ARTICLE IN PRESS

Journal of Arid Environments ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Journal of Arid Environments

www.elsevier.com/locate/jnlabr/yjare

Ecoregions and land cover trends in Senegal

G.G. Tappan[a,*], M. Sall[b], E.C. Wood[a], M. Cushing[a]

[a] *SAIC, US Geological Survey (USGS)/Earth Resources Observation Systems (EROS) Data Center, Sioux Falls, SD 57198, USA*

[b] *Centre de Suivi Ecologique, B.P. 15532, Dakar-Fann, Senegal*

Received 24 November 2003; received in revised form 22 March 2004; accepted 23 March 2004

Abstract

This study examines long-term changes in Senegal's natural resources. We monitor and quantify land use and land cover changes occurring across Senegal using nearly 40 years of satellite imagery, aerial surveys, and fieldwork. We stratify Senegal into ecological regions and present land use and land cover trends for each region, followed by a national summary. Results aggregated to the national level show moderate change, with a modest decrease in savannas from 74 to 70 percent from 1965 to 2000, and an expansion of cropland from 17 to 21 percent. However, at the ecoregion scale, we observed rapid change in some and relative stability in others. One particular concern is the decline in Senegal's biodiverse forests. However, in the year 2000, Senegal's savannas, woodlands, and forests still cover more than two-thirds of the country, and the rate of agricultural expansion has slowed.

Keywords: Desertification; Land use change; Land cover change; Environmental monitoring; Remote sensing; Natural resources; Senegal; Sahel

1. Introduction

Senegal's National Environmental Action Plan (NEAP) speaks of an environmental and social crisis characterized by accelerated degradation of natural resources, decline in agricultural productivity, rapid population growth, and deterioration in the quality of life (MEPN/CONSERE, 1997). The National Action

*Corresponding author.

E-mail address: tappan@usgs.gov (G.G. Tappan).

0140-1963/$ - see front matter © 2004 Published by Elsevier Ltd.
doi:10.1016/j.jaridenv.2004.03.018

Program to Combat Desertification casts a similar picture of environmental deterioration: 'the process of natural resource degradation seems to be increasing and accelerating under the combined effect of a worsening climate and human pressures' (MEPN/CONSERE, 1998). These are only some of the more recent in a long string of environmental-crisis reports that paint a gloomy picture of environmental destruction. On one hand, it is difficult to dispute that Senegal, like its West African neighbors, is experiencing rapid change at many levels—climatic, environmental, agricultural, demographic, political, and socio-economic. For example, a recent study indicates that the West African Sahel has experienced the most substantial and sustained decline in rainfall recorded in the world since rain gauge measurements began in the late 1800s (Nicholson, 2000). Senegal experienced four serious droughts during the 20th century. Senegal's population has grown ten-fold since 1900, which has placed unprecedented pressure on its limited land resources. Agricultural statistics show only modest increases in the primary food crops in recent decades (Bucknall et al., 1997).

Despite this backdrop of discouraging social and economic indicators, very few studies have examined the state of the natural resources over time. There are several exceptions, but these studies are limited to local or subnational scales. Gonzalez (1997, 2001) conducted a noteworthy study in northwestern Senegal in which he tracked declines in forest species richness and tree density from 1945 to 1993. Lericollais (1987) examined long-term trends in the agricultural tree parkland around a Serer village in Senegal's 'Peanut Basin.' He found an overall decrease of 23 percent in tree density from 1965 to 1985 that he attributed to increasing human pressure. Tappan et al. (1994) provided evidence of changing vegetation and land uses at numerous field sites visited at 10–12 year intervals. In another study, Tappan et al. (2000a) used 30 years of satellite imagery to assess land resource changes in the southern Peanut Basin. Stephenne and Lambin (2001) attempted to reconstruct past land use and land cover changes in the Sahel over the past 30 years using a dynamic simulation model. There have been several efforts to map the natural resources of Senegal, but these represent a snapshot in time (Roberty, 1962; Maignen, 1965; Stancioff et al., 1986). Although objective studies on land cover changes over time are lacking, the rates and magnitudes of change are still very much debated, including whether these changes are related to short-term climate perturbations or longer-term anthropogenic impacts (Nicholson, 1989; Hulme, 1996).

