Satellite Remote Sensing of Land-use in Northern Burkina Faso - The Case of Kolel Village

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On the basis of SPOT satellite images from 1986, 1988 and 1989, the millet fields of the village Kolel in northern Burkina Faso have been mapped, and changes in land-use pattern from year to year have been identified. This article demonstrates that it is feasible to map fields on the basis of images taken shortly after the rainy season, and that images from other periods of the year do not add much to the precision obtained. The field pattern and the changes from year to year are discussed with reference to the agricultural system. The observations point to the presence of both a rotation- and an infield-outfield system. Finally the implications of these findings for the future application of satellite images in agricultural and environmental monitoring are discussed.

Keywords: *Remote sensing, land-use, agricultural systems, Burkina Faso.*

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The trends of both agricultural and environmental change in the Sahel have been widely discussed in recent years because of the recurrent food-shortages and the desertification (or land degradation) processes, both issues of considerable public interest. The use of satellite images for studying such trends has been relatively widespread, as is apparent from a recent review (Prince et al, 1990). This is, however, not an easy task, since the long-term trends, which are of particular interest, are often blurred by short-term variations, and because the physical and biological variables to be monitored are often difficult to estimate with the precision required.

The present study aims at providing an example of how one important parameter, the millet acreage, may be assessed and monitored, using satellite images combined with fieldwork. The results will be discussed with reference to both the agricultural system and its stability and the environmental problems of the area.

The focus will be upon a single village, Kolel, in the Oudalan Province of northern Burkina Faso. Kolel is considered as a good example of a village depending primarily upon millet cultivation, supplemented by livestock production, and therefore typical of the region.

THE REGION AND THE VILLAGE OF KOLEL

The Oudalan province constitutes the northernmost part of Burkina Faso and belongs to the Sahelian zone (here used to describe the zone between the 200 and 600 mm isohyets). The mean annual rainfall, (based on the period 1930-60), increases from around 300 mm in the north to around 500 mm in the south, yet variations from year to year, and village to village, are large. With a potential evapotranspiration of 5-6 mm per day, it is exceptional if rainfall exceeds potential evapotranspiration on a monthly basis, even in the wettest month. Kolel is situated in the central part of the region with a mean annual rainfall around 400 mm. The location of Burkina Faso and the study area is shown in fig. 1. The main elements of the land-use in the Oudalan Province are shown in fig. 2.

The geomorphology of the area may be described as a very flat, ancient pediplain, cut by broad, temporary river valleys. A few inselbergs rise to 200 m above the plain, of which the most notable is the Kolel Hill just west of Kolel village. During two (or more) drier, climatic periods in the

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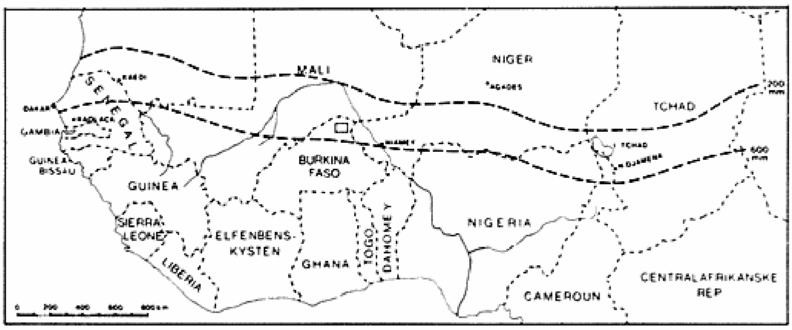


Fig. 1. Location of the study area. The frame in Burkina Faso is equivalent to the map shown in fig. 2.

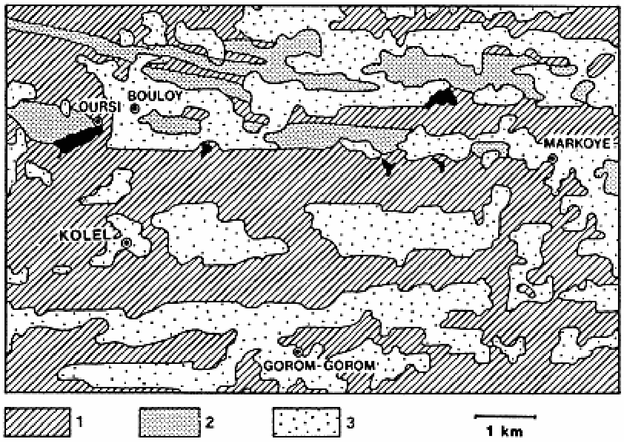


Fig. 2. The main elements of the land-use pattern in part of the Oudalan Province. A distinctive feature is the east-west oriented 'bands' of sandy soils, which are ancient dune systems, of which some are now cultivated. The intervening loamy soils are almost entirely utilized as pastures. Legend: (1) Pastures on loamy soils, (2) pastures on sandy soils, (3) cultivated areas. Black indicates seasonal lakes ('mare's). (Partly after Krings, 1980).

