172

REMOTE SENS. ENVIRON. 35:243–255 (1991)

Global Land Cover Classification by Remote Sensing: Present Capabilities and Future Possibilities

John Townshend, Christopher Justice, Wei Li, Charlotte Gurney, and Jim McManus

Department of Geography, University of Maryland, College Park

Reliable information on global land cover is required to assist the solution of a wide range of environmental problems. Information from conventional ground-based data has significant deficiencies as demonstrated by an analysis of these sources. Data from the Advanced Very High Resolution Radiometer has been used to carry out land cover classification at continental scales. The specific data sets that have been used, have substantial limitations and the need for the use of alternate data bases is outlined. The Moderate Resolution Imaging Spectrometer (MODIS) of the Earth Observing System (EOS) will be a substantially better instrument in terms of several spectral, radiometric, and geometric properties than the AVHRR. However, in terms of its total field of view and frequency of imaging, the instrument will be comparable to the AVHRR for global land cover monitoring.

INTRODUCTION

There is considerable ignorance concerning the global distribution of vegetation types. This is an issue of increasing concern given the rate of transformation of the Earth's vegetation cover, and the profound impacts that these changes are having on the global environment and its habitability. Changes in land cover for agriculture, human settlements, and other purposes are among the most pervasive and obvious impacts of human activities on the global environment (Turner, 1989). Changes in land cover have profound implications for the functioning of ecosystems, biogeochemical fluxes, and climate (NRC, 1988; IGBP, 1990). Despite the fundamental transformations that humans have made to the surface of the Earth, there is no reliable, comprehensive data base of changes in the vegetative cover of the land surface on a global scale.

In this paper our initial objective is to examine the adequacy of traditional approaches for the derivation of global information on land cover. The contribution of coarse resolution satellite data from the NOAA series of satellites will then be discussed. Finally the potential of one of the future sensor systems of NASA's Earth Observing System, namely MODIS, will be evaluated for the purposes of global land cover monitoring. Attention is restricted largely to the role of remotely sensed data in deriving information on land cover classes. For many purposes, the derivation of biophysical properties of the Earth's surface by direct

Address correspondence to J. Townshend, Department of Geography, 1113 Lefrak Hall, University of Maryland, College Park, MD 20742.

Received June 1990; revised 12 November 1990.

0034-4257/91/$3.50
Elsevier Science Publishing Co. Inc., 1991
655 Avenue of the Americas, New York, NY 10010

inversion of remotely sensed data is ultimately a more desirable objective. Notwithstanding recent advances in the estimation of biophysical characteristics such as leaf area index and canopy resistance (e.g., Nemani and Running, 1989; Running, 1990), comprehensive derivation of canopy characteristics including nonfoliar properties must await the derivation of more refined procedures and better global data sets, which almost certainly will have to include microwave data. However, deriving maps of the current distribution of land cover classes and how they are changing is a much more feasible objective and hence current and future prospects will be evaluated for these tasks.

LIMITATIONS OF CURRENT GLOBAL VEGETATION MAPS

It has been argued that existing maps are adequate for the depiction of global vegetation cover (Thomas and Henderson-Sellers, 1987), but comparison of estimates of the areas occupied by the major vegetation types suggests this is an overly optimistic viewpoint (Fig. 1). Clearly estimates vary considerably, and even where there is correspondence for particular categories, such as agricultural land, this can arise simply because the estimates are derived from the same source. The variations of these global compilations arise from a number of reasons. First, they rely on compilation from numerous separate sources, since direct ground observations using an agreed system of classification has never been directly attempted at a global scale. Integrating local studies into regional ones and thence into global maps raises problems if only because the original maps were often produced at different dates. A greater problem is that widely varying criteria are used in classification (Fosberg, 1967; Kuchler, 1967; Mueller-Dombois, 1974). For example, although classifications are usually based on inherent vegetation properties, these may rely either on physiognomic properties such as growth and life forms, three-dimensional structure, and seasonal periodicity or on floristic properties related to the species present (Box, 1981; Whittaker, 1970). Alternatively various environmental properties may be used as surrogate criteria for discriminating between vegetation types (e.g., Ehrlich and Roughgarden, 1987) relating to factors such as climate, topography,

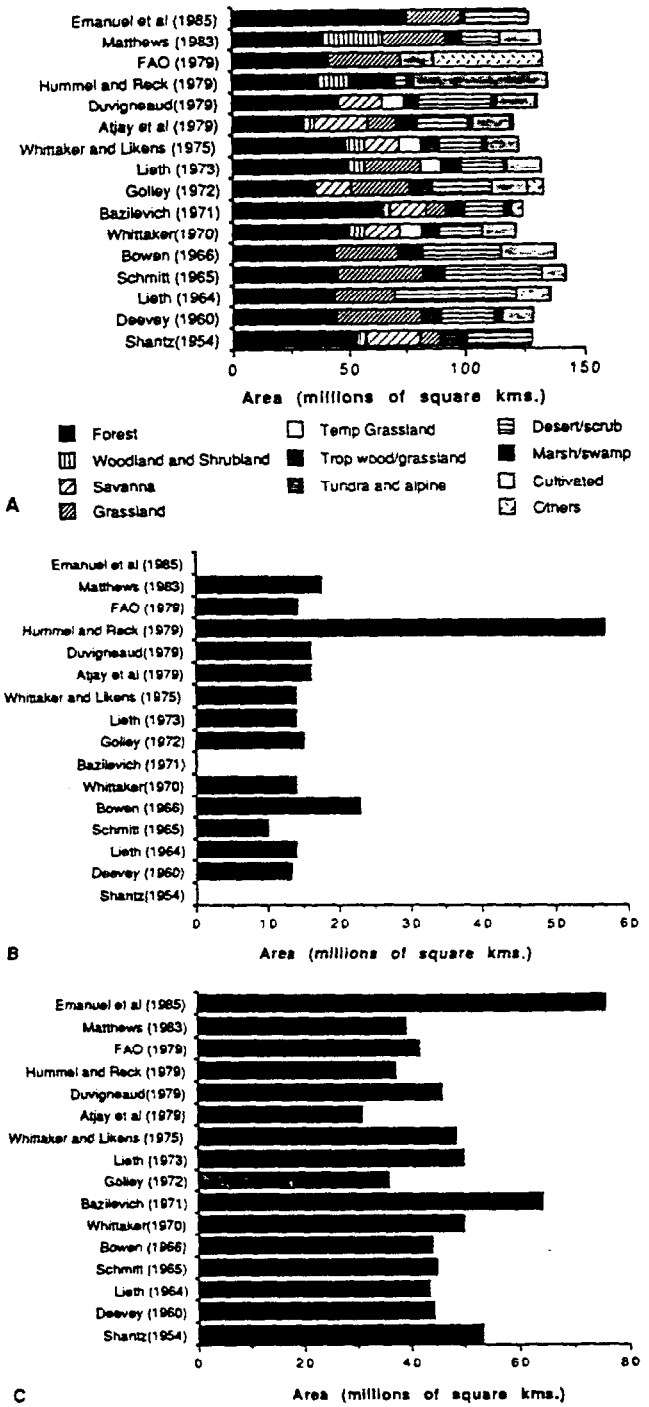


Figure 1. Variations in estimates of the global extent of cover types for: (a) ten main cover types (the apparent total area varies because of different estimates of the extent of unvegetated categories such as desert, and ice caps); (b) cultivated land; (c) forest land.