This paper addresses a critical need to provide a better quantitative understanding of how the West African environment is actually changing. A major challenge facing policy-makers and scientists is that there is generally a lack of comprehensive data on the types and rates of land use and land cover changes (Loveland et al., 2002). Results from the study can feed into such environmental models as future land cover scenarios, climate modeling, and biogeochemical modeling, including past, current, and potential carbon sequestration in soils and vegetation. Land use and land cover conditions, and the driving factors that change them, have direct implications for the quantity and distribution of carbon storage. Clearing natural vegetation for agriculture, harvesting trees for woodfuel, and other land cover modifying activities release carbon into the atmosphere, resulting in a net loss of total system carbon. Conversely, maintaining vegetation cover both on-farm and off-farm, and using soil and water conservation practices, have been shown to contribute significantly to carbon sequestration in the system (Tiessen et al., 1998; Lal, 2002).

We focus primarily on the following research objectives: (1) develop and apply a methodology for estimating land use and land cover changes using readily available time-series imagery and practical sampling and change analysis techniques, (2) characterize the spatial and temporal nature of land use and land cover change in Senegal for three periods in time (1965, 1985, and 2000), and (3) provide a national picture of land use and land cover change.

We document actual land use and land cover trends that occurred from 1965 to 2000. While the analysis and results focus primarily on land cover *conversions*, i.e. transitions from one cover or use type to another (e.g. woodland to agriculture), we also attempt, where possible, to present evidence of the more subtle *modifications* in land cover that involve the maintenance of the broad land cover or use type but exhibit changes in their attributes. We begin by reviewing a spatial framework that stratifies Senegal into ecological regions. We then discuss the methodology used for characterizing the land use and land cover change from time-series imagery. Next, we present land use and land cover trends by ecoregion. Finally, we present a national picture of land use and land cover change and discuss some of its implications.

2. Approach and methods

This study is the product of two ongoing collaborative projects: one that is being conducted by environmental scientists at the US Geological Survey (USGS) Earth Resources Observation Systems (EROS) Data Center (EDC) and at Senegal's *Centre de Suivi Ecologique* (CSE) on carbon sequestration in Senegal's landscapes, and a second project, involving EDC, the Regional Agricultural-Hydrological-Meteorological (AGRHYMET) Center in Niamey, and its national partners in West Africa, focusing on characterizing long-term land use and land cover trends across West Africa.

2.1. Stratification into ecoregions

Landscape changes were mapped by using ecological regions that had similar patterns of biophysical conditions and human management. These ecological regions, or ecoregions, are generally considered to be regions of relative homogeneity in ecological systems involving interrelationships between organisms and their environment (Omernik, 1987). There is a growing consensus that effective research, inventory, and management of natural resources should be undertaken with an ecosystem perspective (Omernik, 1995). Ecoregions have been used in Senegal for decades as a regional land use planning tool. Several ecoregion stratifications exist,

