Vegetation monitoring by remote sensing: Progress in calibrating a radiometric index and its application in the Gourma, Mali*

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SUMMARY

ILCA CARRIED OUT *studies in the Sahel to evaluate the merits and limitations of a satellite-derived normalized difference vegetation index (NDVI) in estimating vegetation cover, above-ground biomass and/or production. The index was calibrated on 30 ground sites in the Gourma region of eastern Mali, using biomass clippings and radiometer measurements taken during the 1985 growing season.*

The results of the analysis indicated that because of atmospheric interference and technical constraints, the relationship between NDVI and above-ground biomass is not direct. A modified form of the index, the integral of NDVI increments over time, proved to be a better indicator of above-ground biomass accumulation, despite its sensitivity to soil background reflectance. Integrated index increments were calibrated for sandy, clayey and conglomerate soils and applied in computerised mapping of plant biomass.

INTRODUCTION

Quantifying the temporal and spatial changes in forage resource availability has long been a stumbling block in rangeland survey and mapping. Remotely sensed data could provide a solution to the problem, if they can be turned into meaningful variables.

Collaborating with the Global Inventory Monitoring and Modelling Studies (GIMMS) group of the National Aeronautics and Space Administration (NASA), ILCA's team in Mali carried out research in 1984/85 aimed at testing and calibrating a spectral vegetation index calculated from data sensed by the advanced very high resolution radiometer (AVHRR) on board the NOAA-7 satellite. This research was prompted by interest in the inter-seasonal dynamics of primary production (see Cissé, 1982; Hiernaux, 1983; Hiernaux et al, 1984; Diarra et al, 1986) and by previous remote sensing work elsewhere in the Sahel (see Tucker et al,1983;1985).

The results of monitoring changes in vegetation cover in the Gourma region of Mali during the 1984 growing season were reported in Hiernaux and Justice (1986). An overview of ILCA's remote sensing activities in 1985 is given in Hiernaux and Diarra (1986). In this paper, three types of relationship are evaluated – between NDVI and above-ground biomass; between maximum NDVI and end-of-growing season biomass; and between the integral of the NDVI curve or NDVI increments over time and actual biomass. Atmospheric interference and technical problems affecting the spectral vegetation index are described, as are also two initial applications of the multitemporal integration technique in computerised mapping of plant biomass in the region.

METHODS

The index

A normalized difference vegetation index was calculated from radiance data simultaneously measured in the visible (R) and near-infrared (IR) wavelength bands, such that:

$$\text{NDVI} = (\text{IR} - \text{R})/(\text{IR} + \text{R})$$

Values ranging between +1 and –1 were interpreted on the basis of relationships established between the red and near-infrared radiances and green biomass. The red radiance decreases with increased green biomass as a result of greater absorption of incident radiation by plant chlorophylls, and the near-infrared radiance increases slightly with increased green biomass because of radiation scattering by the hydrated walls of leaf cells.

The index was calibrated at 30 sites in the Gourma region of eastern Mali, by comparing remotely sensed data with ground measurements of above-ground biomass taken in 1985 and recorded in Diarra et al (1986). To determine more precisely the relationship between the index and actual above-ground biomass, further comparisons were made with reflectances sensed on the ground (1.5 m above plant canopy) and from the air (610 m).

Ground monitoring

Thirty 4 × 4 km^2 ground sites were selected in the central Gourma for their floristic homogeneity. Visual observations and sample clippings were repeated every 2 or 4 weeks on 12–24 one m^2 plots randomly distributed along two 1-km long, permanent linear transects.

For each plot, plant species were identified and percentage green cover was estimated. Above-ground dry biomass was measured by clipping, drying and weighing. Sampling on the ground combined random sampling and stratification at two levels – by plant community and by quantitative stratum within each community. The results were weighted by the relative area covered by each stratum and community along the transect.

Communities of woody species were sampled once in 1984 and again in 1985. Measurements were taken of the length of the transect segments overlayed by tree or shrub canopies and of such physical parameters as crown area, trunk circumference and height. Total foliage biomass was estimated on the basis of allometric relationships found to exist between biomass and individual physical parameters (Hiernaux, 1980; Cissé, 1980). These relationships were weighted by monthly clippings of leaf biomass on standard branchlets (values given by Cissé,1982).

