0-365		0-390	0-720		0-859		0-862	

MIN = Minimum value, MAX = Maximum value, MEAN = Mean value, SD = Standard deviation, R² = Coefficient of determination.

more homogeneous, even at the measurement scale of the GAC data. Figure 11 shows how the scatter is reduced. This trend is equally obvious in the graphs for both the Savannah and transition zones.

The GAC HRPT correlations for channel 3 data are generally poorer. This can largely be attributed to the incidence of bush fires. Depending on the spatial characteristics of the fires, the undersampling of the full resolution data used to create the GAC may miss some potential fire sites whilst over emphasizing the importance of others (Belward and Lambin 1990). This is clearly seen in figure 11 where the main scatter is found at the high values, i.e., the fire pixels. The tendency for increasing scatter with increasing digital value is evident in all the graphs, however a definite temporal spatial pattern can be seen. At the beginning of the dry season bush fire activity is at a maximum in the northern savannah and moves south into the transition zone and forest areas as the dry season advances (Grégoire 1990).

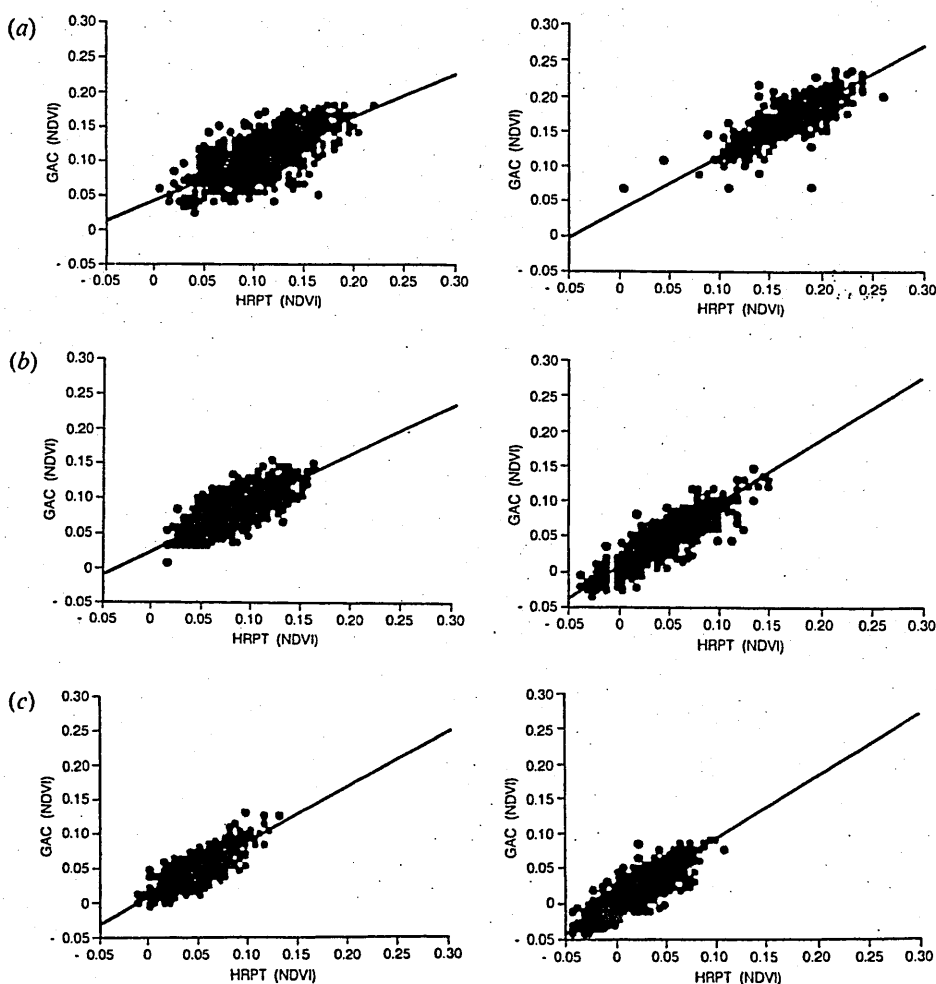


Figure 10. Scattergrams showing the correlation between contemporaneous GAC and HRPT NDVI data for (a) 22 November 1987, (b) 25 January 1988 and (c) 2 February 1988 over the savannah left column and the savannah/forest transition zones right column, of Sierra Leone and Guinea. The data are the same as shown in table 1.

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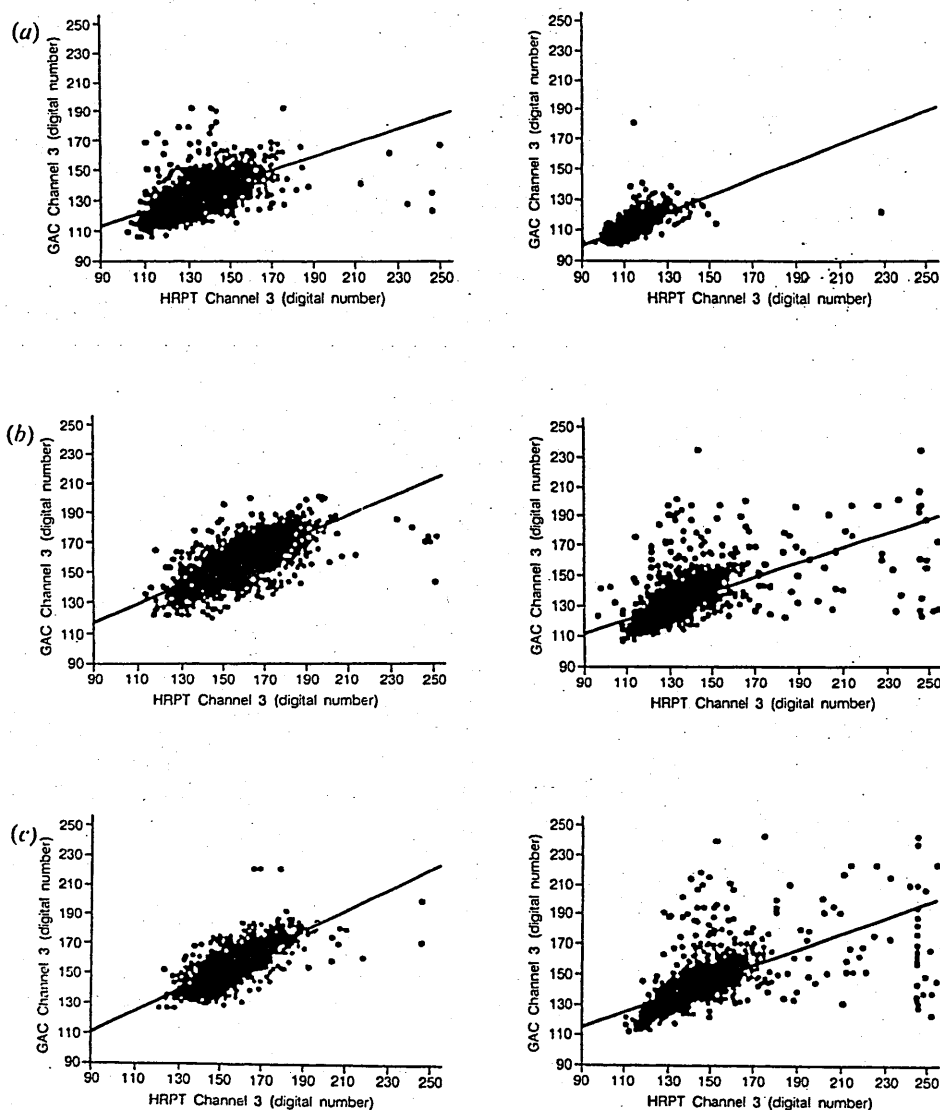
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Figure 11. Scattergrams showing the correlation between contemporaneous GAC and HRPT channel 3 data for (a) 22 November 1987, (b) 25 January 1988 and (c) 2 February 1988 over the savannah left column and the savannah/forest transition zones right column, of Sierra Leone and Guinea. The data are the same as shown in table 1.

Because the undersampling can either completely miss fires or over-represent the area actively burning, a high incidence of fire leads to poor correlation between the GAC and HRPT, hence early in the dry season (November) we have the poorest correlations in the savannah whilst it is later, January and February, that the poorest correlations are found in the transition zone. Thus we can see that the level of agreement between GAC and HRPT depends on time and geographical zone

(changes in either of which will lead to changes in the spatial distribution of ground features), and on the channels used. In this example the point phenomena associated with fires lead to increasingly poor correlation between channel 3 of the two data sets as we move south and as the dry season extends, whilst the same geographical and temporal progression leads to increasingly good correlations between the NDVI derived from each format.

5. Conclusions

The exploratory study presented here shows that information concerning environmental parameters can be obtained through a consideration of the scale of earth observations in both the temporal and spatial dimensions. The Earth observation satellite sensor data sets are currently reaching such large dimensions that their semi-empirical exploration using broad guide-lines can lead to new hypotheses. By doing experiments with data sets of extensive proportions such as those offered by the AVHRR, the spatio/temporal structure of the measurement, and in many cases of the ground features themselves, can be better approached. In addition, the exploratory method can be used to define guide-lines for a more flexible approach to the selection of scales in remote sensing.

The combination of time series and spatial scale appears to indicate that not only is there a level of information associated with a particular scale, but in addition, the transition from one scale to another itself carries useful information. The changing relationship between measurements taken at different ground resolutions is an important landscape characteristic which can be exploited to infer information on the spatial organization of, say, the primary production process. The dynamic characteristics of transition across scales should now be explored in terms of hierarchical organization of ecosystems, or assemblages of ecosystems; a first approximation shows that interpolation across scales is time controlled, and that at certain periods in landscape evolution, more intermediate scales of measurements may be needed. These preliminary assessments also point to a promising avenue of investigation in the detection of critical thresholds showing discontinuities in measured phenomena. Investigations of time series of satellite sensor data at various resolutions are also necessary for assessing the spread of external forcing functions such as climate anomalies, across ecosystems and biomes. It is clear that the richness of a multiple scale approach could be better exploited to design remote sensing analyses more responsive to scales of ecological features and processes.

The specific comparison related to biomass burning features shows, for example, the strong dependency of detection upon the spatial organization of the ground features. The existing global data sets (GVI and GAC), are both derived by the undersampling of higher resolution data sets. It is clear that such undersampling places limitations on the use of these data for surveys of point phenomena. The point phenomena, typical of burning in the tropics, can be diversely under-represented in some cases and spatially over-represented in others. The analysis of the ultimate sampling effect will not be complete, however, until more complete time series have been investigated. Once again, it will be important to assess if there is a periodicity in the scaling effect as one goes from fine to coarse resolution over fire scenes.

From the perspective of global monitoring, it is indeed crucial to determine the scale at which observations must be made to provide the required information. Considering the constant technical improvements in the resolution of observation

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instruments available to the civilian sector (10 metre ground resolution data are now available on a routine basis) it is equally urgent to address the question of the congruence between information needs and scale of observation. This may represent one way to prevent earth observations from being predominantly driven by technical know-how.

The spatial distribution of features at the surface of the earth is a key characteristic for classifying, monitoring and discriminating between components of the biosphere. We have shown that the interactions between surface features and the spatio-temporal scales are extensive and complex. Scale experiments of the kind reported here must now be systematically explored.

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Chapter 7. Use of AVHRR data for monitoring biomass burning as part of large area vegetation studies: Spatial and scale considerations

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Saturation du signal dans la bande 3 du senseur AVHRR: Handicap majeur ou source d'information pour la surveillance de l'environnement en milieu soudano-guinéen d'Afrique de l'Ouest?

J-M GREGOIRE, A. S. BELWARD and P. J. KENNEDY

Centre Commun de Recherche des Communautés Européennes - Etablissement d'Ispira Institut des Applications de la Télédétection T.P. 440 - 21020 ISPRA (VA) - ITALIE

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Résumé. Les enregistrements dans l'infrarouge moyen fournis par la bande 3 du senseur Advanced Very High Resolution Radiometer (AVHRR) sont utilisés, entre autre, pour la détection et la surveillance des feux en zone inter-tropicale. La méthode consiste à détecter les "points chauds" provoquant une saturation du capteur. Certains travaux concernant la zone soudano-sahélienne d'Afrique de l'Ouest, ont cependant montré que l'effet de saturation pouvait être provoqué par des états de la surface sans lien direct avec des feux actifs.

Il a été tenté ici de suivre la dynamique spatio-temporelle de saturation et d'en tirer des informations utiles en matière de surveillance des conditions du milieu dans la zone de transition entre milieux de savannes et de forêts d'Afrique de l'Ouest. L'approche s'est avérée riche d'enseignements et de potentialités dans quatre grands domaines: 1) associée à l'exploitation de l'indice Normalized Difference Vegetation Index (NDVI), elle permet d'améliorer les résultats de classification de la couverture végétale et du mode d'occupation du sol, la définition de nouvelles classes pertinentes aux échelles continentale et globale; 2) elle peut être exploitée pour la modélisation des échanges de chaleur et d'eau à l'interface biosphère-atmosphère; 3) elle constitue un cadre d'analyse pour la surveillance de l'activité des feux; 4) elle peut être utilisée pour le suivi des dynamiques de dégradation des écosystèmes.

Abstract. Saturation of data from channel 3 of the Advanced Very High Resolution Radiometer (AVHRR) is used as an indicator of fire activity in the soudano-sahellien zones of West Africa. Surface phenomena other than fire are also found to cause channel 3 saturation. The variation in space and time of saturation is found to be a potentially valuable source of information for environmental monitoring in West Africa. Results suggest that monitoring the spatial - temporal dynamics of channel 3 saturation 1) can significantly improve land cover / land use classifications based on AVHRR data when used alongside the Normalized Difference Vegetation Index (NDVI) and can help in the definition of new cover classes, particularly at continental and global scales 2) could play an important role in modelling energy and water exchanges at the biosphere - atmosphere interface 3) forms a framework for the analysis of fire activity and 4) could act as a good indicator of rapid ecosystem change.

Introduction

Couremment utilisés dans l'étude des conditions environnementales en milieu intertropical, et ce dans des domaines très diversifiés, (Malingreau and Kaswanda, 1986; Kerber and Schutt, 1986; Justice, 1986; Grégoire *et al.*, 1988; Yokoyama *et al.*, 1989; Belward and Lambin, 1989), les enregistrements dans l'infrarouge moyen fournis par la

bande 3 du senseur Advanced Very High Resolution Radiometer (AVHRR) suscitent depuis quelques années des controverses sérieuses au sein de la communauté scientifique. Les premières applications terrestres de ces données dans l'infrarouge moyen se sont vérifiées quelques années après celles basées sur les enregistrements visible et proche infrarouge (Townshend et Tucker, 1981) et furent probablement celles rapportées par Malingreau *et al.* (1985) dans le cadre d'étude des feux en Indonésie.

Associant une composante émise et une composante réfléchie, ces rayonnements permettent d'exploiter au mieux les contrastes thermique et visible entre couvert forestier dense et zones défrichées, ce qui les rend particulièrement utiles pour l'étude des processus de déforestation (Malingreau and Tucker, 1988).

Ces mêmes données ont été utilisées dans différentes régions de la ceinture intertropicale du globe (Matson *et al.*, 1987) et en particulier pour la détection et la surveillance des feux (Goldammer, 1990). Les travaux portant sur ce dernier thème, et concernant l'Afrique de l'Ouest, ont mis en évidence une limitation de ce type de données, à savoir la saturation du capteur AVHRR dans l'infrarouge moyen en milieu soudano-sahélien pendant une partie de la saison sèche (Langaas and Muirhead, 1988; Grégoire et Ferrari, 1989).

Pour certains, cet effet de saturation du capteur AVHRR dans la bande 3 constitue un handicap majeur en particulier pour la surveillance de l'activité des feux. Ce qui a incité de nombreux chercheurs à développer de nouvelles méthodes d'exploitation des données AVHRR.

Sans pour autant sous-estimer les limitations objectives liées à cet effet de saturation, on peut se demander si ce même inconvénient ne constitue pas une source d'information utiles pour la surveillance des conditions de milieu dans cette partie du globe.

Après un bref rappel du mode d'exploitation des données AVHRR 3 pour la détection et le suivi des feux en milieu inter-tropical, le travail présenté se propose de décrire la dynamique spatio-temporelle de ce phénomène de saturation telle qu'elle est observée sur un vaste espace géographique couvrant l'essentiel de l'Afrique de l'Ouest du Sénégal au Ghana et du Sud Saharien au Golfe de Guinée pendant la saison sèche 1988/1989. Suite à quoi, cette dynamique sera analysée plus en détail, pour les deux saisons sèches 1987/88 et 1988/89, sur un territoire plus restreint correspondant à la zone de transition entre milieux soudanien et guinéen d'Afrique de l'Ouest: dans la zone frontalière Guinée-Mali tout d'abord, sur les bassins des affluents du fleuve Niger en Guinée ensuite.

Les résultats de la recherche ouvrent des perspectives dans au moins trois domaines: la compréhension de la dynamique spatio-temporelle des feux, la caractérisation des processus de dégradation du milieu en fonction des domaines climatiques concernés, la modélisation des échanges de chaleur et d'eau à l'interface biosphère-atmosphère.

1. Méthode de détection et de suivi des feux à partir des enregistrements dans la bande 3 (infrarouge moyen) du senseur AVHRR

Le senseur AVHRR équipant les satellites de la série NOAA (National Oceanic and Atmospheric Administration) présente la particularité de fournir des enregistrements tant dans le domaine du visible que de l'infrarouge moyen et de l'infrarouge thermique; et ce sur une base régionale puisque la trace au sol est de l'ordre de 2700 km de large et avec une très haute répétitivité (24 h). Ces caractéristiques spectrales et spatio-temporelles font des images NOAA-AVHRR l'outil le plus adapté actuellement à la surveillance de l'activité des feux de brousse en zone tropicale.

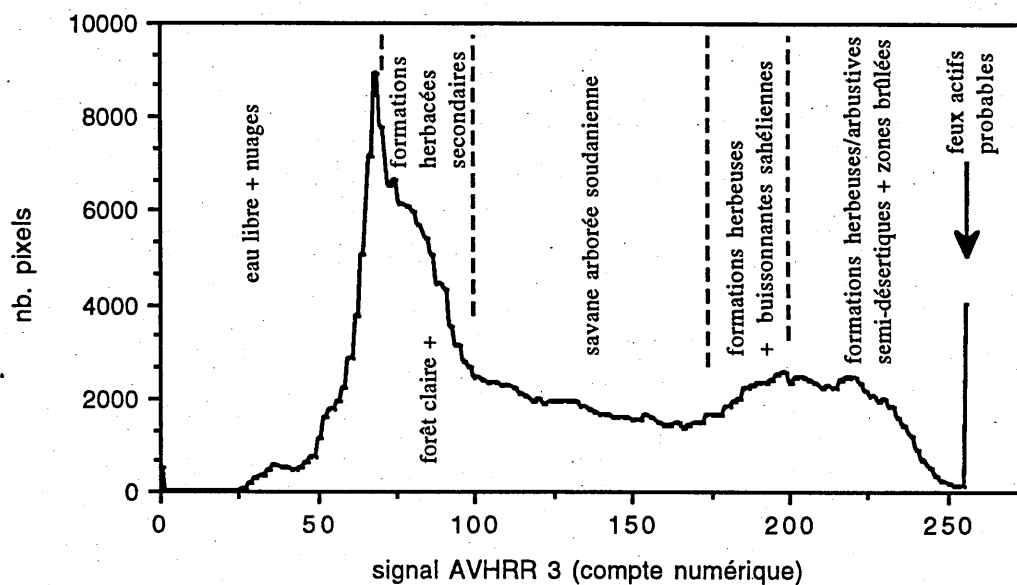


Figure 1. Histogramme de distribution des valeurs dans la bande 3 du senseur AVHRR enregistrée le 25 octobre 1988 en mode HRPT sur un espace de 250.000 km² au Sénégal.

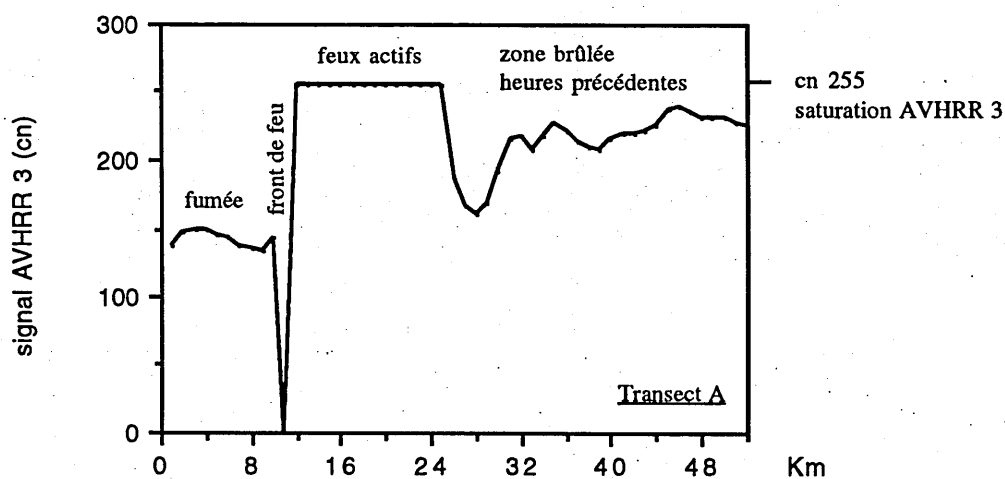


Figure 2. Transect radiométrique, dans la bande 3 du senseur AVHRR, en milieu de savane herbacée affecté par des feux actifs au Sénégal.

La détection des feux s'appuie en grande partie sur le repérage des "points chauds" c'est à dire des pixels présentant un signal très élevé dans l'infrarouge moyen (canal AVHRR-3 centré sur 3.5 μm) après inversion des valeurs en compte numérique. Il s'agit en fait d'éléments de l'image pour lesquels il y a saturation du signal dans cette bande spectrale.

La figure 1 illustre la position que ces "points chauds" occupent dans la distribution des valeurs dans l'infrarouge moyen; l'exemple présenté concerne un cas représentatif d'une situation de début de saison sèche en milieu soudano-sahélien d'Afrique de l'Ouest.

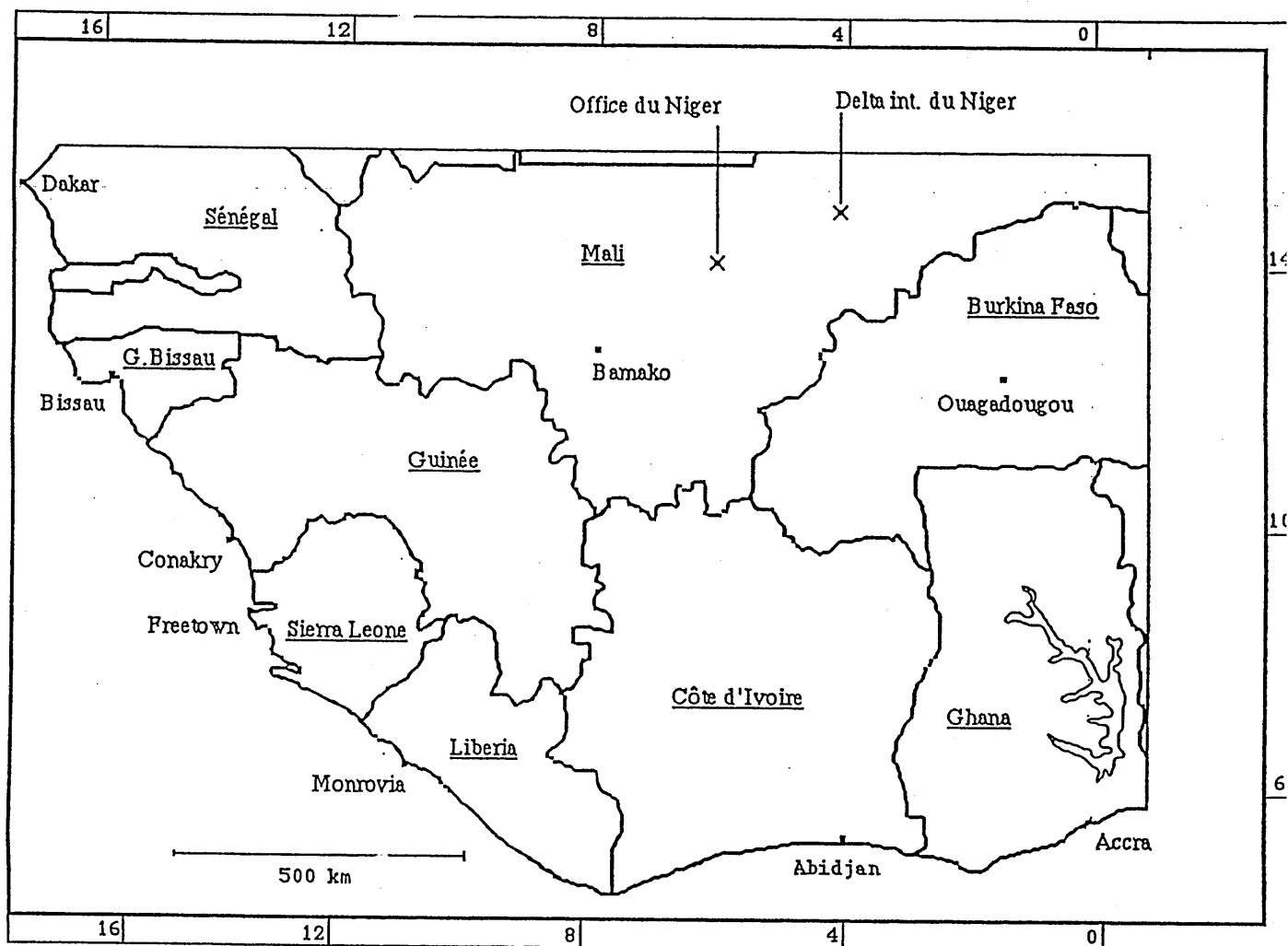
S'il est vrai que la présence de feux actifs au sein d'un pixel AVHRR provoque dans la majorité des cas une saturation totale du signal dans l'infrarouge moyen, c'est à dire des valeurs en compte numérique de 1023 sur la figure 1, il est également vrai que des feux de taille très réduite ou des événements de feu se vérifiant quelques heures avant le passage du satellite peuvent ne pas provoquer une saturation du même signal. La figure 2 illustre cet aspect du problème par le biais d'un transect radiométrique recoupant des feux actifs en milieu de savane herbacée au Sénégal: partant de ce type de résultats et de travaux antérieurs concernant la surveillance des feux en Afrique de l'Ouest (Grégoire, 1990), il est permis de penser qu'un seuillage à 1023 est quelque peu restrictif pour le suivi des feux dans cette région et à cette période de l'année. Il a donc été adopté un seuillage à 960 et, tout au long du texte qui va suivre, la notion de "saturation" du signal infrarouge moyen est définie sur la base de cette fenêtre 960-1023 en compte numérique. Il ne s'agit pas là d'un abus de langage mais d'une convention qui, bien que discutable, dérive de l'observation.

Cette méthode de détection par seuillage dans l'infrarouge moyen peut être utilisée pour définir la dynamique spatio-temporelle de l'activité des feux tout au long de la saison sèche pour un domaine écologique donné, ou pour la détection des feux actifs au sein d'un ensemble géographique recoupant plusieurs domaines écologiques (sahélien, soudanien et guinéen par exemple). Dans ces deux derniers cas, suivi multi-temporel et diversité des conditions écologiques rencontrées, elle comporte cependant un handicap majeur: l'effet de saturation du signal infrarouge moyen permet de détecter les feux actifs mais également d'autres éléments de paysage tels que surfaces de roche nue (inselberg par exemple), zones urbaines, sols secs privés de végétation vivante ou encore espace affecté par les feux dans les jours précédents. En effet, compte tenu du passage des satellites NOAA 7/9 et 11 en début d'après-midi, de telles surfaces peuvent avoir, en saison sèche, une température de surface suffisante pour provoquer la saturation du canal AVHRR-3. Les travaux de Kaufman *et al.* (1990) ont ainsi montré qu'un feu couvant d'une température de l'ordre de 500°K et ne couvrant que 1/1000ème du pixel AVHRR provoquait la saturation du signal dans l'infrarouge moyen. On peut donc s'attendre qu'un sol nu et sec à une température de surface de l'ordre de 320 °K, chose courante en début d'après midi en zone soudanienne, puisse aussi provoquer la saturation du signal si l'entière du pixel AVHRR correspond à cet état de surface.

Dans ces conditions il devient difficile de se prononcer sur la signification des points chauds détectés: feux actifs ou surfaces nues et sèches ?

Cette limitation apparaît sévère pour le suivi spatio-temporel des feux sur la seule base du seuillage dans le canal infrarouge moyen. De nombreuses équipes de recherche s'attachent donc à développer des méthodes plus sophistiquées d'exploitation de l'imagerie NOAA-AVHRR. En particulier en analysant conjointement les enregistrements dans l'infrarouge moyen et dans l'infrarouge thermique (bande 4) du senseur AVHRR (Kaufman *et al.*, 1990; Flannigan and Vonder Haar, 1986), ainsi qu'en exploitant les passages nocturnes du satellite NOAA et non pas uniquement les enregistrements diurnes (Langaas, 1991).

Figure 3. Espace géographique retenu pour l'étude de la dynamique de saturation à l'échelle régionale: 2.6 millions de km² touchant l'essentiel des domaines écologiques observables en Afrique de l'Ouest.



Sur un plan strictement scientifique, ces travaux présentent bien sûr un grand intérêt en particulier parce qu'ils visent à préciser 3 éléments essentiels: 1) le nombre de points chauds correspondant effectivement à des événements de feu à la date d'observation; 2) la surface effectivement atteinte par ces feux (Langaas S., 1989); 3) la gamme de variation de la température radiative des feux, très variable suivant le milieu (Langaas, 1991). Information indispensable pour des études visant à quantifier le rôle joué par les feux dans les transferts chimiques biosphère-atmosphère, par exemple (Graedel et Crutzen, 1989; Ferrare *et al.*, 1990; Mohnen *et al.*, 1991) ou la cartographie fine des surfaces brûlées. Il est donc fort tentant d' "attendre" l'aboutissement de ces recherches avant d'exploiter l'imagerie NOAA-AVHRR pour une surveillance routinière de l'activité des feux en Afrique de l'Ouest. Mais il est également permis de penser que cette dynamique de saturation du signal infrarouge moyen, non liée aux feux actifs, contient une information utile pour les études de surveillance des conditions du milieu et qu'il serait dommage de ne pas l'exploiter; d'autant plus qu'elle peut être mise en évidence par le biais d'une méthode très simple de traitement et exploitation des images NOAA-AVHRR. Partant d'un suivi de la dynamique temporelle de saturation, il est possible d'individualiser les espaces géographiques et les périodes de l'année pour lesquels la détection des feux actifs est possible ou au contraire sujette à caution.

C'est précisément ce qui a été tenté à partir d'une série temporelle d'images NOAA-AVHRR-HRPT couvrant les saisons sèches 1987, 1988 et 1989; un premier examen a été réalisé à l'échelle régionale sur un ensemble géographique de 2.6 millions de km² touchant l'essentiel des domaines écologiques observables en Afrique de l'Ouest; une deuxième analyse a ensuite été faite sur un espace plus restreint de 130.000 km² recoupant les domaines soudanien, soudano-guinéen et guinéen dans la zone frontalière Guinée-Liberia-Mali-Côte d'Ivoire.

2. Dynamique régionale de saturation sur l'ensemble de l'Afrique de l'Ouest

2.1. Préparation d'une série temporelle d'images NOAA

Quatorze images AVHRR-HRPT ont été sélectionnées pour couvrir la période allant de Novembre 1988 (début de la saison sèche) à fin Mars 1989 (fin de la saison sèche). L'espace géographique concerné est présenté sur la figure 3.