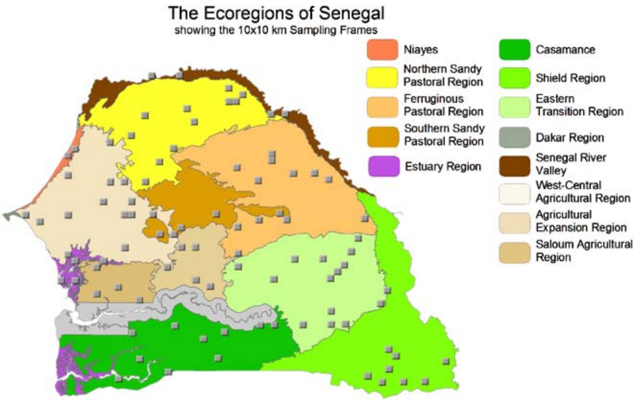

Fig. 1. The ecoregions of Senegal

and we adopted the version published by the Direction de l'Aménagement du Territoire (DAT et al., 1984). The ecoregions were defined through the integration of various components of the natural and socio-economic landscapes of Senegal, including both biophysical (climate, geology, hydrology, soils, vegetation) and human factors (settlement patterns, land use). Using Landsat images and the vegetation maps published in Stancioff et al. (1986), we made slight modifications and aggregations of the original stratification, resulting in 13 ecoregions. These were done to better reflect the biophysical and land use realities visible in the imagery and in the field. This ecoregions map (Fig. 1) was included in Senegal's NEAP (MEPN/CONSERE, 1997) and is also serving as the geographic framework for modeling soil and biomass carbon using the CENTURY Model (Parton et al., 2004). Table 1 summarizes some of the key geographic characteristics of each ecoregion.

2.2. Imagery for assessing land use and land cover change

This study relied primarily on three dates of imagery to assess trends in land use and land cover in each ecoregion: Corona satellite photographs from 1965 (1968 in some areas), Landsat thematic mapper (TM) images from 1984 to 85, and Landsat enhanced thematic mapper plus (ETM+) images from 1999 to 2000. Since 1972, the Landsat series of Earth resources satellites has provided considerable time-series coverage of Senegal, which makes it feasible to map land use and land cover change at a medium scale appropriate for detecting large-area changes and with minimal bias from seasonality. Furthermore, a tremendous boost to long-term monitoring occurred in 1995 when the United States declassified the space-based reconnaissance satellite systems of Corona, Argon, and Lanyard. Beginning in 1960, these missions collected the first satellite photographs of the Earth (McDonald, 1995). The earliest coverage of Senegal dates back to May 1962, with extensive, virtually cloud-free Corona coverage in 1965, 1966, and

1968 (Tappan et al., 2000a; Wood, 2002). Corona photography has provided an invaluable baseline for our work in Senegal. It provides a high-quality, high spatial resolution (approximately 2 m) record of the land surface. The timeframe is significant because it gives us a baseline before the major droughts of the 1970s and 1980s. In addition, the photographs were acquired when Senegal's population was about one-third of its current level.

In addition to Corona and Landsat, a wealth of ancillary data was consulted for additional historical perspectives, and for strengthening the image analyses. We examined dozens of aerial photographs taken in 1942–43 over Senegal by the US Army Air Force. A significant recent source of imagery came from aerial videography acquired by EDC and CSE in 1994 (Wood et al., 1995). Both vertical- and oblique-looking color videography was collected along north–south transects spaced systematically every 20 km across Senegal, providing high-resolution (0.3 m) coverage along the flight path. Perhaps the most important source of background information stems from the extensive fieldwork, aerial surveys, and semi-structured interviews conducted by the authors during the early 1980s (Stancioff et al., 1986) and mid-to-late 1990s (Tappan et al., 1994; Wood et al., 1995, 1998; Tappan et al., 2000a, b; Wood, 2002; Wood et al., this issue). Particularly useful for documenting local-scale changes were before-and-after photographs taken at 10–15 year intervals at hundreds of ground-monitoring sites.

In assessing land use and land cover change, we relied heavily on vegetation cover as a primary indicator. Vegetation, particularly woody vegetation, lends itself to analysis because it can be readily observed and measured in the field, and is visible in remotely sensed imagery. In contrast, studying change in soil conditions is more complicated and difficult to quantify. Woody vegetation integrates numerous factors acting on the environment, including topography, soil conditions, recent climate, fire, wildlife and livestock, and anthropogenic pressures. Vegetation can be used as a proxy for overall ecosystem health and productivity. Interviews with local people provide valuable complementary information on vegetation conditions over the past half century.