past, longitudinal dune systems have been superimposed on the pediplain. These have a distinct E-W orientation and may be followed for hundreds of kilometres. The youngest of these systems attain heights of several tens of metres, while the older series can hardly be discerned in the terrain, giving rise instead to bands of sandy soils. For at least a hundred years, the latter have attracted millet cultivators because of the relative ease of cultivating their light soils. The soils of the pediplain are heavier, sometimes lateritic, and typically very hard. They are often virtually impossible to cultivate with simple tools. In the vicinity of Kolel, an ORSTOM research station has been carrying out studies for many years with the emphasis on hydrology, see e.g. Chevallier et al. (1985). The results of these studies indicate that a major part of the rainfall, at least on the pediplains, runs off and ends up in lakes ('mares'), some of which are seasonal. This is due to the high intensity of the rainfall and the relatively low permeability of the soils, in particular those on the pediplain.

LAND-USE AND THE AGRICULTURAL SYSTEM OF KOLEL

Land-use is the one aspect of the agricultural system that may be observed by use of satellite images. In order to understand the pattern of land-use observed, its changes over time and its environmental implications, it is necessary to regard it in the context of the local agricultural system, including the management of plant nutrients, water and human labour. The agricultural system in Kolel will be briefly described in the following. The information presented stems partly from earlier studies by Milleville (1980), Yabre (1988), and Krings (1980) and partly from relatively limited fieldwork carried out by the authors in 1989 (Reenberg & Rasmussen, 1990 and 1991). Findings from more extensive fieldwork in the village of Bidi, 30 km south of Kolel, have, to some extent, been relied upon.

Most of the fields in the vicinity of the village are reported to have been cultivated more or less continuously with millet, the only crop of any great significance in the area, apart from a little (⟨10%) sorghum, which is mostly grown in the river valleys. Fields may be left fallow, or sown but not weeded and harvested, when the household lacks manpower, or when the soil fertility appears to have declined to an unacceptable level. The ratio of the fallow area to the total cultivated area (incl. fallow) is difficult to assess, mainly because of the difficulty in distinguishing badly tended fields and fallow, yet it is certainly lower than in regular shifting cultivation and rotation systems (Reenberg & Rasmussen, 1991).

In the rainy season, the availability of labour may, in many cases, limit the area that may be cultivated efficiently. In particular, the two weedings are very demanding. Often, a relatively large area is sown, but only part of it is weeded properly. The labour-peak coincides with the time of year when food may be scarce, and farmers often claim that they are not physically fit for the hard work. A considerable part of the young male population leaves Kolel, mostly in the dry season, to seek paid labour in the gold mines in Oudalan, in Ouagadougou or Abidjan.

The fertility of the soil is maintained by the application of manure, but the methods used and the amounts applied vary considerably. Livestock may eat the leaves and stems of the millet plants after the harvest while staying in the field and leaving a certain amount of droppings. In this way, they contribute to an efficient recycling of plant nutrients within the field. In addition, manure may be gathered by hand, often taken from kraals used by nomadic or transhumance pastoralists (usually peul- and bella-groups), before being transported to the field and spread out. This latter transport of plant nutrients from grazing areas to the cultivated fields is typical of an 'infield-outfield' system, and the work input associated with this transport is substantial. It may, however, be done during the dry season and, in this case, will not coincide with other labour-demanding tasks within the agricultural system.

In view of the points made above, the field pattern, and its change through time, will be mainly determined by the following factors:

1. The water-budget, depending upon rainfall (incl. both the amount and its distribution through time), and

run-off (influenced by the physical properties of the soil).
2. Plant nutrient availability, depending upon soil characteristics (physical as well as chemical), and agricultural techniques, in particular the application of manure.
3. The amount of labour available, especially in the weeding phase.

In addition, socio-economic and land tenure factors will, of course, influence the field pattern, but this will not be dealt with here.

SOURCES OF LAND-USE DATA

As mentioned above, a detailed analysis of the land-use and the way in which it changes is important in several contexts, not least in relation to hypotheses relating land degradation to the intensification of agriculture and the encroachment of cultivation upon areas with more fragile soil-types, as discussed by Reenberg & Rasmussen (1991). Sources of sufficiently precise land-use data are, however, scarce, and it will be argued below that, in spite of the high cost and technical complexity of digital satellite images, this data source may in many cases be the only realistic one, when it comes to providing land-use data on the village level over a span of years. To substantiate on this, other available sources will be briefly reviewed in the following.