soils, or human influences. Other approaches combine inherent vegetation characteristics and environmental properties (e.g., UNESCO, 1973; Walter, 1985). Consequently the compilers of the global estimates have to reclassify maps into a common scheme based on inherently incompatible

classifications. Even if the same classificatory approach has been adopted, the size of the specific parameters used to separate classes can vary. Hence the proportions occupied by classes with the same label in Figure 1 are usually not directly comparable. Not only does the total area occupied by different classes vary substantially between authorities, but the detailed spatial distribution often varies substantially even where the total global estimates of a cover type are similar. Major attempts have been made to synthesize our current knowledge to generate digital global data bases, notably by Matthews (1983) and Henderson-Sellers et al. (1986), and, although they represent improvements on previous knowledge, the previous discussion inevitably casts doubt on their internal consistency.

USE OF DATA FROM THE ADVANCED VERY HIGH RESOLUTION RADIOMETER FOR LAND COVER CLASSIFICATION

The absence of satisfactory land cover maps at very broad scales has encouraged attempts to use remote sensing data to provide this information. Data from conventional Earth resources satellites such as Landsat and SPOT are unsuited to this task, because their data volumes at global scales are extremely large. However, such data have been used as a complementary source of information for the production of maps at continental scales (e.g., UNESCO, 1981). An alternative source of data is coarse spatial resolution data from the Advanced Very High Resolution Radiometer (AVHRR) from the NOAA series of satellites. These data are obtainable globally on a daily basis and have been shown to have considerable potential for monitoring vegetation (e.g., Tucker et al., 1985; Justice et al., 1985; Goward et al., 1985; Sellers, 1985), notably through the use of a spectral ratio, known as the normalized difference vegetation index (NDVI), which is sensitive to vegetation activity. It is derived from the ratio of the red (R) and near infrared (NIR) spectral bands as follows: $NDVI = (NIR - R)/(NIR + R)$. The daily availability of these coarse resolution data has enabled automated methods of preprocessing to be carried out allowing global data sets to be produced in which the effects of clouds and other atmospheric effects are substantially reduced

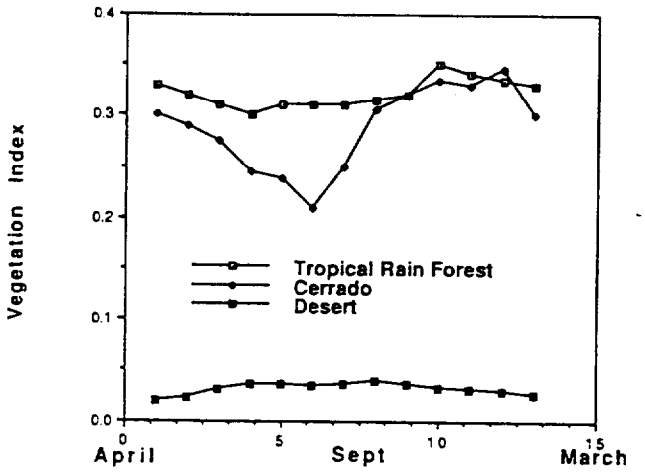


Figure 2. Variations in the NDVI with time for three contrasting vegetation types in South America. The desert area is always distinct from the other two categories. However, the cerrada (savanna woodland) and the tropical rain forest are similar for much of the year, but during the dry season the cerrado has a distinctively lower NDVI value. This graph emphasizes the need to consider variations in the NDVI throughout the year rather than for individual dates when trying to discriminate between land cover types. [Based on data from Townshend et al. (1987).]

(Holben, 1986), especially when they are resampled to coarser resolutions.

The basic spatial resolution of AVHRR data is 1.1 km, but no global data sets exist at this resolution. However, global data are collected and archived daily at a resolution of 4 km through an on-board sampling process. No data at this resolution have been directly used for global land investigations because of the difficulties of handling the resultant large volumes of data, but instead resampled data sets have been used with a resolution of 15–20 km in the form of NOAA's Global Vegetation Index (GVI) product (Kidwell, 1990) and with a resolution of 7.6 km in the form of NASA's Laboratory for Terrestrial Physics product generated by the GIMMS group at the Goddard Space Flight Center (Townshend and Justice, 1986).

The value of these AVHRR data arises primarily from their multi-temporal use, since this allows vegetation types to be characterized using their seasonal (or phenological) variations in the NDVI (Townshend et al., 1987). In Figure 2 it can be seen that for substantial portions of a year different vegetation types may have similar NDVI values, but that at other times they may display very different ones. A multitemporal approach using data from throughout the year is essential for satisfactory discrimination between most cover classes, when using the NDVI (cf. Thomas and

what type of classificat. system/criteria was being used in comparing the AVHRR NDVI Values? How many classes 2 or 10? How was percent Accuracy (calculated)? (derived)

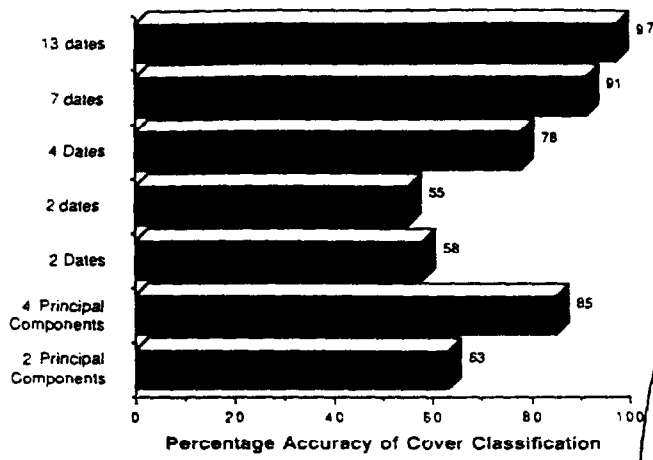


Figure 3. Variations in the accuracy with which training set data are classified for South American cover types. Note that accuracies based on training data give overestimates, and they should be used only to gain a comparative indication of the relative success of the methods. [Based on data from Townshend et al. (1987)]

Is seasonality = principal components?

Henderson-Sellers, 1987; Henderson-Sellers, 1989). Initial work on continental land cover classification used a measure of the mean annual NDVI value and seasonality (Tucker et al., 1985), as represented by the first two principal components of an annual set of AVHRR data. Subsequently, multiple images from different dates throughout the year have been used in attempting land cover classifications (Townshend et al., 1987; 1989) and considerable improvements in accuracy were found as the number of images was increased (Fig. 3).