2.3. *Land use and land cover sampling strategy*

Although we had full Corona and Landsat coverage of Senegal, practical considerations of time and cost precluded mapping the entire country over the three time periods. We chose a sampling strategy, using a random sample of 10 km × 10 km area frames stratified by ecoregion. Each sample frame was randomly selected within each ecoregion (Fig. 1). The frames were selected from a fixed 10-km grid that was placed over the entire country. The sample size chosen for each stratum followed closely the sample design used in a similar, ongoing land cover trends project in the United States (Loveland et al., 2002). The objective was to estimate the percentage of gross change with a margin of error of ± 1 percent for an 85 percent confidence interval. The initial stratum sample sizes generally ranged from 2 to 12, depending upon the size of the ecoregion. A total of 93 10-km frames were analysed, amounting to 4.6 percent of the total land area.

Table 1
Overview of biophysical characteristics of Senegal's ecoregions

Ecoregion	Climate/rainfall	Geomorphology	Predominant soils	Predominant vegetation
West Central Agricultural Region, or "Peanut Basin" (25,915 km^2)	Sahelo-Sudanian and Coastal Sudanian; Rainfall: 400–800 mm (1960s); 200–600 mm (1990s)	Flat to gently rolling eolian sands overlying a sandstone plateau of the continental sedimentary basin	Ferruginous tropical sandy soils, slightly leached	Agricultural tree parkland, dominated by two species of acacia
Senegal River Valley (6323 km^2)	Continental Sahelian to Sahelo-Sudanian; Rainfall: 300–800 mm (1960s); 150–600 mm (1990s)	Broad alluvial valley, with a complex of levees, flatlands, and shallow depressions subject to annual flooding	Hydromorphic soils, and vertic soils; texture is sandy clay loam and clay.	Open steppes, shrub steppes, and localized acacia woodlands
Northern Sandy Pastoral Region (24,763 km^2)	Continental Sahelian; Rainfall: 300–500 mm (1960s); 150–300 mm (1990s)	Flat to gently rolling eolian sands overlying a sandstone plateau of the continental sedimentary basin	Red-brown sandy soils, and ferruginous tropical sandy soils	Open shrub steppes and grasslands
Ferruginous Pastoral Region (30,908 km^2)	Continental Sahelian and Sahelo-Sudanian; Rainfall: 400–800 mm (1960s); 300–600 mm (1990s)	Sandstone plateaus of the continental sedimentary basin, dissected by valleys from an ancient drainage system	Shallow loamy and gravelly ferruginous tropical soils, and lithosols; deep, sandy to loamy, leached tropical ferruginous soils in the valleys	Shrub savannas, and bushland, often relatively dense
Southern Sandy Pastoral Region (10,852 km^2)	Continental Sahelo-Sudanian; Rainfall: 500–700 mm (1960s); 300–500 mm (1990s)	Flat to gently rolling eolian sands overlying a sandstone plateau of the continental sedimentary basin	Ferruginous tropical sandy soils, slightly leached	Shrub and tree savannas
Niayes, or Long Coast (1049 km^2)	Coastal Sahelo-Sudanian (Southern Canarian); Rainfall: 400–600 mm (1960s); 200–400 mm (1990s)	Rolling, stabilized continental dunes; coastal live and semi-stabilized dunes	Ferruginous tropical sandy soils, and poorly developed coastal sands	Shrub savanna; wetlands fringed with trees in inter-dunal depressions (*niayes*)