The Topographical Map

The only topographical map of the area is the Dori sheet in the IGN 1:200,000 scale series of West Africa. It was produced in 1960 based on aerial photos (scale 1:50,000) from 1955-56, and field mapping in 1958-59. At the local scale of individual villages such as Kolel, it provides negligible information on the land-use.

Aerial Photos

Aerial photos from 1981 have been available at a scale of 1:50,000. They contain a wealth of spatial information. The village, roads and tracks, individual trees, field boundaries and drainage patterns may be identified. However, due to the fact that the aerial photos are panchromatic and were acquired during the dry season, it is difficult to determine the extent of active millet cultivation and fallow land solely on this basis.

Thematic Maps

Krings (1980) presented, in his study of the region, a series of maps, including a regional land-use/land-cover map. It is based on the above-mentioned IGN map and is at a scale of 1:200,000. Aerial photos, Landsat MSS imagery and fieldwork data have also been utilized. Once again the scale is insufficient for use in studies at village level, and the land-use information is rather generalized.

Sow (1989) has produced a map of 'ecological units', covering the Oursi-area, including Kolel, at a scale of 1:50,000. Aerial photos from 1981 and a SPOT HRV false colour composite image from Sept. 1986 at a scale of 1:50,000 have been utilized, and fieldwork was carried out in Oct. 1988. However, the main theme of the map is not agricultural land-use, and the utilization of aerial photos, satellite imagery and fieldwork data from different years makes it inadequate for assessing land-use at any given time and for detecting changes. Our fieldwork in 1989 showed that quite considerable areas, shown on Sows map as being cultivated, had actually been abandoned between 1981 and 1988.

Satellite Images

SPOT HRV X-mode digital images covering the area from the following dates are available: Sept.4 1986, Sept.27 1988, Jan.19, July 15, Sept.5, and Oct.27 1989. The fact that the spatial resolution of SPOT images is 20 m (i.e. each picture element (= pixel) represents 20mx20m on the ground), and that images from shortly after the rainy season are available, implies that they may be used to map the extent of millet cultivation. This will be demonstrated below. The use of satellite data does, however, presume that ground data, supporting the satellite image interpretation, are available. Field observations to aid the interpretation of aerial photos and satellite images were made in Oct. 89 and 91. An interview with a group of farmers was carried out in 89 in order to identify trends in land-use, agricultural practices and environmental conditions.

SATELLITE IMAGE PROCESSING AND INTERPRETATION

Pre-processing

The satellite images have all been geometrically corrected to the UTM coordinate system, (as shown on the IGN maps), with the emphasis on obtaining the best possible image-to-image correction. Co-registration accuracies better than one pixel are generally obtained. This allows pixel-by-pixel monitoring of land-use changes.

The three bands of the SPOT images have been replaced by the first two principal components, as calculated from each image. These two principal components represent in all cases the 'brightness' and 'greenness' components of the images (Rasmussen & Hagen-Olesen, 1988). The compression of information from three bands into two principal components has proved to make the classification of millet fields simpler and faster, and eases interpretation.

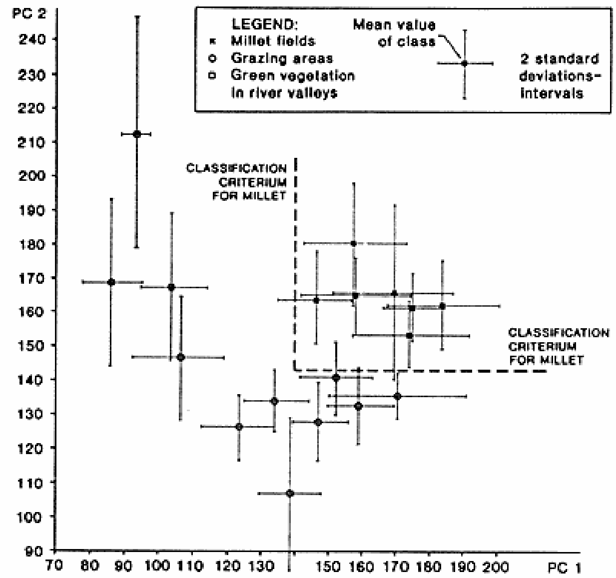


Fig. 3. Spectral signatures of millet fields, grazing areas and green vegetation in river valleys, calculated on the basis of the SPOT image from Sept.5 1989. The two axes represent the first two principal components (PC1 and PC2) calculated on the basis of the entire subimage being studied. PC1 may be interpreted as a measure of 'brightness', PC2 as a measure of 'greenness'. 'Training areas', known to represent the three classes, have been selected on the basis of field observations. For each training area, the mean values and 5/95 percentile intervals have been shown for PC1 and PC2. A certain overlap between spectral signatures of millet fields and grazing areas may be observed. The classification criteria for millet are also shown.