Les images, de couverture nuageuse minimale et issues d'orbites présentant la même longitude de passage à l'équateur, ont été corrigées géométriquement et superposées avec une précision inférieure à 1500 mètres. Pour chaque image de la série les enregistrements dans la bande AVHRR-3 ont été convertis en images binaires en attribuant la valeur 0 à tous les comptes numériques originaux compris entre 0 et 959, la valeur 1 à ceux compris entre 960 et 1023. Suite à quoi, la série temporelle a été divisée en 7 périodes définies à partir de travaux antérieurs (Grégoire, 1990) concernant le suivi des effets/ les modalités d'installation de la saison sèche en Afrique de l'Ouest. Enfin, une image de "saturation" a été produite pour chacune des 7 périodes par composition des images unitaires.

Bien que la procédure de composition ait permis dans une large mesure de minimiser le problème de la couverture nuageuse, limité en saison sèche, il a tout de même été nécessaire de produire un masque pour trois dates de la série.

L'étape finale de préparation de cette série temporelle a été le codage des images binaires obtenues pour chacune des sept périodes mentionnées plus haut: la valeur 0 a été attribuée au pixel non saturé, et les valeurs 1, 2, 4, 8, 16, 32 et 64 attribuées respectivement aux pixels saturés des périodes novembre, décembre, début janvier, fin

janvier, début février, fin février début mars et fin mars. Par simple addition de ces valeurs au cours de l'avancement de la saison sèche, il a été possible de décrire la dynamique spatiale et temporelle de saturation pour l'ensemble de l'Afrique de l'Ouest: les 108 catégories individualisées à la fin de cette procédure (tableau 1) ont été regroupées en 12 classes (tableau 2) qui ont servi à produire une image synthétique présentée sur la figure 4.

2.2 Analyse de la dynamique de saturation

En première approximation on peut considérer qu'en Afrique de l'Ouest l'installation de la saison sèche se fait progressivement du nord vers le sud et que cette saison est d'autant plus tardive et courte que l'on se déplace vers le sud. Partant de ce schéma, on pourrait s'attendre à une dynamique de saturation relativement simple allant des zones nord, saturées dès le mois de novembre et ce tout au long de la saison sèche, aux zones sud montrant une saturation uniquement vers la fin du mois de mars. Les résultats obtenus montrent qu'il n'en est pas du tout ainsi. Les données du tableau 1 mettent bien en évidence la remarquable complexité, tant spatiale que temporelle, de la variabilité dans la dynamique de saturation du milieu; le nombre de catégories univoques (108) est remarquablement élevé considérant le fait que la combinaison des 7 images binaires peut produire un maximum de 128 classes.

La combinaison des catégories en 12 classes, tel que cela est fait dans le tableau 2 et illustré sur la figure 4, montre qu'il n'y a pas une simple tendance à la saturation du nord vers le sud, même en prenant en compte les zones n'étant jamais à saturation telles que les surfaces d'eau libre, les franges littorales, les zones de bas-fond et les espaces forestiers dans le sud. A l'exception des zones de bas-fond, tous ces milieux appartiennent à la zone équatoriale humide (FAO-Unesco, 1977).

La dynamique de saturation dans les franges côtières/zones littorales est assez variable suivant le lieu concerné. Ainsi au Sénégal, au nord de Dakar, seule une étroite bande côtière n'est jamais saturée. Elle semble correspondre à une limite morphopédologique dérivant de formations dunaires récentes. Ailleurs, le long de la côte, les zones non saturées s'inscrivent également dans le cadre morpho-pédologique; tout particulièrement les plaines inondables du Saloum et de la Casamance, ainsi que la vallée de la Gambie. D'autres zones côtières non saturées correspondent à des formations végétales spécifiques, telles que les mangroves de Guinée Bissau. On peut observer enfin une saturation très locale le long de la côte sur les péninsules rocheuses comme celle abritant la ville de Conakry en Guinée.

Les zones inondables, situées à l'intérieur des terres, forment deux brèches évidentes dans la répartition des zones saturées au nord de l'image (figure 4). Il s'agit du Delta Intérieur du fleuve Niger et des périmètres rizicoles de l'Office du Niger dans la région de Ségou au Mali. L'installation de la saison sèche provoque une saturation progressive de la périphérie vers le centre de ces espaces inondables. Pour chaque site, Delta Intérieur et aménagements rizicoles, la partie centrale n'est jamais saturée. Dans les deux cas, il s'agit de formations alluviales pour lesquelles la teneur en eau élevée entraîne des températures de surface et des albédo relativement bas. L'avance progressive du front de saturation, de la périphérie vers le centre de ces zones, reflète le retrait des eaux et l'assèchement graduels des formations superficielles.

Bien que d'une manière générale non saturée, les formations de type forêt ombrophile planétaire guinéo-congolaise (UNESCO, 1981) de la partie sud de l'image présentent quelques points isolés à saturation. Il s'agit presque certainement d'événements de feu. En dehors de ces cas particuliers, les surfaces à couvert végétal dense de cette partie de l'image constituent un milieu frais et humide qui n'entraîne pas de saturation du signal dans l'infrarouge moyen.

Tableau 1. Nombre de pixels dans chaque catégorie de saturation, en fonction du temps

No. Cat. lb. Picela		La mois de sauridon					Classe (cf. tableau 2)
		Nov	Dec	D. Jan	F. Jan	D. Fév	
1	127	X					Classe 1
2	739	X					
3	1	X					
4	2	X					
5	8	X					
6	1142	X					
7	2	X					
8	18	X					
9	9	X					
10	995	X					
11	167	X					Classe 2
12	1149	X					
13	997	X					
14	5	X					
15	10	X					
16	1	X					
17	43	X					
18	3	X					
19	396	X					
20	3	X					
21	150	X					Classe 3
22	6401	X					
23	24	X					
24	50728	X					
25	79	X					
26	290	X					
27	28	X					
28	3	X					
29	10	X					
30	414	X					
31	2	X					Classe 4
32	8	X					
33	8	X					
34	5	X					
35	4	X					
36	388	X					
37	129	X					
38	384	X					
39	2	X					
40	303	X					
41	8	X					Classe 5
42	5	X					
43	3	X					
44	233	X					
45	909	X					
46	24	X					
47	1	X					
48	3	X					
49	16	X					
50	144	X					
51	9947	X					
52	18512	X					
53	38152	X					

No. Cat. lb. Picela		La mois de sauridon					Classe (cf. tableau 2)
		Nov	Dec	D. Jan	F. Jan	D. Fév	
54	71	X					Classe 6
55	290	X					
56	324	X					
57	3	X					
58	4	X					
59	402	X					
60	3	X					
61	8	X					
62	161	X					
63	550	X					
64	3	X					Classe 7
65	410	X					
66	1	X					
67	10	X					
68	58	X					
69	320	X					
70	5	X					
71	9	X					
72	1	X					
73	7243	X					
74	915	X					Classe 8
75	16	X					
76	1954	X					
77	41	X					
78	323	X					
79	1163	X					
80	40	X					
81	8	X					
82	223	X					
83	1118	X					
84	49287	X					Classe 9
85	4294	X					
86	2358	X					
87	12175	X					
88	22350	X					
89	1892	X					
90	904	X					
91	43271	X					
92	29559	X					
93	13847	X					
94	5153	X					Classe 10
95	7071	X					
96	2	X					
97	158	X					
98	22	X					
99	3513	X					
100	22040	X					
101	12065	X					
102	9819	X					
103	6085	X					
104	35363	X					
105	18345	X					
106	241564	X					
107	12689	X					
108	57250	X					
109	144	X					
110	9947	X					
111	18512	X					
112	38152	X					

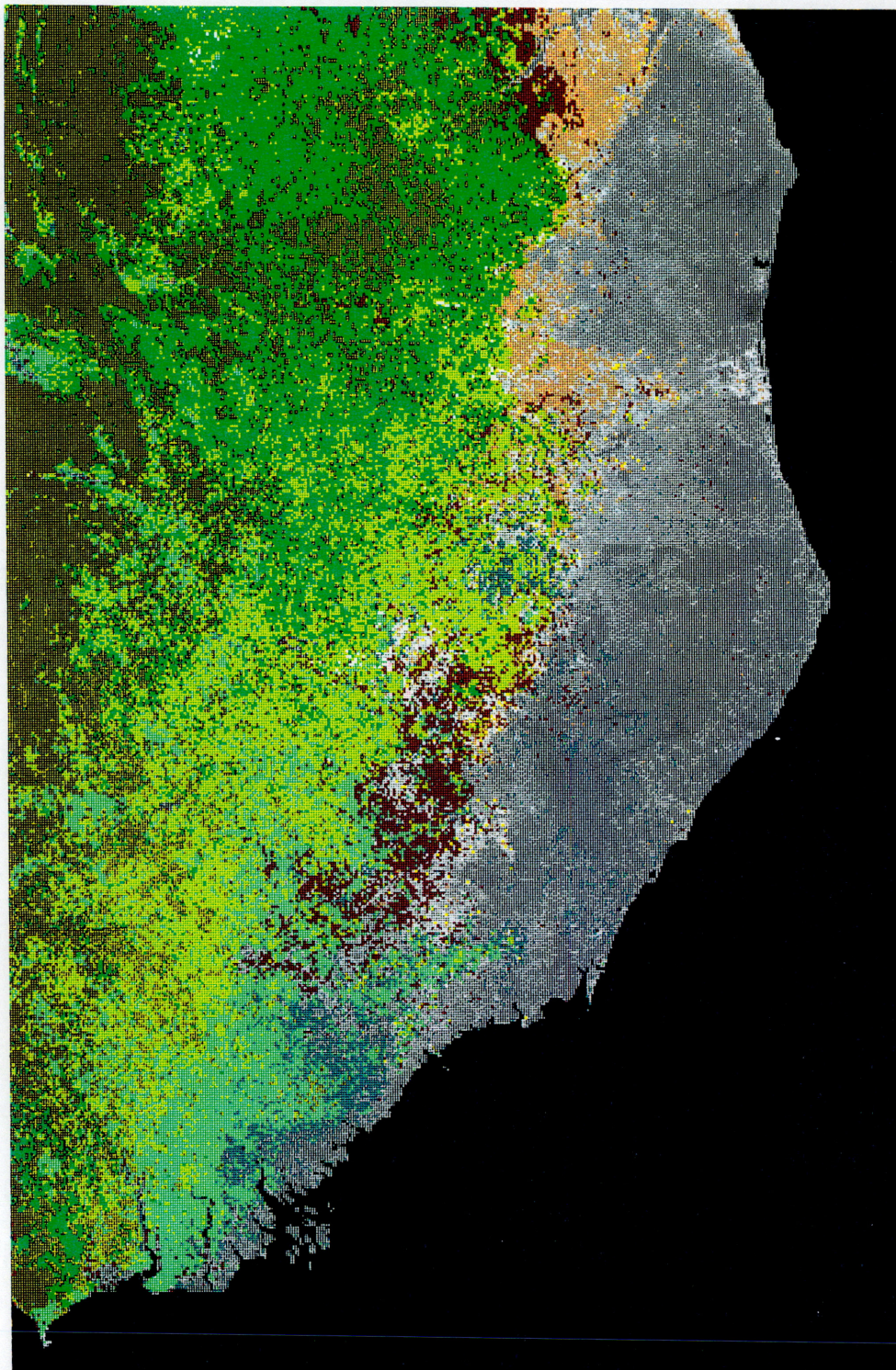
Tableau 2. Classes temporelles de saturation dans l'infarouge moyen

<u>Classe</u>	<u>Description</u>
1	saturation avenant uniquement au début de la saison sèche
2	saturation du début de la saison jusqu'à début février mais pas au delà
3	saturation observée uniquement début février
4	saturation du début de la saison jusqu'à début mars mais pas au delà
5	saturation observée uniquement début mars
6	saturation observée en début et fin de saison mais sans continuité
7	saturation quasi continue tout au long de la saison
8	saturation observée à partir de début janvier et ce jusqu'à la fin de la saison
9	saturation observée à partir de fin janvier et ce jusqu'à la fin de la saison
10	saturation observée à partir de début février et ce jusqu'à la fin de la saison
11	saturation observée à partir de fin février et ce jusqu'à la fin de la saison
12	saturation observée uniquement à la fin de la saison

Legende pour figure 4.

LEGENDE: ■ UNIQUEMENT AU DEBUT DE LA SAISON ■ EN DEBUT ET FIN DE LA SAISON
 ■ DU DEBUT DE LA SAISON JUSQU'A DEBUT FEV MAIS PAS AU DELA
 ■ UNIQUEMENT DEBUT FEV
 ■ DU DEBUT DE LA SAISON JUSQU'A DEBUT MAR MAIS PAS AU DELA
 ■ UNIQUEMENT DEBUT MAR ■ CONTINUE TOUT AU LONG DE LA SAISON
 ■ DU DEBUT JAN A LA FIN DE LA SAISON ■ DE LA FIN JAN A LA FIN DE LA SAISON
 ■ DU DEBUT FEV A LA FIN DE LA SAISON ■ DE LA FIN FEV A LA FIN DE LA SAISON
 ■ UNIQUEMET A LA FIN DE LA SAISON

Figure 4. Dynamique spatio-temporelle de saturation dans l'infrarouge moyen observée en Afrique de L'Ouest durant la saison sèche 1988 / 89.



Ce sont en fait les zones de savane des milieux soudanien et sahélien, au nord, qui montrent une dynamique de saturation "généralisée" à l'ensemble du domaine géographique concerné. Phénomène qui peut bien sûr être du à l'activité des feux, directement ou indirectement; directement par le biais de fronts de feux actifs provoquant la saturation du capteur, et indirectement parce que les surfaces brûlées présentent, quelques temps après le passage du feu, des températures et des albedo relativement plus élevés que les surfaces non atteintes par le feu. Cependant, l'activité des feux ne peut, à elle seule, expliquer toute la variabilité spatiale et temporelle observée dans le phénomène de saturation.

La progression, à laquelle on pourrait s'attendre, d'un front chaud (i.e., à saturation) du nord vers le sud au fur et à mesure de l'installation de la saison sèche ne s'observe vraiment que dans le coin ouest de l'image dans la zone frontalière entre le Sénégal, la Gambie et la Guinée Bissau. La limite sud du front de saturation s'observe début février en Côte d'Ivoire et au Ghana. Après cette date, le front chaud remonte vers le nord. De la même façon, dans la région frontalière Mali-Guinée la limite sud du front de saturation est atteinte début mars, c'est à dire avant la fin de la saison sèche.

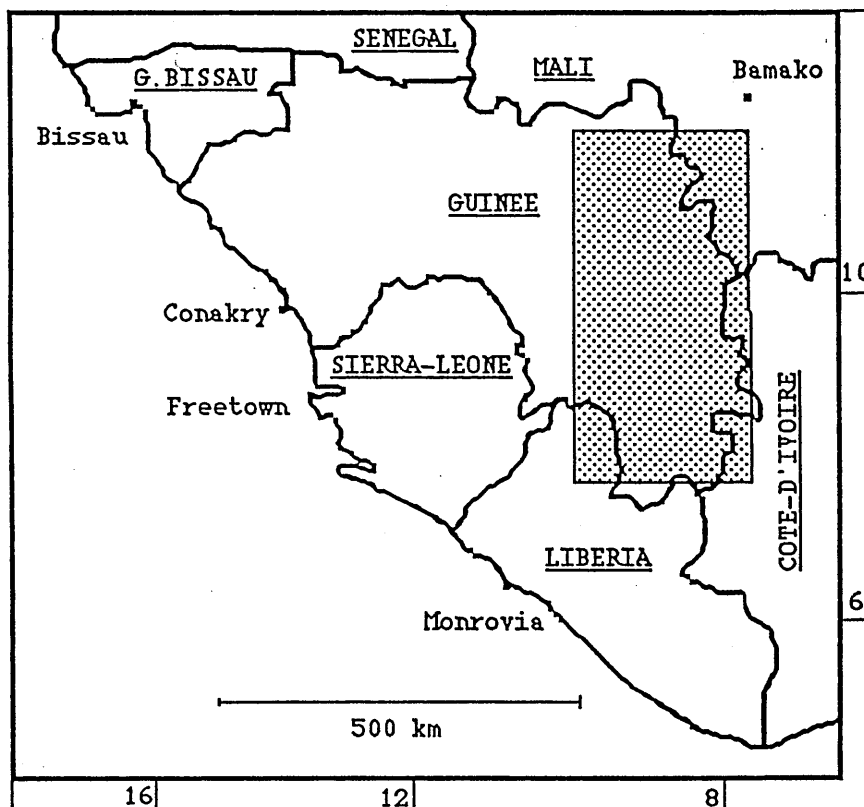
Certaines de ces limites suivent clairement des découpages géologiques; c'est le cas par exemple de la limite sud du front au Ghana. Ailleurs, la stratification semble plus influencée par le mode d'occupation des terres, comme par exemple dans la région frontalière Mali/Guinée où les surfaces brûlées tôt dans la saison montrent une reprise de la végétation avant le début des pluies, entraînant ainsi une disparition du phénomène de saturation. Dans d'autres cas, la forme du front de saturation dépend d'une combinaison de facteurs; c'est le cas par exemple pour la forme en dents de scie que prend le front de saturation en Côte d'Ivoire dans la région dite du "V Baoulé", zone qui voit se conjuguer les limites morphopédologiques, de formations végétales, de conditions climatiques et d'utilisation du milieu par les populations.

Un examen quelque peu approfondi de la figure 4 permet la mise en évidence de nombreux détails ou éléments du paysage, tels que le massif de Mali à l'extrême nord de la Guinée, ou la vallée du Serpent au nord de Bamako. De même on note que les fonds de vallée des cours d'eau importants présentent à peu près tous une période de saturation à un moment de la saison sèche tout en maintenant un contraste permanent avec le milieu environnant. Les variations spatiales et temporelles du phénomène de saturation visualisés sur la figure 4 dérivent sans aucun doute d'interactions complexes entre climat, sols, couvert végétal naturel et utilisation du milieu par l'être humain. Comme cela est indiqué dans le tableau 1, les divisions définies arbitrairement au sein de la base de données s'appuient sur deux critères: le moment de l'année qui voit apparaître la saturation, et celui qui la voit disparaître. En fait, il se peut très bien que ce soit les discontinuités dans la dynamique de saturation qui constituent les périodes les plus importantes ou significatives; les recherches actuelles visent à répondre à ces questions, sur la base d'une étude plus détaillée du processus de saturation et la prise en compte d'une série de saisons sèches et non pas d'une seule comme cela a été le cas ici.

3. Suivi de la dynamique de saturation pendant la saison sèche 1988/1989 en "Haute-Guinée" et "Guinée Forestière"

Compte-tenu des résultats obtenus lors de l'étude régionale effectuée sur l'ensemble de l'Afrique de l'Ouest, il est apparu intéressant de préciser l'analyse sur un espace géographique plus restreint dans la région frontalière Guinée-Liberia-Mali-Côte d'Ivoire (Figure 5) et d'en tirer des enseignements en matière de surveillance de l'activité des feux.

Figure 5. Site d'étude retenu pour le suivi de la dynamique de saturation pendant la saison sèche 1988/89 en Haut-Guinée Forestière.



Le suivi s'est appuyé sur 7 images sélectionnées pour couvrir la période allant de novembre 1988 à fin février 1989, ce qui correspond à la saison sèche 88/89 pour cette partie de l'Afrique de l'Ouest. Pour chacune des images, les pixels montrant une valeur à saturation dans l'infrarouge moyen ont été individualisés par simple seuillage selon la procédure détaillée plus haut. Un zonage grossier a ensuite été superposé à chacune des images. Il s'agit (Figure 6) d'un découpage en 3 grandes zones effectué sur la base du substrat géologique (BRGM, 1970), du domaine climatique et des formations végétales dominantes (UNESCO, 1981). Il a ainsi été distingué ainsi du nord au sud:

- la zone I: domaine soudanien sur formations schisteuses, à couvert de type savanes arborées. Cet ensemble est limité à l'Ouest par la chaîne du Niandan-Banié et au Sud par une ligne Est-Ouest passant immédiatement au Sud de la ville de Kankan;
- la zone II: domaine soudano-guinéen sur formations granitiques, à couvert de type savanes arborées et forêts claires. La limite Sud de cet ensemble a été fixée très grossièrement le long d'un axe joignant les villes de Kissidougou, Macenta et Boola;
- la zone III: domaine guinéen sur formations granitiques et gneissiques, à couvert de type forêts et savanes secondaires.

Ce découpage ne représente bien sûr pas la complexité effective du milieu, mais il fournit par contre un cadre de spatialisation des éléments d'image, ayant des valeurs à saturation dans la bande AVHRR-3, détectés au fur et à mesure de l'avancée de la saison sèche.

L'examen de la dynamique spatio-temporelle de saturation, illustrée sur les figures 6 et 7, apporte les enseignements suivants:

- entre la mi-novembre 1988 et la fin février 1989, un phénomène marqué de saturation, certainement non imputable à 100% aux feux actifs, ne s'observe pas encore le 4 janvier mais devient évident en zone I (soudanien sur schiste avec savanes arborées) le 15 du même mois (figure 7). Pour cette saison sèche, et en première approximation, on peut conclure que la dynamique de saturation généralisée ne constitue un handicap majeur, pour la détection des feux actifs, qu'à partir de la deuxième semaine de janvier; et ce sur un seul domaine écologique.
- pour un domaine donné, l'avancée ou l'installation progressive de la saison sèche n'entraîne pas forcément une augmentation parallèle du nombre de points d'image à saturation. Ceci apparaît clairement pour la zone I au nord: entre novembre 1988 et début janvier 1989, le nombre de pixels à saturation est à son maximum le 16.11.88, diminue ensuite jusqu'au 4.01.89 et "explose" littéralement entre le 4 et le 15.01.1989. Il est donc fort probable que la signification de cette saturation, en termes d'état de la surface, n'est pas la même en novembre (début de saison sèche) que début janvier (milieu de saison sèche). En d'autres termes, les points à saturation de novembre ne devraient pas être attribués à des surfaces sèches et nues, du seul fait des effets de la saison sèche, mais plus probablement à des feux plus ou moins récents, du moins pour ce domaine écologique. A l'inverse, l'"explosion" du phénomène de saturation de la 1ère quinzaine de janvier serait plus directement lié aux effets de la saison sèche.

En zone III, il y a peu ou pas de points à saturation jusqu'à l'observation du 15 janvier 1989.

En zone II, on observe un premier pic de points à saturation dans la deuxième décade de décembre 1988, une reprise dans la première quinzaine de janvier 1989 et une explosion début février 1989. Tout comme en zone I, il est difficile d'interpréter de la même façon, en termes d'état de la surface, les épisodes de décembre/janvier et celui de février.

Cette non linéarité, observée entre dynamique de saturation et installation de la saison sèche, constitue certainement une des clefs de décision pour l'attribution des points chauds à des feux actifs ou à des surfaces chaudes parce que nues et sèches: en première

Figure 6. Localisation des points d'image à saturation (en blanc sur la figure) dans l'infrarouge moyen (bande AVHRR 3) en Haut-Guinée et Guinée-Forestière. Résultat d'exploitation d'une image NOAA-AVHRR-HRPT du 16 novembre 1988.

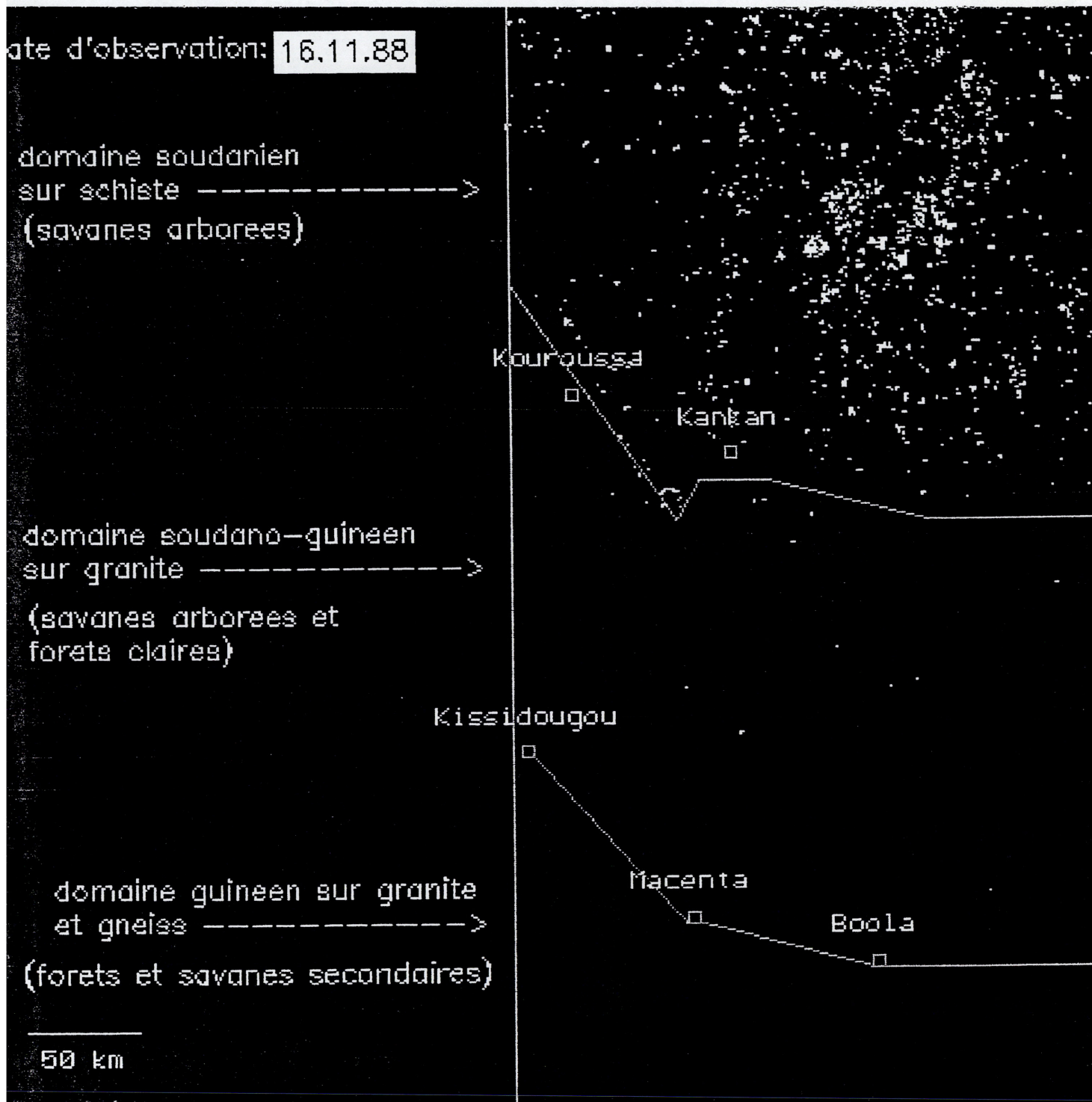


Figure 7. Localisation des points d'image à saturation (en blanc sur la figure) dans l'infrarouge moyen (bande AVHRR 3) en Haut-Guinée et Guinée-Forestière. Résultat d'exploitation d'une série d'images NOAA-AVHRR-HRPT entre le 28 novembre 1988 et le 15 janvier 1989.

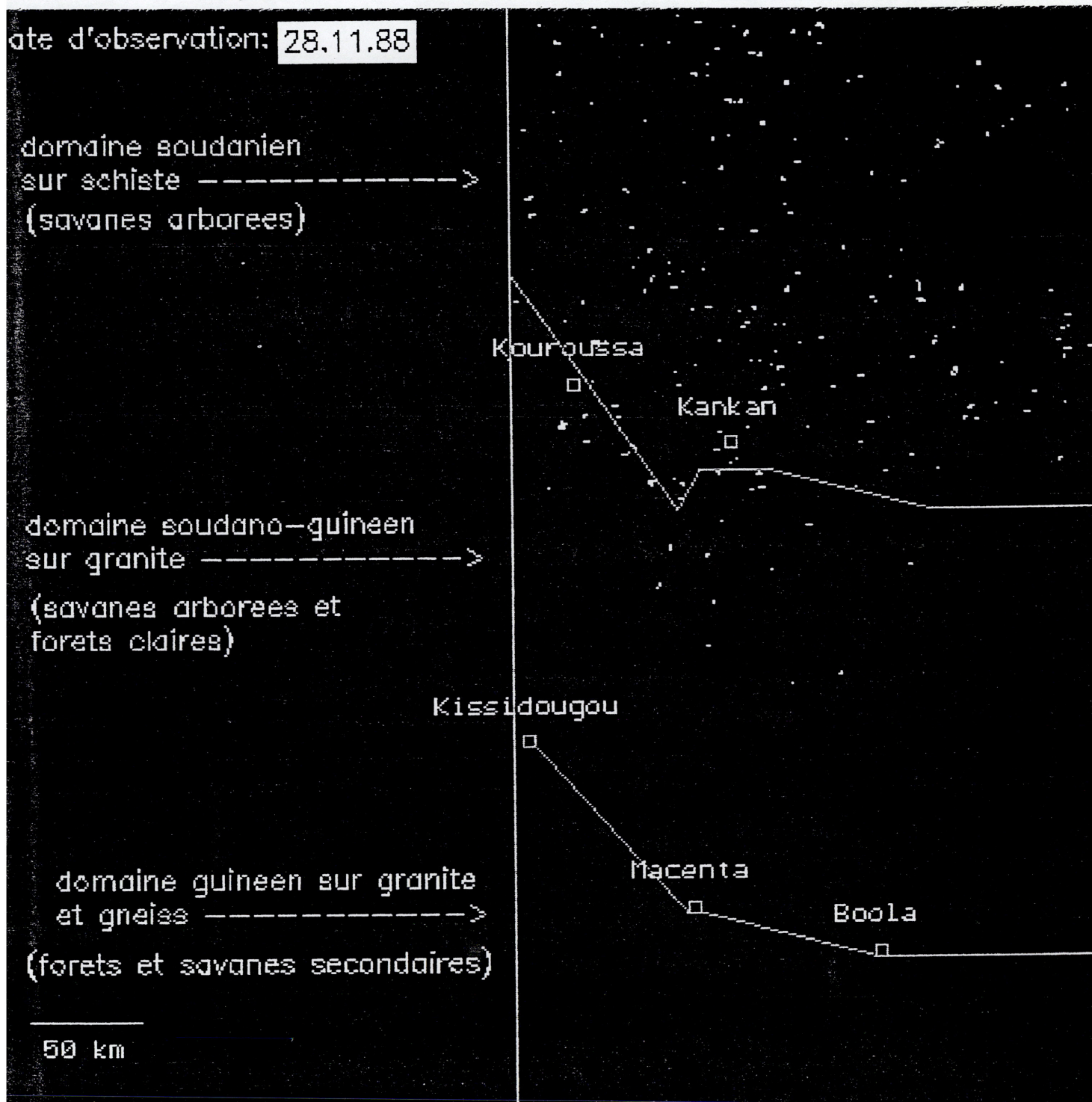


Figure 7. Cont.