Saloum Agricultural Region (6413 km^2)	Coastal Sudanian; Rainfall: 700–800 mm (1960s); 600–700 mm (1990s)	Gently rolling plains derived from an ancient dune field overlying a continental sedimentary basin	Ferruginous tropical and ferralitic soils; loamy sands over fine sandy loam at depth	Agricultural tree parkland; a few degraded wooded savannas and woodlands
Agricultural Expansion Region (8436 km^2)	Continental Sudanian; Rainfall: 700–800 mm (1960s); 500–600 mm (1990s)	Residual plateaus and buttes of the continental sedimentary basin, dissected by broad valleys from an ancient drainage system	Shallow loamy and gravelly soils over laterite on plateaus; deep, sandy to loamy, leached tropical ferruginous soils in the valleys and terraces	Degraded shrub and tree savannas, somewhat denser in the south; open agricultural parkland in the broad valleys and terraces
Eastern Transition Region (27,869 km^2)	Continental Sudanian; Rainfall: 700–1000 mm (1960s); 500–800 mm (1990s)	Sandstone plateaus of the continental sedimentary basin, dissected by broad valleys from an ancient drainage system	Shallow loamy and gravelly soils over laterite on plateaus; deep, sandy to loamy, leached tropical ferruginous soils in the valleys and terraces	Tree savannas and wooded savannas; small areas of agricultural parkland
Shield Region (28,660 km^2)	Continental Sudanian and Sudano-Guinean; Rainfall: 800–1200 mm (1960s); 600–1100 mm (1990s)	Erosional remnants (plateaus, hills, terraces and valleys) of the Precambrian shield	Very shallow, loamy, gravelly, rocky, highly leached ferruginous soils over laterite and Precambrian parent material	Open to dense wooded savannas, and grasslands on *bowé* (outcrops of impermeable laterite, often treeless)
Casamance (24,540 km^2)	Continental and Coastal Sudano-Guinean; Rainfall: 1000–1800 mm (1960s); 800–1400 mm (1990s)	Plateaus of the continental sedimentary basin, dissected by broad valleys from an ancient drainage system	Predominantly ferralitic tropical; ferruginous tropical sandy to clayey soils over laterite in the east; hydromorphic in the valleys	Predominantly wooded savannas and woodlands; grasslands on *bowé*; riparian and gallery forests along valleys; agricultural parkland
Estuaries (4095 km^2)	Coastal Sudanian and Sudano-Guinean; Rainfall: 700–1600 mm (1960s); 500–1400 mm (1990s)	Deltaic flats forming lower portion of a fossil drainage system	Hydromorphic, overlying pyretic muds; high organic matter content	Mangroves and halophytic vegetation of tidal flats

2.4. Land use and land cover classes

In a workshop with our national AGRHYMET partners from eight West African countries, we defined 13 general land use and land cover classes applicable to the West African region. The classes needed to be general enough that they could be readily identified on Landsat and Corona imagery. This meant that the classes needed to be rather general in definition, and their total number kept to a minimum. This approach led to better interpretation accuracy and consistency. The classes are as follows:

- Agriculture: irrigated, flood recessional, garden, rain-fed.
- Water bodies.
- Natural sandy barren.
- Natural rocky barren.
- Bare soil, disturbed or degraded.
- Settlements and urban.
- Vegetation: steppes.
- Vegetation: savannas, wooded savannas, open woodlands.
- Vegetation: gallery forests and forests.
- Vegetation: wetlands.
- Vegetation: desert oases.
- Vegetation: mangroves.
- Vegetation: plantations.

Several classes are not found in Senegal, although they do occur in neighboring countries. The class represented by 'vegetation: savannas, wooded savannas, open woodlands' encompasses a broad spectrum of vegetation types defined by varying ranges of percentage of woody cover. The common element in this case is a more-or-less continuous herbaceous understory of annual and perennial grasses, in contrast to 'vegetation: steppes,' characterized by discontinuous herbaceous cover.