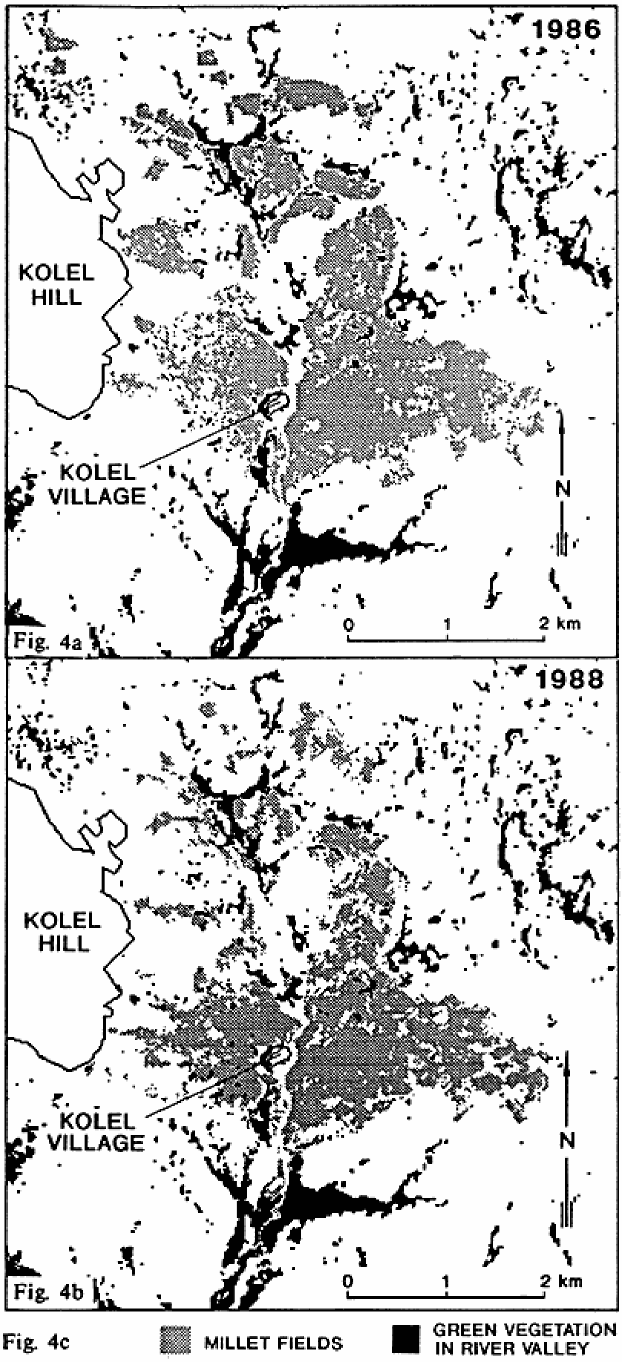
Classification of Millet Fields

Based on field observations in Kolel and neighbouring villages, a number of 'training areas', representing known millet fields, have been selected in the images, and the 'spectral signatures', i.e. the statistical distribution of image values in the three bands of the SPOT images, of millet fields and other objects have been determined for each image. In fig. 3, the spectral signatures in the image from Sept.5 1989 of millet fields, grazing areas and green vegetation in valleys are shown. Millet fields are characterized by having both a high 'brightness' due to the relative low plant density and the high reflectance of the mostly sandy soils, and a high 'greenness' due to the fact that millet generally stays green longer than grasses and herbs towards and after the end of the rainy season. It should be noted that spectral signatures, obtained from one image, cannot generally be used as a basis for identifying the corresponding surface types in other images because of the differences in the time of image-acquisition, dissimilarities between growing seasons, and the fact that image values have not been calibrated and corrected for atmospheric effects.

Using the spectral signatures of the millet fields in each image, a classification on the sole basis of spectral reflectance properties may be carried out. This is only meaningful if millet fields differ, in terms of spectral signature, from all other objects in the image, which is not always the case, as demonstrated by fig. 3. In particular, only images taken shortly after the growing season may be applied. Information other than per-pixel spectral signature, concerning image texture, linear features (field boundaries) and spatial context may be utilized in the classification. This is probably most efficiently done by combining digital and visual interpretation techniques. Such a procedure has the disadvantage of being less reproducible than purely digital classification techniques, but the results are generally better. The results of such a combined digital/visual classification of millet fields, based upon the images from Sept.4 1986, Sept.27 1988 and Sept.5 1989 are shown in fig. 4.