Preliminary land cover maps have been derived at continental scales by Tucker et al. (1985) for Africa and by Townshend et al. (1987) for South America using NOAA's GVI product with pixel sizes of approximately 15–20 km. Shimoda et al. (1986) have used the same very coarse resolution data to derive statistical estimates of global land cover types: more recently Koomanoff (1989) has produced a global map of nine basic vegetation types, using an integrated annual value of the NDVI, though without any consideration of seasonality. At a subcontinental scale Millington et al. (1989) used AVHRR data resampled to 8 km resolution from NASA/GSFC to stratify cover types for eight countries in southern Africa as a basis for estimating the supply of fuelwood.

USE OF DATA FROM THE ADVANCED VERY HIGH RESOLUATION RADIOMETER FOR LAND COVER CLASSIFICATION

Despite the encouraging results from these preliminary investigations, the resultant maps derived from satellite data have substantial limitations. Most attempts have used NOAA's GVI product, which has a number of significant deficiencies. Notable among these is its very coarse resolution of approximately 20 km as a result of a complex set of resampling procedures from the 1 km data of the AVHRR (Townshend and Justice, 1986). The GVI product also has the problem that off-nadir pixels, which suffer markedly from atmospheric effects, are preferentially sampled especially in higher latitudes in generating the 20 km pixels from the finer resolution data (Goward et al., 1991): also in this product the original DN values are used rather than the reflectance or radiances, which yields distorted values of the NDVI.

Additional limitations of previous work include the fact that analyses have relied on only a single year's data, and consequently interannual variability in vegetation response to climatic conditions can lead to errors in the inferred distribution of vegetation types especially in semiarid and seasonally flooded areas. Also, boundaries between cover types with similar phenologies such as those between the moist savannas, tropical rain forest, and degraded tropical rain forest in Africa are unreliable. For example, in the southern Central African Republic the northern boundary of the central African rain forest is difficult to separate reliably from the moist savanna woodlands to the north because the latter have little seasonal variation in their NDVI (Justice and Kendall, forthcoming). In other locations such as the southeastern margins of the Amazonian rain forest this boundary is well defined by the NDVI data (Townshend et al. 1987). Additionally wetlands are not well distinguished from other vegetation types on these maps

ALTERNATE SOURCES OF REMOTELY SENSED DATA

Given these limitations, it is natural to look to other sources of remotely sensed data. Although large quantities of such data exist, they are usually not in an appropriately comprehensive and accessible format to allow their use at broad scales. This problem has already been alluded to in the context of fine resolution Landsat and SPOT data, but even data from the individual bands from the AVHRR sensor are currently unavailable in forms suitable for global land cover classification. The potential of these data is shown in the work of Justice and Kendall (forthcoming), who demonstrate that thermal infrared data from the AVHRR can be used to locate the boundary between tropical rain forest and savanna vegetation, more reliably than with the use of NDVI data.

The use of data from other parts of the spectrum in distinguishing between different land cover types at broad scales has also been demonstrated in the application of microwave data sets from the SMMR (Scanning Multifrequency Microwave Radiometer) sensor, which have been compiled into global data sets (Choudhury and Tucker, 1988). These data use the Microwave Polarized Difference Temperature (MPDT) derived from the difference in temperatures between horizontally and vertically polarized radiation at 37 GHz. The MPDT data can be used to assist the recognition of wetlands (Giddings and Choudhury, 1989) and various other cover types, especially when combined with AVHRR data (Justice et al., 1989b; Townshend et al., 1989). Such data suffer from the limitations of only being available for coarse resolutions at around 20 km and from problems in the interpretation of the factors controlling the MPDT (Townshend et al., 1989).

Another source of coarse resolution data is the Coastal Zone Color Scanner (CZCS) whose short-wave visible bands have been shown to be capable of discriminating between high latitude cover types (Petzold and Goward, 1988). Unfortunately, data from both the CZCS and SMMR sensors are no longer being acquired, though the SMMI (Special Sensor Microwave Imager) of the United States Defense Meteorological Satellite Program is now collecting data comparable with those of SMMR (Schluessel and Emery, 1990).

In terms of existing remotely sensed data, the prospects for global land cover characterization would be much improved by the creation of internally consistent global data bases from existing coarse resolution data sets. This would require a substantial amount of work and resources in resampling the data to common spatial and temporal reference systems and in reducing atmospheric effects; unfortunately, there is little indication at present that this will be carried out in the immediate future.

Spectroradiometer?

THE POTENTIAL OF THE MODERATE RESOLUTION IMAGING SPECTROMETER FOR LAND COVER DISCRIMINATION

The previous sections have illustrated the need for improved land cover information at global scales and the substantial potential of existing data sources from the NOAA series of satellites to provide it. Other existing remotely sensed data sets have the capability to reduce these deficiencies but their practical application is limited by a number of factors including a sparsity of globally composited data sets, the coarse resolution of some of the data sets, and the fact that some data sets are no longer being acquired. It is natural therefore to look to future sensor systems to examine their role in providing improved land cover information. Any assessment of the likely improvements arising from these future sensors is a complex question, because they are dependent on so many different sensor characteristics (Fig. 4). They include the more usual measures of sensor capability, such as spatial resolution and the number and location of spectral bands. Others relate to the consistency of the data sets through time, such as radiometric calibration and bandwidth stability, which are especially important for detecting changes in land cover. Monitoring change reliably is also dependent on the accuracy with which we spatially coregister images if we are not to introduce errors due to a failure to compare the same area of ground at different times. Variations in view angle are also known to be significant because of the non-Lambertian reflectance of most vegetative surfaces. Hence apparent changes in ground characteristics may be simply a result of the bidirectional reflectance function of the vegetation. The precision with which we measure radiation, as characterized by the radiometric resolution, also strongly affects our ability to monitor, especially where the changes are radiometrically

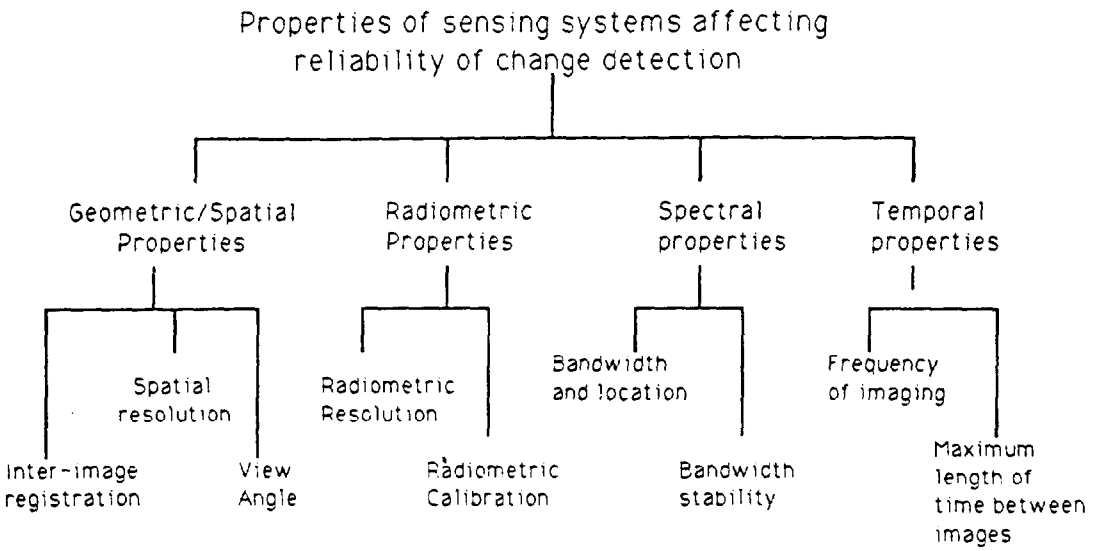


Figure 4. Factors affecting ability of sensing systems to detect change.