2.5. Image preparation, interpretation, and analysis

For each 10-km frame, image data were extracted from the full Landsat scenes. False color composite digital and hardcopy images were produced from TM and ETM+ bands 3, 4, and 5. The corresponding 10-km frames were accurately located on Corona black-and-white film positives, and their boundaries were temporarily marked. Next, the area frame Landsat images were interpreted, mainly from the hardcopy prints at a scale of 1:100,000. A manual interpretation approach was used to identify and delineate the land use and land cover classes on image overlays. After testing manual and automated techniques for mapping change, we found that the manual approach gave much more reliable results. First, the manual method lends itself well to working with analog, film-based photographs (Corona). Second, manual photo-interpretation is effective for integrating the photographic elements of tone, hue, texture, shape, size, pattern, shadow, and geographic context, whereas these elements are often disregarded by more automated mapping techniques. Third, we were better able to integrate our intimate field knowledge into the interpretation process. Fourth, we were able to disregard such potentially confusing ephemeral features as annual grass fires and ground reflectance changes related to seasonal influences. In most cases, the dates of imagery corresponded to early-to-mid dry season. The Corona photographs, with their very high (2-m) resolution, were often used as a crosscheck when interpreting the Landsat frames. We think all of these factors contributed to providing good local mapping accuracy.

After completing a detailed delineation of each 10-km frame, we measured the area of each class by randomly placing a fine dot grid over the frame. Dot counts were tallied for each class and converted to a percentage of the frame area. The results were entered into a database, where the area of each class was summarized by ecoregion and by period.

In an attempt to begin to address the subtler land cover *modification* changes that affect the condition of the land cover without changing its overall classification, we examined high-resolution historical photographs taken in 1942–43, Corona photographs, and aerial videography acquired in 1994. Except in areas of dense vegetation cover, we found that the percentage of woody vegetation cover could be estimated because individual trees and shrubs could be resolved against the soil background in the dry season. Because we were generally able to examine woody vegetation cover quantitatively in most regions, we were able to discuss the cover using the more specific nomenclature often associated with vegetation types in francophone West Africa. References to nomenclature are based on the Yangambi classification system, which is particularly tailored to tropical Africa (Trochain, 1957) and used widely on vegetation maps of West African countries.

In discussing the trends by ecoregion, a useful reference on the diversity of landscapes of Senegal is the land use and land cover map of Senegal (Fig. 2). The map is the product of multidate Landsat image interpretations and extensive fieldwork carried out in the 1982–84 period (Stancioff et al., 1986). This reproduction is a generalization of the original detailed map published at a scale of 1:500,000. It portrays the land use and land cover situation of approximately 1982–84.

3. Trends in Senegal's ecoregions[1]

3.1. West central agricultural ecoregion, or peanut Basin

Of all of Senegal's ecological regions, the Peanut Basin has been the most fundamentally altered by centuries of human activity. In particular, the last 150 years have witnessed a nearly complete transformation of its landscapes. In the mid 1800s, small farming communities were scattered throughout a mosaic of wooded savannas

[1] Only 12 of Senegal's 13 ecoregions are presented here. The 'Dakar Region' is omitted due to its very small area and highly urban composition.

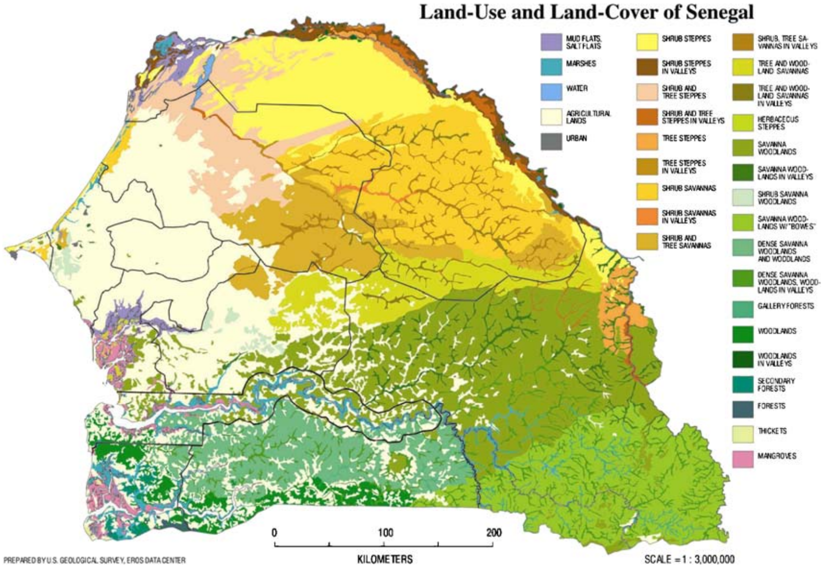

Fig. 2. Land use and land cover of Senegal, modified from the "Carte du Couvert Végétal du Sénégal" in Stancioff et al. (1986). The map was produced from Landsat images and extensive field work carried out in 1982–84.