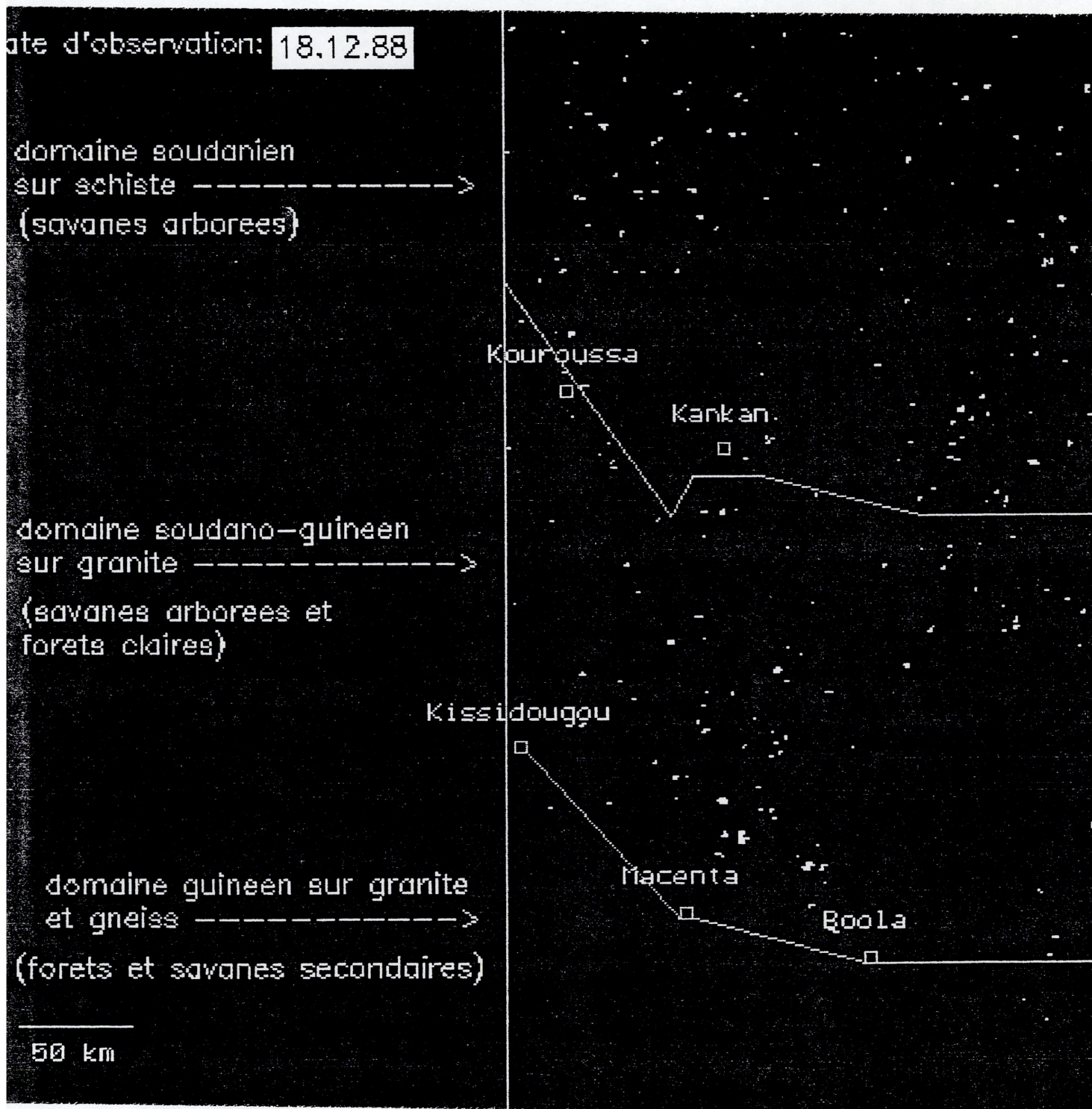


Figure 7. Cont.

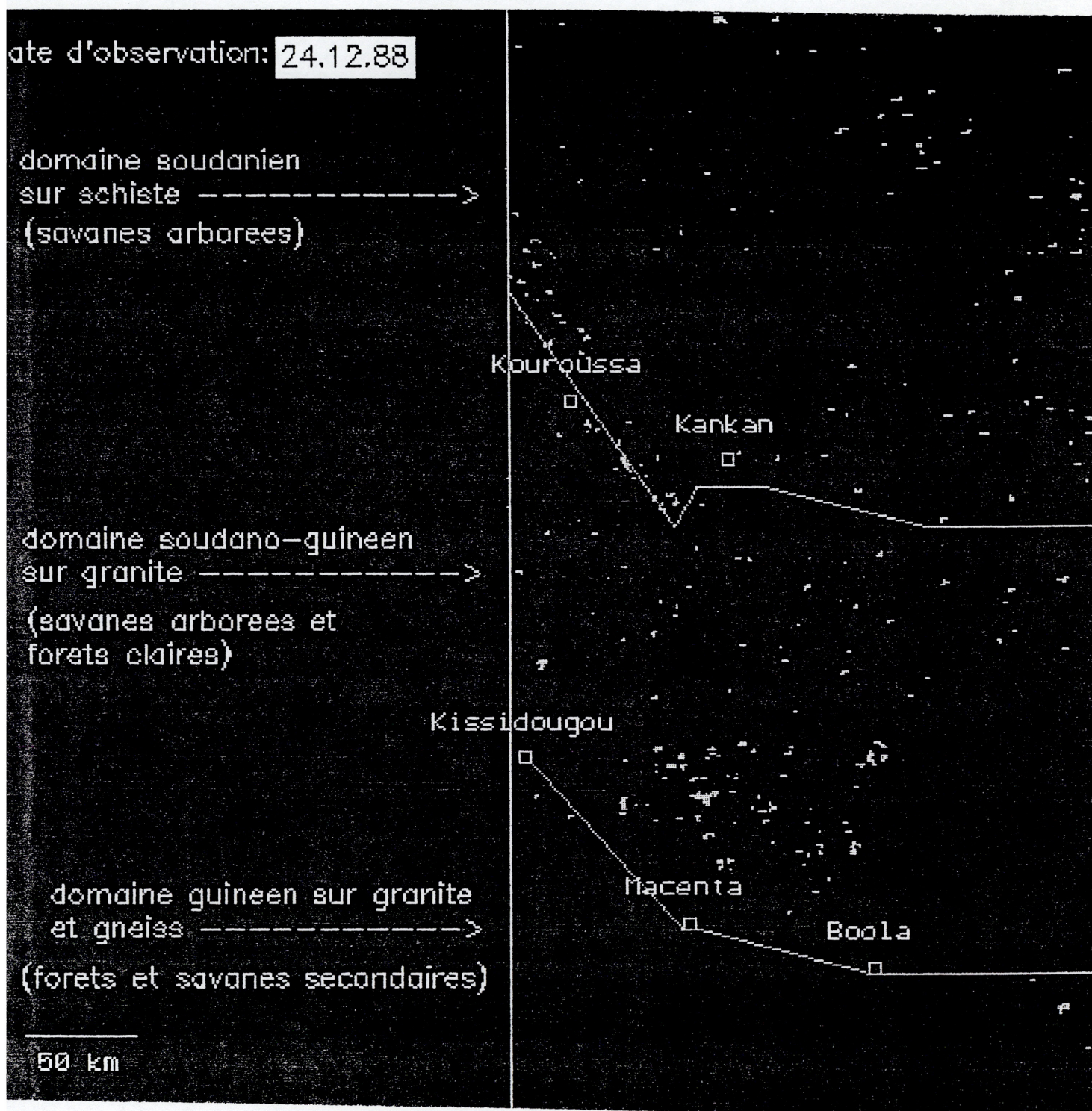


Figure 7. Cont.

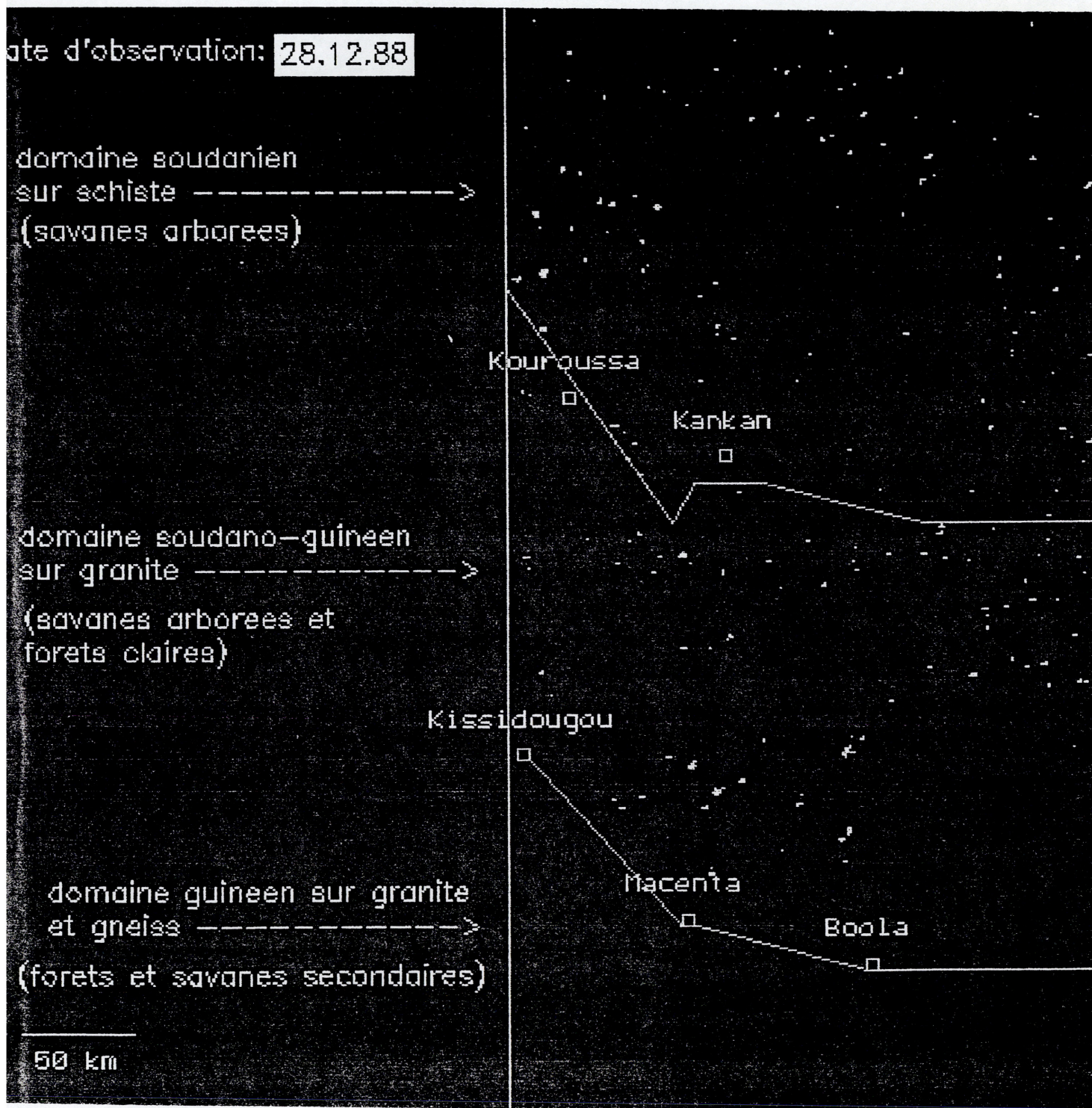


Figure 7. Cont.

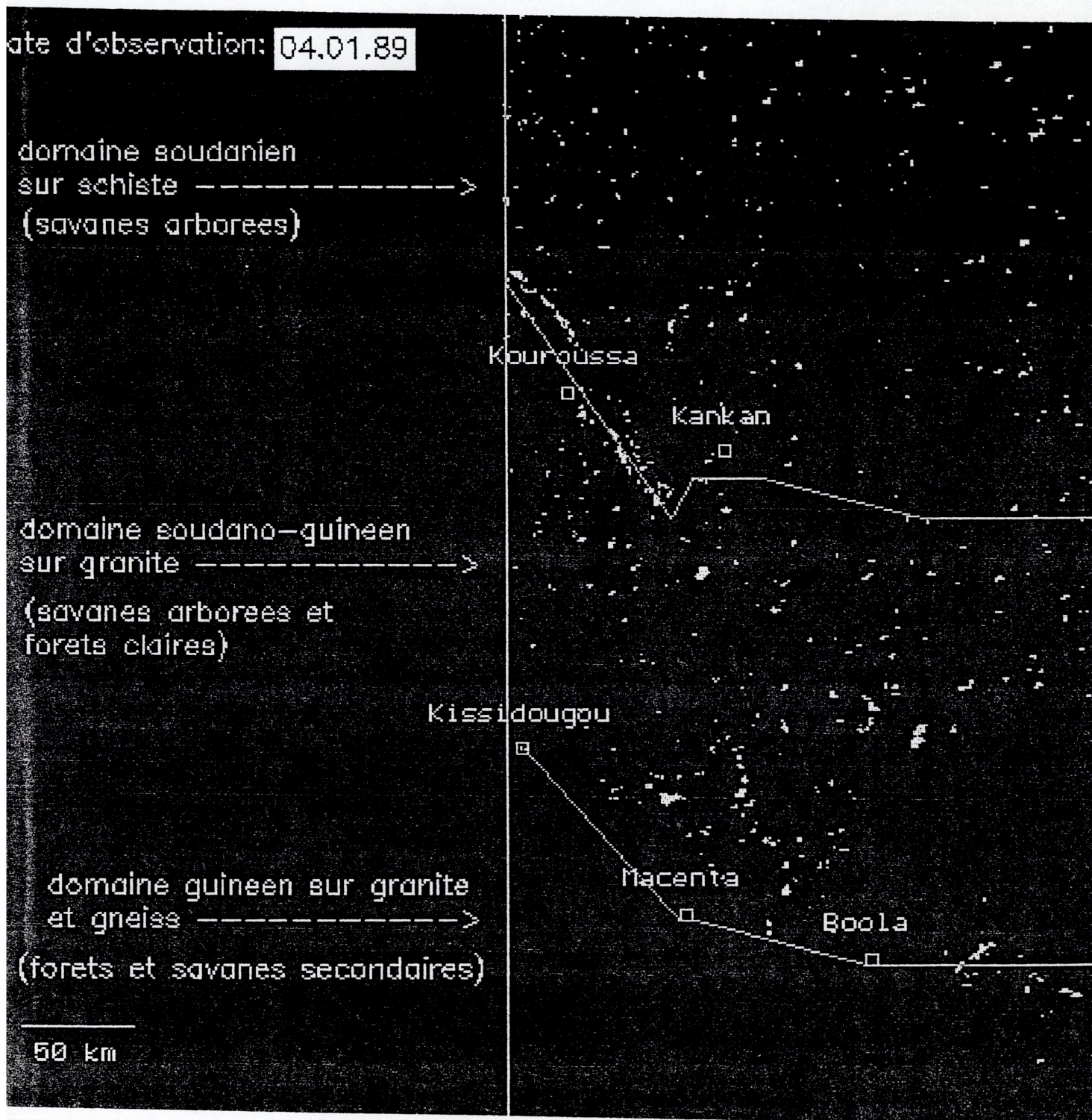
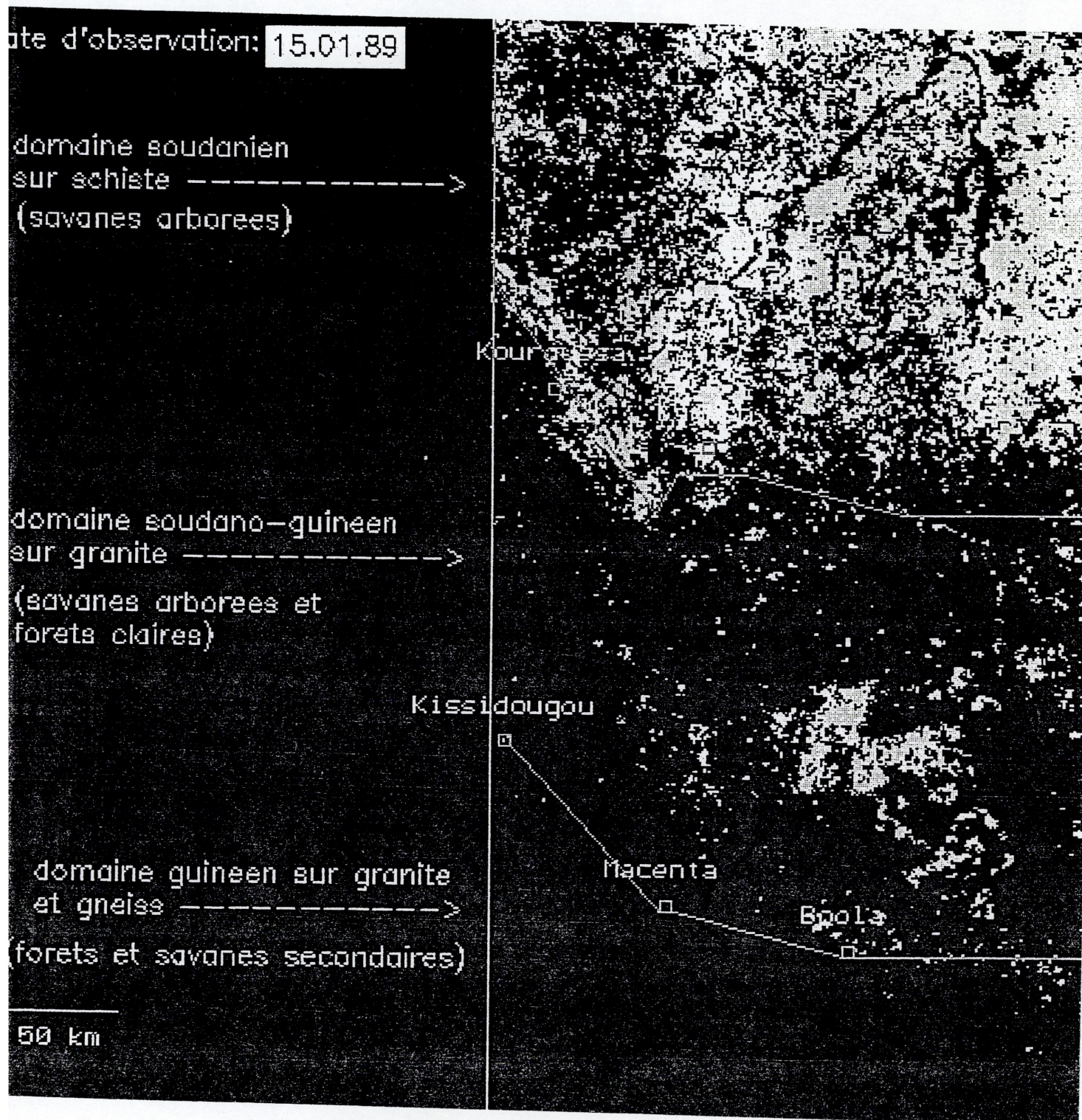


Figure 7. Cont.



approximation, on peut estimer que les points chauds détectés avant la soudaine augmentation du phénomène de saturation correspondent effectivement à des points de feu actif.

- la remarque précédente amène à faire une observation un peu surprenante: la logique voudrait que l'état de saturation quasi généralisée, imputable plus ou moins directement aux effets de l'assèchement du milieu, s'observe avant le déclenchement des feux (Paltridge and Barber, 1988). Or il semble, en première approximation, que ce ne soit pas le cas (c.f. en particulier zone I) et qu'au mieux les deux phénomènes soient simultanés (c.f. en particulier zone II).

En fait il est permis de penser que cette inversion dans les séquences temporelles ne concerne que les feux dits précoces de début de saison sèche. Les séquences semblent plus logiques pour les feux tardifs.

On peut également penser que les pratiques de mise à feu, très variables suivant le but recherché par les populations, viennent perturber la séquence temporelle attendue.

- en termes d'impact du phénomène feu sur le milieu, on peut se demander si la distinction recherchée entre pixels saturés, parce que occupés par une surface sèche et nue, et pixels saturés parce que contenant un feu actif d'une certaine taille, ne constitue pas un faux problème en zone soudano-guinéenne ? Cette distinction est-elle un passage obligé pour évaluer les effets du feu sur l'environnement ? En d'autres termes: à une date d'observation x , les surfaces à signal très élevé sinon saturé dans l'infrarouge moyen, parce que sèches et nues, ne sont-elles pas en grande partie la résultante de l'activité des feux dans les décades précédentes ? Le feu agit sur le couvert végétal, c'est l'évidence même, mais il a également des effets secondaires sur d'autres composantes du milieu; effets tendant à renforcer encore réflexion et émission dans l'infrarouge moyen. Un exemple en est la formation de sols hydrophobes comme l'ont montré les travaux de Almendros *et al.* (1990) en zone méditerranéenne.

- l'adjonction de données exogènes à l'imagerie satellitaire, tel que le zonage très grossier utilisé ici, augmente de beaucoup les "performances" de la méthode simple de seuillage dans l'infrarouge moyen. Les situations observées le 16.11.88 (figure 6), le 28.12.88 (figure 7b) et le 04.01.89 (figure 7c) sont très démonstratives: les limites définies sur base du domaine climatique, du substrat géologique et du couvert végétal dominant, enveloppent de façon logique les amas de points à saturation. Des programmes visant le suivi routinier des feux à des fins de gestion du milieu au niveau national, tel celui proposé par Frederiksen *et al.* (1989) pour le Sénégal ou par la Commission des Communautés Européennes (Grégoire, 1990b) pour la Guinée, ne peuvent se passer de cette approche multi-sources.

- sur un plan strictement méthodologique, et dans l'optique d'un système routinier sinon opérationnel de surveillance des feux sur l'ensemble de l'Afrique soudano-guinéenne et soudano-congolaise (c'est à dire du Sénégal à la République Centre-Africaine), il serait recommandable de documenter les dynamiques de saturation dans le temps et l'espace et d'utiliser ensuite les résultats obtenus comme clefs de décision pour la détection des feux actifs.

- enfin, il ressort de ces résultats que le contenu informatif de la dynamique de saturation, non directement liée aux feux actifs, est loin d'être négligeable et surtout que le processus ne se fait pas de façon purement aléatoire; ce qui avait été clairement démontré au niveau régional (paragraphe 2). Loin d'être inutilisables, ces pixels à saturation mettent en évidence des portions de territoire où les états de la surface pourraient être analysés dans le cadre d'étude des transferts d'eau et d'énergie à l'interface biosphère-atmosphère. Les recherches en cours s'attachent à exploiter cette méthode de suivi de la dynamique de saturation pour compléter les travaux que le Centre Commun de Recherche (CCR) mène sur la surveillance écologique du bassin du fleuve Niger en Guinée.

Conclusions et perspectives

Malgré sa simplicité apparente, la méthode de suivi de la dynamique spatio-temporelle de saturation dans la bande AVHRR-3 s'est avérée riche de potentialités pour la surveillance de l'environnement en milieu soudano-sahélien d'Afrique de l'Ouest.

Contrairement à ce qu'il est possible de faire dans la partie visible et proche infrarouge du spectre, à savoir une interprétation bio-physique des dynamiques observées, il est très difficile de mener une interprétation dans les mêmes termes pour les enregistrements dans l'infrarouge moyen. En partie du fait de l'existence d'une composante émise et réfléchie. Malgré ce, on a pu observer un lien étroit avec des caractéristiques essentielles du milieu, telles que substrat géologique, distribution des grands ensembles végétaux, zonage climatique, mode d'occupation du sol.

La plupart des limites visibles sur l'image de saturation correspondent étroitement à celles que les travaux de Arino *et al.* (1991) ont mis en évidence sur la même région, à partir d'une série temporelle d'indice de végétation (Normalized Difference Vegetation Index, NDVI) dérivée des enregistrements AVHRR. Cependant, le document de saturation montre une nette séparation entre les domaines de savannes et de forêts tropicales humides, ce qui n'est pas le cas avec l'indice de végétation; il y a par ailleurs une très bonne différenciation entre les zones inondables, tant côtières que continentales, et les formations végétales environnantes. Ce qui est particulièrement intéressant car il est reconnu qu'en zone africaine l'usage de l'indice NDVI ne permet que très difficilement de séparer les domaines de savannes de celui des forêts tropicales humides d'une part, de classer les milieux inondables d'autre part (Townshend *et al.*, 1991). Sur ce sujet, nous pensons que l'utilisation de la dynamique spatio-temporelle de saturation dans la bande AVHRR-3, en association avec l'indice NDVI, peut grandement améliorer les résultats de classification de la couverture végétale et du mode d'occupation du sol, à partir des données AVHRR.

Deux autres aspects plaident en faveur de l'utilisation de la dynamique de saturation dans la bande AVHRR-3 pour la classification du mode d'occupation du sol: on peut noter en effet que beaucoup d'éléments, mis en évidence sur l'image de saturation, dérivent de l'action de l'être humain sur le milieu et seraient à ce titre de bons indicateurs de modifications plus ou moins profondes de l'écosystème; ces éléments pourraient également être pris en compte dans la définition de nouvelles classes de couverture végétale et d'occupation du sol. Ce dernier aspect est particulièrement important: en effet, malgré le besoin clairement reconnu (IGBP, 1989) d'une remise à jour des connaissances en matière de mode d'occupation du sol aux échelles continentale et globale, la communauté scientifique se heurte à des difficultés pour définir les classes significatives ou pertinentes à ces échelles de perception (Malingreau and Belward, 1991).

En matière de surveillance de l'activité des feux, et d'évaluation de son impact sur le milieu, il a été montré comment la dynamique de saturation dans l'infrarouge moyen peut servir de cadre d'analyse. L'objectif est d'appliquer cette approche au niveau continental.

Le lien étroit avec des caractéristiques essentielles du milieu est somme toute logique dans la mesure où la dynamique spatio-temporelle du signal dans l'infrarouge moyen est fortement dépendante de l'état hydrique du milieu, tant par sa composante émise que réfléchie. Etat hydrique lui-même fortement dépendant des caractéristiques du milieu citées plus haut. Des recherches sont en cours pour exploiter cette relation dans les travaux que le CCR mène sur la surveillance écologique des bassins versants de grands fleuves en Afrique de l'Ouest.

Enfin, il apparaît nettement que cette approche peut constituer une source d'information essentielle pour l'évaluation et le suivi des dynamiques de dégradation des écosystèmes en Afrique au sud du Sahara.

En matière de perspectives de recherche, deux grands axes sont actuellement suivis:

- la paramétrisation de ce qui a été dénommée "dynamique de saturation" dans ce travail; ce qui suppose un approfondissement du concept physique qui y est attaché ainsi qu'une méthode de quantification;
- l'intégration des échelles spatiales de perception, du niveau local au niveau continental: cette intégration constitue en effet un passage obligé pour l'exploitation de la méthode dans les études des interactions entre biosphère et atmosphère.

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An improved approach to fire monitoring in West Africa using AVHRR data

P. J. KENNEDY, A. S. BELWARD and J-M GREGOIRE

Institute for Remote Sensing Applications, Monitoring Tropical Vegetation Project, TP440 CEC Joint Research Centre, 21020 Ispra (Va) Italy.

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Abstract. Data from the Advanced Very High Resolution Radiometer (AVHRR) have been used for the detection of fires in various ecosystems throughout the world. In this study the most often used methods have been applied to a time-series of 63 AVHRR day time images for the whole of West Africa for the 1991 / 1992 dry season. The West African region includes ecosystems ranging from dry Sahelian grasslands to moist tropical forests. Furthermore, these ecosystems show considerable seasonal variability. Existing methods were found inadequate for automated fire detection for the whole region because of the spatial and temporal heterogeneity of the region's environments. A number of changes were made to the established methods and the new fire detection procedure was applied to the time-series. Field verification and interpretation of the results in the context of the main ecological divisions of the region, showed the new method to give good results for all ecosystems throughout the season. Finally, interpretation of fire counts using a Geographical Information System illustrates how such data can improve our knowledge of fire activity at national and sub-continental scales.

1. Introduction

Quantitative information about the spatial and temporal distribution of fires in vegetation is indispensable to such disciplines as fire ecology and management, atmospheric chemistry and forestry (Levine 1991). Such information for fire in West Africa is notable for its absence in the literature related to this topic. With the increasing interest in the contributions of biomass burning to global emissions of carbon dioxide, methane and other greenhouse gases (Greenberg *et al.* 1984, Crutzen *et al.* 1985, Hao *et al.* 1990), it is becoming increasingly important to improve our understanding of fire activity at national, continental and even global scales. This growing concern has been the stimulus for the formation of many international research programmes, such as the International Global Atmospheric Chemistry programme of the IGBP (International-Geosphere-Biosphere Programme; IGBP 1990). The request is without doubt both scientifically demanding and challenging, requiring both the means and the methods to obtain timely, frequent, reliable and preferably inexpensive quantitative data for monitoring the phenomenon of fire over extensive areas and long periods of time.

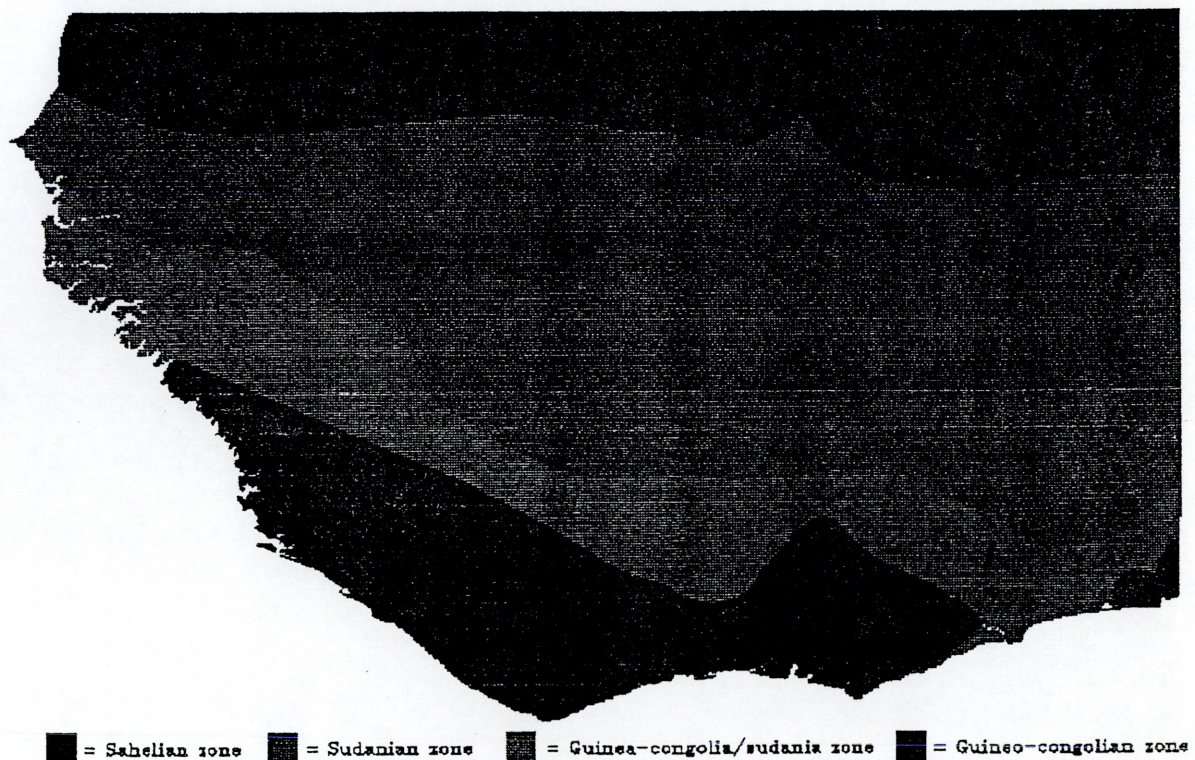
Several characteristics of the data acquired by the Advanced Very High Resolution Radiometer (AVHRR) on-board the National Oceanic and Atmospheric Administration's (NOAA) satellites offer a means of obtaining fire information at scales which for practical, political, economical or scientific reasons are not available from other currently existing data sources.

The aim of this paper is to illustrate the type and quality of the fire information which can be derived on a regional scale in a semi-automatic way from full resolution (nominally 1km by 1km pixel size), daytime High Resolution Picture Transmission (HRPT) data from the AVHRR. Methods of fire detection from AVHRR which have been successfully used elsewhere are compared with a new method developed specifically for the West African region. Statistics describing the fire activity during part of the 1991-1992 dry season are presented.

2. Fire in West Africa

In this paper the term *fire* is used to describe wildfires. In West African savannas, such fires, whether deliberate, accidental or natural are commonly referred to as bushfires, where *bush* refers to uninhabited and non-cultivated areas. The *fire regime* describes the type and number of fires, their seasonal occurrence and periodicity (Frost and Robertson, 1987). In West Africa fire regime's are extremely variable and strongly correlated to the different bioclimatic and phytogeographic zones of the region and to the different social customs of the population. The main burning season may last for six months, with early burns occurring in September/October at the end of the wet season, and late burns in March, the beginning of the following rainy season.

Figure 1. Boundaries of the four vegetation zones defined by UNESCO/White (1983)



In both the Guinean-Congolia/Sudania and the Sudanian savannas (figure 1), the peak burning period tends to occur in November, December and January, when the vegetation is 'ripe' in terms of flammability. Much of the region is burnt each year, though there are a few local areas where fire may occur twice in a season. In the more arid Sahelian zone to the north, fire events are rare and largely depend on antecedent meteorological conditions and fuel availability.