subtle. The frequency of imaging has major effects on our ability to monitor change at a global scale and the presence of clouds makes the required frequency of imaging much higher than frequency with which changes have to be monitored. Because changes in land cover occur at very different rates, reliable monitoring requires that a minimum period elapses before a change can be detected; consequently, the total active lifetime of a sensor will impact on its usefulness for monitoring change.

A large number of sensor systems are expected to be placed in orbit during the 1990s for environmental monitoring: including those of the first European Earth Resources Satellite (ERS-1), and those associated with the international Earth Observing System (EOS) of NASA, the European Space Agency, and the Japan National Space Agency (Ormsby and Soffen, 1989; NASA, 1990). For the purposes of global land cover monitoring, the sensor with the greatest potential is arguably the Moderate Resolution Imaging Spectrometer (NASA, 1986; Salomonson et al., 1989). MODIS has been designed for land, oceanic, and atmospheric sensing and will consist of two instruments, a nadir-pointing version (MODIS-N) primarily for land and atmospheric applications and a tilting version (MODIS-T), which was designed primarily for oceanic purposes, but which also will have value in exploitation of bidirectional land properties. In MODIS-N a subset of its 36 spectral bands has been designed specifically for land applications in terms of their spectral, radiometric, and spatial resolution properties. It is beyond the scope of this article to assess the role of microwave remote sensing in contributing to global monitoring of land cover, though clearly such data have the potential to provide complementary information on the physical structure of vegetation.

The current AVHRR has only two bands in the reflective part of the spectrum (though there are plans to add a third middle IR band from NOAA-K onwards) and three bands in the thermal infrared. In contrast MODIS-N has 19 bands in the reflective part of the spectrum with seven designed specifically for land applications (Table 2), and 10 thermal bands within atmospheric windows, though most of the latter were not chosen for land applications. Five of the seven land reflectance bands are based mainly on experience derived from the Thematic Mapper, their precise bandwidths having been carefully chosen to minimize atmospheric effects and solar absorption (Fraunhofer lines). The bands on MODIS-N will be only 20–50 nm wide compared with a typical figure of 60 nm for the Thematic Mapper: The reflective bands are all only 20 nm wide. The near infrared band will be much narrower than that of the AVHRR in order to avoid the water absorption band centered near 900 nm. Consequently, ratios such as the NDVI or the soil-adjusted vegetation index (SAVI) of Huete (1989) will be far less affected by the atmosphere than the NDVI of the AVHRR. All of the additional bands similar to those of the Thematic Mapper are likely to have

Table 1. Comparison of the Principal Sensor Characteristics of MODIS and AVHRR Relevant for Land Cover Characterization

	AVHRR	*MODIS-N*		*MODIS-T*
		Center	*Bandwidth*	
Spectral bands for land cover applications	580–680 nm	470 nm	20 nm	32 bands
	725–1100 nm	555 nm	20 nm	(400–880 nm[b])
	1580–1750 nm[a]	659 nm	20 nm	
		865 nm	40 nm	
		1240 nm	20 nm	
		1640 nm	20 nm	
		2130 nm	50 nm	
	3 thermal bands	9 thermal bands		
IFOV (nadir)	1.1 km	500 m 250 m (659 and 865 nm)		1.1 km
Swath width	2700 km	2330 km		1500 km
Calibration	absent	lunar		lunar and solar
Radiometric quantization	10 bit[c]	12 bit		12 bit
Global frequency	1–2 days	1–2 days		2 days
View angle	55.4°	55°		45°
Tilt capability	none	none		± 50°

[a] Proposed future spectral band.
[b] Bands selected primarily for ocean color purposes, but also of potential value for sensing soil and vegetation.
[c] Plans exist to increase the quantization to 12 bits from NOAA-K onwards.

value in land cover discrimination (Townshend et al., 1983; Townshend, 1984; Atkinson et al., 1985). Of these bands the middle IR band centered at 1640 nm is likely to be of greatest value (Benson and DeGloria, 1985; Toll, 1985), because of its sensitivity to foliar moisture (Tucker, 1980), especially when ratioed with the band centered at 1240 nm. The latter band is additional to those found on the Thematic Mapper and is also expected to be useful in the discrimination between different forest types (Rock, 1982). The existence of these several bands offers the opportunities to derive linear band combinations, in which vegetation effects are enhanced and background soil effects are reduced (Crist and Cicone, 1984). It is also anticipated that the thermal bands will be of some use in the discrimination between vegetation types, though a lack of knowledge of the spectral response of vegetation in this region makes their precise role difficult to evaluate at this stage. In order to monitor changes in the spectral sensitivity of each band, there are plans to provide spectral calibration on MODIS (Salomonson et al., 1989).

One of the major limitations of the AVHRR system is its lack of any internal calibration to monitor changes in the radiometric sensitivity of its reflective spectral bands through time. Evidence has accumulated to show that the various

Table 2. MODIS Bands in the Visible and Reflective Infrared Designed for Land Applications

470 nm	detection of changes in chlorophyll/carotenoid ratios indicative of plant stress
555 nm	reflectance peak controlled by the presence of chlorophyll (Tucker, 1980)
659 nm	absorption by chlorophyll as well as tannin and anthocyanin
865 nm	related to physical structure of mesophyll layer
1240 nm	reflectance feature related to discrimination of forest types (Cox, 1983; Rock, 1982)
1640 nm	absorption due to leaf moisture content (Cox, 1983)
2130 nm	absorption due to leaf moisture content (Cox, 1983), foliar nitrogen and protein absorption (Petersen et al., 1985)
	Band Combinations
659 nm and 865 nm	can be used in various combinations to derive vegetation indice such as the NDVI (Tucker, 1980; Running, 1990) useful for estimating absorbed photosynthetically active radiation (Sellers, 1985)
1240 nm and 1640 nm	can be used in to estimate leaf moisture content (Cox, 1983)