Ground and aerial radiometer measurements

Ground clippings and visual observations of grass and tree samples were often preceded by *in situ* radiometer measurements using a hand-held Exotech radiometer equipped with a 15° lens and Thematic Mapper filters in the red (0.63-0.69 µm) and near-infrared (0.76–0.90 µm) wavebands. All measurements were taken 1.5 m above the plant canopy and replicated three times. The spectral reflectance of soil background cleaned of all vegetative material was similarly measured.

For comparison, soil/vegetation reflectance mixtures were determined on 1-m^2 plots. This was done by taking hand-held radiometer measurements of whole leaves or segments of leaves clipped from*Musa sinensis, Cassia tora* and *Diospiros mespiliformis* and arranged flat on six different backgrounds (black soil, sand, clay, loam, sandstone and water). The treatments were replicated six times.

In situ measurements were complemented by aerial radiometer measurements of above-ground biomass on 24 May, 24 August, 13 October and 11 November 1985. The radiometer in this exercise was fixed to the floor of a light aircraft flying at an altitude of 610 m, enabling data sensing at an instantaneous field of view (IFV) of 160 m in diameter. In addition, aerial photographs with a field of view of 915×610 m were taken at the same sampling frequency.

Satellite data

The advanced very high resolution radiometer on board NOAA-7 records spectral reflectances in the visible (0.58-0.68 µm) and near-infrared (0.725 -1.1µm) channels in the form of 10-bit digital data. The data were 'merged' on the Hewlett-Packard 1000 interactive image display system and mapped to Mercator grid coordinates using the geographical coordinates embedded on the AVHRR data tapes. The resultant grid image was modified by geometric corrections to the Niger course and the Gossi lake.

To limit registration errors and atmospheric distortions, only full-resolution data (i.e. 1.1 km^2 at the nadir) were used to composite 'local area coverage' (LAC) scenes. Scenes were then selected that were within a scanning angle of less than 30° from the nadir and had optical thickness of <1 in the near-infrared channel. Pixels obscured by cloud cover were eliminated using a cloud mask with a threshold of 290° K in the thermal infrared.

After selection, 27 scenes based on data acquisitions during July – December 1985 were available for analysis: of these 13 (July to September) were analysed. The NDVI values derived for each ground site were mean values calculated from 3 to 9 pixels, depending on the size of the site.

RESULTS AND DISCUSSION

NDVI and biomass

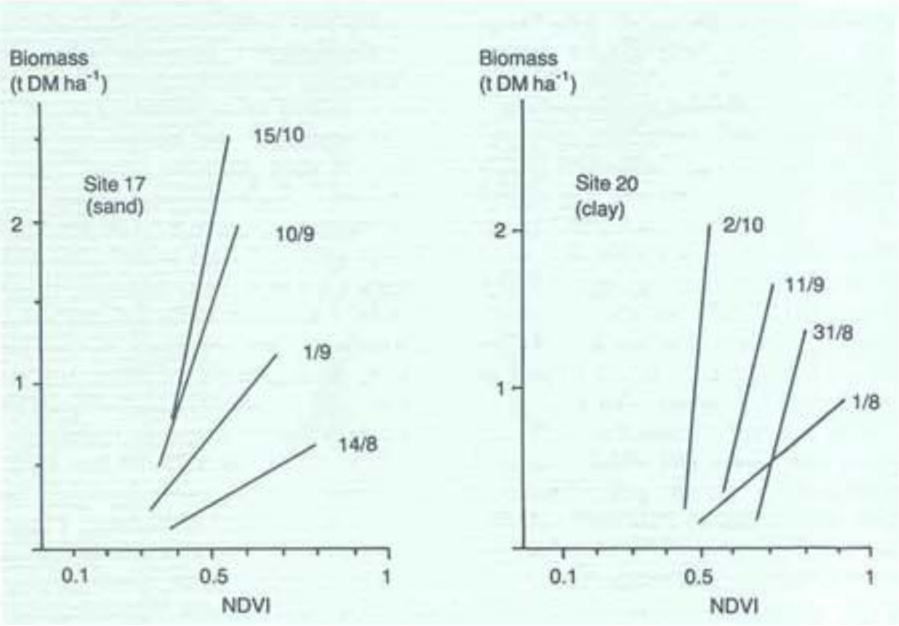
Ground-collected reflectances from the Gourma confirm that there is a close relationship between NDVI and above-ground biomass (Table 1). But they also show that the index is specific to both the type of vegetation monitored (Grouzis and Methy, 1983) and stage of growth (Gaston et al, 1983; Wagenaar and de Ridder, 1986). The relationship between the index and actual biomass at a given site thus changes as the season progresses (Figure 1).