Multitemporal Classification

For the 1989 growing season, a number of SPOT images are available, and millet fields may, in this case, be identified on the basis of the seasonal variation of their spectral signature. Fig. 5 shows how the spectral separability - here quantified using the 'Jeffries-Matusita' (JM) measure of separability (Swain & Davis, 1978) - of millet fields and grazing areas depends on the inclusion of bands from images taken at other times of year. If all 12 bands from the 4 SPOT images are used, the JM-separability is close to the maximum, 1.41, indicating perfect separability. Visual inspection indicates, however, that the January image contributes relatively little, and when this is removed from the data-set, the JM-separability is only reduced slightly. When the July image is also removed from the data-set, only 6 bands remain, and again the reduction in JM-separability is only slight. Since the two bands from the visible part of the spectrum, bands 1 and 2, of a SPOT image are usually highly correlated, the loss of separability caused by removing one of them will be small. In the 4-band case, shown in fig. 5, bands 1 of both the September and October images have been removed from the data-set, and, as expected, the resulting reduction of JM-separability is slight. Finally, a reduction from 4 to 3 bands has been attempted in 4 different ways: In (1) only the 3 bands of the September image have been retained, in (2) only the 3 bands of the October image, in (3) bands 2 and 3 from the September image and band 3 from the October image, and in (4) the 3 bands of the July image. In all these four cases the reduction of JM-separability is significant, and it may be concluded that an improvement of the classification results may be obtained by utilizing



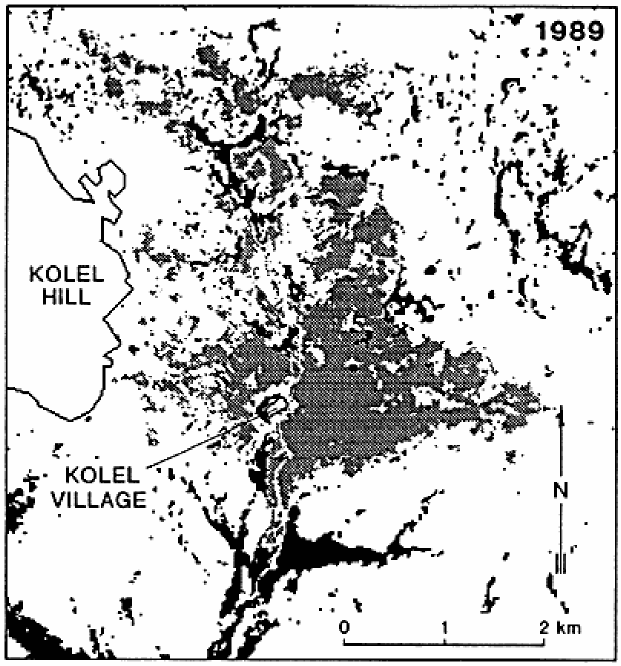


Fig. 4. Classification of millet fields around Kolel, based on the images from Sept.4 1986 (fig. 4a), Sept.27 1988 (fig. 4b) and Sept.5 1989 (fig. 4c). The classification method applied involved two steps: 1) On the basis of a visual interpretation of the images, utilizing both spectral signature, texture, linear features and spatial context-information, likely areas of millet fields have been identified. 2) For these areas a digital, pixel-wise classification, in the form of a 'box-classification' involving the first two principal components for the image in question, has been carried out. The figures also indicate the location of Kolel village and the Kolel Hill, as well as river valleys with green vegetation classified on the basis of the image from Sept.4 1986.

bands from the October image in addition to the September image, while use of the July and January images does not contribute significantly. In fig. 6, mono- and bitemporal classifications of millet fields in 1989 are juxtaposed. The bitemporal classification has been based on the September and October images.

Identification of Changes

The classification results given above may be directly used to indicate areas where changes have taken place. Figs. 7a and 7b show the changes between 1986 and 1989. Changes identified in this way are, of course, extremely sensitive to the accuracy of the individual classifications. Even minor changes in the classification criteria for millet fields in a given image may create significant changes in the area that is actually classified as millet fields, which in turn may lead to a relatively larger uncertainty in the estimates of changes between images. For years where fieldwork data are available, the classification of millet fields is, of course, relatively reliable, yet for studies of long-term trends in the cultivated area, where field data for the years studied are seldom at disposal, this problem may become serious, and a quantitative assessment of accuracies will be difficult to make.