The reasons for burning are numerous, though it is generally accepted that the majority of fires are caused by human activity and not by natural causes. In West Africa, the reasons vary largely in relation to the different bioclimatic characteristics of the environment and the occupation of the people. In the Sudanian zone, for example, fire is important to the pastoralist tribes where it is used to control shrub population and as a stimulant for the regeneration of palatable pastures. Further south, in the Guinean Congolia/Sudania zone, fires are used less for improving pastures but more commonly for hunting. Such fires, although deliberately started can be left to spread and burn uncontrolled for several days. In the forested areas, reasons are commonly linked either to the clearing of land for the construction of communication routes or for the preparation of new agricultural land. More complete lists of the different reasons for burning in West African savannas can be found, for example, in Rose-Innes (1972) and Langaas (1992).

3. Fire detection using AVHRR data: Background

3.1 Physical basis

All objects with a temperature above absolute zero emit electromagnetic radiation. The temperature of an object determines the level of energy emitted at any particular wavelength (figure 2). In accordance with the laws of Stefan-Boltzmann and Wien radiant emittance increases as the blackbody temperature of an object increases, and maximum radiant emittance is shifted to shorter wavelengths (figure 2). The maximum value of spectral radiant emittance of the sun (which has a temperature of around 6000 K) occurs around 0.5 μm in the middle of the visible region of the spectrum. For the Earth, (with a temperature of around 300 K) it occurs around 9.7 μm in the middle of the thermal-infrared region.

In terms of the AVHRR sensor, channel 3 (3.55 μm to 3.93 μm), is located near the spectral maximum for radiative emissions for objects radiating at temperatures around 800 K *i.e.* the near-normal temperature for burning grass (Langaas and Muirhead 1988), whilst channel 4 (10.3 μm to 11.3 μm) and channel 5 (11.5 μm to 12.5 μm) are located near the spectral maximum for normal environmental temperatures, around 300 K (figure 2). As a consequence, in the case of burning grass (800 K) channel 3 will receive much more radiant energy than channel 4 (figure 3). For a pixel, with the nominal 1.1 km by 1.1 km resolution, containing a single surface element of uniform temperature (300 K) the averaged radiant energy in channels 3 and 4 would be 0.442 $\text{W m}^{-2} \mu\text{m}^{-1} \text{sr}^{-1}$ and 9.68 $\text{W m}^{-2} \mu\text{m}^{-1} \text{sr}^{-1}$ respectively, assuming an emissivity of 1 and no attenuation of signal by the atmosphere. For a pixel containing two equal area elements with different temperatures, a fire of 800 K and the non-fire background of 300 K, the averaged radiant energy for channels 3 and 4 would be 670.0 $\text{W m}^{-2} \mu\text{m}^{-1} \text{sr}^{-1}$ and 49.92 $\text{W m}^{-2} \mu\text{m}^{-1} \text{sr}^{-1}$ respectively. The radiance received by channel 3 increases by a factor of 1516, compared to a factor of 5 for channel 4. The averaged radiance received by channel 3 for this 'two class' example is over 13 times greater than that received by channel 4. It is this differential response which is the basis for AVHRR fire detection.

Figure 2. Planck radiances for blackbody temperatures from 300 K to 800 K. For a given increase in temperature the increase in area under the channel 3 segments of the curves is much greater than under the channel 4 segments.

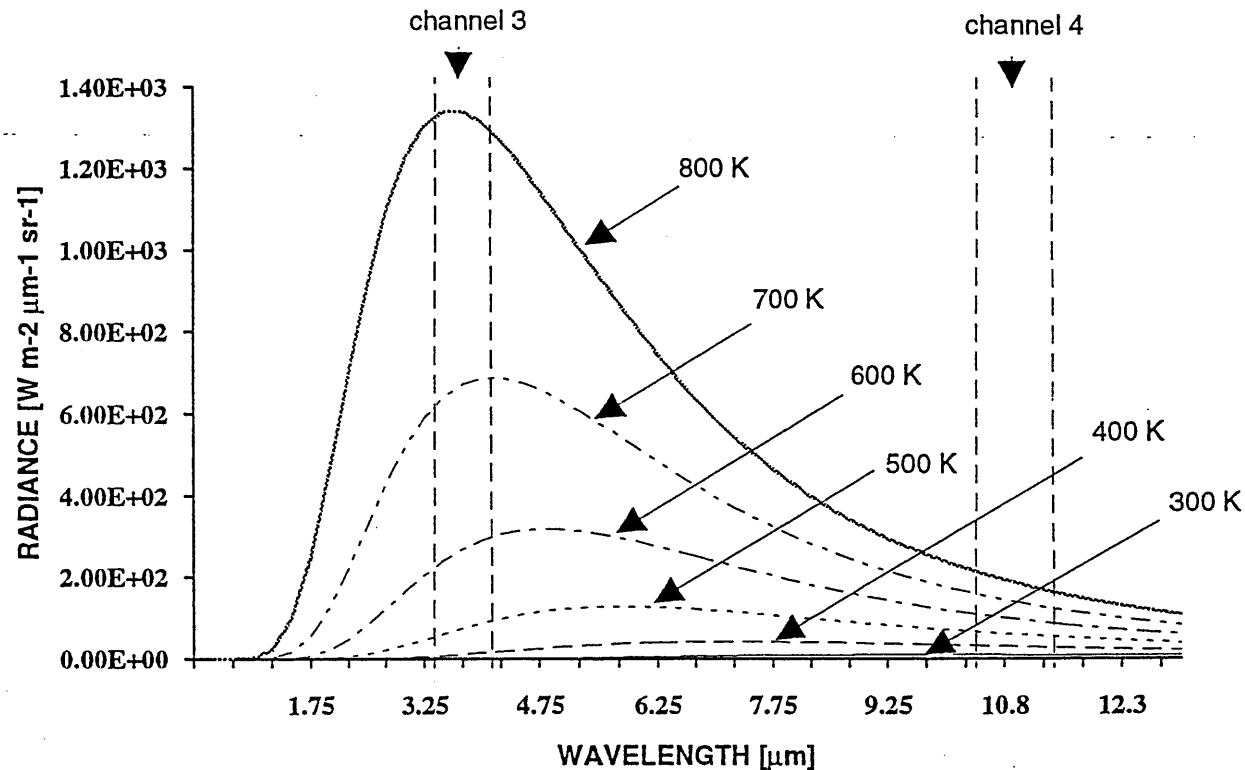
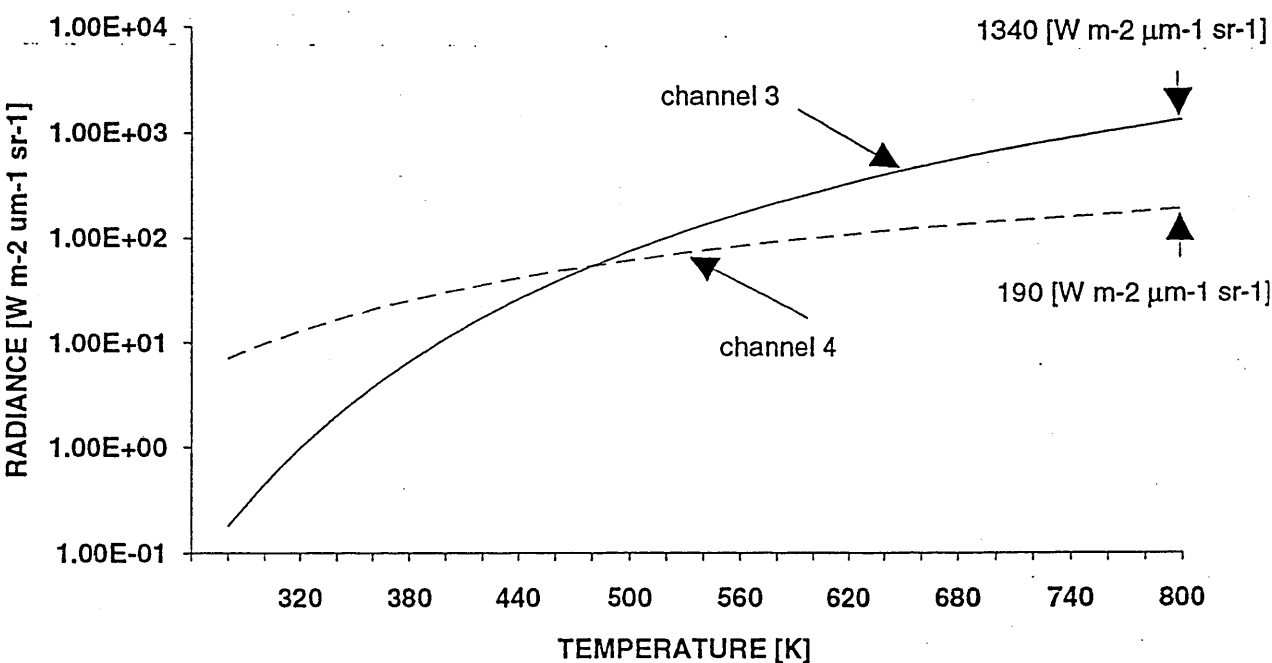


Figure 3. NOAA-11 radiances for channel 3 and 4 for temperatures between 300 K and 800 K.



3.2 Sensor related considerations

A limitation of the AVHRR sensor for fire characterisation is the low temperature at which channel 3 saturates *i.e.* around 321 K (Robinson 1987, Matson and Holben 1987). A sub pixel hotspot (fire) will cause saturation if hotspot radiance plus background radiance exceeds the energy flux for sensor saturation. Channel 3 will saturate when the received radiant energy exceeds $0.988 \text{ W m}^{-2} \mu\text{m}^{-1} \text{ sr}^{-1}$. Kaufman *et al.* (1990), suggested that fires with temperatures exceeding 500 K occupying 0.01 - 0.1% of a pixel would be enough to saturate the $3.7 \mu\text{m}$ channel. Results from our research suggest that in an environment of 300 K a fire occupying 0.01%, (100 m^2) of the pixel would have to have a temperature of over 1000 K in order to saturate channel 3. In the same environment a fire of 800 K would have to occupy 0.04% (400 m^2) to saturate channel 3. In cooler environments of temperatures of around 285 K, fires of the same temperature (800 K) would have to occupy a larger proportion of the pixel *i.e.* 0.05% (500 m^2) in order to saturate channel 3.

Problems set by the contribution of reflected solar radiation in channel 3 have been reported by Langaas and Muirhead (1988), however, Dowty (1993) suggests that reflection of solar radiation has a negligible effect on the actual ability to detect fires. Matson and Dozier (1981) and Flannigan and Vonder-Haar (1986) considered the quantitative errors arising from this contamination either irrelevant or insignificant. In West Africa, reflected solar radiation in channel 3 was most commonly associated with extensive areas of bare, light coloured soils and not, as expected from clouds or cloud edges. A more detailed description of the spectral, spatial and temporal characteristics of AVHRR data relevant to fire detection and monitoring is given in Kennedy (1993). Table 1 summarises the general characteristics of the NOAA/AVHRR system.

3.3 Fire terminology

It is important to clarify what is being referred to as a fire event, as detected by the AVHRR sensor. Firstly, all the pixels which are identified as being probable fire pixels represent a sample in time. This is to say that the number of fires and their distribution are representative of the situation on the ground only for that point in time when the satellite passes overhead. Secondly, each fire pixel is assumed to represent a single fire event, whereas, in reality the 1 km by 1 km AVHRR pixel may contain many small fires which are below the spatial resolving capabilities of the sensor and therefore not detectable as individual events. These two considerations alone introduce errors of under sampling, which could, in theory be reduced if data were acquired from all passes of the four currently orbiting satellites of the NOAA series (9, 10, 11 and 12). This same under sampling is of course also valid, and perhaps even more critical, when studying the spatial patterns of fire over time. Thirdly, it is not possible to describe the type of fire which is detected, other than to be able to distinguish, (by incorporating additional knowledge about the environment), whether, for example, the fire is likely to be a surface fire or a crown fire.

4. Fire detection using AVHRR data: Methods

The methods which have been adopted for AVHRR based fire detection and monitoring have generally relied either upon some empirically defined threshold values of DN (Digital Number) or temperature, to discriminate between pixels containing hot spots and those of the non-burning surroundings and cloud-contaminated pixels (Pereira and Setzer 1993, Setzer and Pereira 1991, Kaufman *et al.* 1990), or upon a visual comparison of enhanced channel 3 and channel 4 data (Matson *et al.* 1984).

Table 1. Characteristics and status of the NOAA-AVHRR systems**NOAA satellites and periods of operational use:**

TIROS-N	19.10.1978 - 30.01.1980	(NASA funded protoflight)
NOAA-6	27.06.1979 - 05.03.1983	
	03.07.1984 - 16.11.1986	
NOAA-7	19.08.1981 - 07.06.1986	
NOAA-8	20.06.1983 - 12.06.1984	
	01.07.1985 - 31.10.1985	
NOAA-9	25.02.1985 - 07.11.1988	
NOAA-10	17.11.1986 - 17.09.1991	
NOAA-11	08.11.1988 - present	
NOAA-12	17.09.1991 - present	

Orbital Parameters:

Orbital Type:	sun synchronous, near polar	
Orbital Inclination:	98.8°	
Nominal Altitude:	833 - 870 km	
Orbital Period:	102 min	
Orbits : Day:	14.2	
Orbit Repeat Cycle:	9 days	
Equatorial Crossing	Descending	Ascending
Times ^a (at launch)	02:30 h	14:30 h (NOAA-7, NOAA-9, NOAA-11)
	07:30 h	19:30 h (NOAA-6, NOAA-8, NOAA-10, NOAA-12)

Viewing Parameters:

Scan Angle:	55.4° on either side of nadir
Total Swath Width:	2700 km
Ground Resolution:	1.1 x 1.1 km at nadir
	2.4 x 6.9 km at maximum scan angles

Sensor Characteristics:

Channel:	1	2	3	4	5
Spectral Range (µm):	0.5 - 0.68 ^b	0.725 - 1.10	3.55 - 3.93	10.3 - 11.3 ^c	11.5 - 12.5 ^d
IFOV ^e (milliradians):	1.39	1.41	1.51	1.41	1.30
S/N Ratio ^f :	3:1	3:1	-	-	-
Saturation:	100% reflectance for channels 1 and 2				
	320 K for channels 3 to 5				
Quantisation level:	10 bit for all channels				

^a Local solar time^b On TIROS-N: 0.55 - 0.90 µm^c 10.5 - 11.5 µm for NOAA-6, NOAA-8, NOAA-10^d Not on NOAA-6, NOAA-8, NOAA-10^e IFOV: Instantaneous Field of View^f Signal to noise ratio for 0.5% reflectance

(Taken from Vogt, 1992)

The simplest approach is to assume that all pixels saturated in channel-3 are pixels containing fires (e.g., Malingreau and Tucker 1988, Malingreau *et al.* 1985). Since saturation occurs at a brightness temperature around 321 K, which is higher than the temperatures for most non-fire features on the ground, it is reasonable to assume for most observations that a saturated pixel represents a response from a fire. However, this assumption loses validity when the combined emitted and reflected radiance from hot sparsely vegetated surfaces causes channel 3 to saturate.

Unfortunately, for much of West Africa this is the case. Grégoire *et al.* (1993) report that, with a few exceptions, the Sahelian zone reaches saturation in early November and remains saturated throughout the dry season; the Sudanian zone is saturated from January on, the Guinean-congolian zone shows extensive areas of saturation in February and March, whilst the congolian zone shows only isolated saturation points (almost certainly fires). Under these circumstances the temperature contrast between the hotspot and the environment background can be more important in determining if, or how confidently a fire can be detected, than the actual energy flux from the hotspot itself.

One approach to overcome this problem is to use night time imagery (e.g., Lee and Tag 1990, Langaas 1992). Langaas (1992) used 26 AVHRR night-time images from NOAA-10 (19.30-20.30 hrs) and NOAA-11 (01.30-02.30 hrs) and a semi-automatic classification scheme based on Dozier's (1981) bi-spectral model to identify and characterise the savanna fires in The Gambia and Senegal, between October 1989 and May 1990. This approach clearly avoids two problems i) that of saturation in channel 3 caused by warm, bare surfaces and ii) the problem of dealing with the contribution of daytime reflected solar radiation. A drawback to using night-time imagery is that the satellite overpass time may be less optimal with respect to the time of maximum fire activity. Many fires are lit in the early afternoon when winds tend to be stronger, the ground dew has evaporated and the vegetation is dry enough for efficient ignition. However, not all these fires burn for long periods of time. A large number of fires are short-lived, lasting for no more than one to two hours, and even fires persisting many days can show a strong diurnal cycle whereby they die down during the night and do not burn strongly again until the following afternoon (Belward *et al.* 1993). Night-time imagery therefore provides a very restricted sample.

An alternative which allows day time observation is to use channel 4 as well as channel 3. Kaufman *et al.* (1988, 1990) suggested that fire pixels could be identified using a set of three thresholds. These are that i) channel 3 temperature must be equal to, or greater than 316 K, ii) channel 3 temperature is equal to or greater than channel 4 temperatures plus 10 K and iii) channel 4 temperature is greater than 250 K. The first criterion requires that in order for a pixel to be considered to contain a fire it has to have a high radiant temperature in channel 3. The second criterion imposes that this radiant temperature is higher than in channel 4 thus enabling discrimination between pixels containing a fire and those containing warm surfaces. The third criterion, has the role of providing a crude check for clouds, ensuring, or at least reducing the likelihood that the pixels contain strongly reflective clouds which may saturate channel 3. This method was used to undertake a fire count for the 1987 dry season in the tropical forest of Brazil's Amazonia. The identified pixels were additionally examined in the visible channel (0.58 μm -0.68 μm) to verify that there was an associated smoke plume (Kaufman *et al.* 1990, Setzer and Pereira 1991).

Given the restrictive sample of night-time imagery and the extensive nature of channel 3 saturation for West Africa the most applicable of the existing algorithms for fire detection is that of Kaufman *et al.* (1988, 1990). To test the effectiveness of this and other algorithms we applied them to a sample of images for the West African region.

5. Fire detection for West Africa

5.1. Data acquisition

Between 1st December, 1991 and 29th February 1992, all NOAA-11 descending node (equatorial crossing time of 14.30-16.00 hrs) scenes covering the region of West Africa between 4°N and 15°N and 2°W and 16°W were acquired. The 63 scenes were processed following the routine outlined below. Each image is a standard ESA 4 minute SHARP scene. All processing steps were applied to whole scenes.

5.2. Pre-processing

All channels are first converted to radiance. Post-launch calibration coefficients are used for channels 1 and 2 (Holben *et al.* 1990), on-board calibration for channels 3, 4 and 5. Channel 2 radiance's are converted to 'top of atmosphere' (ToA) reflectance's which account for variations in solar zenith angle, Sun-Earth distance and exoatmospheric solar irradiance. Brightness temperatures for channels 3, 4 and 5 are calculated using the inverse Planck function, where the channel response is described by a single central wavenumber for each channel (Eq 1).

$$Bt_i = \frac{C_2 * v_i}{\ln[1 + (C_1 / Li) * v_i^3]}$$

(Eq 1)

Bt_i = brightness temperature in channel i (K)
 Li = radiance in channel i ($\text{mW m}^{-2} \text{sr}^{-1} \text{cm}$)
 v_i = central wavenumber of the corresponding AVHRR channel (cm^{-1})
 C_1 = constant $1.1910659 * 10^{-5}$ ($\text{mW m}^{-2} \text{sr}^{-1} \text{cm}^4$)
 C_2 = constant 1.438833 (cm K)

Corrected brightness temperatures are calculated for channels 4 and 5 using the pre-launch satellite and channel related non linearity correction coefficients (Planet 1988). All calculations use full 10 bit data, though the final brightness temperatures are scaled to 8 bit.

The data are geometrically corrected following two main steps - navigation using earth location points (ELPs) from the raw data and correlation with a reference image data base to provide additional ground control points for fine correction to a specific 'window' of interest. Accuracy is approximately one pixel, resampling is by nearest neighbour (Belward *et al.* 1992).

5.3. Applying the fire detection methods

5.3.1. Channel 3 saturation

As implied above, the simplest fire detection algorithm, namely retaining all pixels that are saturated, or near saturated in channel 3, is not applicable to regional scale fire studies for West Africa. Much of the dry Sahelian and Sudanian zone reaches saturation without fire. Examples from January and February 1992 are shown in figure 4. Almost all of the Sahel and much of the Sudanian zone are included as probable fires in the February image.

5.3.2. Kaufman *et al.* (1990)

As described in §4 the approach used by Kaufman *et al.* (1990) identifies a pixel as a potential fire pixel if it fulfils three criteria. These are: (i) $Bt_3 \geq 316$ K, (ii) Bt_3 minus

$Bt4 \geq 10$ K, (iii) $Bt4 \geq 250$ K. Applying these criteria to images of West Africa can have both a positive effect, that of reducing the number of retained non-fire pixels (due to the difference criteria) and a negative effect, that of introducing many non-fire pixels (due to the lower channel 3 threshold). The magnitude of these effects is neither consistent with time nor space, but strongly influenced by environmental conditions specific to individual images or regions within a single image. Results for the same two images used in figure 4 are presented in figure 5. For the February image, the approach clearly eliminates some of the large blocks retained by the channel 3 threshold alone. However, new blocks are introduced because of the lower channel 3 thresholds. The central area of the large saturated channel 3 region is removed. These pixels are eliminated by the channel 3 channel 4 difference criteria. However, the approach introduces additional blocks surrounding the margins of the saturated channel 3 region in the Sudanian zone, and some smaller blocks and scattered pixels in the Guinean-Congolia/Sudania zone to the south. This negative effect dominates the resulting image for January, where the lower channel 3 threshold introduces many more pixels in the Sahelian and Sudanian zones with the result of practically doubling the size of the block of pixels fulfilling the channel 3 saturation criteria alone (figure 4).

The three criteria approach and threshold values adopted by Kaufman *et al.* (1990) were developed for fire detection in the relatively cool forest environments of Brazil. Environmental conditions in much of West Africa are quite different. The Sudanian and Sahelian zones in particular are much drier and warmer. A channel 3 threshold of 316 K includes almost all of these two ecological zones, (depending on time of the season) and because the surfaces are generally much warmer than the Brazilian forests, the difference between channel 3 and 4 of 10 K is too small to eliminate the warm, non-fire surfaces.

5.3.3. Modifications to Kaufman *et al.* (1990)

A first step in modifying the Kaufman *et al.* (1990) approach involved changing the thresholds used. A number of iterations through the time-series showed that increasing the channel 3 threshold to ≥ 320 K and increasing the channel 3 channel 4 difference to ≥ 15 K eliminated many of the blocks of pixels found in the Sahel and Sudanian zones, whilst retaining the randomly scattered points, more characteristic of the distribution of fire. The temperature value of 320 K does not represent saturation in channel 3 (>321 K), but covers a range of approximately 60 (10 bit) quantization levels. It is chosen so that fire pixels (known not to saturate channel 3) can also be identified. Some remaining problems (see for example the pixels in figure 5 identified as fire points off the coast of Côte d'Ivoire and Ghana) were removed by increasing the channel 4 cloud detection threshold from 250 K to 295 K.

Results from application of these modified criteria are shown in figure 6 for the same two images taken from January and February 1992. Though improving the results for the February image, the modified thresholds still retained large regions in the northern zones in the January image. This was attributed to large areas of highly reflective bare soils which can cause channel 3 to saturate, yet, which are still cool enough for the channel 3 channel 4 difference to be satisfied. Large regions on both images thus satisfy the thermal criteria for fire, though are patently not fires. This is mainly a temporal problem inasmuch as later in the season these same regions are sufficiently hot for the difference threshold to remove them. Because of this highly variable situation in time and space it is not possible to mask the northern problem areas out of the fire detection procedure on the basis that there is nothing to burn. Though such an approach may seem practical and justifiable for solving the problem area in the January image, the rapidly changing environmental conditions make it virtually impossible to define areas which could be excluded on a consistent basis.

Recognising that this problem originates largely from strongly reflective surfaces, and making the assumption that fire pixels (occupied by fire and burnt areas) will have relatively low reflectance in channel 2 (ToA reflectance) because of the ash covering (Paltridge and Barber 1988), tests were carried out to determine if the response in channel 2 for fire pixels was sufficiently consistent to be used as a fourth threshold. It was found that Channel 2 ToA reflectance values for over 500 fire pixels (the majority confirmed by the presence of smoke) was never greater than 12%. Based on these findings and many iterative tests, a threshold of $\leq 16\%$ ToA channel 2 was found to have the desired effect of reducing the number of falsely identified fire pixels in the north without seriously affecting those pixels more likely to be fires, *i.e.*, those in the savanna and forest biomes further south.

Application of all four criteria - (i) $Bt_3 \geq 320$ K, (ii) Bt_3 minus $Bt_4 \geq 15$ K, (iii) $Bt_4 \geq 295$ K and (iv) ToA reflectance channel 2 $\leq 16\%$ to the two images for January and February 1992 are shown in figure 7. All the extensive blocks to the north are removed, yet the more reasonable (in terms of fire occurrence) shotgun pattern to the south is retained.

Extraction of probable fire pixels from these two different approaches gives the following results. Modification of the three threshold values of Kaufman *et al.* (1990) but without the addition of the channel 2 (ToA reflectance) threshold gives pixel counts of over 49,100 and 15,600 for the same two January and February images respectively. Figure 6 shows their distribution. This compares with counts of 4801 and 1680 obtained from the January and February images (figure 7) respectively after addition of the channel 2 threshold. It became evident when studying the channel 2 threshold over the entire time series that it is very sensitive in time and space. This may be linked to variations in the physical and radiative properties of atmospheric aerosols and in atmospheric ozone and water vapour (e.g., Kaufman *et al.* 1990, Fraser and Kaufman 1985). Changes in these atmospheric conditions can in turn be a direct result of the particulate matter and trace gases emitted from biomass burning (e.g., Setzer *et al.* 1991, Cachier *et al.* 1991, Fearnside 1991), which also suggests that the channel 2 threshold may need to change as a function of time and location.

Finally, extraction of statistics from the February sample image for each of the three approaches *i.e.*, channel 3 saturation, Kaufman *et al.* (1990) and the new set of four criteria reveals that by using channel 3 saturation alone, over 588,300 pixels would be highlighted as probable fire events. For the Kaufman *et al.* (1990) approach the count would be 353,800 probable fire pixels, whilst for the new four criteria approach the count would be 1680. Although it is subjective to suggest that the latter figure must be correct, looking at the results in percentage terms illustrates that 15% or 9% of the image (representing a period of about four minutes in a single day) would be burning when utilising the channel 3 and Kaufman *et al.* (1990) approach respectively. This compares to only 0.04% for the new approach which is more realistic, especially at this date in the fire season.

In the knowledge that application of this single set of four criteria has certain trade-offs it is proposed as being the most appropriate automated approach to study fire throughout all the ecosystems of West Africa for the entire fire season. The new set of four criteria were applied to all 63 images of the time-series.

Figure 4. Results from application of the channel 3 saturation threshold alone for 4th January, 1992 (above) and 21st February, 1992 (below).

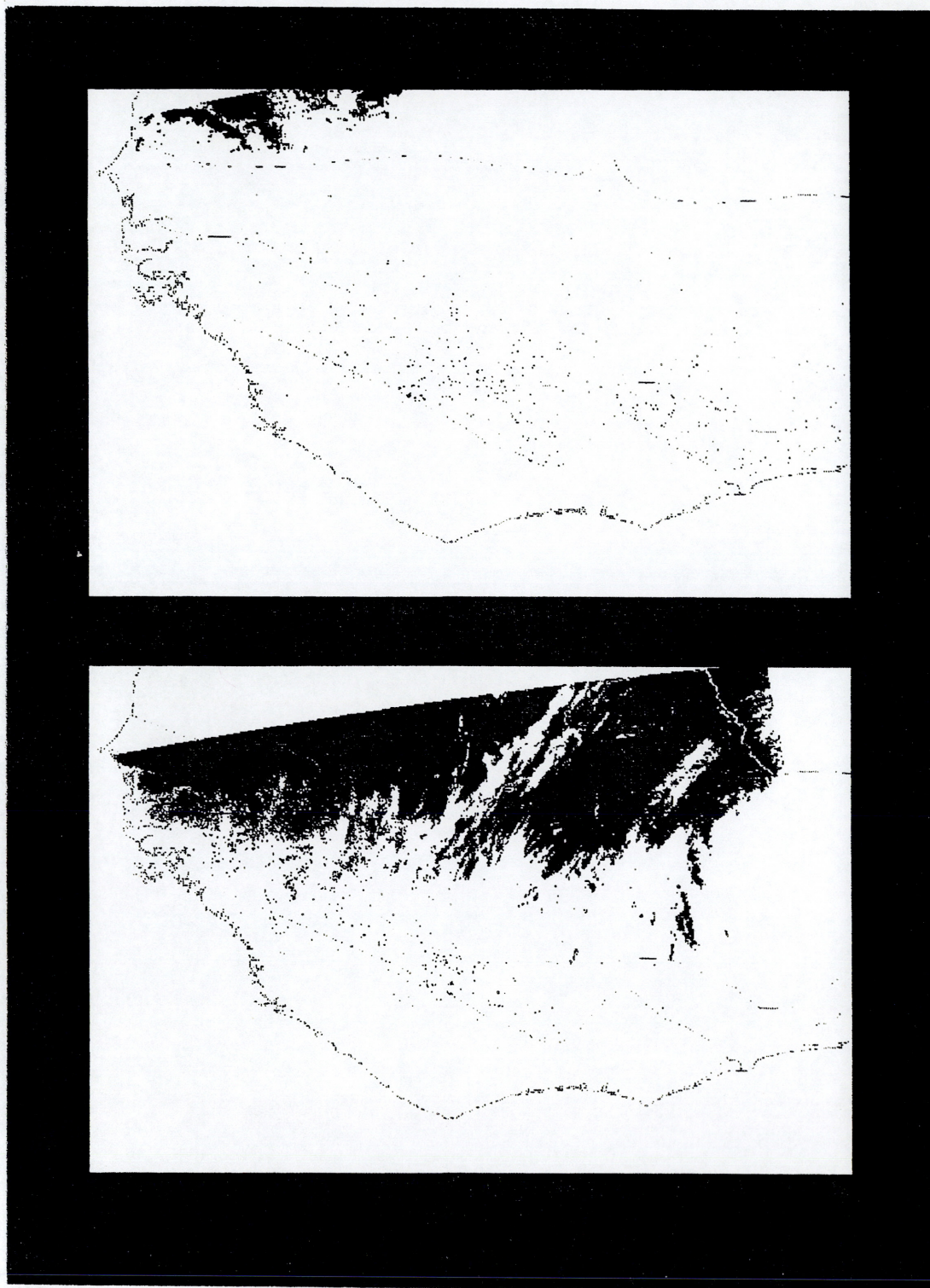


Figure 5. Results from application of the Kaufman *et al.* (1990) approach for 4th January, 1992 (above) and 21st February, 1992 (below).