Table 1. *The relationship between NDVI and above-ground biomass (B) measured during the 1985 growing season, Gourma, eastern Mali.*

Site	Date	Linear regression of NDVI on B (kg DM ha^{-1})	Correlation coefficient (r)	Plant humidity rate (%)
17 (sand)	14/8	NDVI=838*B+256	0.82	83
	28/8	NDVI=405*B+212	0.77	74
	10/9	NDVI=167*B+275	0.61	56
	30/9	NDVI=115*B+312	0.83	35
20 (clay)	2/8	NDVI=565*B+411	0.80	88
	31/8	NDVI=133*B+646	0.58	82
	14/9	NDVI=129*B+521	0.76	73
	2/10	NDVI=46*B+455	0.42	60

Note: Regressions based on 24 measurements.

Figure 1. *Regression lines[1] for NDVI[2] and field-layer biomass at two sites in the Gourma, eastern Mali, 1985 growing season.*

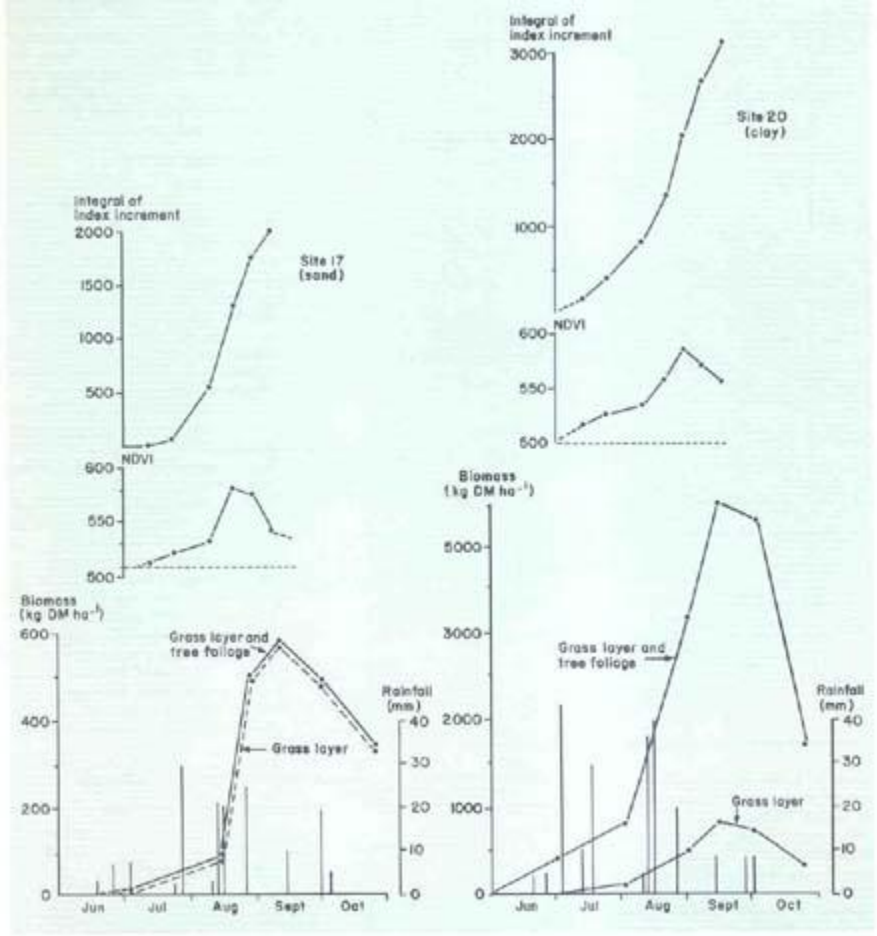


[1] Based on regression equations in Table 1.