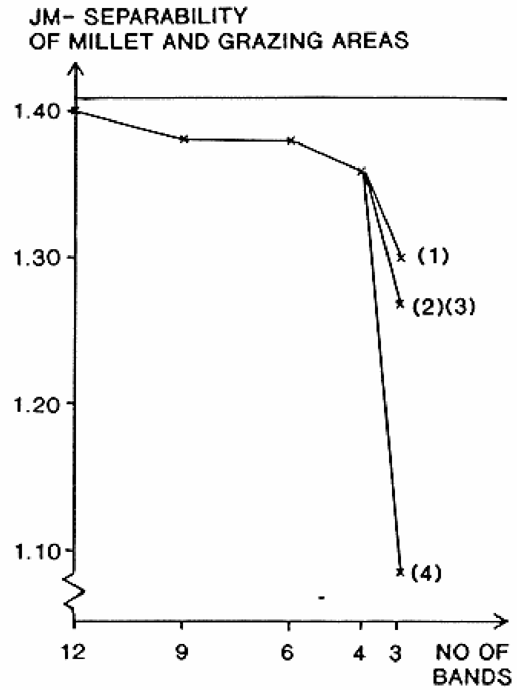


Fig. 5. The relationship between the number of bands in a multitemporal data-set from 1989 and the spectral separability of millet-fields and grazing areas. The Jeffries-Matusita measure of separability has been used. This means that a value of 1.41 indicates perfect separability, and 0 total identity of two classes. The image bands contained in the 12-, 9-, 6-, 4- and 3-band data-sets are specified in the text. It can be seen that reduction from 12 to 4 bands can be done with little loss of separability, but further reduction to 3 bands will result in a serious loss of separability. Thus the Sept. and Oct. images are both necessary for a near-optimal classification of millet-fields.

RESULTS AND DISCUSSION

It has been proved feasible to extract information on the millet field pattern in Kolel from SPOT multispectral data, acquired after the rainy season when the atmospheric conditions are often favourable, by using a combination of reproducible digital methods, working entirely on spectral signatures, and visual interpretation, taking into account spatial information. Still better results have been obtained by using a bitemporal data-set as a basis for classification.

The classifications of cultivated areas in 86, 88 and 89 show that close to the village, (in particular to the east), the field pattern is extremely compact. Virtually no areas with natural vegetation or fallow land can be observed. Further away from the village, the results indicate a less intensive land-use, with natural vegetation, fallow land and abandoned fields alternating with fields under cultivation. This is particularly obvious towards the west and south-west.

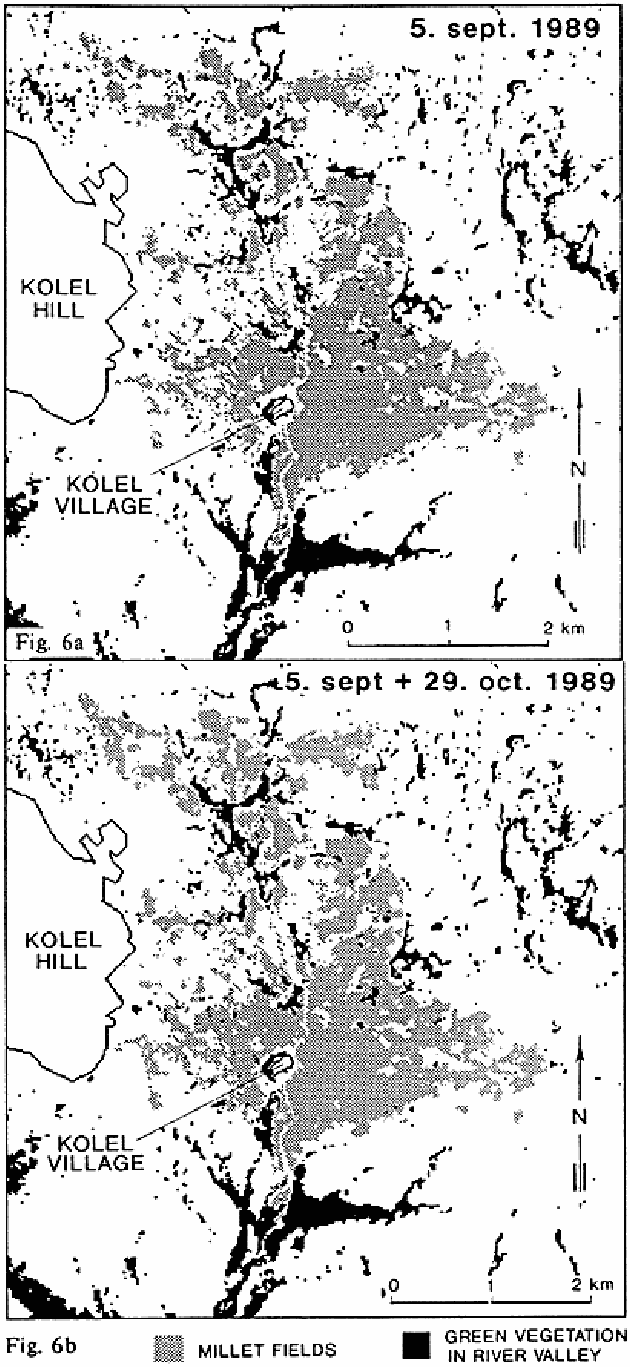


Fig. 6. Result of the classification of the 1989 bitemporal September-October data-set, shown beside the result of the classification based solely on the September-image. The bitemporal classification result appears more 'satisfactory', in the sense that more regular millet fields are visible. The lack of ground observations does not allow a quantitative assessment of classification accuracy.