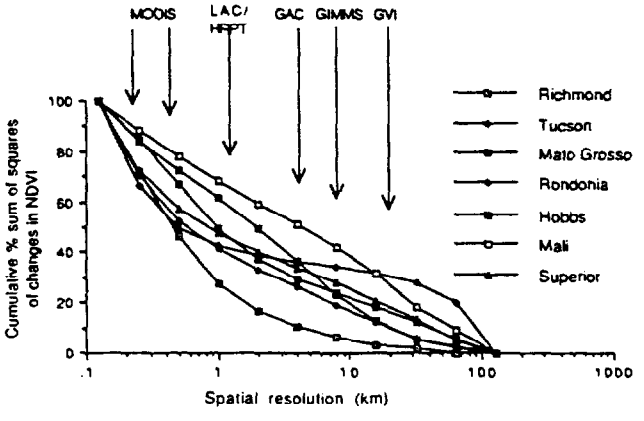
AVHRR sensors have undergone considerable reductions in sensitivity during their lifetime. Empirical corrections based on supposedly unvarying ground targets such as deserts have had to be used to correct the data in order to produce more reliable monitoring over time (e.g., Tucker, 1989). Clearly there is the real prospect of identifying apparent changes in land cover which simply arise from sensor variability. MODIS will have radiometric on-board calibration for all channels. Initial goals were for better than 2% absolute accuracy of the maximum scene radiance for the visible, near infrared, and short wave infrared bands and less than 1% for the other infrared bands (Salomonson et al., 1989), though subsequently the accuracies have been relaxed to 5%. The corresponding temporal stability of these two groups of bands should be less than 1% and 0.5% of the half scale value respectively over a 2-week time span and with 10° temperature excursions.

Of comparable importance to the calibration of the instrument is the inclusion of several spectral bands which are affected in known ways by the atmosphere and which can then be used to correct other spectral bands for atmospheric interference. In this way the influence of gases such as water vapor, oxygen, and ozone can be substantially reduced and the ground leaving radiance can be estimated more accurately. The greatest challenge in reducing atmospheric effects will lie in reducing the effects of aerosols which are especially important in peri-desert areas and in the humid tropics.

As discussed in the third section, although AVHRR data are collected at a resolution of 1.1 km, they are currently available globally at a resolution of 4 km at best. In order to detect important human induced land cover changes, it was originally proposed that the MODIS land spectral bands should have a resolution of 500 m (NASA, 1986). Subsequently, a simulation study was carried out to try and assess quantitatively whether this was indeed an appropriate value. Pairs of images, taken at different times by the Multispectral Scanner System of Landsat, depicting seven areas which have undergone significant land cover transformations, were degraded to different candidate resolutions (Justice et al., 1989a) and the spatial frequency content of the difference between the images was examined (Townshend and Justice, 1988). The sums of squares of changes in the NDVI were used as indicators of land cover change in the absence of detailed land cover information. Figure 5 shows that with a 500 m resolution many more changes will be detected than at 4 km. Moreover, even the change from 1 km resolution [comparable with that of the AVHRR's basic nadir Instantaneous Field of View (IFOV)] to 500 m will result in much improved detection of change (Fig. 6). Subsequent to the initial specification of MODIS-N, it was proposed that the near-infrared and red bands should have an IFOV of 250 m, for improved detection of small clouds and for improved land boundary identification. The impact of these bands on monitoring land cover change will also be substantial in the detection of change on the basis of these simulations (Fig. 6). More detailed observations will rely on the use of sensors with higher spatial resolutions such as HIRIS (High Resolution Imaging Spectrometer), though they will not permit global monitoring.

The accuracy of spatial registration between images of different dates is another property which greatly impacts on our ability to monitor change in land cover, but its impact has been little studied compared with other properties. The impact of misregistration arises because, if less than perfect registration is achieved, differences in detected radiance will have an error term introduced, which is related to the spatial variability in the surrounding land cover. Since land cover often displays considerable local variability, even small errors of misregistration have the potential to introduce

Figure 5. Cumulative frequency distribution of the sum of squares of the NDVI in images depicting changes as a result of various land conversions (Townshend and Justice, 1988). These plots indicate the spatial resolution of current and future data sets in relation to spatial frequencies of changes in vegetation that have to be detected.



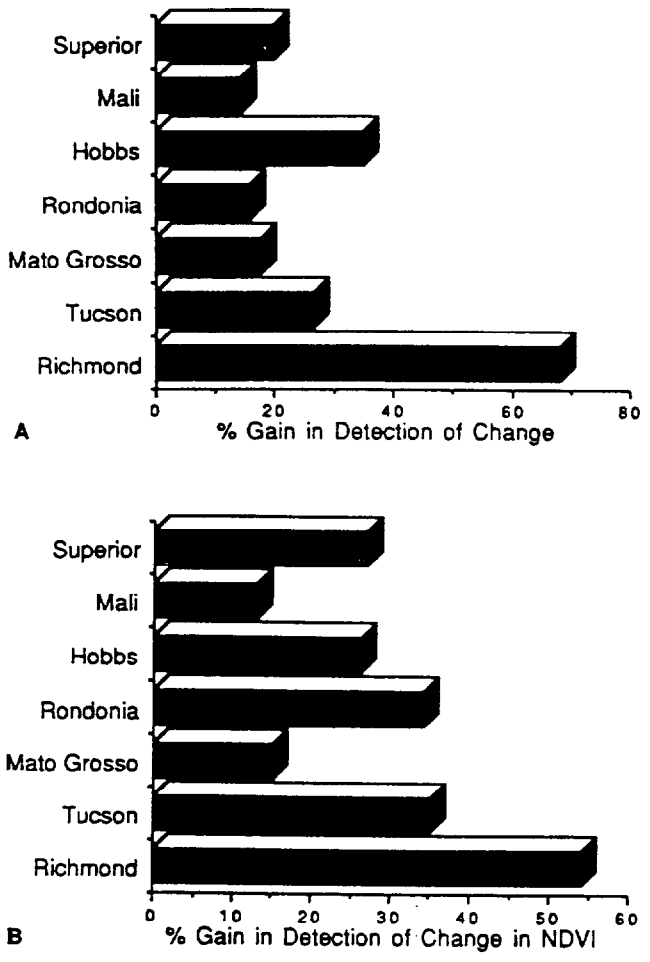
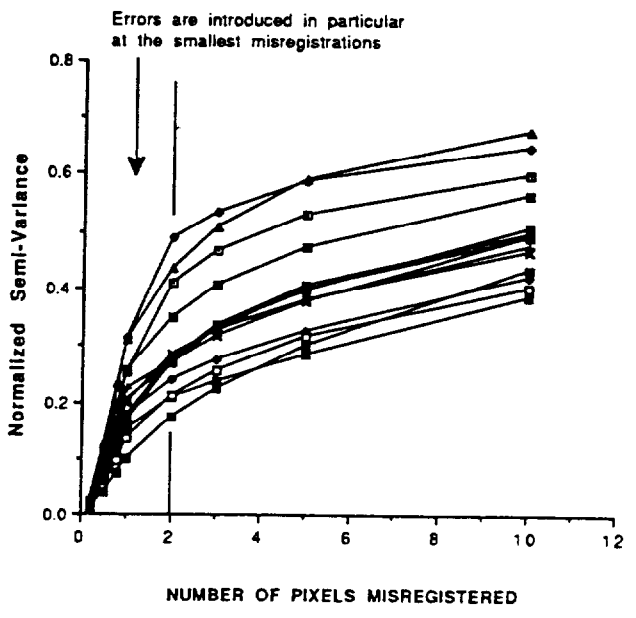