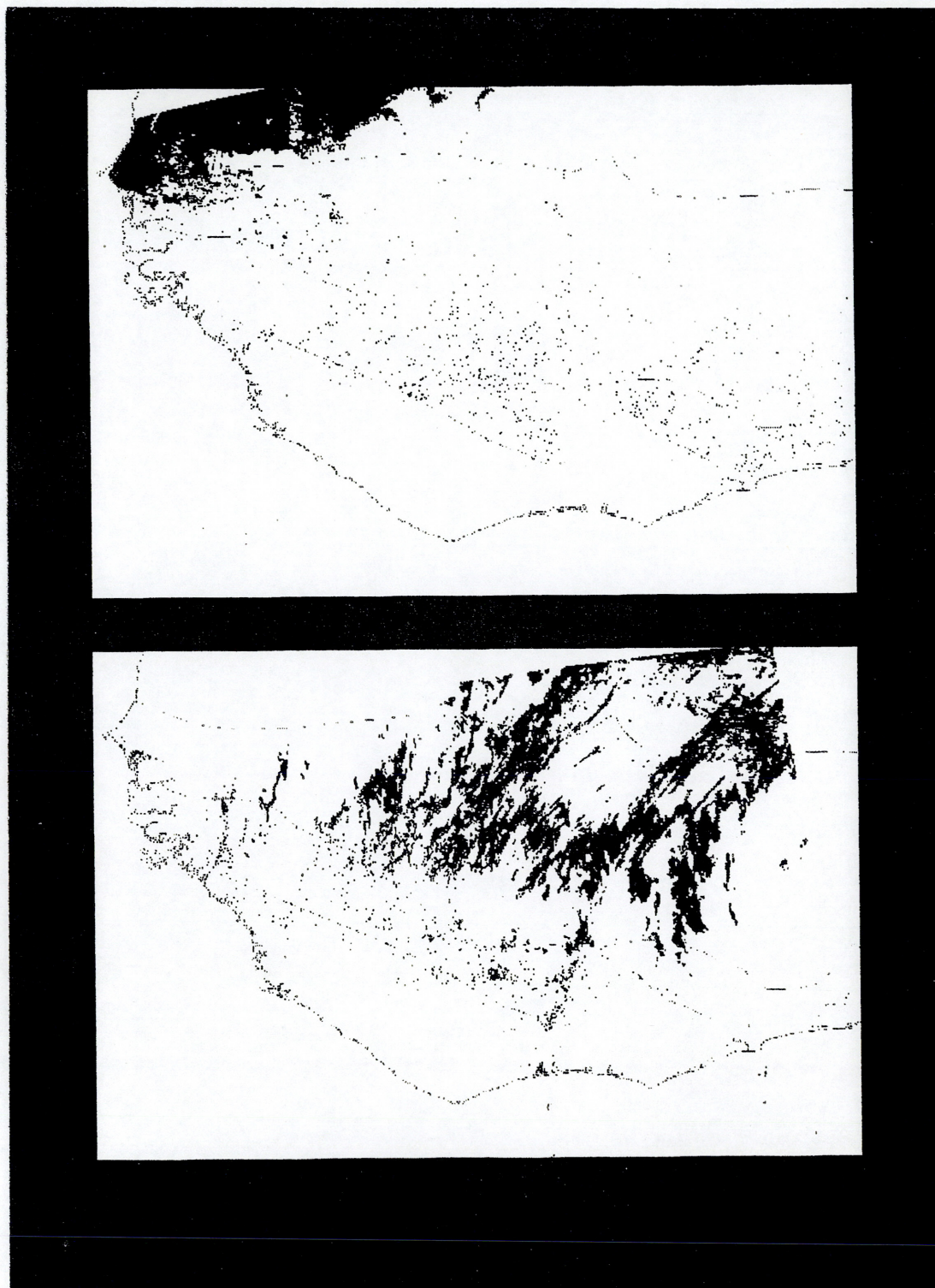


Figure 6. Results from application of modified Kaufman *et al.* (1990) approach for 4th January, 1992 (above) and 21st February, 1992 (below).

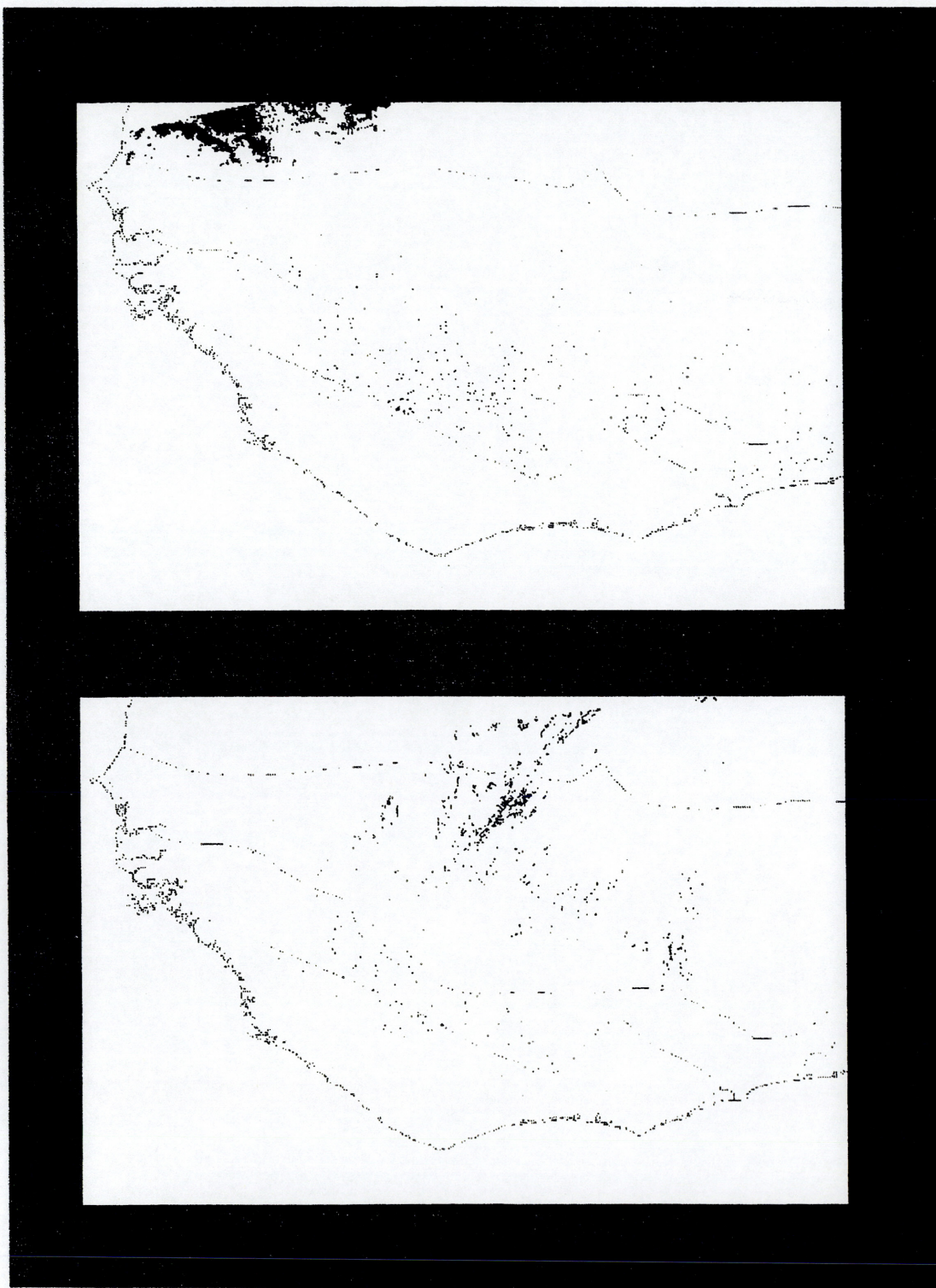
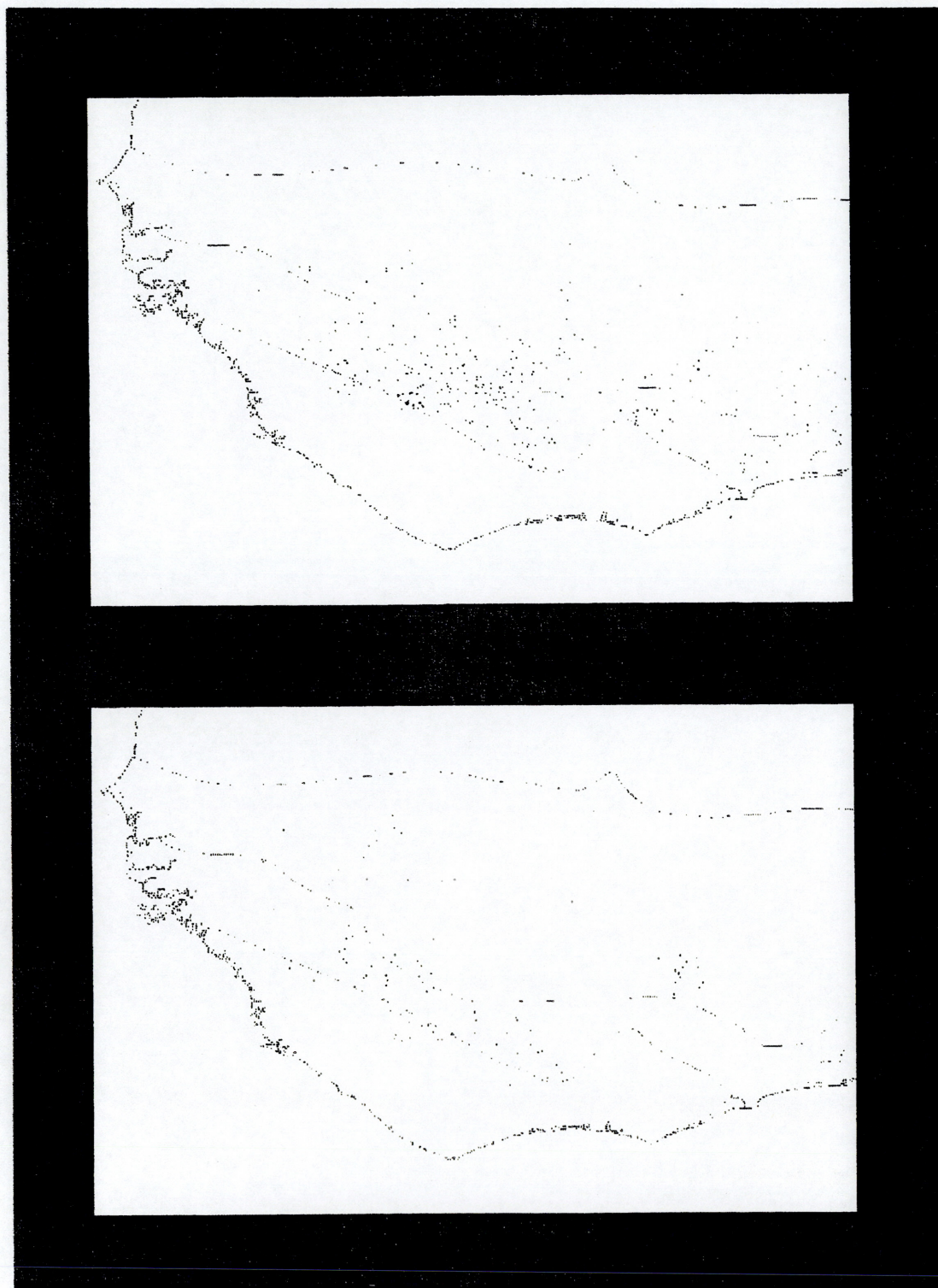


Figure 7. Results from application of newly proposed 4-criteria approach for 4th January, 1992 (above) and 21st February, 1992 (below).



6. West African fire dynamics

6.1 Verification

Verification of results for any such regional scale study for a single date would be impractical and virtually impossible. The use of three months of data makes such a proposition even more unimaginable. As a consequence, the term verification used here, does not refer to being able to validate every single fire pixel as being a fire event on the ground, but more to assessing the results in the light of reported statements for this region and knowledge gained from a localised field campaign.

In other words, verification of the results obtained for the entire time series is undertaken in a generalised way utilising each of the four main vegetation types identified by UNESCO/White (1983) (figure 1). Comparing the AVHRR based fire counts / calendar for each vegetation zone, with past work reported in the fire literature gives a general indication of the areas of agreement whilst highlighting where the proposed approach may be inadequate. In addition, a field campaign undertaken between 30th January and 14th February, 1992 provided much detailed information for a study area of around 62500 km² in the important forest - savanna contact zone of the Republic of Guinea. Whilst a few fires were observed in the field most of the study area had already been affected by fire. Field verification was thus largely limited to establishing the date at which fires occurred for the different zones. This was accomplished through contact with the local population and local government service staff (Grégoire *et al.* 1992).

Figure 8 shows the distribution of all probable fire pixels obtained using the new four criteria approach applied to the 63 images of the 3 month time series. Daily results have been composited for each month - December 1991 (red), January 1992 (green) and February 1992 (blue). From these monthly composites it is immediately obvious that a large percentage of the Sudanian and Guinea-Congolia/Sudania zones are affected by fire throughout these three months of the dry season. This is verified by Menaut *et al.* (1991) who states that the moist Guinea-Congolia/sudania (high green biomass) and the south Sudanian savannas experience the most frequent and severe burnings of the West African Savannas.

No pixels appear to be identified as probable fire pixels in the Sahelian zone for these three months (figure 8). This is not unusual since they are, in any case very limited. Burning in this zone can begin as early as September and continue through the months of October and November to reach a minimum by December (Menaut *et al.* 1991). There is, however, a definite concentration of red points i.e. December fires in the Western Sudanian zone mainly in South East Senegal and Southern Mali. Frederiksen *et al.* (1990) report that for the 1988/1989 dry season bushfire activity in Senegal peaked in December with an estimated 21,275 km² affected by fire. Much of this activity was concentrated in the East and South East of the country. This value dropped to 4,662 km² in the month of January. Using AVHRR night time imagery, Langaas (1992) also found there to be a definite shift of fire activity from central Senegal in November and early December to Southern Senegal and Mali in late December and January.

Figure 8 also shows a very dense clustering of fire activity in January (green points) along the savanna - forest contact zone in Southern Guinea. This activity occurred primarily between the 31st December 1991 and 10th January 1992 i.e. approximately 20 days before our arrival in this area. The impact of these large fires, which lasted five to six days, was clearly evident in the field, and still being spoken about by many of the local people (Grégoire *et al.* 1992). The Guinea-Congolia/sudania zones of the Côte d'Ivoire and Ghana also show intense fire activity in January (figure 8).



Figure 8. Fire distribution for West Africa: December, 1991 (blue), January, 1992 (red) and February, 1992 (green). Results from the newly proposed 4-criteria approach.

It is clear from figure 8 that fire activity in the Guineo-congolian zone is predominantly in February. This follows the now well documented north-south trend of fire activity which starts in September in the Sahelian zone and continues through to March in the Guineo-congolian zone (Gregoire *et al.* 1993). Although this is clearly evident in figure 8 the trend is not simply North-South as there is also evidence of a second trend moving parallel in time, but in an easterly direction.

The monthly total of probable fire pixels extracted for the entire West African region for December 1991, January and February 1992 is 39,007, 39,621 and 33,045 respectively. These of course represent probable fire events which were detectable by the satellite at the time of overpass. The daily totals indicate that fire activity was extremely intense between 23rd December 1991 and 7th January 1992 with daily totals exceeding 6000 pixel counts for 24th December 1991 and 5th January 1992. Although it is impossible to validate these figures, the peak period coincides very well with the observations and information collected during the Guinean field campaign (Gregoire *et al.* 1992).

The results from the new four criteria approach to fire detection show a high degree of reliability for monitoring the spatial and temporal patterns of fire activity throughout the West African region. General trends can either be verified from the literature or by knowledge gained in the field. It is impossible to comment on the accuracy or reliability of absolute fire counts.

COUNTRY	PROBABLE	UNESCO/White (1983)	PROBABLE
	FIRES	ECOLOGICAL ZONES	FIRES
GHANA	31907	SAHELIAN	65
IVORY COAST	30658		
GUINEA	23324	SUDANIAN	79573
MALI	7101		
BENIN	6261	GUINEA-CONGOLIA/SUDANI	51582
UPPER VOLTA	5073		
TOGO	4472	GUINEO-CONGOLIAN	11398
SENEGAL	3765		
SIERRA LEONE	3708		
GUINEA BISSAU	1418		
LIBERIA	138		
THE GAMBIA	136		
NIGER	89		
MAURITANIA	7		

Table 2. Total fire counts for each country and each of the UNESCO/White (1983) vegetation zones for the period 1st December, 1991 - 29th February, 1992.

6.2 Interpretation and discussion

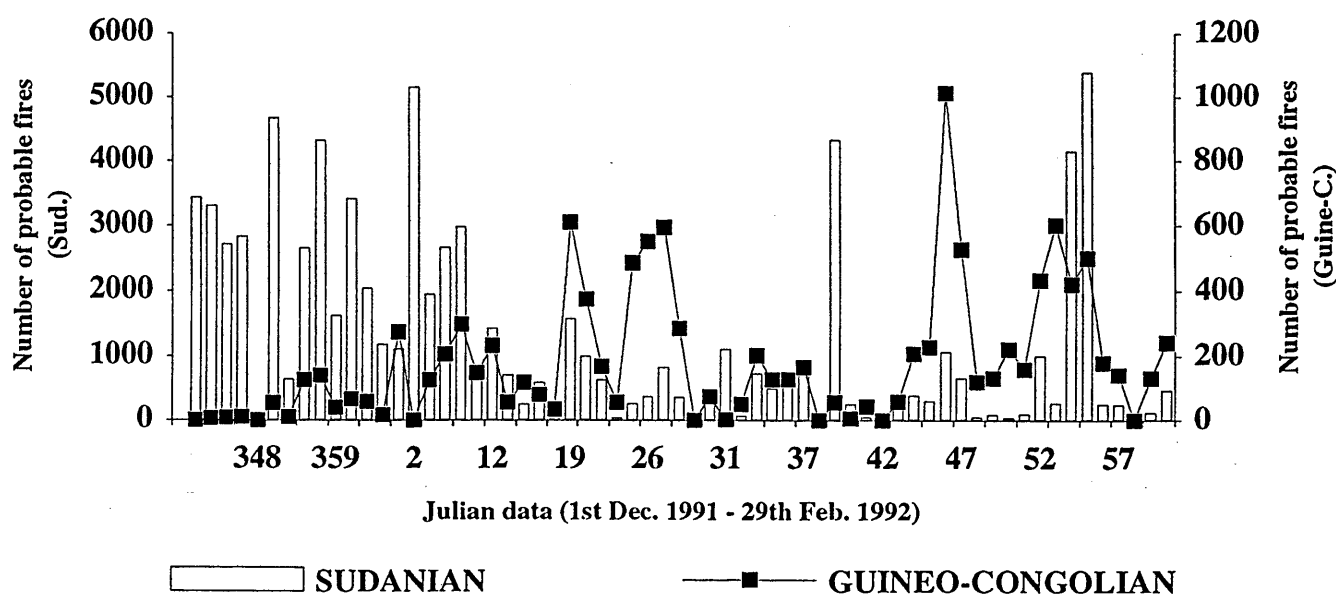
Our knowledge of national and sub-continental scale fire activity in West Africa can be considerably improved by combining the fire information obtained from the newly proposed fire detection approach and a GIS (Geographical Information System) database. The UNESCO/White (1983) ecological zones (figure 1) have already been extensively used throughout discussions in §5 and §6.1. A similar database was compiled for the national boundaries of West Africa and counts of probable fire pixels were extracted for each day for each country and each ecological zone. These statistics are summarised in table 2.

The national scale results indicate that for the three study months, fire activity was greatest in Ghana and the Côte d'Ivoire, both with over 30,000 recorded probable fire pixels. Guinea was the only other country to have over 20,000 probable fire pixels identified. Mali and Benin fall into the next class with over 6000 probable fires, whilst Togo, Upper Volta, Sierra Leone and Senegal all had counts between 3000 and 5100.

Apart from Guinea Bissau the remaining five countries had less than 150 identified probable fire pixels.

Statistics extracted using the UNESCO/White (1983) zones (figure 1) have been discussed in some detail in §5.1. The rather surprising result that fewer probable fire events were recorded in the Guinea-congolia/sudania zone than in the Sudanian zone may be explained by the likelihood that March fires (not included in this study) would contribute proportionally more to the Guinea-congolia/sudania zone total than to the Sudanian zone. The temporal development of fire activity over the 63 day period for the Sudanian and Guineo-congolian zone is shown in figure 9. The two temporal curves illustrate very clearly that by the middle of January 1992 fire activity in the Sudanian zone has already peaked and is decreasing, whilst in the Guineo-congolian zone fire activity is more or less reaching a peak in February. Some of the more dramatic peaks and troughs in these temporal sequences are a result of cloudy or hazy conditions covering large areas of West Africa. This has two important effects. Firstly, the area of land actually sampled by the fire detection procedure will be much less and secondly the actual meteorological conditions on the ground will be less favourable for ignition. Both effects could result in a drop in probable fire counts. Without undertaking a systematic check of each image it is impossible to state whether the actual land surface area considered is reduced (due to cloud cover or reduced areal coverage of the sensor due to being outside the range of the satellite), or whether the meteorological conditions on the ground are unfavourable for fires. The problem is further complicated by the high temporal and spatial variability in these effects, which can easily lead to miss-interpretation of the statistical data if one is unaware of such influences.

Figure 9. Daily fire counts for the Sudanian and Guineo-Congolian vegetation zones as defined by UNESCO/White (1983) (figure 2). Note the shift in peak fire activity from December/January in the Sudanian zone to January/February for the Guineo-Congolian zone.



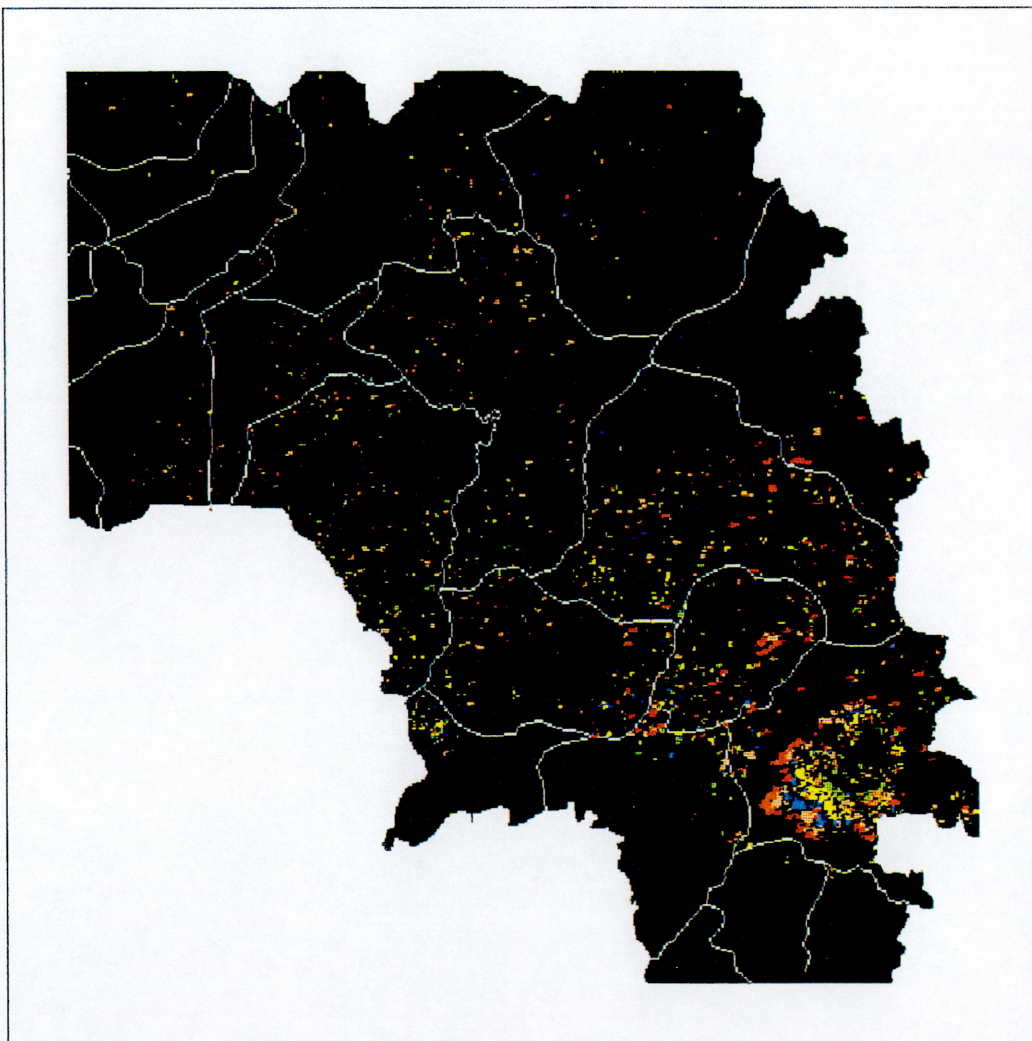


Figure 10. Fire distribution as obtained from the newly proposed 4-criteria approach, for 6 consecutive days (31st Dec. 1991 - 5th Jan. 1992) in southern Guinea. The progression of the fire identified in the south eastern corner can be followed throughout the 6 days period.

One of the many advantages of extracting and archiving daily fire information in a digital format means that the data can be composited over any specified time step. Furthermore, if detailed images illustrating the fire distribution for a single country on a single day are required this can also be obtained. Figure 10 shows the fire distribution throughout the administrative districts of South Eastern Guinea for six consecutive days (31st December 1991 - 5th January 1992). The growth of the large fire burning in the south eastern corner of this image can be monitored in stunning detail. The dates and extent of this fire were verified in the field. Figure 10 illustrates that the size and direction of the advance of such a fire can be monitored daily. In addition, the number of probable fire events identified at the district level for Guinea can be extracted on a daily basis and their distribution presented as in figure 10. The same detailed information can be extracted for the other countries of West Africa.

7. Conclusions

This work clearly demonstrates the complexity of trying to develop an automated fire detection method suitable for large environmentally heterogeneous areas. The new approach proposed in this paper has been shown to give extremely positive results for West Africa, which offer considerable improvements on existing methods.

It is also evident that fire detection methods using AVHRR, based on thresholds, involve a level of compromise. For example, the universal application of a single channel 2 (ToA reflectance) threshold across the entire region of West Africa appears to be highly successful in eliminating large blocks of non-fire pixels in the northern regions but, has the parallel effect of losing some highly probable fire pixels in the forest zones to the south. Just as the Kaufman *et al.* thresholds cannot not be directly used in environments different from those in which they were developed, it is likely to prove the same for the four criteria used in this study. Because of the extreme complexity of environmental, social and political factors associated with the dynamics of fire, we do not believe that a universal AVHRR based fire detection method, relying solely on thresholds is possible. Here we successfully introduced a channel 2 threshold. This may not be appropriate for other continents or even for other regions of Africa. Other thresholds could always be used, but the combinations are so numerous, and the world's ecological conditions so variable that such an *ad hoc* approach is not the way forward in the search for a universal fire detection method.

We strongly propose that it is much better to revert to a one or two threshold procedure for fire detection using the AVHRR (now knowing the limitations), but see it as essential to combine this satellite-derived fire data with GIS information. Results from this study suggest that by utilising the UNESCO/White (1983) vegetation zones it may be possible to fine tune the actual values of the thresholds for specific ecosystems and time of season. This is foreseen as the next step in this research with the ultimate aim of developing a more knowledge based automated fire detection and analysis routine, such as the Biomass Burning Information System proposed by Malingreau *et al.*, (1993).

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The limitations and potential of AVHRR GAC data for continental scale fire studies

A. S. BELWARD, P. J. KENNEDY and J-M GREGOIRE

Institute for Remote Sensing Applications, Monitoring Tropical Vegetation Project, TP440 CEC Joint Research Centre, 21020 Ispra (Va) Italy.

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Abstract. Global Area Coverage (GAC) data from the Advanced Very High Resolution Radiometer (AVHRR) are available on a daily basis, dating back to July 1981. The AVHRR's 3.55 - 3.93 μm channel is suitable for detection of terrestrial hot spots, such as bushfires. The long-term archives and global cover make the GAC a potentially valuable data source for large scale fire studies. However, these data are sampled spatially through a combination of line skipping and averaging. This study shows that the sampling affects the sensitivity of GAC for fire detection in relation to ecosystem and season. The GAC are found to provide a reasonable measure of fire activity in grassland and open bush savannah, but to perform poorly in the forest margins. Overall at least 79% of fires detected with non sampled AVHRR data are missed by the GAC. This severely limits the use of GAC data for quantitative fire studies. The GAC does appear to provide a reasonable measure of fire calendar (*i.e.*, variations in fire activity with time) and on a continental scale successfully identifies the main regions of fire activity. The potential of these data for continental scale fire studies is illustrated through the preliminary analysis of 277 GAC mosaics of Africa for the period September 1988 to August 1989.

1. Introduction

Fire has major impacts on local, regional and global ecosystems. Burning almost instantaneously changes the vegetation characteristics of the burned area and repeated burning can effectively alter the spatial boundaries of ecosystems, forcing transition from one to another (Menaut 1983). Rainfall interception by plant canopies is reduced, as is the water holding capacity of the soil, and rainfall events therefore result in increased runoff, causing soil erosion and loss of nutrients (Morgan 1980). Because evapotranspiration contributes to the recycling of water locally the burning off of the vegetation cover is likely to affect the local or even regional hydrological regime (Salati 1987). Extensive burning, even due to many small localised fires, can have important global implications through the release of large quantities of carbon dioxide and methane into the atmosphere (Crutzen and Andreae 1990). These gases are in part responsible for the greenhouse effect, but also affect the oxidising capacity of the air and thereby the concentrations and life-time of many other atmospheric constituents, including pollutants (Brasseur and Verstraete 1989). Biomass burning also plays a major role in the nitrogen cycle. Fires release nitrogen oxides in the atmosphere, which form nitric acid, thus contributing directly to acid rain (Dignon and Penner 1991). Once the initial covering of

dark ash has dispersed, the albedo of burned out and cleared areas usually increases relative to that of surrounding areas, because of the higher reflectance of soils and the reduced light trapping of the remaining vegetation cover. This alters surface-atmosphere energy exchanges and can directly affect climate (Nobre *et al.* 1991).

Biomass burning is thus a phenomenon of global proportions, capable of causing large scale and long lasting environmental changes. Being linked to vegetation condition, climate and human activities, patterns of biomass burning are unique indicators of such changes. Pressures of population growth, economic demands and demographic shifts are likely to change burning patterns. This can alter the balance between fire as an essential part of ecosystem maintenance and agricultural management, and fire as an agent of environmental destruction. A good example was the massive increase in burning in Amazonia indicative of accelerating deforestation caused by ranching, re-settlement, mining and logging (Malingreau and Tucker 1989). Awareness and understanding of the effects of biomass burning on the Earth system is rapidly growing; the sound management of burning practices is also recognised as vital for sustainable development. However, systematic documentation of global biomass burning patterns and history is unavailable, and even on a national level is often fragmented and unreliable. This lack of information is keenly felt, both by the international scientific community (IGBP 1990), and by policy makers (*e.g.*, Direction Nationale des Forêts et Chasses, République de Guinée personal communication).

To establish if the timing (date of burning), frequency (number of fire events) and recurrence (repeated fire events for the same area) of fire for any given location have changed a history of burning patterns is needed. However, by its very nature fire is a transitory phenomenon which does not lend itself easily to retrospective studies. Building up such a history of burning patterns requires regular earth observation with some instrument capable of detecting fires, and consistent archives of these data to give the required historical perspective.

Fortuitously the characteristics of the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA meteorological satellites are reasonably suited to this task. The spectral channels of the AVHRR are well placed for the detection of hot targets (Matson and Dozier 1981, Muirhead and Cracknell, 1984), and the NOAA satellites' orbits, in combination with the AVHRR's wide field of view, provide daily global earth observation.

Fire detection using AVHRR data currently relies on two approaches. The first uses a simple thresholding of channel 3 (3.55 - 3.93 μm), in which all pixels within a range of values close to sensor saturation are assumed to be fire (Malingreau *et al.* 1985). For the channel 3 sensors of AVHRR instruments saturation occurs at brightness temperatures of between 322 and 331 K (Robinson 1991), however various values for any single instrument can be found in the literature (Kennedy 1993). The second technique uses the difference in the relative response in channels 3 and 4 (10.5 - 11.3 μm); in accordance with Wien's displacement law this difference is much greater for hot than cool targets. For a pixel to be identified as a fire first it has to be above a specified temperature in channel 3 (*e.g.* 316 K), secondly the channel 3 temperature must be equal to or greater than channel 4 plus a specified amount (*e.g.* 10 K) and thirdly the channel 4 value itself must be above a specified value (*e.g.* 250 K), this is to avoid highly reflective cloud edges which can also saturate channel 3. The algorithm is fully documented by Kaufman *et al.* (1989, 1990), from whom the example values quoted are drawn. Note that these values are not fixed because, with the exception of the saturated channel 3 values the others are a function of the ecosystem over which the observations are made. The techniques and their limitations are reviewed in detail by Kennedy (1993).