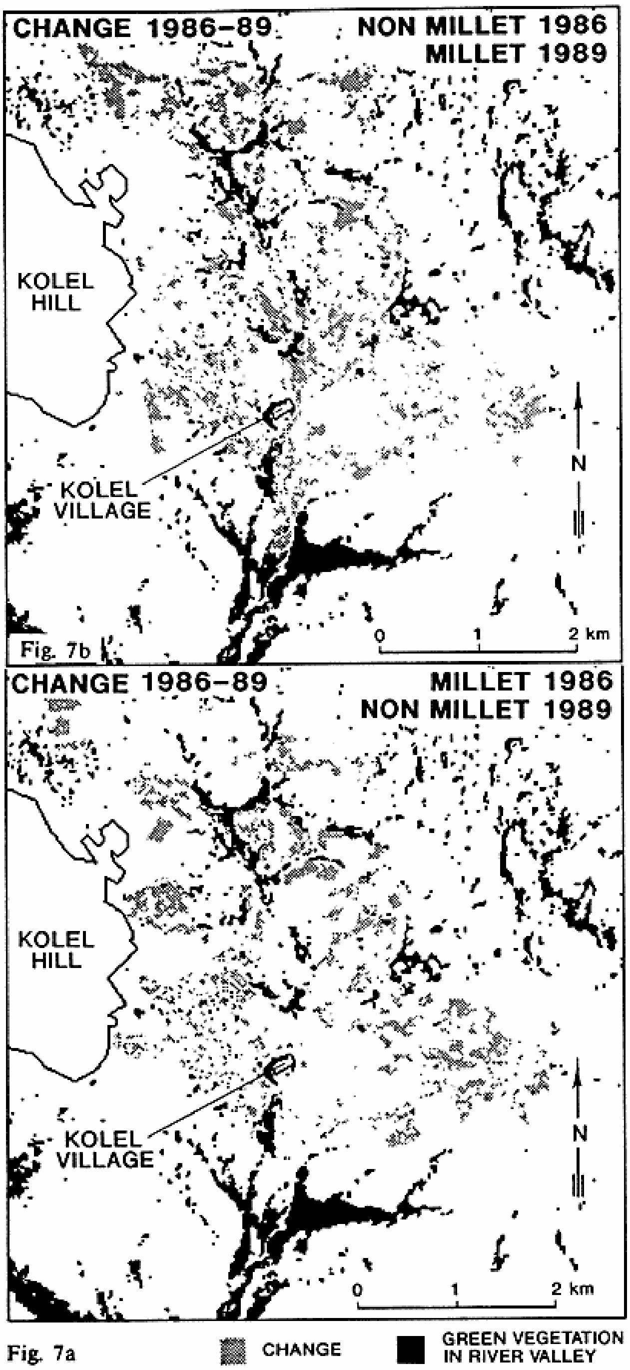


Fig. 7. The changes in the millet field pattern between 1986 and 1989, determined on the basis of the classification results shown in figs. 4a and 4c. Fig. 7a shows areas classified as millet in 1986 and as non-millet in 1989. Fig. 7b shows areas classified as non-millet in 1986 and millet in 1989.

The changes in the field patterns observed are small for the short time-span studied. Yet, in spite of the uncertainties involved in identifying changes, mentioned above, certain trends seem to persist: At some distance from the village, in particular to the north, changes are affecting contiguous areas rather than individual pixels. Apart from this, many 'changes' affecting individual or small groups of pixels may be observed. These may either be errors, i.e. caused by classification errors or small misregistrations of the images, or they may reflect that small parts of fields are left unweeded or fallow.

With reference to the agricultural system, the results summarized above may be interpreted in the following way:

1. The cultivation of millet is, in particular in the vicinity of the village, done on a permanent basis with little or no use of fallow. In view of the low natural fertility of the sandy soils in question, a sustainable yield must presume the application of manure, and thus the system may rightly be termed an 'infield-outfield' system. Field observations in the neighbouring Bidi village indicate that manure may be carried from areas outside the cultivated zone around the village into the fields. The presence and magnitude of this transport of plant nutrients is not known in the case of Kolel. Large variations in manure application from field to field probably exist, and these most likely account for the major part of the difference in yield that is observed in the field and also visible in the satellite images.
2. At some distance from the village, a more irregular and less intensive pattern of land-use can be observed, as mentioned above. This probably indicates that parts of fields are often left unweeded due to lack of labour in the household. This tendency will, of course, be more pronounced when the walking distance to the field in question is so long that it affects labour productivity. In effect, this irregular abandonment of parts of fields will function as a system of fallowing, yet it does not appear planned, and the ratio of actively cultivated acreage to the total cultivated area is still quite high (0.5). In the northern part of the village, the more regular pattern of change observed may indicate that a rotation or fallow system is being practised. However, a precise evaluation of the use of 'fallow' in Kolel will demand data covering a longer time-span.
3. The land-use pattern around Kolel is, to a great extent, determined by soil conditions, in particular the occurrence of light, sandy soils. Visual interpretation of the SPOT-images, particularly the one from Jan.89 where little vegetation is present, indicates that most of these soils are under cultivation, and that darker, probably heavier, soils must be brought into use, if the cultivated

area is to be expanded. Particularly towards the west and south-west, darker soils are already being utilized. This supports the findings reported by Milleville (1981), emphasizing that a strong correlation exists between weeding capacity and the cultivated area of a household, and that cultivation capacity per man-hour is significantly higher on the sandy soils.

PERSPECTIVES

An efficient assessment of the cultivated area at village level, demonstrated here to be possible using satellite data, has several interesting applications:

1. Local food sufficiency may be estimated by balancing the food requirements of the village population with local millet production. Since millet constitutes the dominant element of the diet of the population, a requirement of 200 kg per person per year is a realistic and generally accepted estimate. The population of Kolel is estimated to be around 900 inhabitants, and thus the demand is approximately 180 tons/year. In 1989, the cultivated area was approximately 500 ha. The yield may be assessed by traditional means, used by the local agricultural extension organization CRPA, or by the use of NOAA AVHRR data from the rainy season, as demonstrated by Schultz-Rasmussen (1989). If a yield of 250 kg/ha is assumed, the total production will be 125 tons. Thus, in a typical year, the production only meets approximately 70 % of the demand. Yet, large variations occur from year to year, and early estimations (around the time of harvest) of food sufficiency at village- and/or prefecture-level are necessary to aid decision-making concerning food imports from the south of Burkina Faso or from abroad in order to avoid food shortages at the end of the dry season. Such estimations would obviously benefit from the use of satellite data, combined with field surveys, to assess both millet acreage and yields.
2. Land-use information at village level is an essential input to physical planning in the form presently being proposed in Burkina Faso and a number of other African countries. In this planning, land-use management, involving agronomical, economic, land tenure and environmental aspects, plays a key role. Even though the spatial resolution of satellite images does not allow their use as a basis for individual land registration, their application at village-level is quite realistic.
3. The long-term environmental trends of the region are, to a large extent, influenced by the expansion or retreat of the cultivated area and where, in relation to geomorphology, terrain, soil-conditions and vegetation types, it takes place. Satellite data probably constitutes the only realistic means of establishing a 'long-term', consistent account of the agricultural expansion or retreat in the region.

ACKNOWLEDGEMENTS

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PERSPECTIVES

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1. Local food sufficiency may be estimated by balancing the food requirements of the village population with local millet production. Since millet constitutes the dominant element of the diet of the population, a requirement of 200 kg per person per year is a realistic and generally accepted estimate. The population of Kolel is estimated to be around 900 inhabitants, and thus the demand is approximately 180 tons/year. In 1989, the cultivated area was approximately 500 ha. The yield may be assessed by traditional means, used by the local agricultural extension organization CRPA, or by the use of NOAA AVHRR data from the rainy season, as demonstrated by Schultz-Rasmussen (1989). If a yield of 250 kg/ha is assumed, the total production will be 125 tons. Thus, in a typical year, the production only meets approximately 70 % of the demand. Yet, large variations occur from year to year, and early estimations (around the time of harvest) of food sufficiency at village- and/or prefecture-level are necessary to aid decision-making concerning food imports from the south of Burkina Faso or from abroad in order to avoid food shortages at the end of the dry season. Such estimations would obviously benefit from the use of satellite data, combined with field surveys, to assess both millet acreage and yields.
2. Land-use information at village level is an essential input to physical planning in the form presently being proposed in Burkina Faso and a number of other African countries. In this planning, land-use management, involving agronomical, economic, land tenure and environmental aspects, plays a key role. Even though the spatial resolution of satellite images does not allow their use as a basis for individual land registration, their application at village-level is quite realistic.
3. The long-term environmental trends of the region are, to a large extent, influenced by the expansion or retreat of the cultivated area and where, in relation to geomorphology, terrain, soil-conditions and vegetation types, it takes place. Satellite data probably constitutes the only realistic means of establishing a 'long-term', consistent account of the agricultural expansion or retreat in the region.

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