Figure 6. Proportional increases in the detection of changes in the NDVI with improvements in spatial resolution: (a) from 1 km to 500 m; (b) from 500 m to 250 m.

substantial errors into estimates of the differences between images obtained at different dates. In order to quantify such effects, experiments have been performed using the data sets analyzed in the resolution study described above (Townshend et al., forthcoming). The impact of misregistration was assessed by taking copies of each image and progressively misregistering it against itself. By this procedure only errors due to misregistration were induced rather than any due to actual differences between different time periods. Figure 7 shows that errors increase rapidly between zero and one pixel misregistration and then increase less rapidly thereafter. Clearly this suggests that a high degree of coregistration is essential for reliable depiction of changes in vegetation. Coregistration can be achieved through a variety of procedures including the use of ground control points, image templates, or automated scene matching. However, of crucial importance is accurate knowledge of the pointing of the instrument, which allows images to be brought into approximate coregistration before application of any of the above procedures. For the AVHRR sensor, simple automated navigation systems are capable of routinely correcting AVHRR data to within 5 km: With accurate emphemeris data using a fully elliptical model accuracies of 1.0–1.5 km can be achieved (Emery et al., 1989). In the case of MODIS the accuracy of registration should ideally be equivalent to a fraction of a single 250 m pixel. Although subsequent processing will be required for satisfactory coregistration of the two bands with finer resolutions, the performance of most of the MODIS bands will clearly be superior to AVHRR in this respect.

Even with the near daily global coverage of the AVHRR, cloud-free images cannot be obtained for many areas of the Earth, with a 1- or 2-week frequency, and for some parts of the tropics even monthly images cannot be obtained. Unfortunately

Figure 7. Introduction of noise into images as a result of misregistration. The experiment was carried out by misregistering images against themselves and then measuring the resultant noise by the normalized semivariance. Thus the effects of misregistration can be assessed without the complicating influence of actual changes between images. The plots are for images with a spatial resolution of 250 m from two dates from seven contrasting areas undergoing major land conversions. For further descriptions of the areas, see Townshend and Justice (1988).



with a similar field of view and a lower orbit the swath width of MODIS-N is somewhat smaller than the AVHRR and hence the frequency of imaging by MODIS-N is expected to be slightly worse than that of the current AVHRR.

MODIS-T will have an even coarser temporal frequency achieving global coverage every 2 days. One specific benefit of MODIS-T for land applications relates to its tilting capabilities, which will enable estimates of the bidirectional reflectance distribution function (BRDF) of land cover types to be made (Barnsley and Morris, 1990). This should substantially increase the quality of land cover characterization that is possible (Gerstl and Simmer, 1986; Ross and Marshak, 1988). However, the lower temporal frequency of the MODIS-T instrument, and the need for multiple looks at each area, will substantially reduce its value for regular and comprehensive *global* monitoring. In addition, some of the narrow spectral bands required for ocean color monitoring will provide useful information on soil color especially now that the MODIS-T gain will be adjusted to permit the sensing of land surfaces. The Multi-Angle Imaging Spectro-Radiometer (MISR), another candidate instrument for the first EOS platform, will also provide data on the BRDF, though its characterization will be less comprehensive than that potentially available from MODIS-T (Barnsley and Morris, 1990).

One particularly important agent of land cover change is biomass burning. Recent developments have demonstrated the use of the AVHRR mid-IR channel for fire monitoring (Matson and Holben, 1987; Kaufman et al., 1990). However, the instrument is severely limited by the low saturation level of the detector in relation to the high temperatures associated with burning. MODIS-N will include a mid-IR channel (3.75 nm) along with three long-wave IR channels (8.55, 11.03, and 12.02 nm) channels designed specifically for fire monitoring and the estimation of fire size (as well as the monitoring of other hot objects such as volcanoes).

A further limitation of the MODIS instrument for monitoring land cover will relate, in the first instance, to the short length of time over which observations are made. Detection of many changes will initially have to depend on comparisons between results derived from MODIS with those from other instruments such as the AVHRR. Combining the results from different instruments, especially where one instrument has no on-board calibration, will inevitably raise substantial practical problems.

Although sensor performance impacts strongly upon our capability to monitor land cover change, the way in which data are subsequently processed in the ground segment will also have a major impact on the utility of the data. Considerable effort is being expended on the definition and design of the EOS data and information system (e.g., Dutton, 1989; Billingsley et al., 1989; Chase, 1989). For example, the quality of the data will depend on the effectiveness of algorithms for atmospheric correction, and the availability of global digital elevation models for improved geometric correction. Furthermore, a capability, readily to bring together data sets from several different sensors, will be needed to fully exploit the synergistic benefits of data from different parts of the spectrum, with different spatial resolutions and temporal frequencies.

CONCLUDING COMMENTS

There are immediate requirements for reliable information on land cover at global scales. Traditional sources of land cover information have major limitations, and contain many inconsistencies. As such, it is appropriate to look to remotely sensed data to provide such information. Encouraging results have been obtained at continental scales using a global data set derived from the NOAA's AVHRR sensor. Despite these results, operational provision of global land cover information will require better data sets in terms of spectral, radiometric, temporal, and spatial properties.

One of the important future sources of such information is expected to be the MODIS-N sensor of the EOS program. This instrument will be a substantial improvement as a global sensor of land cover compared with the AVHRR in terms of the number of spectral bands, their location, calibration, spatial resolution, and geometric registration. Additional spectral bands will permit improved atmospheric correction. However, the instrument will be no better in terms of the total swath width and the frequency of imaging. Following the placing of MODIS-N in orbit in the late 1990s, it is inevitable that longer term comparisons will have

to rely on data from earlier sensors such as the AVHRR. Obtaining consistent results between these different sensors will be an essential, if difficult, process for the longer term monitoring of land cover.

The research reported in this paper was partly supported by NASA under grant number NAG-5942.

REFERENCES

Ajtay, G. L., Ketner, P., and Duvigneaud, P. (1979), Terrestrial primary production and phytomass, in *The Global Carbon Cycle* (B. Bolin, E. T. Degens, S. Kempe, and P. Ketner, Eds.), Wiley, New York, pp. 129–181.

Atkinson, P., Cushnie, J. L., Townshend, J. R. G., and Wilson, A. (1985), Improving land cover classification using filtered data, *Int. J. Remote Sens.* 6:955–961.