[2] NDVI = normalized difference vegetation index calculated from ground-collected reflectance data.

Figure 2 shows that the maximum NDVI value occurs well before maximum biomass, which suggests that the index is not a direct function of actual above-ground biomass. As a result, simple linear regressions between the index and biomass give mediocre or even poor results, whatever the altitude from which measurements are taken (Hiernaux and Diarra, 1986). Poor correlations between NDVI and actual biomass result also from physical interference and technical constraints associated with the NOOA-7 and its sensor, both varying according to the altitude at which the radiometer measurements are taken.

Figure 2. *Comparative seasonal changes in plant biomass, NDVI*[1] *and the integral of the NDVI increment, Gourma, eastern Mali, 1985.*

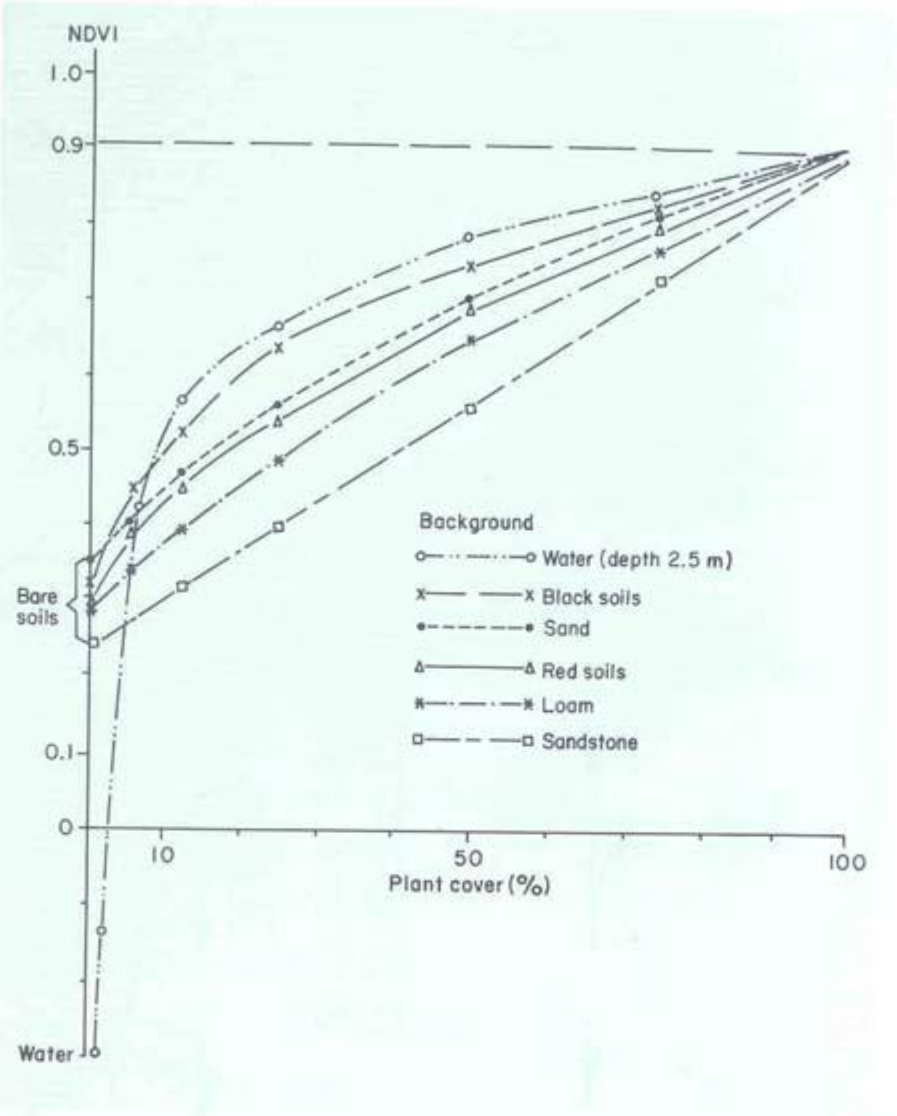


[1] NDVI = normalized difference vegetation index calculated from NOAA-7/AVHRR data.