The techniques are most reliable using full (1 km) resolution High Resolution Picture Transmission (HRPT) data in areas where there is good contrast between high temperature fires and cooler temperatures for the surrounding environment; hence the success of using the AVHRR for detection of fires in tropical forests (Nelson and Holben 1986, Malingreau and Tucker 1988, 1990, Kaufman *et al.* 1990, Setzer and Periera 1991). However, HRPT archives tend to be somewhat fragmented. To document continental burning patterns over long periods of time, for much of the world we have to turn to the AVHRR Global Area Coverage (GAC) data-set. The GAC archive provides daily observations over more than 10 years.

Though all AVHRR channels are available, the GAC data are obtained by on-board sampling of the full resolution data such that for a given scan line the first four pixels out of every five are averaged, and only every third scan line is processed (Kidwell 1991). Previous studies have shown that this sampling gives relatively poor representation of the full resolution data (Justice *et al.* 1989). This is particularly the case with linear features and point phenomena such as fires. It has been shown, for example, that fires detected with HRPT may be missed because of the line skipping (Belward and Lambin 1990, Belward 1992). Malingreau and Belward (1992) have suggested that this under-representation may vary with time, though they state that 'the analysis of the ultimate sampling effect will not be complete, however, until more complete time-series have been investigated'.

Extending the analysis to continental scales, and through a complete burning season raises three key questions. Firstly, because of the averaging involved in generating GAC data, should the radiometric thresholds used for fire detection be based upon those developed with HRPT? Secondly, given the sampled nature of the GAC, what is the magnitude of the miss-representation of fire events? and thirdly, are these effects consistent in space and time? In this paper we address these questions and in doing so, examine the potential of the GAC data for the study of continental scale fire dynamics.

2. Study area

For reasons of data availability and field experience West Africa is used as the study area. In most tropical ecosystems the burning calendar is closely linked to the dry season. For West Africa there is a north to south lag in the start of the dry season. The semi-arid Sahelian area to the north experiences a climate characterised by a prolonged dry season of 8 to 10 months starting around September. This then grades into the Sudanian, Guinea-congolia/sudania and Guineo-congolian vegetation zones, each with successively shorter dry seasons. The broad vegetation classes referred to are from UNESCO/White (1983). These are used as a framework for subsequent analysis. West African fires can appear as early as September, but usually appear as the dry season becomes well established, around late October, early November. Burning continues throughout the season, ending with the onset of the rainy season in late March early April. A north to south shift in burning calendar parallels the vegetation zonation; peak burning in the north occurs in November and in the south occurs in February / March (Grégoire 1990). Figure 1 shows the study area, figure 2 the limits of UNESCO/White's vegetation zones.

3. Data preparation

Eighteen HRPT images (all from NOAA afternoon passes) with minimal cloud cover and similar equator crossing longitudes were identified between September 1988 and the end of March 1989. These were processed as follows: Data are transferred from tape to magnetic disk. The Earth Location Points and solar zenith angles are extracted and the digital counts are converted to radiance ($\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$) using on-board calibration for

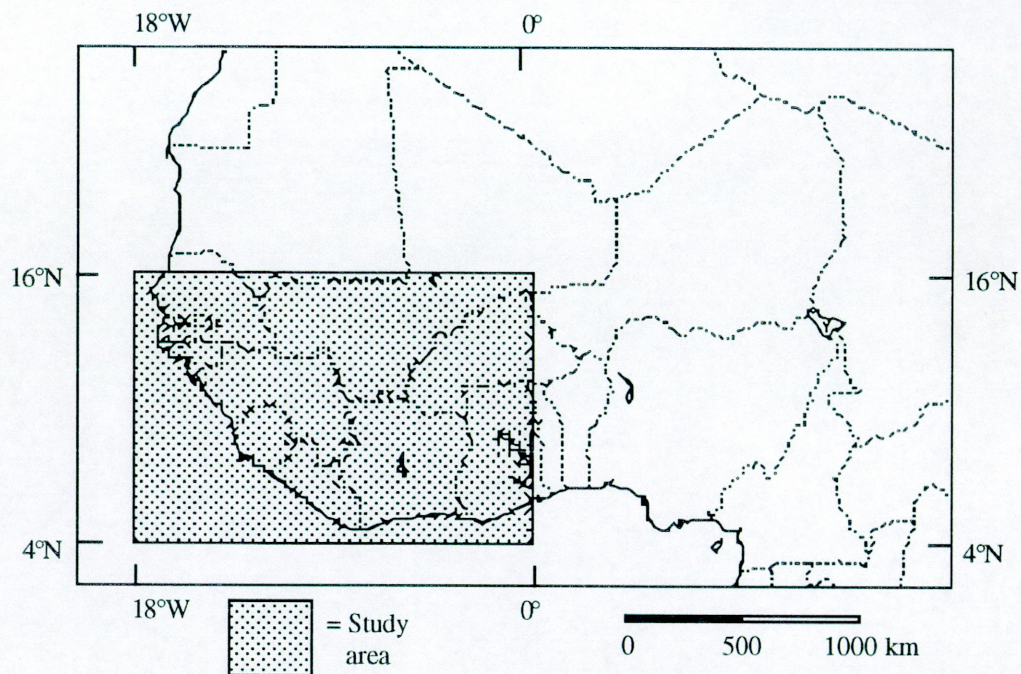


Figure 1. West African Study area

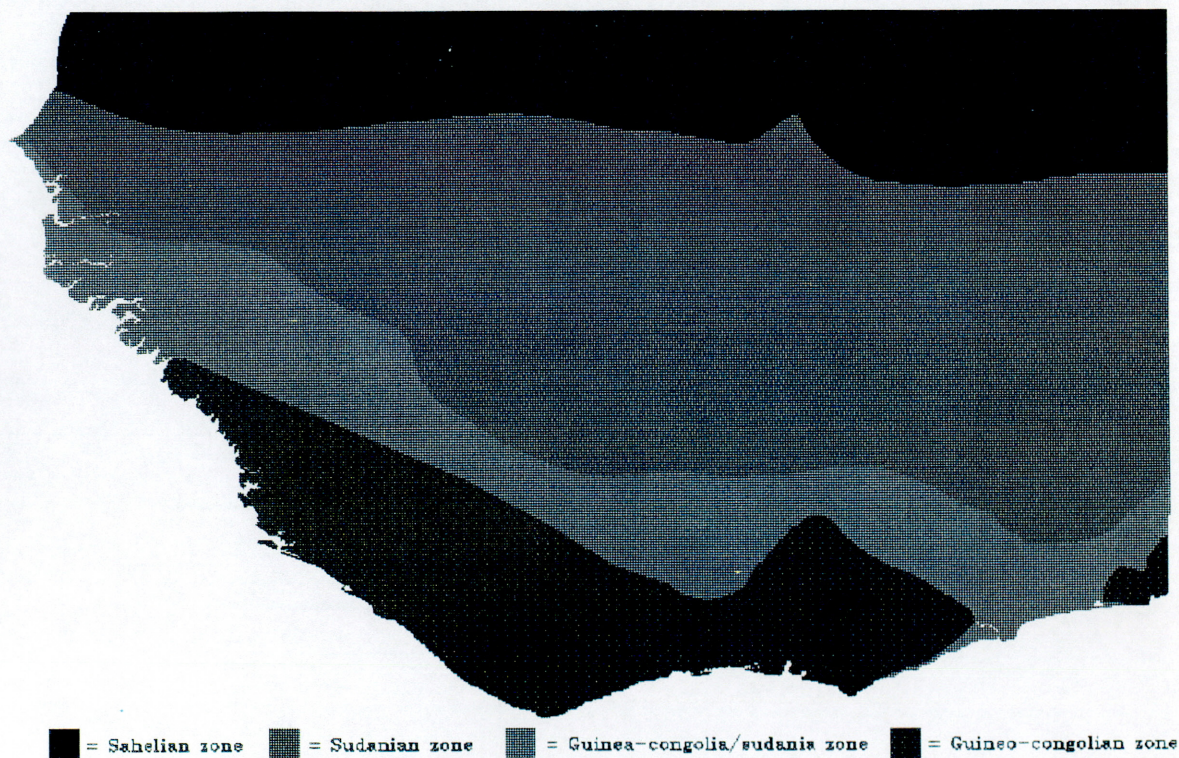


Figure 2. Boundaries of the four vegetation zones defined by UNESCO/White (1983)

channels 3, 4 and 5, post-launch (with linear decay) for channels 1 and 2 (Holben *et al.* 1990). Radiance's in channels 1 and 2 are converted to 'top of atmosphere' reflectance's (ToA) which account for variations in solar zenith angle, Sun-Earth distance and exoatmospheric solar irradiance. Brightness temperatures are calculated for channels 3, 4 and 5 using the inverse Planck function. Channels 4 and 5 are then corrected for non-linearity of sensor response to give true brightness temperatures using pre-launch correction coefficients (Planet 1988). Channels 1 and 2 (ToA reflectance), and channels 3 and 4 (Brightness Temperature) are then geometrically corrected; re-sampling is by nearest neighbour, to a Mercator projection with a 1 km pixel at the equator.

An equivalent GAC data set was simulated by applying the NOAA sampling strategy to the time-series of HRPT images. Each of the simulated GAC pixels was then replicated into a 5 column by 3 row array to create images with the same dimensions as the HRPT but with the radiometric characteristics of GAC.

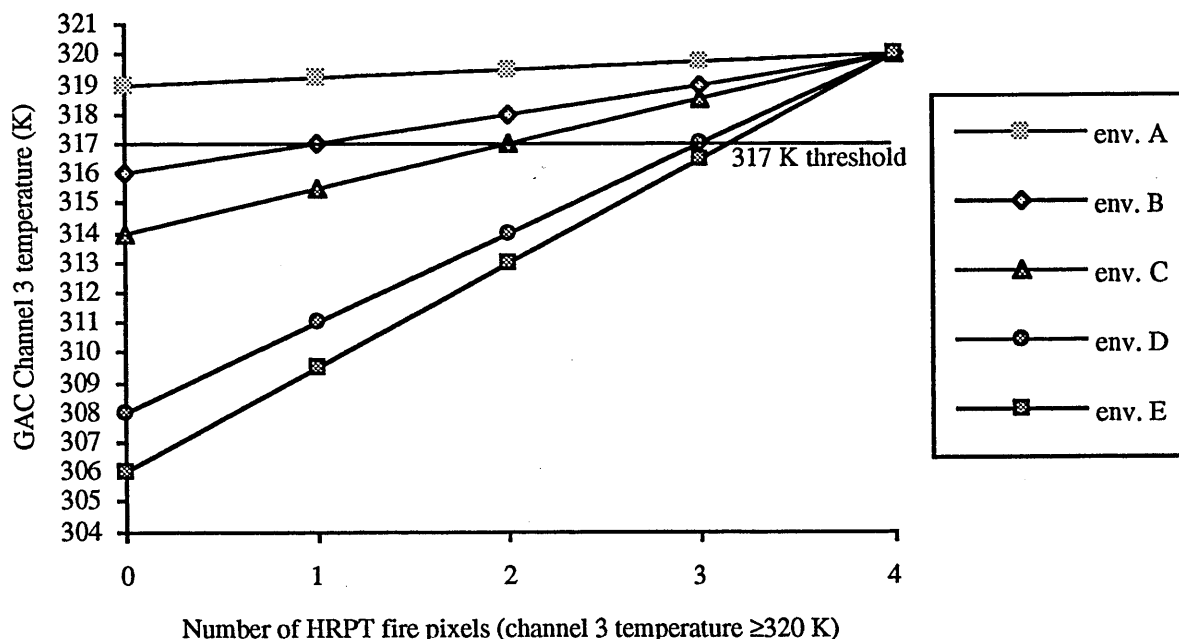
Although some fire detection methods use more than channel 3 alone, this is always a pre-requisite and therefore we consider determining the agreement between channel 3 from HRPT and GAC as a first step in establishing the validity of the GAC for fire detection. Past work has shown that taking only the saturated pixels misses many HRPT fire events. Gregoire *et al.* (1993) found that using a threshold of 320 K considerably reduces the number of missed events for West Africa, and Kaufman *et al.* (1990) use a threshold as low as 316 K over tropical forest. We use a threshold of 320 K, and although this value covers a range of approximately 60 quantization levels (the range varies by up to 3 counts because of day to day variations in the on-board calibration coefficients) we refer to all such pixels as 'saturated'.

4. Channel 3 agreement

In the early part of the dry season, incidence of channel 3 saturation in an HRPT scene tend to be isolated points, and are almost certainly caused by fires. However, as the dry season progresses soils dry out, surface water bodies retreat and vegetation senesces; surface cooling from evapotranspiration is reduced and at the same time albedo increases. This combination of highly reflective, dry and warm surfaces also saturates channel 3. The resulting saturated regions cover extensive areas of contiguous pixels (Grégoire *et al.* 1993), rather than points or lines. In such uniform areas the GAC and HRPT agree as four in-line saturated HRPT pixels will give a saturated GAC pixel, if all four are included in the sample. No other spatial distribution of saturated HRPT pixels will have this effect. Thus where saturated HRPT pixels are scattered they are likely to be missed by the GAC.

Fire fronts simply cannot cover extensive areas, and indeed the more sophisticated fire detection methods eliminate these hot non-fire regions, resulting in images containing many isolated points. For an HRPT pixel to be a probable fire pixel it must have a channel 3 brightness temperature greater than 320 K. The likelihood of a GAC pixel being flagged as a possible fire will depend on the number of saturated HRPT pixels in the block of four sampled, the brightness temperature of the adjacent non-fire pixels, *i.e.*, the background temperature, and the GAC threshold used. Lower channel 3 thresholds in the GAC data would reduce the number of HRPT fire events missed, as those situations where less than four saturated HRPT pixels were sampled by the GAC would be included. The relationship between the threshold used and the number of HRPT fires thus detected will vary depending on the background temperature. In other words, in cooler environments more HRPT fire pixels are needed in the GAC sample or lower GAC thresholds must be used. A simple mixture model illustrates this.

Figure 3. Changes in GAC channel 3 temperature as a function of background temperature and the number of HRPT fire pixels in the GAC sample. Five hypothetical environments are shown. 0 HRPT fire pixels = mean background temperature.

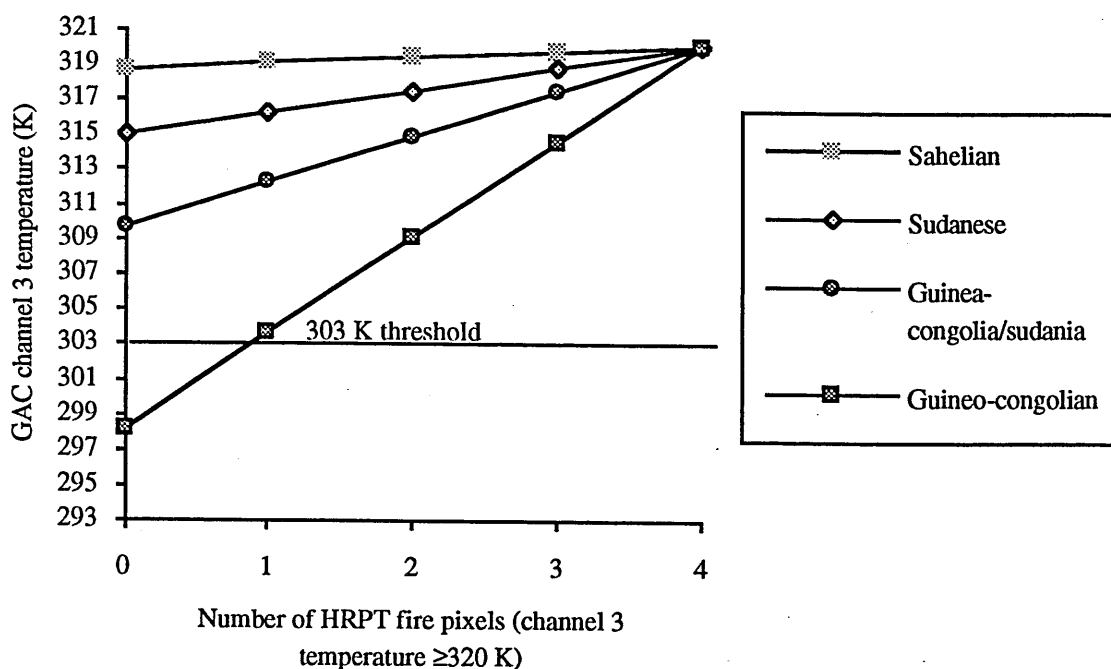


4.1 A GAC fire pixel mixture model

Five environments with different background temperatures are modelled in figure 3. The mixture model used is simply based on varying the number of fire pixels with a value of 320 K and the number of non fire pixels, the temperature of which depends on the environment they are drawn from. The position of each curve for the zero HRPT fire pixels is the mean background temperature. Environment A is typical of the Sahelian zone, B and C equivalent to the more densely vegetated Sudanese conditions, whilst D and E represent the cooler more densely wooded and forested ecosystems of southern West Africa. At the value of 320 K GAC pixels in the cool environments (D & E) are directly comparable with pixels from the warmer environments (C, B & A).

If a threshold of less than 320 K is considered for the GAC then variations in background temperature influence the number of HRPT pixels needed to exceed this given value. For example, a threshold of ≥ 317 K in the model would still only detect those cases where four HRPT fire pixels were sampled for the cool forests of environment E, yet a single HRPT fire pixel in the much warmer environment B is enough to satisfy this requirement, and indeed the background temperature of environment A, *i.e.*, zero HRPT fire pixels, is already over this threshold.

Figure 4. Changes in GAC channel 3 temperature as a function of background temperature and number of HRPT fire pixels in the GAC sample. Mean background temperatures (0 HRPT fire pixels) are taken from a year's GAC observations.



The range of environmental conditions represented by the five model environments are found in West Africa. This is illustrated in figure 4. The background temperatures from the environments were obtained from analysis of a time-series of near daily GAC data throughout the West African dry season of 1988 - 89 (described in §6.1. below). The mean channel 3 brightness temperatures were calculated and used for the zero HRPT fire pixel position in the model. If small fires, equivalent to a single HRPT fire pixel, are to be detected in the cool forest margins of the Guineo-congolian zone a GAC channel 3 threshold as low as >303 K must be used. For the other ecosystems the same threshold would include all surfaces, regardless of if there was fire present or not.

If a GAC threshold of 320 K is used, all possible fires thus detected have the same characteristics for all environments, *i.e.*, they are equivalent to four in-line HRPT fire pixels. For this reason we use the same thresholds with GAC data as with HRPT data.

5. Fire detection

5.1 Methods

A modified version of the fire detection method developed by Kaufman *et al.* (1989) was applied to each HRPT and its derived GAC image. The criteria used were; channel 3 value ≥ 320 K, difference between channel 3 and channel 4 ≥ 15 K, channel 4 value ≥ 295 K and channel 2 top of atmosphere reflectance $\leq 16\%$. The rationale behind the modifications is explained in Kennedy *et al.* (1993).

Julian date	Sahelian zone		Sudanian zone		Guinea-congolia/ sudania zone		Guineo - congolian zone		Whole region	
	HRPT	GAC	HRPT	GAC	HRPT	GAC	HRPT	GAC	HRPT	GAC
88321	408	19	4377	97	372	3	2	0	5159	119
88331	21	1	2615	43	709	4	10	0	3355	48
88353	4	0	3457	32	1666	4	150	0	5277	36
88360	-	-	1687	18	518	0	158	1	2363	19
88362	-	-	2910	9	1484	6	205	0	4599	15
89004	3	0	2069	44	2012	18	570	1	4654	63
89016	2	0	89	44	608	18	169	1	868	63
89035	-	-	26	0	265	0	88	0	379	0
89036	-	-	30	0	761	11	352	4	1143	15
89037	-	-	19	0	553	4	290	3	862	7
89054	-	-	25	0	74	0	30	0	129	0
89063	-	-	42	2	19	1	3	0	64	3
89082	-	-	15	0	-	-	-	-	15	0
89084	-	-	-	-	-	-	15	0	15	0
Total	438	20	17361	289	9041	69	2042	10	28882	388

Table 1. Number of fire pixels detected with HRPT and GAC for the 1988-89 West African dry season. Counts are shown for each of UNESCO/White's vegetation zones

5.2. Results

For each image a fire count and location was obtained. Surprisingly no fires were detected in the two images from September and the two from October. All results refer to images from the 16th November onward, thus reducing the time series to 14 dates.

For each date, fire counts were made for the four UNESCO/White's ecological zones. These are given in table 1. An extract from the 4th January 1989 GAC and HRPT classified images is shown in figure 5. To directly compare the HRPT and GAC fire counts we adjusted both counts on the basis of the following. A GAC fire pixel can only result from four HRPT fire pixels so we first multiply the GAC pixel counts by 4. Each GAC image is a 27% sample of the pixels making up an HRPT image; if the fire pixels are randomly distributed throughout an HRPT image we should only compare the GAC counts with 27% of the HRPT counts. On the basis of these two assumptions the adjusted fire counts are shown in table 2.

5.3. Discussion

It is evident from tables 1 and 2 and figure 5 that *most* of the HRPT fires are missed by the GAC. In table 2 the percentage of the HRPT pixels missed by the GAC are given. Over the whole region and the whole season the GAC missed more than 79% of the fires. When viewed by vegetation region the agreement between the GAC and HRPT shows considerable variation. The two match up very well for the Sahelian zone, with the overall loss for the whole season being around 32%. However, the value of this good agreement is largely negated by the fact that fires in the Sahel are a rare occurrence, there being very little biomass to burn. The agreement is much poorer to the south, where fires are much more common. Losses rise to 79.09% for the grassland and bush savannah of the Sudanian zone, 88.69% for the tree savannah of the Guinea-congolia/sudania zone

Julian date	Sahelian zone			Sudanian zone			Guinea-congolia/ sudanica zone			Guineo - congolian zone			Whole region		
	HRPT	GAC	% loss	HRPT	GAC	% loss	HRPT	GAC	% loss	HRPT	GAC	% loss	HRPT	GAC	% loss
88321	110	76	30.91	1182	388	67.17	100	12	88	1	0	100	1393	476	65.83
88331	6	4	33.33	706	172	75.64	191	16	91.62	3	0	100	906	192	78.81
88353	1	0	100	933	128	86.28	450	16	96.44	41	0	100	1425	144	89.89
88360	-	-	-	455	72	84.18	140	0	100	43	4	90.7	638	76	88.09
88362	-	-	-	786	36	95.42	401	24	94.01	55	0	100	1242	60	95.17
89004	1	0	100	559	176	68.52	543	72	86.74	154	4	97.4	1257	252	79.95
89016	1	0	100	24	0	100	164	72	56.1	46	4	91.3	235	76	67.66
89035	-	-	-	7	0	100	72	0	100	24	0	100	103	0	100
89036	-	-	-	8	0	100	205	44	78.54	95	16	83.16	308	60	80.52
89037	-	-	-	5	0	100	149	16	89.26	78	12	84.62	232	28	87.93
89054	-	-	-	7	0	100	20	0	100	8	0	100	35	0	100
89063	-	-	-	11	8	27.27	5	4	20	1	0	100	17	12	29.41
89082	-	-	-	4	0	100	-	-	-	-	-	-	4	0	100
89084	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	119	80	32.8	4687	980	79.09	2440	276	88.69	553	40	92.77	7799	1376	79.3

Table 2. Adjusted fire counts as detected with HRPT and GAC for the 1988-89 West African dry season. Counts are shown for each of UNESCO/White's vegetation zones. GAC counts x4, HRPT x0.27 from table 1. Percentage of HRPT pixels missed by GAC are calculated from the adjusted counts.

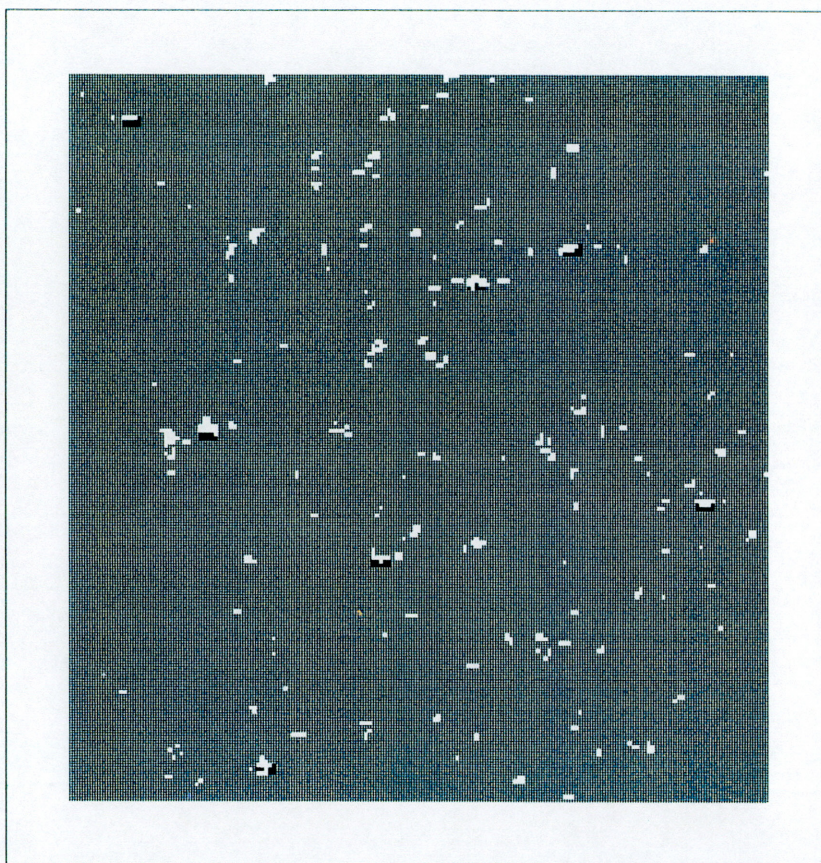


Figure 5. 185 by 185 pixel extract from the GAC and HRPT fire classifications for 4th January 1989. The extract is taken from the Guinea-congolia/sudania zone. The fires identified with HRPT are shown in white (462 in total). The HRPT fire pixels overlay the fires identified from GAC, shown in Black (7 in total). Each GAC pixel has been copied 15 times into 5 by 3 pixel blocks (reversing the sampling procedure) so the two images overlay. Note that the top left of each GAC pixel corresponds to four HRPT fires.

and 92.77% for the heavily vegetated Guineo-congolian zone. Even on individual days there is considerable variation in the GAC / HRPT agreement for the different vegetation types. On day 89004, 559 HRPT fires were found in the Sudanian zone and an almost identical number, 543 were found in the Guinea-congolia/Sudania zone, around 68% of the Sudanian fires were lost by the GAC compared with nearly 87% of the fires in the Guinea-congolia/Sudania zone. This bias in sensitivity also distorts the overall picture of the region's fire activity. Table 3 shows the fire count for each zone as a percentage of the region's total. The HRPT data, quite reasonably, rank the Sahel as the least important zone of fire activity, whilst the GAC places the Guineo-congolian zone in this position.

From field observation we have found that Savannah fires tend to form a single burning front which runs until it reaches either a man made, or more usually a natural fire break such as gallery forest (Grégoire *et al.* 1992, Belward *et al.* 1993). Fire morphology also varies depending on its use; fires for pasture regeneration or hunting are extensive whilst fires for land clearance associated with agricultural expansion are far more localised (Malingreau 1990). In the Sudanian and Sahelian grasslands and bush savannah, fire is mainly used by hunters and pastoralists, fire breaks are few and in

	HRPT	GAC
Sahelian zone	1.5	5.8
Sudanian zone	60.1	71.2
Guinea-congolia/sudania zone	31.3	20.1
Guineo - congolian zone	7.1	2.9

Table 3. Percentage of the fire counts from HRPT and GAC accounted for by each of the UNESCO/White's vegetation zones

consequence the fires tend to be large, with fronts covering many kilometres. The north to south transition from Sudanian to Guineo-congolian vegetation zone is matched by increasingly cooler and moister conditions, more widespread arable land use and much denser vegetation. Whilst fires in the southern forested areas may persist for many days, the fronts move slowly and the fires are relatively small. Larger fires are far more likely to give four in-line saturated HRPT pixels than the more localised fires to the south, hence the south north improvement in HRPT and GAC agreement.

In spite of this trend, there is no systematic relationship between the percentage of HRPT fire pixels missed by the GAC and the number of HRPT fires occurring, even within a single vegetation type. In the Sudanian zone, for example, on Julian day 88331, 706 HRPT fires were detected, 75.64% of which were missed by GAC, on day 88362, 786 HRPT fires were found yet 95.42% of these were lost by GAC. At least from the images used in this study, GAC fire counts cannot be corrected to those from HRPT in a way which is consistent with time for a single vegetation type, or indeed consistent from one ecosystem to another.

For each vegetation type, changes in fire activity through the season are seen as changes in number of HRPT fire pixels with time. Though the number of fire pixels from GAC are far less, the GAC counts in general follow the temporal pattern of the HRPT. Where HRPT fire counts are minimal so too are the GAC. In other words the two do agree well as far as fire calendar is concerned. This is best seen in figures 6 - 9. These are graphs of fire count as a function of time for each of the vegetation zones. In all cases the GAC data provide a reasonable approximation of the calendar as described with the HRPT. Trends in fire activity (increases and decreases) agree, periods of peak fire activity coincide, as do the non-burning periods. The north south shift in calendar is retained. Both the GAC and HRPT show that in the Sahel and Sudanian zones the fire activity is declining through November and over by January, whilst in the southern Guinea-congolia/sudania and Guineo-congolian zones the fire activity starts later and peaks later. The worst agreement is in the Guineo-congolian zone, where the GAC data miss both the start and end of the fire season.

These results show that the GAC does not provide the same measure of fire activity in all ecosystems if a fire detection method based on a universal set of thresholds is used; in this case it is biased in favour of the more open ecosystems and against the denser tree savannah / forest margins. The fire calendar is well represented in the Sahel, Sudanian and Guinea-congolia/sudania zones, though is poor in the Guineo-congolian. Likewise, the GAC fire counts correctly portray the relative importance of the Sudanian and Guinea-congolia/sudania zones in terms of overall fire activity, though the importance of the Guineo-congolian zone is underplayed.

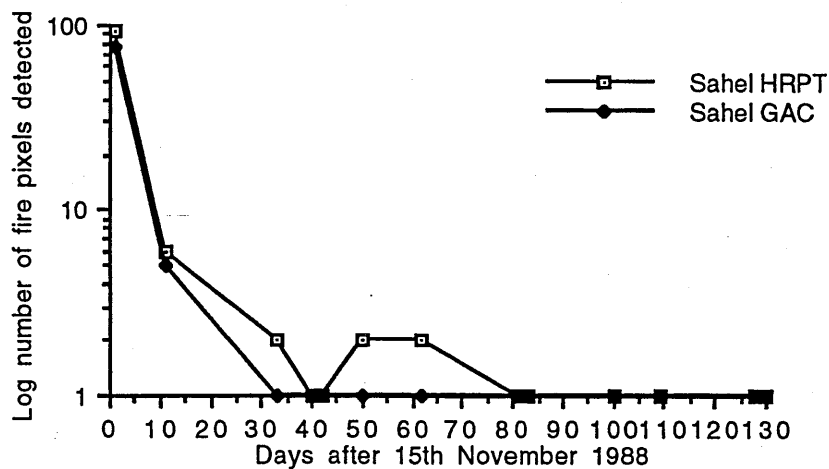


Figure 6. Variations in the number of fire pixels detected with GAC and HRPT data through the 1988 - 89 dry season for the Sahelian zone.