Barnsley, M., and Morris, K. (1990), On the relative utility of MODIS-N/T, HIRIS and MISR for sampling the BRDF of earth surface materials, in *Proceedings of the Conference on Remote Sensing and Global Change*, Remote Sensing Society, Swansea, 19–20 September 1990.

Bazilevich, N. I., Rodin, L. Ye, and Rozov, N. N. (1971), Geographical aspects of biological productivity, *Sov. Geogr. Rev. Transl.* 12:293–317.

Benson, A. S., and DeGloria, S. D. (1985), Interpretation of Landsat-4 Thematic Mapper and Multispectral Scanner data for forest surveys, *Photogramm. Eng. Remote Sens.* 51:1281–1290.

Billingsley, F. C., Johnson, J., Greenberg, E., and MacMedan, M. (1989), Facilitating information transfer in the EOS era, *IEEE Trans. Geosci. Remote Sens.* 27:117–124.

Bowen, H. J. M. (1966), *Trace Elements in Biochemistry*, Academic, London.

Box, E. O. (1981), *Macroclimate and Plant Forms*, Dr. W. Junk, Boston.

Chase, R. R. P. (1989), Towards a complete Eos data and information system, *IEEE Trans. Geosci. Remote Sens.* 27:125–131.

Choudhury, B. J., and Tucker, C. J. (1988), Monitoring global vegetation using NIMBUS-7 37 GHz data: some empirical relations, *Int. J. Remote Sens.* 8:1085–1090.

Cox, S. C. (1983), The multispectral imaging science working group: Final report, NASA Conference Publication 2260, NASA, Washington, DC.

Crist, E. P., and Cicone, R. C. (1984), A physically-based transformation of Thematic Mapper data—the TM tasselled cap, *IEEE Trans. Geosci. Remote Sens.* GE-22:256–263.

Deevey, E. S., Jr. (1960), The human population, *Sci. Am.* 203:195–204.

Dutton, J. A. (1989), The EOS data and information system: concepts for design, *IEEE Trans. Geosci. Remote Sens.* 27:109–116.

Duvigneaud, P., Bolin, B., Degens, E. T., and Kempe, S. (1979), The global bio-geo-chemical carbon cycle, in *The Global Carbon Cycle* (B. Bolin, E. T. Degens, S. Kempe, and P. Ketner, Eds.), Wiley, New York, pp. 1–56.

Ehrlich, P. R., and Roughgarden, J. (1987), *The Science of Ecology*, MacMillan, New York.

Emanuel, W. R., Shugart, H. H., and Stevenson, M. P. (1985), Climatic change and the broad-scale distribution of terrestrial ecosystem complexes, *Climate Change* 7:29–43.

Emery, W. J., Brown, J., and Nowak, Z. P. (1989), AVHRR image navigation: summary and review, *Photogramm. Eng. Remote Sens.* 55:1175–1183.

FAO (Food and Agricultural Organisation) (1979), *FAO Production Yearbook*, FAO Statistics Series 22, Vol. 32, pp. 45–56, Rome.

Fosberg, F. R. (1967), A classification of vegetation for general purposes, in *Guide to the Checksheet for IBP Areas* (G. F. Peterken, Ed.), IBP Handbook No. 4, Blackwell, Oxford, pp. 73–120.

Gerstl, S. A. W., and Simmer, C. (1986), Radiation physics and modelling for non-Lambertian surfaces, *Remote Sens. Environ.* 10:1–29.

Giddings, L., and Choudhury, B. J. (1989), Observation of hydrologic features with NIMBUS-7 37 GHz Data, applied to South America, *Int. J. Remote Sens.* 10:1673–1686.

Golley, F. B. (1972), Energy flux in ecosystems, in *Ecosystem Structure and Function* (J. A. Wiens, Ed.), Ann Biol. Colloq. 31, Oregon University Press, Corvallis, OR, pp. 69–90.

Goward, S. N., Tucker, C. J., and Dye, D. G. (1985), North American vegetation patterns observed with the NOAA-7 advanced very high resolution radiometer, *Vegetatio* 64:3–14.

Goward, S., Markham, B., Dye, D. G. Dulaney, W. and Yang, J. (1991), Normalized difference vegetation index measurements from the Advanced Very High Resolution Radiometer, *Remote Sens. Environ.* 35:257–277.

Henderson-Sellers, A. (1989), Climate, models and geography, in *Remodelling Geography* (B. MacMillan, Ed.), Basil Blackwell, Oxford, pp. 117–146.

Henderson-Sellers, A., Wilson, M. F., Thomas, G., and Dickinson, R. E. (1986), *Current Global Land-Surface Data Sets for Use in Climate-Related Studies*, NCAR Technical Note 3 272-STR, National Center for Atmospheric Research, Boulder, CO.

Holben, B. N. (1986), Characteristics of maximum value composite images from temporal AVHRR data, *Int. J. Remote Sens.* 7:1417–1434.

Huete, A. R. (1989), Soil influences in remotely sensed vegetation-canopy spectra, in *Theory and Applications of Optical Remote Sensing* (G. Asrar, Ed.), Wiley, New York, pp. 107–141.

Hummel, J., and Reck, R. (1979), A global surface albedo models, *J. Appl. Meteorol.* 18:239–253.

IGBP (International Geosphere Biosphere Programme) (1990), *The International Geosphere Biosphere Programme: A Study of Global Change*, The Initial Core Projects Report No. 12, International Council of Scientific Unions, Stockholm, Sweden.

Justice, C. O., and Kendall, J. D. (forthcoming), Assessment of the forests of Central Africa using coarse resolution satellite data.

Justice, C. O., Townshend, J. R. G., Holben, B. N., and Tucker, C. J. (1985), Analysis of the phenology of global vegetation using meteorological satellite data, *Int. J. Remote Sens.* 6:1271–1318.

Justice, C. O., Markham, B. L., Townshend J. R. G., and Kennard, R. L. (1989a), Spatial degradation of satellite data, *Int. J. Remote Sens.* 10:1539–1561.

Justice, C. O., Townshend, J. R. G., and Choudhury, B. J. (1989b), Comparison of AVHRR and SMMR data for monitoring vegetation phenology at a continental scale, *Int. J. Remote Sens.* 10:1607–1632.

Kaufman, Y. J., Tucker, C. J., and Fung, I. (1990), Remote sensing of biomass burning in the Tropics, *J. Geophys. Res.*, 95, 9927–9939.

Kidwell, K. B. (1990), *Global Vegetation Index User's Guide*, U.S. Department of Commerce, NOAA, Camp Springs, MD.

Koomanoff, V. A. (1989), Analysis of global vegetation patterns: a comparison between remotely sensed data and a conventional map, Biogeography Research Series, Report #890201, Department of Geography, University of Maryland, College Park.

Kuchler, A. W. (1967), *Vegetation Mapping*, Wiley, New York.