Interference associated with soil background

Transforming the IR/R ratio into a normalized difference vegetation index reduces distortions caused by differences in brightness between soil backgrounds, but does not eliminate them, especially when the soil is moist or flooded, the latter giving negative index values. Index values calculated for different soil backgrounds indicate that while the spectral responses of bare soils differ only slightly, the reflectance mixtures of green vegetation and soil background vary according to soil type (Figure 3). The mixed-response curves are almost linear for light loams and sandstones, but inflected for red and black soils and for water, the degree of the inflectance increasing with increasing light absorption by the background (Huette et al, 1985).

Figure 3. *Impact of background type on NDVI calculated from ground radiometer measurements*[1]*, Bamako, Mali, July 1985.*



[1] Measurements taken with a hand-held radiometer on 7 July between 13:00 and 16:00 h.

These differences indicate that background-related interference will not be eliminated by merely calculating a standard increment between the index values for bare soil and vegetation/soil mixtures. The relationship between NDVI and actual biomass must be established separately for each soil background, by subtracting its reference value from the observed index.

Atmospheric interference

A comparison of ground, aerial and satellite data from the Gourma confirmed that, despite various technical problems, atmospheric conditions exert a major influence on NDVI (Hiernaux and Justice, 1986; Wagenaar and de Ridder, 1986).

Because of the frequent presence of dust particles in the air, ground-collected soil reflectances tend to increase in the Sahel, the visible incoming radiation being reflected by dust in suspension more than the incoming near-infrared radiation. In comparison, aircraft- and, particularly, satellite-derived index values are lower, approaching those of dust which are comparable with bare-soil values. This is because radiance measured in the air consists of both radiation reflected from the ground (which is affected by the crossing of the dust-ridden atmosphere) and radiation reflected by dust in suspension, the density of which increases as the dust becomes thicker.

The accuracy of remotely sensed data depends greatly on the clarity of the atmosphere, quantified in the inverse form of optical thickness (Holben, 1986). Atmospheric conditions during the 1985 growing season were not very favourable: daily measurements at 14:30 h in Gossi, central Gourma, show that in only 41% of the cases were conditions clear enough (optical thickness 0.75 in the near-infrared wave band), while 23% were cloudy and the remaining 36% were dusty. To reduce the effect of unclear atmospheric conditions on NDVI, data were selected using a cloud mask and scene compositing, in addition to calculating optical thickness.

The cloud mask helps select cloud-free pixels on the basis of thermal differences in the far infrared, but it is not effective for all types of cloud and haze. The other procedure, scene compositing, involves the selection of the highest index value for each pixel in a set of consecutive days' data acquisitions, as this value is most likely to be least affected by atmospheric interference. In scene compositing much depends on the length of the period over which data are composited: using a large number of acquisitions over a long period increases the chances of selecting for clear atmospheric conditions, while using fewer acquisitions over a shorter period enables more precise monitoring of temporal changes in vegetation cover. Invariably, however, a compromise must be struck between the two options.

The compositing period used in the Gourma project varied between 9 and 27 days, depending on the optical thickness at 14:30 h, the overpass time of the NOAA-7 satellite. The daily optical thickness values were calculated from ground measurements of solar radiation at seven sites in the region, as reported by Holben (1986).