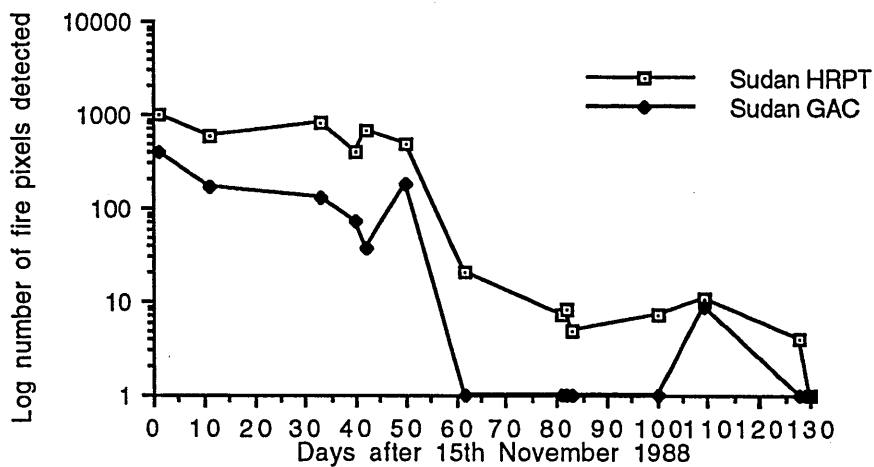


Figure 7. Variations in the number of fire pixels detected with GAC and HRPT data through the 1988 - 89 dry season for the Sudanese zone.

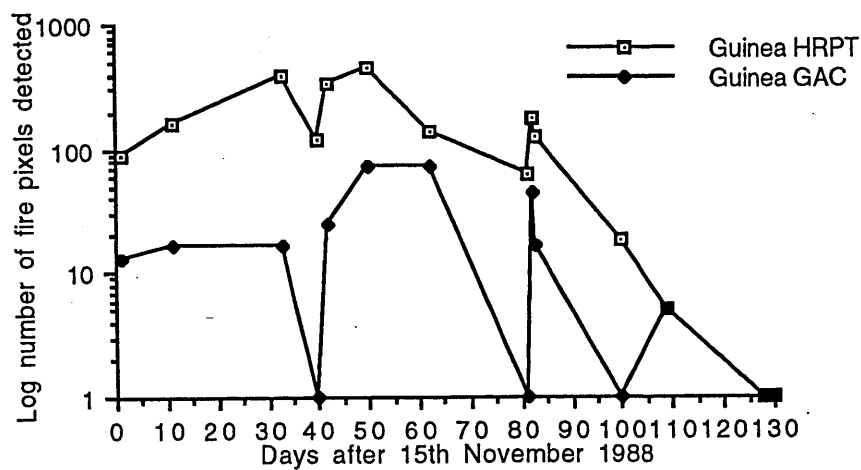


Figure 8. Variations in the number of fire pixels detected with GAC and HRPT data through the 1988 - 89 dry season for the Guinea-congolia/sudania zone.

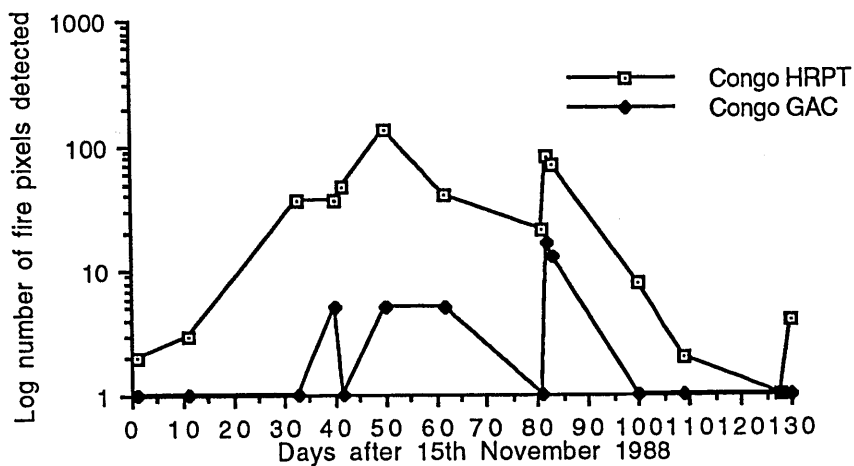


Figure 9. Variations in the number of fire pixels detected with GAC and HRPT data through the 1988 - 89 dry season for the Guineo-congolian zone.

This bias can be seen as a serious limitation to the use of GAC data for fire studies. Fire counts in grasslands will be overestimated relative to bush and tree savannahs, and counts in woodland and forest margins will be underestimated. Furthermore, from the 14 images used in this work there are no systematic ways of correcting GAC fire counts to those of HRPT. It is not recommended to use GAC if quantitative information concerning fire number or area is required. More positively though, with the exception of the forest ecosystems, good estimates of the burning calendar can be had from the GAC. Furthermore, figure 5 shows that GAC provides some indication of the spatial location of fires detectable with HRPT, so the datasets could be used to identify *regions* of fire activity. To further evaluate the potential of the GAC for continental scale fire studies we applied the fire detection method to a time-series of near daily GAC data for the whole of Africa.

6. Continental scale fire observations

Africa was chosen because of the availability of an archive of suitably processed imagery and our familiarity with west African burning patterns from field observations. This can be regarded as fortuitous as biomass burning in Africa is greater than in any other continent (Delmas *et al.* 1991); around 75% of the African savannah burns annually, an area of more than 300 million hectares. These savannah fires account for nearly one third of the global carbon emissions from biomass burning (Andreae 1991), and after all, it was on this continent that "the history of both mankind and man-made fire began" (Schüle 1990).

6.1. Time-series preparation

Near daily mosaics covering the full continent for the period 1st September 1988 to 11th August 1989 were created from radiometrically and geometrically corrected imagery. Up to 4 orbits per day of level 1b GAC are processed such that channels 1 and 2 (ToA reflectance), and channels 3 and 4 (Brightness Temperature) of all orbits for each day are geometrically corrected to a Mercator projection with a 5 km pixel at the equator, all images are re-sampled by nearest neighbour, into a multi-channel daily mosaic for the whole continent. Calibration follows the data processing steps described in §3 above. A more complete description may be found in Belward *et al.* (1992).

6.2. Fire identification

The fire detection method as used above (§ 5.1) was applied to each GAC mosaic (277 in total). The output for each image is a binary fire / non fire image. From these data monthly, quarterly and annual fire distribution maps for the whole continent were created. These composites were made in such a way that pixels flagged as a fire on a single date and on more than one date were separated. Table 4 gives the fire counts.

6.3. Discussion

The experience in West Africa suggests that the fire counts in table 4 are an underestimate of at least 79%, probably more. As stated in §5.3., we have little faith in any fire counts derived from GAC, believing the potential to lie in the capacity for derivation of fire calendar, and for locating zones or regions of concentrated fire activity.

Figure 10 shows a continental scale fire distribution map derived from a sample of daily GAC mosaics from December and January (peak burning in the northern hemisphere) and June and September (peak burning in the southern hemisphere). There is an almost unbroken belt of fire activity along the entire west to east savannah of northern hemisphere Africa.

Figure 10. Spatial patterns of fire activity for the African continent as derived from AVHRR GAC data from September and December 1988, January and June 1989. Background image is a channel 3, 2, 1 red, green, blue composite from 15 of the images. Areas shown in white indicate presence of fire activity.

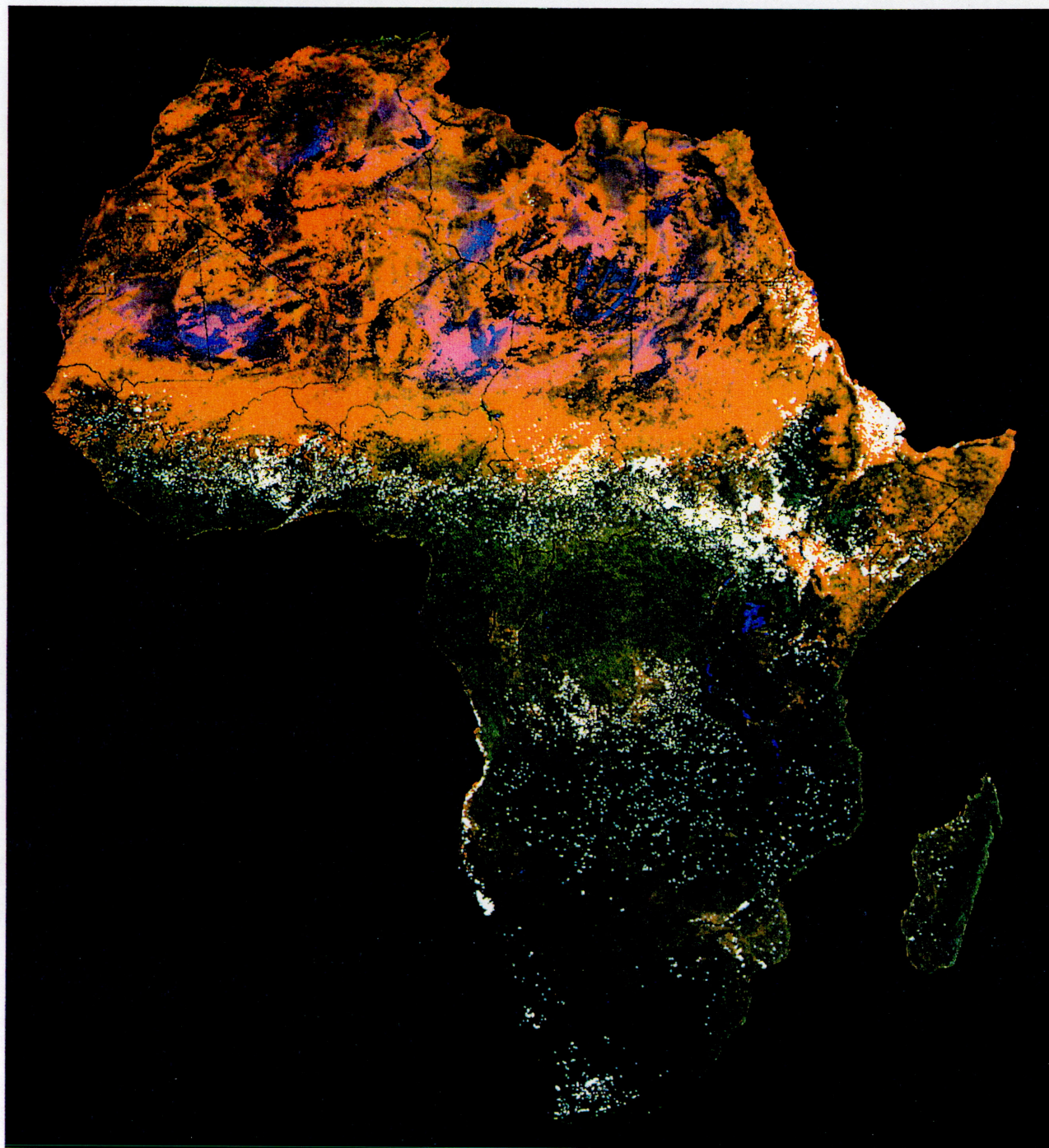


Figure 11. Fire calendar for Zaire, Fire counts are from 277 GAC mosaics for Africa combined with WBDbII

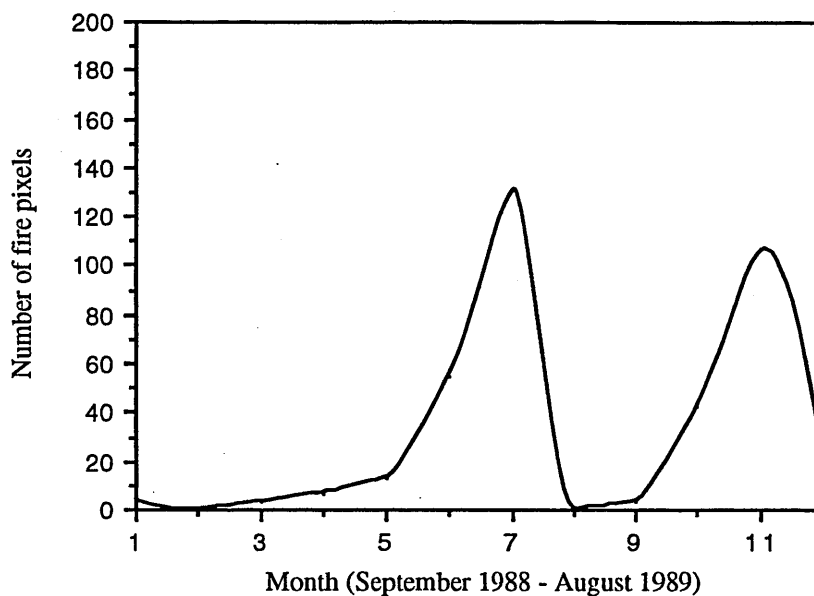
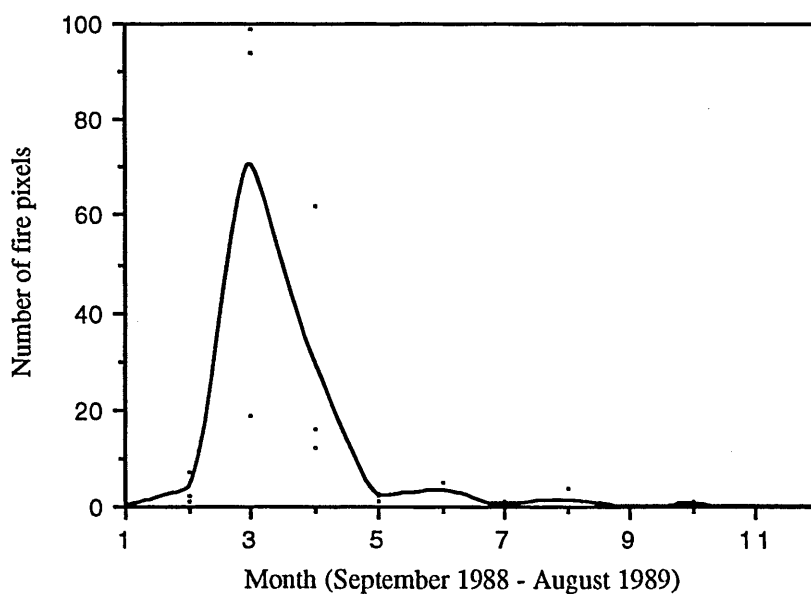


Figure 12. Fire calendar for Senegal and Mali. Fire counts are from 277 GAC mosaics for Africa combined with WBDbII



Fires per Month	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
No. single date events	135	73	8937	7697	3502	3571	3118	1119	794	705	948	130
No. muliti date events	0	0	1886	1518	830	573	537	110	35	72	42	0
Fires per Quarter	1st Ouarter			2nd Ouarter			3rd Ouarter			4th Ouarter		
No. single date events	9121			11870			4365			1635		
No. muliti date events	12			1395			329			73		
Fires for Year	Annual total											
No. single date events	21995											
No. muliti date events	2420											

Table 4. Monthly, quarterly and annual fire counts from GAC for Africa, September 1988 to August 1989
Single day events refer to locations identified once only in each compositing period, multi day events are those locations identified as fire on more than one date.

In West Africa the form of the so called 'V Baoulé' in Côte d'Ivoire is clearly seen (the V Baoulé corresponds to the pronounced 'V' in the shape of the Guinea-congolia/sudania vegetation zone shown in figure 2). A marked concentration of fire activity is evident in Ghana. This corresponds closely to the results obtained by Kennedy *et al.* (1993) working with 1991 / 1992 dry season HRPT data for the West African region. The other major concentration in this northern fire belt is in eastern Central African Republic and south-western Sudan. This is consistent with the savannah fire patterns reported by Cahoon *et al.* (1992) in their work using data from the U.S. Defence Meteorological Satellite Program (DMSP). Cahoon *et al.* (1992) also identify southern Zaire and Angola as areas with high fire frequency; these too appear as zones of concentrated fire activity on the GAC composite. It is also clear from the figure that the fire algorithm developed and tested for West Africa requires some further tuning for use on a continental scale. There are obvious anomalies in Eritrea, the Nubian desert, the coastal strip of Angola and the Namib desert. Combining the image data with other spatial databases, such as vegetation maps, for fire classification will we believe help eliminate some of the mis-identification and bias found in this study. For example, the use of lower GAC thresholds over cool forest ecosystems should reduce the under-estimation of fires, and elimination of desert areas on the basis that there isn't anything there to burn in the first place would certainly improve GAC derived fire location maps.

Whilst integration with other data is likely to improve the fire classification process, it is also increasingly evident that interpretation of the results should be related to other data sets. The biomass burning information system, proposed by Malingreau *et al.* (1993), shows that such an approach is the most realistic way of obtaining information concerning global fire behaviour and fire emissions. The GAC derived fire data can be used in this way. Analysis of the GAC fire calendars in relation to vegetation types, distribution of road networks, centres of population and national parks is currently being investigated. As a first step we combined the daily fire distribution maps with country boundaries from World Boundary Data base II (WBD bII) to derive a fire calendar per country for the whole of Africa. These were then combined if more than one country showed the same calendar. Figure 11 shows the calendar for Zaire. This had a unique bimodal distribution. The first peak occurs in March which is towards the end of the dry season in northern Zaire and the time at which fires most often occur in forest margins. The second peak is in July. This corresponds to the dry season in the south of the

country. The two regions of fire activity in Zaire, to the north and south of the equator are clearly seen in figure 10. Figure 12 shows the combined fire calendar for Senegal and Mali. Both countries are in the Sudanian zone. The first fires were detected in mid September, peak activity is in November and falls off rapidly, with only a few fires found after January. The pattern is consistent with other fire studies over this region (*e.g.*, Langaas 1992) and serves to illustrate that the GAC archives do have a role in continental scale fire studies. The high *temporal* sample provided by the GAC data can provide new information; for example, our limited sample of four HRPT scenes over Senegal/Mali for September and October 1988 failed to indicate any fire activity; the coarse resolution, but daily, GAC data did pick up some fire activity in this period.

7. Conclusions

This work reinforces the view that the sampling employed in the GAC data generation severely compromises these data as a source of quantitative environmental information related to fire. The GAC archives do however provide a good description of fire calendar, and on a continental scale provide a good indicator of the locations of intense fire activity. A daily measure of fire activity for the whole African continent (albeit on these coarse scales) over a period of almost 12 years will provide a new perspective on changes in continental scale fire patterns, on the transport of fire emissions and for the study of environmental degradation and ecosystem change, especially when the results are related to other data sets.

Given the difficulties in correcting fire counts from GAC we believe absolute measures of fire activity, in terms of fire count or fire area are not possible from these data. For such work the use of full resolution AVHRR data is mandatory. Under the auspices of the IGBP-DIS (International Geosphere Biosphere Programme Data and Information System) daily, global, full resolution AVHRR data sets have been archived at the EROS data center since April 1992. One of the expected uses of this archive is global fire detection (Townshend 1992, Malingreau *et al.* 1993). Handling such data sets is a formidable challenge. Preparation of the first two channel, geometrically corrected, single day, full resolution, whole world scene alone took more than 20 *days* of CPU time (J. Eidenshink, EROS data center, personal communication). Any way of validating fire detection methods on continental scales before embarking on such costly data processing can only be seen as beneficial. The anomalies seen in figure 10 already provide evidence of the difficulties in transferring fire detection methods developed in one part of the world to another. Even within the same continent our results show that a single set of thresholds is unlikely to be sufficient. The relatively low data volumes and multi-annual nature of the GAC Africa data set provides us with a unique test bed for evaluating continental and global scale approaches to fire detection.

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Chapter 8. Conclusions

The use of AVHRR data for large area vegetation studies: current status and future perspectives

The preceding chapters have emphasised the importance of vegetation studies in the context of global change research. The value of the AVHRR as a potential source of data for such work has been highlighted and examples of the use of these data presented. The discussion and conclusion sections of each of the individual papers making up the thesis review the results in detail. Rather than reiterate these, this concluding chapter discusses the use of available processed AVHRR data archives for large area vegetation studies in the light of the results presented earlier.

1. AVHRR data archive availability

Despite the perceived value of the AVHRR data for global change research, suitably processed AVHRR data archives covering large areas for long periods of time are not widely available. Chapter 5 reviews the different AVHRR data formats in depth, this section reviews the current status of the processed data archives.

Long term, large area processed HRPT data archives do not exist. The JRC's Agricultural Information Systems (AIS) has begun to prepare daily, multi-channel HRPT mosaics for Europe. Though the European HRPT archive is complete (*i.e.*, includes data from all NOAA satellites), AIS will only process data for specific years. The North American continent has extensive archives of raw HRPT and LAC data, held at the EROS Data Center, Sioux Falls and the Canadian Center for Remote Sensing, Ottawa. However, these data are not systematically processed. Finally, as reported in the opening chapter, the IGBP-DIS has put together the first global HRPT archive, though data processing has yet to begin.

Long time-series of processed GAC data are more readily available. The NASA Goddard Space Flight Center's Global Inventory Monitoring and Modelling Studies (GIMMS) group have produced a GAC derived NDVI time series for Africa dating back to July 1981 (Justice 1986), and the same processing chain is to be applied to other continents (Justice *et al.* 1991). JRC's Monitoring of Tropical Vegetation (MTV) unit has created a daily, multi-channel GAC archive for Africa. The final data set will cover the period July 9th 1981 until the present day. Full details of the processing chain are given in appendix 2 (Belward *et al.* 1992). Finally, in 1992 the NASA GAC pathfinder activity began. This has the goal of producing an 11 year global GAC data set. Operational processing will begin in late 1993 (M. E. James, NASA Pathfinder project, personal communication).

The GVI is the only currently available long term global processed AVHRR product. Essentially the GVI data set consists of a 7 day NDVI maximum value composite calculated from the GAC data. Only one GAC pixel is selected for each GVI pixel. Thus the GVI is produced by both spatial and temporal sampling of the already sampled GAC data. This massive undersampling severely limits the use of these data for studies requiring precise location or detailed spatial information. The main advantages of the GVI are the global availability of a decade's data set of manageable proportions. However, recent advances in computer power, both in terms of data processing and storage, plus the imminent availability of global GAC and HRPT/LAC make the continued use of these data doubtful.

2. Suitability of available AVHRR data archives for large area vegetation studies

The value of the AVHRR data for vegetation studies has been emphasised throughout this thesis. The analysis also identifies a number of drawbacks to the use of these data. These are discussed below in terms of the spatial, spectral and temporal characteristics of the available AVHRR data archives.

2.1. Spatial contrast and artefacts

The AVHRR data archives have all been prepared so that the remapped final products maintain almost the full resolution of the raw data. The HRPT data are resampled to a 1 km pixel (IGBP 1992a), the GAC to a 5 km pixel (Belward *et al.* 1992) or an 8 km pixel (Justice *et al.* 1991), and the GVI to a 19.5 km pixel (NOAA 1990).

Chapter 4 shows that spatial contrast is low in full resolution HRPT images because of the autocorrelation between neighbouring pixels, and artificially high in full resolution GAC images because of the sampling method used in GAC data generation. The low spatial contrast in the HRPT data exacerbates the problems of accurate ground location and detection of fine scale changes. The opposite is true of the GAC data, where spatial contrasts observed in the full resolution imagery can be artefacts introduced by the sampling. This effect is all the more limiting because it varies from ecosystem to

ecosystem. In consequence, spatial information derived from GAC at the scale of a single pixel is compromised.

A recommendation for dealing with the artificial spatial contrast in the GAC data sets clearly emerges from the analysis presented in chapter 5. Averaging 3 by 3 blocks of GAC pixels, giving a nominal 12 kilometre resolution (actual 15 km by 9 km), was shown to suppresses the sampling induced spatial effects consistently for all West African ecosystems, independently of whether the observations were made with the AVHRR's channel 3 data or with NDVI. This averaging should be retrospectively applied to the existing GAC data archives to give information directly comparable with that derived from HRPT.

However, producing time-series of GAC data with such an averaging scheme built in is not recommended. As shown in chapter 7 this would, for example, make it impossible to use GAC data for biomass burning studies. A more flexible approach is to create full resolution time-series, but to ensure that users are aware of the spatial limitations this implies. Descriptions of any such time-series should contain recommendations to the effect that while full resolution observations are available, their spatial integrity is low and only observations made after degrading the time-series to a 12 km resolution will be comparable to observations made with unsampled AVHRR data.

The low spatial contrast in HRPT data is more difficult to deal with. Approaches have focused on the use of high resolution satellite imagery, such as that from Landsat, as a means of improving ground location (as discussed in chapter 3), or in an attempt to resolve the heterogeneity of an individual AVHRR pixel, so called mixture modelling (*e.g.*, Iverson *et al.* 1989). However, because of the limited geographical coverage of single high resolution images and their high cost, neither technique has been widely adopted.

2.2. Temporal characteristics

All the available AVHRR data archives (with the exception of the MTV GAC Africa data set) use the Maximum Value Composite (MVC) technique proposed by Holben (1986) as a means of removing cloudy scenes from time-series. The technique involves creation of the NDVI, and then retention of the highest NDVI value (and equivalent pixels from the individual AVHRR channels if required) for each location over a given period of time. For example, the GVI is created on a weekly basis (NOAA 1990), the GIMMS GAC archive and the IGBP 1 km data set both on a 10 day basis (Justice 1986, IGBP 1992a).

The effects of using the MVC method are fourfold. Firstly, only one set of values is retained per compositing period. Secondly, long compositing periods, around 2 to 4 weeks, are effective at removing cloudy scenes, but can completely mask short term changes in vegetation condition and will always distort vegetation temporal NDVI profiles. Thirdly, short compositing periods retain more data points, but are less efficient at removing cloud contamination. Finally, not all contamination depresses NDVI values, data transmission errors, such as line drop out, can cause localised NDVI increases, these erroneous data will be included in any final product.

In consequence, the AVHRR data archives prepared with the MVC cannot be used for vegetation studies requiring high frequency temporal observations. Chapter 7, for example, showed that much of the potential of the GAC data for bush fire studies was found to lie in the availability of daily images. Likewise improved methods for extracting NDVI temporal profiles, such as the Best Index Slope Extraction (BISE) method proposed by Viovy *et al.* (1992), or the AIS's Greatest Local Slope (GLS) method (M. Sharman, personal communication) require daily observations as a starting point. As such, neither BISE nor GLS are viable options for users of the established data archives.

2.3. Spectral characteristics

The previous chapters have consistently shown that there are huge benefits in having access to all of the individual AVHRR spectral channels. Chapter 3 demonstrated that the PVI can be more effective than the NDVI for vegetation monitoring in grassland environments. Chapters 4, 5 and 6 all emphasised the value of the AVHRR's channel 3 in vegetation studies, and chapter 7 showed that the use of AVHRR data for fire detection requires the near, middle and thermal-infrared channels.

The established archives, such as the GIMMS GAC archive are made up of the NDVI alone. Only the more recent data archives, such as the MTVs Africa GAC archive, and the planned IGBP and NASA Pathfinder archives, offer (or will offer) access to the separate AVHRR channels, and even these include the NDVI.

This universal adoption of the NDVI can in part be explained by the widespread use and acceptance of the NDVI as a surrogate measure of biophysical parameters, partly because calculation of the NDVI requires no *a priori* information concerning the imaged scene and partly because the calculation of the NDVI is such that there is some normalisation for variations in viewing conditions (Justice *et al.* 1985). Though the NDVI has undoubtedly played a major role in highlighting the scientific value of the AVHRR data for vegetation studies, there is increasing circumspection in using this index.

2.3.1. The NDVI and vegetation spectral properties

The NDVI is not dependent upon vegetation dynamics alone. As shown in chapter 2, the red channel used in the computation of NDVI is sensitive to chlorophyll content, the near-infrared to leaf structure and orientation. In consequence, the index can only be used to monitor vegetation dynamics which are associated with changes in chlorophyll content, leaf structure and leaf orientation.

Chapter 2 also shows that there comes a point where changes in chlorophyll content or leaf structural characteristics no longer result in measurable changes in red or near-infrared reflectance, the so called points of infinite reflectance. Because of this the NDVI tends to produce a saturation response to high green leaf densities (Tucker 1979).

As clearly demonstrated in chapter 3, the NDVI is not independent of substrate so that at low vegetation covers soil background reflectance can exert a considerable influence on NDVI values; higher NDVI's were retrieved from bare bright sandy soils than from thin bush savannahs (page 54).

The value of the NDVI as a measure of vegetation dynamics is also compromised because the reflectance field of vegetation is known to be anisotropic (Deering and Eck 1987). As a consequence of this surface anisotropy, specific viewing angles and/or atmospheric conditions can produce NDVI values which are completely unrelated to vegetation dynamics (Pinty *et al.* 1989, Gutman 1991). The Global Environmental Monitoring Index (GEMI) recently proposed by Pinty and Verstraete (1992a) offers some improvements over the NDVI as it has much reduced sensitivity to atmospheric effects and soil background. However, GEMI has yet to gain wide recognition, and in any case does not address the issue of surface anisotropy.

2.3.2. Implications for the use of NDVI

Because the NDVI is not dependent upon vegetation dynamics alone, relationships between the index and biophysical parameters, such as yield or fractional cover tend to be only locally applicable. For example, it is unlikely that a regression equation between NDVI and the yield of wheat will apply to sugar beet, or even wheat on another soil type or from another year. Similarly the idea that spectral temporal vegetation index profiles will be unique to a single vegetation class is also difficult to defend. Identical plant communities under different environmental conditions can have different profiles. Different populations in that community and individuals in the populations will also have different profiles. It is easy therefore to see that the chances of a consistent and unique community spectral temporal signature are extremely low, and that the chances of different communities having the same profiles are very high.

One consequence of this is that land cover classifications based on temporal spectral profiles very often bear little resemblance to classes recognised by ecologists (*e.g.*, Arino *et al.* 1991). However, there is no reason for us to expect that a view of the earth's biomes from an altitude of 800 km in a restricted part of the spectrum should match that of the ecologist on the ground. New functional descriptions of vegetation classes, based on factors such as seasonality or phenology may have to be found.

For example, the West African cover classes shown in chapter 7, page 132 are derived solely from patterns of channel 3 saturation. These have little meaning in terms of the established ecology of the region, as they are not vegetation classes *per se*. Yet they are functional descriptions of the vegetation, strongly related to land use practices, particularly biomass burning.

Unfortunately, this approach ignores the fact that in some cases the information required from the AVHRR has to fit in with existing work where a description of vegetation or vegetation dynamics using established taxonomic groups or accepted ecological process is required. Extraction of such focused information has to recognise the limitations of the AVHRR discussed above, and calls for alternative ways of using these data sets.

3. Alternative ways of using AVHRR data sets

3.1. Physical measurements from AVHRR data

As pointed out above in §2.3.1 the reflectance field of vegetation is anisotropic. Because of this, AVHRR observations of the same vegetation target will vary depending on the relative positions of the satellite and the Sun. However, this 'bidirectional' reflectance will also vary depending on the physical and morphological properties of the particular vegetation target being viewed (Verstraete *et al.* 1990). Eliminating this variation from satellite observations requires the inversion of the satellite data with a model of the bidirectional reflectance of vegetation canopies (Pinty *et al.* 1990). This would have the highly desirable effect of allowing satellite based measurement of the single scattering albedo, rather than the bidirectional reflectance.

The single scattering albedo is a physical measurement which does not vary with viewing conditions. It is directly related to the absorbing properties of the target, so in the case of vegetation at red wavelengths would relate directly to chlorophyll absorption, and hence photosynthesis.

Resolving the multiple equations making up such models requires multiple observations of the same target with different viewing geometry. Ideally the observations should all be made at the same time and therefore through identical atmospheres. In common with all currently operational earth observation satellites, this is impossible with AVHRR. Less sensitive models of bidirectional reflectance with fewer parameters may provide an interim solution, though this still remains a focus for future research (Pinty and Verstraete 1992b).

3.2. *The need for stratification*

The lack of physically based measurements, and therefore universal relationships between AVHRR observations and vegetation parameters points to the need for stratification. This was suggested in chapter 7 as a way of improving the use of AVHRR data for fire detection on regional or continental scales. The technique for detection of fire in the cool, moist forest ecosystems of Africa is quite different to that used in the hot dry grassland savannahs; *i.e.*, no universal fire detection method exists. Some predefined stratification of the region or continent would allow the automated application of the most appropriate fire detection method in each vegetation zone.

Such stratification could be based on analysis of the AVHRR data themselves. The saturation land cover classes mentioned above in §2.3.2. could provide geographical strata with functional links to land use practice in which different fire detection methods are applied. A natural extension of this is to use spatial and non spatial criteria from sources other than the AVHRR in conjunction with the AVHRR data.