Lieth, H. (1964), Versuch einer kartographischen Darstellung der Produktivitat der Pflanzandecke auf der Erde, in *Gegr. Taschenbuch*, 72–80, Franz Steiner Verlag, Wiesbaden.

Lieth, H. (1973), Primary production: terrestrial ecosystems, *Hum. Ecol.* 1:312–313.

Matson, M., and Holben, B. N. (1987), Satellite detection of tropical burning in Brazil, *Int. J. Remote Sens.* 8:509–516.

Matthews, E. (1983), Global vegetation and land use: new high resolution data bases for climate studies, *J. Appl. Meteorol.* 22:474–487.

Millington, A. C., Townshend, J. R. G., Kennedy, P., Saull, R., Prince, S., and Madams, R. (1989), *Biomass Assessment: Woody Biomass in the SADCC Region*, Earthscan Publications, London.

Mueller-Dumbois, D., and Ellenberg, H. (1974), *Aims and Methods of Vegetation Ecology*, Wiley, New York.

NASA (1986), *MODIS Moderate-Resolution Imaging Spectrometer: Instrument Panel Report*, NASA, Washington, DC.

NASA (1990), *Earth Observing System 1990 Reference Handbook*, Goddard Space Flight Center, NASA, Washington, DC.

Nemani, R. R., and Running, S. W. (1989), Estimation of regional surface resistance to evapotranspiration from NDVI and Thermal-IR AVHRR data, *J. Appl. Meteorol.* 28:276–284.

NRC (National Research Council) (1988), *Toward an Understanding of Global Change: Initial Priorities for US Contributions to the International Geosphere Biosphere Program*, National Academy Press, Washington, DC.

Ormsby, J. P., and Soffen, G. E. (eds.) (1989), Special Issue on the Earth Observing System (EOS), *IEEE Trans. Geosci. Remote Sens.* 27(2):106–242.

Peterson, D. L., Lawless, J. G., Matson, P., Aber, J. D., Vitousek, P., and Running, S. (1985), Biogeochemical cycling in terrestrial ecosystems, in *Proceedings of the 26th Congress of the IAF*, Stockholm, Sweden.

Petzold, D. E., and Goward, S. N. (1988), Reflective spectra of sub-Arctic lichens, *Remote Sens. Environ.* 24:481–492.

Rock, B. N. (1982), Mapping of deciduous forest cover using simulated Landsat data, *Int. Geosci. Remote Sens., Symp. Proc.* 5:3.1.

Ross, J. K., and Marshak, A. L. (1988), Calculation of canopy directional reflectance using the Monte Carlo method, *Remote Sens. Environ.* 24:213–225.

Running, S. W. (1990), Estimating terrestrial primary productivity by combining remote sensing and ecosystem simulation, in *Remote Sensing of Biosphere Functioning*, (R. J. Hobbs and H. A. Mooney, Eds.), Springer-Verlag, New York, pp. 65–86.

Salomonson, V. V., Barnes, W. L., Maymon, P. W., Montgomery, H. E., and Ostrow, H. (1989), MODIS: Advanced facility instrument for studies of the Earth as a system, *IEEE Trans. Geosci. Remote Sens.* 27:145–153.

Schluessel, P., and Emery, W. J. (1990), Atmospheric water vapour over oceans from the SSM/I measurements, *Int. J. Remote Sens.* 11:753–766.

Schmitt, W. R. (1965), The planetary food potential, *Ann. NY Acad. Sci.* 118:645–718.

Sellers, P. J. (1985), Canopy reflectance, photosynthesis and transpiration, *Int. J. Remote Sens.* 6:1335–1372.

Shantz, H. L. (1954), The place of grasslands in the earth's cover of vegetation, *Ecology* 35:143–145.

Shimoda, H., Fukue, K., Hosomura, T., and Sakata, T. (1986), Global vegetation monitoring using NOAA GAC data, in *ESA Symposium on Remote Sensing for Resources Development and Environmental Management*, Enschede, European Space Agency, Paris, pp. 505–508.

Thomas, G., and Henderson-Sellers, A. (1987), Evaluation of satellite derived land cover characteristics for global climate modelling, *Climate Change* 11:313–348.

Toll, D. L. (1985), Landsat-4 Thematic Mapper scene characteristics of a suburban and a rural area, *Photogramm. Eng. Remote Sens.* 51:1471–1482.

Townshend, J. R. G. (1984), Agricultural land cover discrimination using Thematic Mapper spectral bands, *Int. J. Remote Sens.* 5:681–698.

Townshend, J. R. G., Gayler, J. R., Hardy, J. R., Jackson, M. J., and Baker, J. R. (1983), Preliminary analysis of Landsat-4 Thematic Mapper products, *Int. J. Remote Sens.* 5:681–698.

Townshend, J. R. G., and Justice, C. O. (1986), Analysis of the dynamics of African vegetation using the normalized difference vegetation index, *Int. J. Remote Sens.* 7:1189–1207.

Townshend, J. R. G., and Justice, C. O. (1988), Selecting the spatial resolution of satellite sensors required for the modelling of land transformations, *Int. J. Remote Sens.* 9:187–236.

Townshend, J. R. G., Justice, C. O., and Kalb, V. T. (1987), Characterization and classification of South American land cover types using satellite data, *Int. J. Remote Sens.* 8:1189–1207.

Townshend, J. R. G., Justice, C. O., Choudhury, B. J., Tucker, C. J., Kalb, V. T., and Goff, T. E. (1989), A comparison of SMMR and AVHRR data for continental land cover characterization, *Int. J. Remote Sens.* 10:1633–1642.

Townshend, J. R. G., Justice, C. O., McManus, J., and Gurney, C. (forthcoming), The effect of image misregistration on the detection of vegetation change.

Tucker, C. J. (1980), Remote sensing of leaf water content in the near infrared, *Remote Sens. Environ.* 10:23.

Tucker, C. J. (1989), Comparing SMMR and AVHRR data for drought monitoring, *Int. J. Remote Sens.* 10:1663–1672.

Tucker, C. J., Townshend, J. R. G., and Goff, T. E. (1985), African land cover classification using satellite data, *Science* 227:233–250.

Turner, B. L. (1989), The human causes of global environmental change, in *Global Change and Our Common Future: Papers from a Forum* (R. S. DeFries and T. Malone, Eds.), National Academy Press, Washington, DC.

UNESCO (1973), International classification and mapping of vegetation, *Ecol. Conservation* 6:15–16.

UNESCO (1981), *Vegetation Map of South America* (1:5 million), and accompanying explanatory notes, UNESCO, Paris.

Walter, H. (1985), *Vegetation of the Earth*, Springer-Verlag, Berlin.

Whittaker, R. H. (1970), *Communities and Ecosystems*, Macmillan, London.

Whittaker, R. H., and Likens, G. E. (1975), The biosphere and man, in *Primary Production of the Biosphere* (H. Lieth and R. Whittaker, Eds.), Springer-Verlag, New York, pp. 306–328.