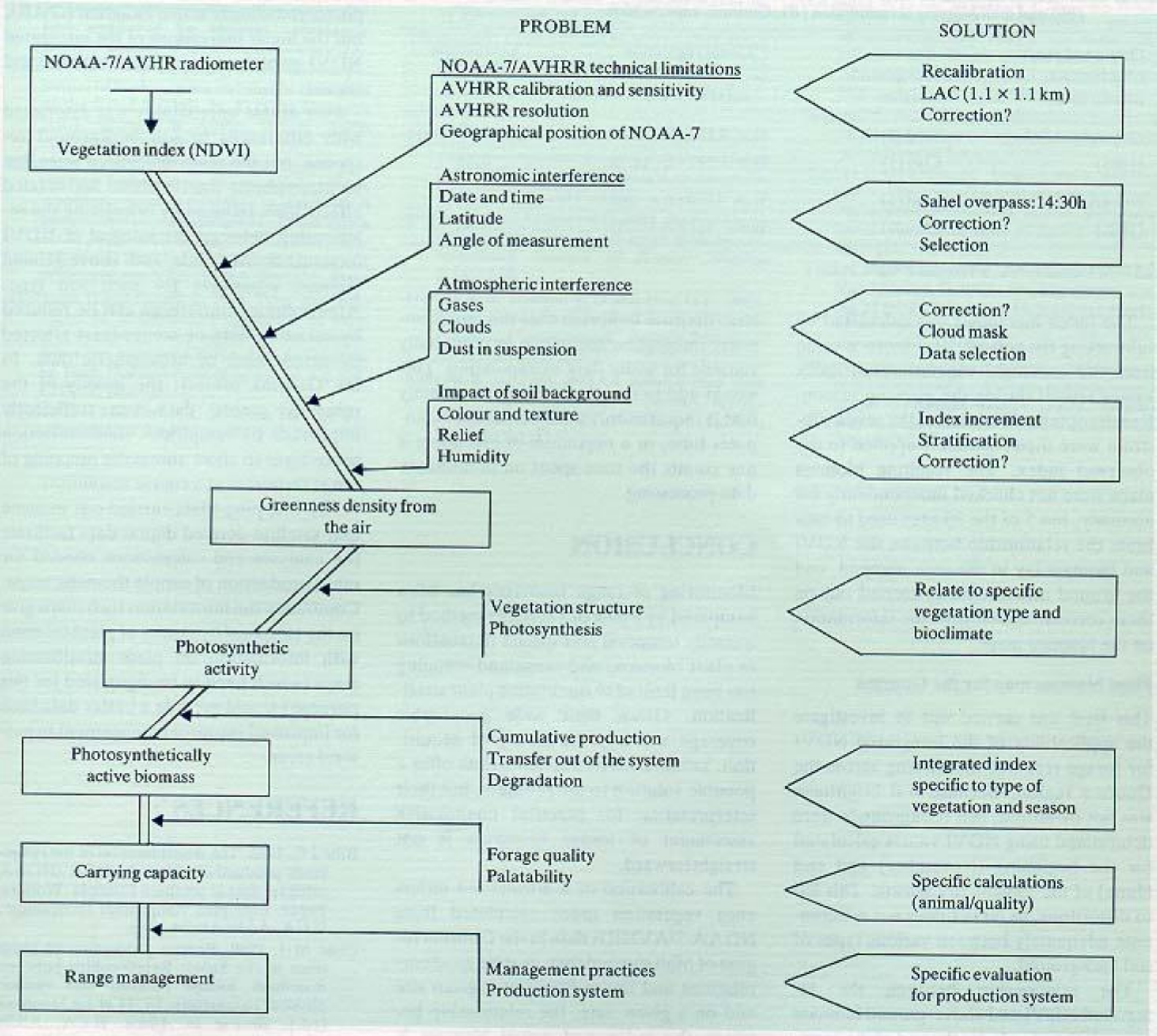
Technical constraints

In remote sensing, problems due to atmospheric interference are often confounded by technical constraints associated with the characteristics of the orbit of the satellite, but also with differences in sensor instrumentation and optical fields (Figure 4). The major constraints encountered with the AVHRR on board the NOAA-7 satellite are:

- The two wavelength bands used, the visible and near infrared, are not ideally positioned to calculate the index. Moreover, once launched, the scanner is not recalibrated; in the Gourma project, calibration error occurred on 20 September 1985, preventing the analysis of data sensed after this date.
- The size of the basic pixel and the scanning angle of the sensor cause geographic distortions and increase atmospheric interference which cannot be completely corrected (Holben and Fraser, 1984).
- The scanning frequency of the NOAA-7/AVHRR is twice daily with one daylight crossing over the Sahel at about 14: 30 h, but the scanning angle is variable and limits the frequency of usable data to 3 consecutive days out of every 9.

- Resampling the data into a 'global area coverage' type of product reduces geographic resolution by a ratio of 1:15 and multiplies errors (Kidwell, 1984). In the Gourma project, only the 'local area coverage' data (pixel size 1.1 km2) were calibrated, although their availability was limited.

Figure 4. *Problems of using NDVI for remote sensing of forage resources.*



Maximum NDVI and end-of-season biomass

The difference in the dates at which maximum NDVI and maximum biomass values occur (Figure 2) would support the hypothesis, already verified experimentally by Bille (1986), that there is a direct relationship between the index and the greenness density of biomass, albeit affected somewhat by soil background, vegetation pattern and shadowing. This hypothesis was also tested in the Gourma.