3.3. *An integrated strategy*

The integration of AVHRR based observations and non satellite data in the framework of an expert system is a key to more effective use of the AVHRR data. The example introduced in chapter 7 is the Biomass Burning Information System (BBIS), proposed at the Dahlem workshop on Global change in the perspectives of the past (Malingreau *et al.* 1993). BBIS is based on the integration of established fire behaviour and emission models, with ecosystem characterisation using AVHRR observations of fuel loading and moisture content (Paltridge and Barker 1988) and identification of fire occurrence using AVHRR middle-infrared and thermal data. The spatial-temporal distribution of fires, as detected with the AVHRR, are linked with other spatial data sets, non spatial attributes and dynamic models. For example, land use (spatial data) influences burning practices (non spatial attribute). Burning practices in turn influence fire morphology, propagation, fuel loading and fuel structure (all of which may be described using dynamic models), which in turn affects the likelihood of detection from satellite. In the framework of BBIS this could also be reversed, so that a particular fire pattern as measured with the AVHRR data can be used to infer burning practices or land use. Such synergistic use of AVHRR observations and other data should now be investigated for other applications.

4. Conclusions

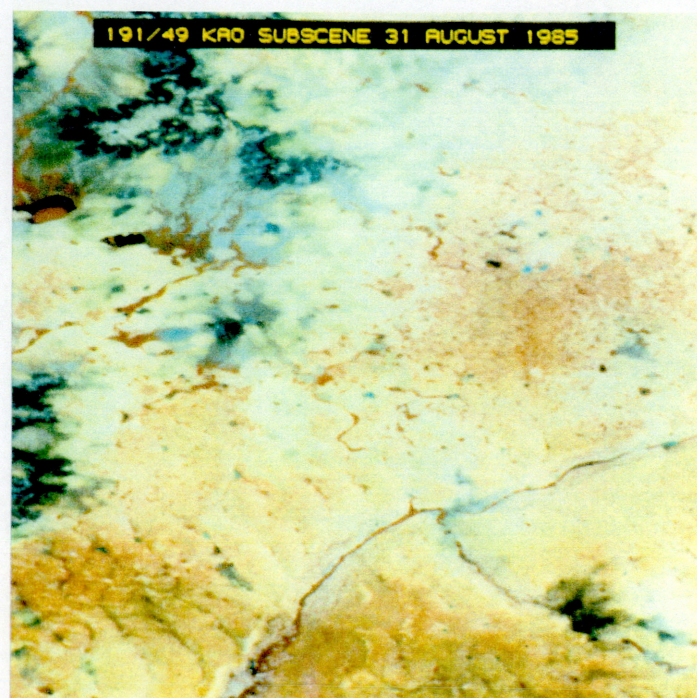
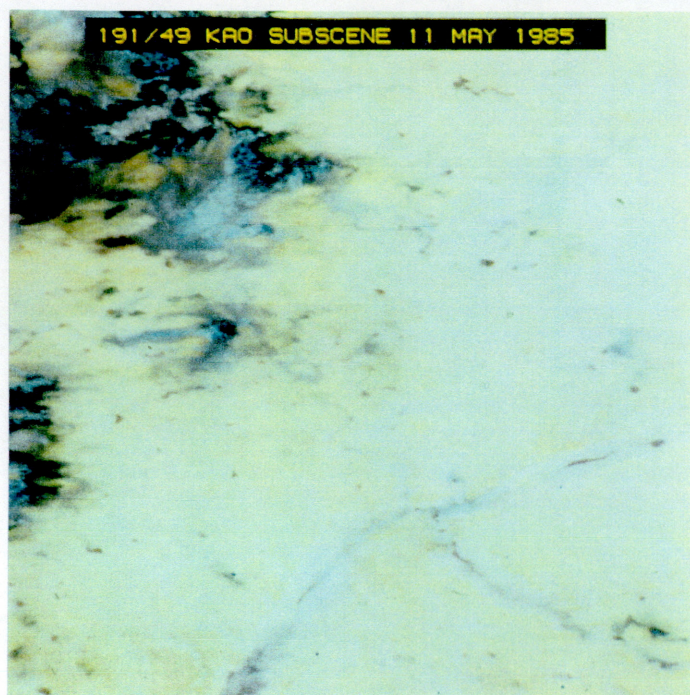
The AVHRR was never designed as an instrument for large area vegetation studies. Yet, as this thesis has shown, the data from this meteorological instrument have a major role to play in such work. The various papers have discussed both the limitations and attributes of the data. Although there are unresolved problems, particularly relating to the anisotropy of vegetation, progress is being made with bidirectional reflectance models to address these issues. New indices, such as GEMI offer new possibilities for the use of AVHRR data and take us one step closer to the derivation of true physical measurements. Previously unforeseen applications such as continental scale fire monitoring, benefiting from the synergistic use of AVHRR and ancillary data sets, are already contributing to the global change research programmes, and new products such as up to date land cover maps will emerge from the imminent global GAC and HRPT data archives.

Our understanding of the AVHRR data has improved dramatically since they were first used for vegetation work in 1981. Coincidentally, this same year saw the establishment of the GAC global archive. Thanks to this vision we now have an uninterrupted, daily view of the dynamics of our planet's vegetation spanning the last 12 years, providing a unique source of data for global change research.

Appendix 1. Colour plates for chapter 3



Plate 1. Band 4, 2, 1 Red, Green, Blue Landsat MSS false colour composites of the Kao study area from October 1984, May 1985 and August 1985. The full resolution image for 7th October 1985 can be seen in plate 6a.



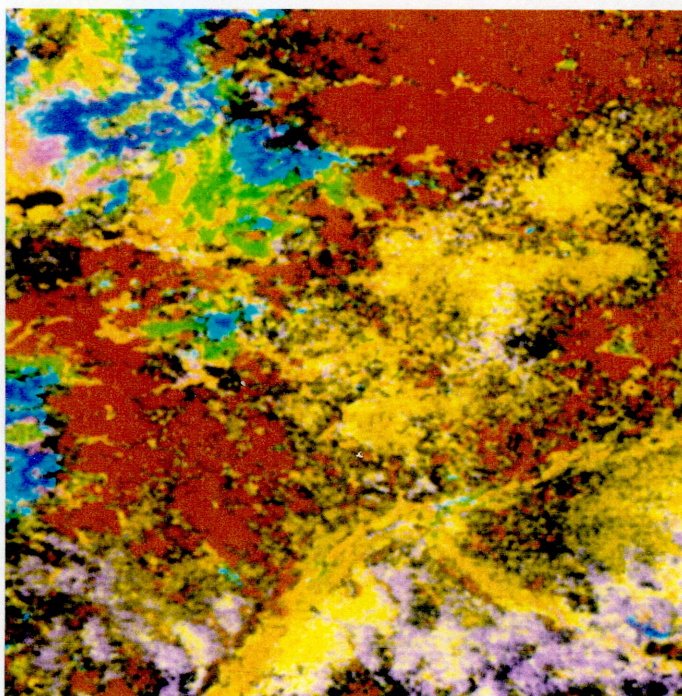


Plate 2. 10-class supervised Maximum likelihood classification of the Kao study area (7th October 1984). Median smoothed image.

<u>Cover class</u>	<u>Colour</u>
Laterite	Blue
Clay / laterite mix	Cyan
Clay outwash	Green
Sand	Red
Dense bush	Orange
Bush on laterite sands	Yellow
Medium bush	Brown
Thin bush	Purple
Very thin bush	White
<u>Water</u>	<u>Black</u>



Plate 3. Example of land cover classes. Photographs are of the Kao Agadez road junction. The top photograph shows conditions at the end of March (dry season) the bottom photograph is the same area at the end of August (wet season).

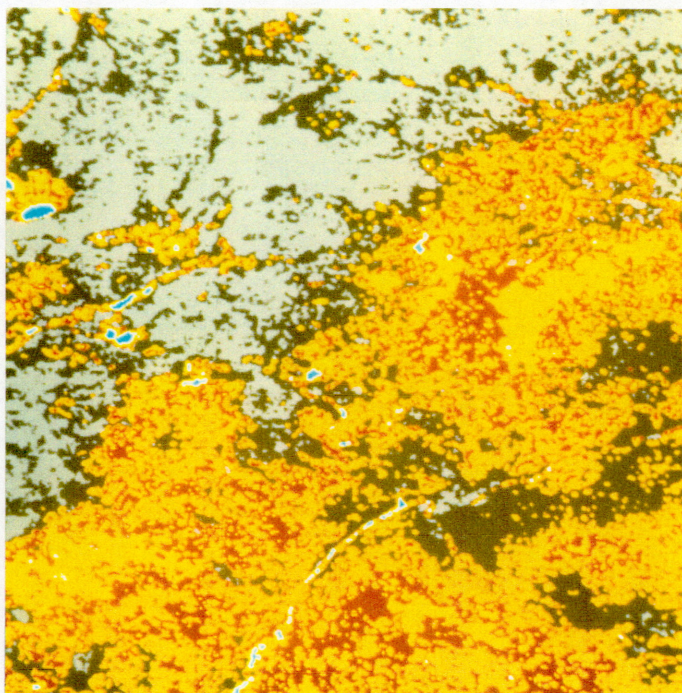


Plate 4. Perpendicular Vegetation Index image of the Kao study area from August, 1985. Grey = 0 T/Ha, brown = 0 - 0.5 T/Ha, gold = 0.5 - 1.0 T/Ha, red = 1.0 - 2.0 T/Ha, yellow = >2.0 T/Ha, cyan = dense bush.

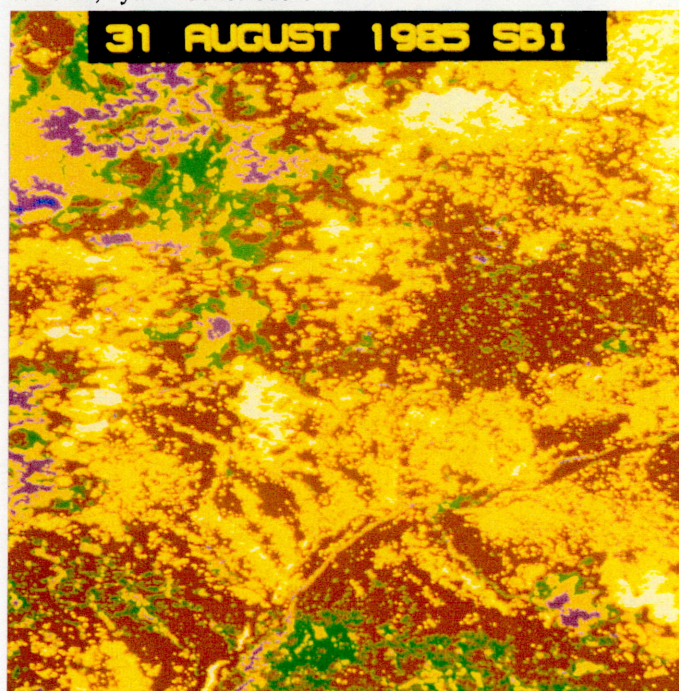


Plate 5: Soil Brightness Index image of the Kao study area from August, 1985.



Plate 6a Band 4, 2, 1 Red, Green, Blue Landsat MSS false colour composites of the Kao study area from October, 1984.

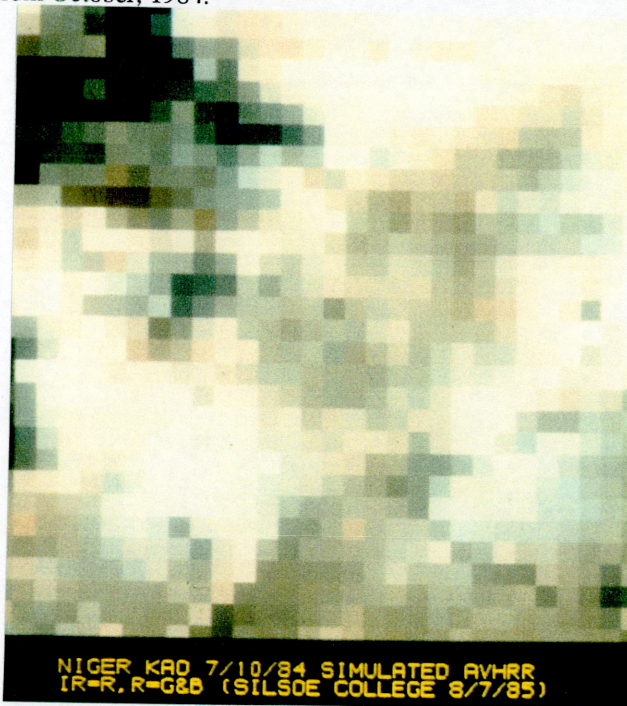


Plate 6b Simulated AVHRR HRPT resolution, band 2, 1, 1, false colour composite of the Kao study area from October, 1984.

Appendix 2. Continental scale GAC processing chain

PREPARATION OF AVHRR GAC DATA SETS FOR GLOBAL CHANGE STUDIES

A. S. Belward¹, J. V. Vogt¹, A. Falk-Langemann², S. Saradeth² and H. Cambridge³

¹Institute for Remote Sensing Applications, CEC Joint Research Centre, 21020 Ispra (Va) Italy.

²Gesellschaft für Angewandte Fernerkundung mbH, Leonrodstr. 68, D-8000 München 19, Germany.

³Serco Space Ltd, Lincoln Way, Sunbury-on-Thames, TW16 7HW, U. K.

1. ABSTRACT

This document describes the design of an Advanced Very High Resolution Radiometer (AVHRR) data base for global climate and environmental studies (global change). The assembly and pre-processing of long term AVHRR Global Area Coverage (GAC) data sets for the African continent is presented.

Keywords: AVHRR, GAC, pre-processing, global change

2. BACKGROUND

Data from the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA satellites (Ref. 1) are often used in global climate and environmental studies. Existing (suitably pre-processed) global long term AVHRR data sets are available mainly as the Normalized Difference Vegetation Index (NDVI) e.g., the Global Vegetation Index (GVI) product (Ref. 1). The GVI data are sampled in the spatial, spectral and temporal domains. This limits their use in the framework of 'global change' research.

The other truly global, long term AVHRR data, Global Area Coverage (GAC - Ref. 2), are also sampled, though just spatially; the GAC archive consists of global daily data in all channels for the last decade, though pre-processed GAC long term data sets are only available for selected areas, and again largely as the NDVI.

NDVI alone does not realize the full potential of the GAC archives as a source of data for global change studies; other geophysical parameters also have a vital role in such work.

As a first step in the development of improved global AVHRR GAC data sets, the Commission of the European Communities' Institute for Remote Sensing Applications (IRSA) has established an advanced GAC pre-processing chain to prepare continental, and ultimately global, multi-channel time series. The strategy adopted for the processing chain has been driven by specific requirements arising from the global change research activities of IRSA. The data are to be used in the study of continental scale biomass burning dynamics, for continental scale land cover / land use mapping, for tropical deforestation monitoring, for the study of upwelling phenomena and for the study of climate change (Refs. 3 - 5).

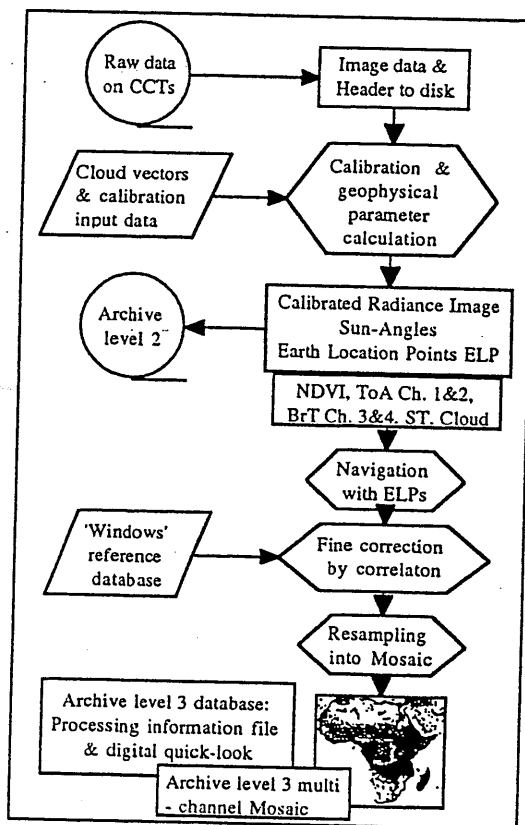
The burning studies require brightness temperatures in channels 3 and 4 for the detection of active fires, NDVI for fuel loading studies and channel 2 reflectance for burned area assessments. The land cover / land use work uses NDVI for work on vegetation seasonality, and channels 1, 2 and 3 for discrimination between vegetation types. These

parameters are also used for monitoring tropical deforestation by forest mapping, determining seasonal characteristics of forest communities, detecting fire in forest ecosystems and identifying new deforestation fronts. Quantitative description of the land and ocean surfaces through estimates of surface temperature and albedo will also be used to study the state and evolution of the climate system in the climate change work.

It is within this framework that pre-processing of the Africa GAC archive (1981 to 1989, day-time overpass from the odd-numbered satellites) has begun.

3. PRE-PROCESSING OVERVIEW

Figure 1. The GAC pre-processing chain



- Raw data (archive 1), up to 4 orbits per day, are transferred from CCT to magnetic disk. The Earth Location Points (ELP) and solar zenith angles are extracted from the scan lines and the digital counts are converted to radiance ($W m^{-2} sr^{-1} \mu m^{-1}$) using on-board calibration for channels 3, 4 and 5, post-launch (with linear decay) for channels 1 and 2. These are scaled to a 10 bit integer and stored in 2 byte image files. The radiance channels, Earth Location Points, and Sun angles form archive level 2 of the data base.
- Radiances in channels 1 and 2 are converted to 'top of atmosphere' reflectances (ToA) which account for variations in solar zenith angle, Sun-Earth distance and exoatmospheric solar irradiance. Data are scaled to 8 bits.
- Brightness temperatures are calculated for channels 3, 4 and 5 using the inverse Planck function. Channels 4 and 5 are then corrected for non-linearity of sensor response to give true brightness temperatures using pre-launch correction coefficients. Again data are scaled to 8 bits.
- The ToA reflectances and brightness temperatures are then used to flag cloudy pixels (Mahalanobis classification). The result is held as an 8 bit cloud probability channel.
- Channels 1 and 2 (ToA reflectances) are used to calculate a ToA NDVI, and approximate surface temperatures are calculated from channel 4 and 5 brightness temperatures. These geophysical parameter data are scaled from 1 to 250.
- The geophysical parameters, together with channels 1 and 2 (ToA reflectance), channels 3 and 4 (Brightness Temperature) and the cloud mask are then geometrically corrected, all images are re-sampled once, by nearest neighbour, into a multi-channel daily mosaic for the whole continent (archive 3 in the data base).
- A digital quick look is created (figure 2). This, and an information file containing processing parameters, are fed into the archive database, and ultimately a GIS.



Figure 2. Digital quick look (channel 2). Full cover of Africa is provided by mapping 3 separate orbits from the 8th March, 1989 into a single mosaic. Quick looks are produced for each day's continental cover. Most, but not all, are full windows, as occasional orbits are missing.

4. ALGORITHM DESCRIPTION FOR CALIBRATION

Calibration involves conversion of raw digital numbers to radiance (level 2 archive), calculation of top of atmosphere (ToA) reflectance for channels 1 & 2 and calculation of true brightness temperature for channels 3, 4 and 5, (Ref. 6).

4.1. Channel 1 & 2 radiance and ToA reflectance

The digital numbers of the raw data are first converted to radiance ($W m^{-2} sr^{-1} \mu m^{-1}$), equation 1.

$$L_i = \alpha_i \cdot DN_i + \beta_i \quad (W m^{-2} sr^{-1} \mu m^{-1}) \quad (1)$$

L_i = at satellite spectral radiance ($W m^{-2} sr^{-1} \mu m^{-1}$)

α_i = calibration gain channel i ($W m^{-2} sr^{-1} \mu m^{-1} count^{-1}$)

β_i = calibration offset for channel i ($W m^{-2} sr^{-1} \mu m^{-1}$)

DN = digital numbers for channel i

Pre-launch calibration coefficients are available for channels 1 and 2 though it is known that the sensitivity of these sensors changes with time. The offsets are relatively stable, but degradations in gain from 4% to more than 30% per year have been reported, depending on satellite and channel. A number of attempts at in-flight calibration have now established post-launch calibration coefficients for channels 1 and 2 (Refs. 7 - 12). Decay is assumed to be linear for the life of NOAAs 7 and 9, and during the first 6 months of operation for NOAA 11. The post-launch coefficients are used to convert the digital numbers to radiances, which are then scaled to a 10 bit integer and stored in 2 byte image files.

Radiances in channels 1 and 2 are converted to 'top of atmosphere' reflectances which account for variations in solar zenith angle, Sun-Earth distance and exoatmospheric solar irradiance, equation 2. These data are scaled to 8 bits.

$$\rho_i = \frac{\pi L_i}{E_{oi} \cos \phi} * 100 \quad (2)$$

ρ_i = 'top of atmosphere' reflectance for channel i

L_i = at satellite measured spectral radiance for channel i

E_{oi} = exoatmospheric solar irradiance for channel i

ϕ = Sun zenith angle

d = Sun-Earth distance (astronomical units)

4.2. Channel 3, 4 & 5 radiance and true brightness temperature

The digital numbers of the raw data are again converted to radiance ($W m^{-2} sr^{-1} \mu m^{-1}$), equation 3.

$$L_i = \alpha_i \cdot DN_i + \beta_i \quad (W m^{-2} sr^{-1} \mu m^{-1}) \quad (3)$$

All symbols as equation 1. In this case the in-flight calibration values are used. Brightness temperatures are then calculated using the inverse Planck function, equations 4, 5 and 6.

$$Tb_i(L_i, v) = \frac{\frac{(c/v)}{2}}{\ln(1 + \frac{(c/L_i)}{v})} \quad (K) \quad (4)$$

Tb_i = brightness temperature for channel i (K)
 L_i = at satellite measured spectral radiance for channel i
 v = Wavenumber of corresponding channel (cm^{-1})
 c_1 = constant $1.1910659 \cdot 10^{-5}$ ($\text{mW m}^{-2} \text{sr}^{-1} \text{cm}^{-4}$)
 c_2 = constant 1.438833 (cm K)

$$c_1 = 2h c^2 \quad (5)$$

$$c_2 = \frac{hc}{K} \quad (6)$$

h = Planck's constant
 c = Speed of light
 k = Boltzman's constant

The brightness temperatures for channels 4 & 5 are then corrected for non-linearity of sensor response to give true brightness temperatures using pre-launch correction coefficients from the literature (Ref. 13), equation 7.

$$T_i = Tb_i + \Delta T \quad (K) \quad (7)$$

T_i = true brightness temperature for channel i (K)
 Tb_i = brightness temperature for channel i (K)
 ΔT = correction coefficient

5. ALGORITHM DESCRIPTION FOR CLOUD DETECTION

Many cloud detection algorithms are based on the cloud tests of the APOLLO routine (Refs. 14 - 15); a series of checks based on reflectances and brightness temperatures are used. Analysis of a number of test images showed that certain checks are unreliable on the continental scale. This is because of the difference in the seasons north and south of the equator and confusion with extensive desert areas. As an alternative to using different thresholds for different regions and images, cloud detection is implemented through a Mahalanobis classifier. This gives a cloud probability image, rather than an absolute cloud mask. Once processing is complete the user can tune the cloud mask for different areas and/or seasons. Users can also choose the sensitivity, i.e., a threshold can be selected which will include all clouds but possibly also some non-cloudy regions, or conversely a more conservative threshold could be chosen to only identify those regions with a very high probability of being cloudy. The routine is based on a reference data file containing the mean vectors in p_1 and p_2 , Tb_3 and T_4 from a number of different orbits, regions, dates and satellites for clouds, equation 8.

$$ICD = 255 - \text{INT} \left[\frac{T}{(X-U) \cdot \text{COV} \cdot (X-U) \cdot \text{SCF}} \right] \quad (8)$$

ICD = Inverted Mahalanobis classification distance
 X = (p_1 and p_2 , Tb_3 and T_4) Vector from image data
 U = (p_{1m} and p_{2m} , Tb_{3m} and T_{4m}) Mean vector from reference data file
 COV = Covariance matrix from reference data file
 SCF = Scale factor of 30

The values for ICD are then stored as an 8 bit image file.

6. ALGORITHM DESCRIPTION FOR GEOPHYSICAL PARAMETERS

Before geometric correction the separate calibrated channels are used to create two geophysical parameters; the Normalised Difference Vegetation Index (NDVI) and surface temperature.

6.1. Normalised Difference Vegetation Index (NDVI)

Channels 1 and 2 (ToA reflectances) are used to calculate a ToA NDVI, equation 9.

$$NDVI = \left\{ \frac{p_{ch2} - p_{ch1}}{p_{ch2} + p_{ch1}} \right\} 200 + 50 \quad (9)$$

p_{ch2} = 'top of atmosphere' reflectance for channel 2
 p_{ch1} = 'top of atmosphere' reflectance for channel 1

6.2. Surface temperature

Approximate surface temperatures are calculated from channel 4 and 5 true brightness temperatures using a 'split window' technique (Ref. 16), equation 10. This does not take variations in emissivity into account, which can result in errors of up to 4 K.

$$T_s = aT_4 + b(T_4 - T_5) + c \quad (10)$$

T_s = surface temperature (K)
 T_4 = true brightness temperature in channel 4 (K)
 T_5 = true brightness temperature in channel 5 (K)
 a, b, c = split window coefficients

7. ALGORITHM DESCRIPTION FOR GEOMETRIC CORRECTION

Geometric correction involves three steps; navigation using the earth location points (ELPs) from the raw data, correlation with a reference image data base to provide additional ground control points for fine correction and resampling into a daily continental scale mosaic. Information from the first two steps is held with all channels in archive level 2. All three steps are applied to the NDVI, surface temperature, channels 1 and 2 (ToA reflectance), channels 3 and 4 (brightness temperature) and the cloud probability channel. The final product forms archive level 3.

7.1. Navigation

The navigation procedure assumes that all input images are to be corrected to a pre-defined mapped output image. In this case we use a Mercator projection map covering the continent of Africa (the map centre coordinates are 0° , 17.25° E, pixel size at the Equator is 5 by 5 km, which gives an image of 1800 lines by 1600 columns, with top left coordinates 37.59° N, 18.64° W, bottom right 37.59° S, 53.64° E).

Because the map is fixed, the input image pixel coordinates can be computed for each location of the map, assuming the ELPs to be correct. The ELPs form a regular grid (every 5 rows and 8 columns), thus any one input pixel will be

bound by four ELPs. The input pixel for each map position can thus be identified from a two-dimensional interpolation function, equation 11.

$$\begin{aligned}x &= a_1 + a_2X + a_3Y + a_4XY \\x &= b_1 + b_2X + b_3Y + b_4XY\end{aligned}\quad (11)$$

x, y = input image pixel coordinates
 X, Y = Map image coordinates
 a_n, b_n = coefficients determined by least squares fit between lat / long of the ELPs and the output map positions.

By repeating this process for each block of 4 ELPs the input image pixel location for each map location can be identified. Off nadir there will be considerably fewer input image pixels than map locations, hence the same input pixel will be mapped more than once. *i.e.*, the step from one input pixel location to the next for two adjacent map locations is zero. As nadir is approached then the number of input pixels and map locations becomes nearly identical and so the step between input pixels increases. In practice this step rarely exceeds one position, though the step may be in any direction to one of the eight surrounding positions. This step between input pixels for adjacent map pixels is determined for every location, and coded. The coded geometric correction information is used for preliminary location of the templates from the input data (see §7.2.), it considerably speeds up the resampling step once fine corrections have been determined, and it also allows location information to be stored alongside non-resampled radiance data in the level 2 archive.

7.2. Correlation

A correlation between each input image and a reference data base is then performed to create additional ground control points used for fine correction. This is performed by polynomial approximation, in which the coefficients of the transform are calculated by a least squares fit; the input data being based on residual shifts identified from the correlations. Test data showed that the best correlations were obtained with channel 2 ToA image data using a frequency correlation function.

Templates from the input image are correlated with a data base of 'image windows', previously corrected to the standard base map using manually selected ground control points. The reference data base can contain an unlimited number of windows. This allows flexibility regarding season, latitude / longitude location and position with respect to satellite nadir.

Template size must be > 11 pixels, window size is 2 x maximum expected error + template size. For GAC the maximum error encountered to date is ± 15 pixels so the window size is 41 pixels. At present up to 50 matched templates are used to compute the coefficients of the polynomial, though the number of windows, and therefore attempts at matching is unlimited.

Window / template matching takes a window from the reference data base;

- checks if it is within the geographic area of the input image;
- checks reasonable match in position re. satellite nadir;
- if selected, the equivalent template is identified in the input image and corrected on the basis of the coded geometric information from § 7.1.;
- cloud content of template is checked,
- if cloud cover exceeds a threshold value, template is rejected;

- if variance of template is low (e.g. due to cloud or viewing geometry), template is rejected;
- if accepted, correlation matrix is computed;
- if maximum correlation value is below a pre-defined threshold, then point is rejected;
- if confidence threshold is below pre-defined value, point is rejected (nb confidence threshold is a function of the mean and the maximum correlation values);
- if correlation performance is accepted, the point is stored in a control point file;
- finally all accepted points are compared and outliers rejected.

A fine correction based on a linear function can then be calculated from a least squares fit of the information in the control point file.

7.3. Resampling to continental mosaic

One day's complete cover is processed at a time (three to four input images). Using the polynomial transform computed in the navigation step and the fine tuning from the correlation step, each part orbit is resampled, using nearest neighbour, into the continental output map. The overlap between adjacent orbits is dealt with by selecting pixels nearest to satellite nadir. Image to image registration is within one pixel in both the X and Y directions.

8. CURRENT STATUS

The processing chain is fully operational, running on a VAX 3900. Processing time varies depending on the number of tapes being processed. For a single tape (4 days data) it takes around 2 hours connect time. 5 tapes in batch take around 6.5 hours. Run times for a single tape obtained during a normal batch run are shown in table 1. Current throughput is approximately one month's data per day. Daily multi-channel continental mosaics are now available from October 1988 to August 1989. Pre-processing of the 1981 - 1989 archive will be completed by the end of 1992.

Table 1. Processing speeds for the different steps. Times for one tape (14 orbits, from 4 days) in batch with 4 others.

Processing step	Time (minutes)
Tape dumping	32
Geophysical parameter calculation	206
Navigation	28
Fine correction by correlation	38
Resampling to Mosaics	60

n.b. all these times vary, depending on other users and on the number of orbits held on the tape

9. FUTURE DEVELOPMENTS

Development is still needed concerning the atmospheric correction of GAC data on a global scale, particularly with respect to variations in atmospheric moisture content and aerosols (Ref. 17). Current corrections require detailed meteorological profiles. Although analysed data can be produced by assimilation procedures in General Circulation Models (GCMs), these constitute another very large data set, and no systematic operational use of such a scheme has been developed yet. It is proposed to use the level 2 data for further research in this area.

Other developments foreseen concern correction for angular effects. The reflectance field of vegetation is known to be anisotropic (e.g., Ref. 18) and the characteristics of the AVHRR system result in considerable spatio-temporal variation in the geometry of illumination and observation. Even on the most localized of scales these directional effects must be taken into account. Preliminary work using models of simple vegetation canopies has shown for example that directional effects may significantly influence NDVI (Ref. 19), however further theoretical work is needed before suitable corrections for angular variations can be envisaged over the highly complex canopies of real terrestrial ecosystems (Refs. 20 - 21). Level 2 data will again be used for this research.

The software has been adapted to handle HRPT SHARP data, though not for the entire continent. This runs on PCs. Other software developments will see adaptation to other platforms, specifically IBM RS6000s, and other areas of interest, specifically Asia.

10. ACKNOWLEDGEMENTS

The GAC data are provided as part of the 'NASA - JRC AVHRR remote sensing collaboration'. The processing chain was designed by the IRSa's MTV project in collaboration with GAF; cloud detection uses method developed by GAF. The operational processing chain was coded, tested and installed by GAF under JRC contract 4607 - 91 - 12 EP ISP D. Operational processing is run at JRC by SERCo Space under JRC contract 4456-91-08 ED ISP GB.

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