A cause-and-effect relationship was assumed to exist between the maximum greenness density during the growing season and maximum biomass at the end of the season (Hatfield et al, 1984; Sellers, 1985; Lamprey and de Leeuw,1986). End-of-growing-season biomass depends, however, on cumulative production and the amount of losses through degradation and transfers in photosynthetically inactive vegetation. It is therefore not surprising that simple linear regressions between the maximum NDVI and end-of-growing season biomass give highly variable results, regardless of the altitude from which radiometer measurements are taken.

Subtracting bare-soil reflectance values from the index only marginally improves the relationship, which is better on sandy than on clayey or conglomerate soils (Table 2). The relationship also seems to improve when actual biomass is lower, as was the case in 1984 (Hiernaux and Justice, 1986). Nonetheless, the high temporal and spatial variability in the relationship limits the relevance of the maximum NDVI parameter for forage resources assessment.

Table 2. *The relationship between maximum NDVI and end-of-growing season biomass at 5 sites in the Gourma, eastern Mali, 1984–85.*

Origin and year of measurement	Soil background and site	Linear regression of NDVImax[a] on Bmax[a] (kg DM ha^{-1})	Correlation coefficient r
Ground	Sand (7)	NDVImax = 85*Bmax+375	0.67
(1985)	Clay (5)	NDVImax = 70*Bmax+465	0.37
NOAA-7[b]	Sand (11)	NDVImax = 66*Bmax+524	0.71
(1985)	Clay (9)	NDVImax = 12*Bmax+528	0.74
NOAA-7[b]			
(1984)	Mixed (13)	NDVImax = 22*Bmax+46	0.67

[a] NDVImax = maximum normalized difference vegetation index; Bmax = maximum growing-season biomass.
[b] Index covers grass and tree foliage biomass.

Integrated NDVI

Assuming there are direct relationships (Figure 4) between NDVI and greenness density and between greenness density and photosynthetic activity, and assuming further that biomass is proportional to gross cumulative production, then the integral of the NDVI curve over time should correlate with actual above-ground biomass. This also assumes, however, that the other factors affecting biomass – organic degradation and transfers out – are either insignificant or do not vary over time.

In fact, though, the integral of the index curve calculated over the 1985 growing season did prove to be a good indicator of total biomass accumulation to which it was linearly related (Table 3), especially when soil-background reference values were deducted from the combined index values for vegetation and soil. Separate regressions were calculated for sandy and clayey soils, and the integral of index increments over the growing season was also applied to different phases of growth, irrespective of whether radiometer measurements were made on the ground or from the air (Table 4). Correlations for aerial measurements were improved by estimating the foliage biomass of trees and shrubs besides that of the field layer, in proportion to their cover.

Table 3. *The relationship between the integral of the NDVI curve (Ii) for end of June to mid-September 1985 and total biomass accumulation (B), Gourma, eastern Mali.*

Origin and year of radiometer measurement	Soil background and site	Linear regression of Ii on B (t DM ha^{-1})	Correlation coefficient (r)
Ground	Sand (7)	$Ii = 8.152*B - 2.43$	0.89
(1985)	Clay (5)	$Ii = 3.347*B - 14.78$	0.48
NOAA-7[a]	Sand (11)	$Ii = 1970*B + 262$	0.67
(1985)	Clay (9)	$Ii = 521*B + 553$	0.88

[a] Satellite-derived index covers tree foliage.

Table 4. *The relationship between the integral of index increments (Iii) over the 1985 growing season and biomass (B), Gourma, eastern Mali.*

Origin and date of radiometer measurement	Soil type and site	Linear regression of Iii on B (t DM ha^{-1})	Correlation coefficient (r)
Ground(1985)	Sand (13)	(a) $Iii = 4.878 * B - 0.538$	0.88
	Clay (12)	$Iii = 5.722 * B + 3.997$	0.79
NOAA-7(1985)	Sand (36)	$Iii = 2.162 * B + 1.491$	0.85
	Clay (25)	$Iii = 0.520 * B + 178.0$	0.85

The choice of the integration period modified both the intercept and slope of the NDVI/biomass regressions, indicating that this may affect the application of the technique in general situations. Sensitivity to the dates for beginning and ending the data integration should therefore be tested for several sites, seasons and vegetation types before adopting the integrated NDVI for large-scale forage resource assessment.

Mapping trials

The next stage of the calibration exercise in the Gourma included trials to map changes in above-ground biomass during the growing season and to determine the potential of the multitemporal integration technique for data extrapolation to wider ecological settings. Two distinct mapping trials were carried out: one around Gossi town (15°49’ N, 01°18’ W) in central Gourma, and one covering the whole of the Gourma region (about 150 000 km^2).

Plant biomass maps for Gossi

The mapping trial in Gossi involved 250 km^2 of highly diverse environment. A set of seven grid maps was made, each grid cell covering an area of 1.5 km^2, the approximate size of the local area coverage pixel of the NOAA-7/AVHRR data. The maps show changes in grass and tree foliage biomass from 2 July to 15 September.

Biomass was expressed in seven classes, with limits of 75, 150, 300, 600, 1200, 2400 and 4800 kg DM ha^{-1}. Pixels were classified within this scale according to the integrated value of index increments at a given date. Seven soil backgrounds were distinguished from a plant ecology map derived by photo-interpretation. Soil background reflectance was taken into account twice: first, when calculating an index increment, and again when calculating separate regressions for the seven soil backgrounds identified.

The index increment was calculated by subtracting the soil NDVI reference value from the combined vegetation/soil index values sensed during the growing season. Results obtained for each of the seven sub-strata were then separately applied to the observed index. The resulting biomass maps were not checked independently for accuracy, but 5 of the 30 sites used to calibrate the relationship between the NDVI and biomass lay in the area mapped, and the ground measurements carried out on them correlated well with the information on the biomass maps.

Plant biomass map for the Gourma

This trial was carried out to investigate the applicability of the integrated NDVI for forage resource monitoring across the Gourma region. Because soil brightness was not measured, soil backgrounds were determined using NDVI values calculated for the beginning (November) and end (June) of the 1984/85 dry season. This led to distortions, as NDVI does not differentiate adequately between various types of soil background.

The relationship between the integrated NDVI and above-ground biomass was calculated only for the end of the growing season (15 September), and the resulting 1.5 km^2 grid map was of value merely from a methodological standpoint. Nevertheless, the trial indicated that the multitemporal integration technique is potentially suitable for wider data extrapolation. This would add to its other advantage, namely that it requires only a few minutes of computer time, or a maximum of few hours if one counts the time spent on preliminary data processing.

CONCLUSION

Monitoring of range resources has been hampered by a lack of a suitable method to quantify temporal and spatial fluctuations in plant biomass, and rangeland mapping has been limited to qualitative plant stratification. Given their wide geographic coverage and high frequency of acquisition, satellite-derived spectral data offer a possible solution to the problem, but their interpretation for practical quantitative assessment of forage resources is not straightforward.

The calibration of a normalized difference vegetation index calculated from NOAA-7/AVHRR data in the Gourma region of Mali showed that, despite good correlations and linear fitting at a given site and on a given date, the relationship between the index and actual biomass is neither direct nor consistent. The integral of the index curve should theoretically be better related to actual biomass, as it is a function of the cumulative, intercepted, photosynthetically active radiation (IPAR), but the linear regressions of the integrated NDVI on biomass also varied with site and season.

Part of this unreliability was associated with differences in soil background response, but the main distortions were due to atmospheric interference. Soil-related effects were reduced by calculating the relationship between the integral of NDVI increments over time and above-ground biomass separately for each soil type. Atmospheric interference can be reduced by selecting data or scenes least affected by cloud, haze or atmospheric dust. In the Gourma project, the quality of the remotely sensed data was sufficiently improved by empirical data selection procedures to allow automatic mapping of range resources at a coarse resolution.

The mapping trials carried out indicate that satellite-derived digital data facilitate the analyses and calculations needed for rapid production of simple thematic maps. Combining the information such maps give on the temporal dynamics of plant biomass with information on plant stratification maps (which need to be digitalized for this purpose) would provide a better data base for improved resource management in pastoralareas.

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