Fig. 3. Low aerial view of vegetation cover east of Mbour in the Peanut Basin, taken in the 1930s (source: Trochain, 1940).

and open woodlands. Early aerial photographs taken in the 1930s and 1940s (reproduced in Figs. 3 and 4) provide a glimpse of the former agricultural landscapes that included patches of diverse vegetation cover and traditional bush fallow. Today, continuous cultivation under an acacia tree parkland has replaced all vestiges of the natural vegetation (Figs. 5a and b).

Time-series analysis of 12 area frame samples using Corona and Landsat imagery shows a curious land use and land cover trend. In 1965, approximately 67 percent of

Fig. 4. Aerial photograph taken over the Bambey Dept. on November 26, 1943, showing extensive bush fallow (dark gray areas).

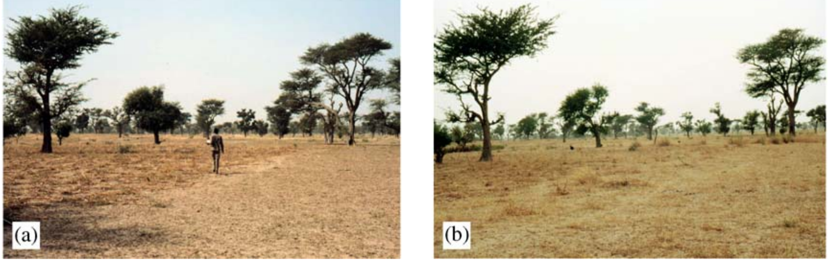

Fig. 5. (a and b). Photographic comparison of a monitoring site near Thiadiaye (Peanut Basin) showing the stability of the acacia tree parkland between 1983 and 1997. Both photographs were taken from precisely the same location.

the Peanut Basin was cultivated, with most of the remainder (31 percent) in large blocks of grazing land and grassy fallow. The cultivated area is presumed to have peaked sometime in the mid-1980s, when farmers still benefited from agricultural subsidies. In 1984, our assessment found 80 percent of the land under cultivation. This trend then reversed itself, declining to about 67 percent under cultivation in 2000.

Recent Landsat images show that large blocks of grassy fallow and grazing land are occurring throughout the northern parts of the Peanut Basin. Semi-structured interviews that we conducted in numerous villages shed some light on the phenomenon. The reasons local informants gave are complex and interrelated. They recalled the droughts and declining rainfall of the past 30 years, bringing about such risks in rain-fed cultivation that farmers are abandoning their crops in favor of other economic activities. They also point to a breakdown of the agricultural economy, including a lack of seeds, agricultural credits, and agricultural equipment that to a great extent resulted from the withdrawal of government support since the mid 1980s. The region is experiencing a major exodus of young people toward urban centers. Thus, we are seeing a rise in 'unplanned fallow,' rather than a conscious effort to restore the fertility of the land. Tschakert and Tappan (2004) further discuss this trend.

3.2. The Senegal River Valley

The Senegal River is the second longest river in West Africa. It flows through a broad valley that cuts through the semiarid Sahelian landscapes of Senegal, Mali, and Mauritania, creating a unique, complex environment determined largely by the hydrological, soil, and topographic conditions of the floodplain. Remnants of a once extensive riverine woodland dominated by *Acacia nilotica* (L.) Willd. ex Del. and *Acacia raddiana* (Savi) Brenan are today restricted to shallow depressions and levees along the river (Fig. 6). Twenty-eight of these woodlands were designated as forest reserves (Giffard, 1974). Most of the floodplain, known as the Walo, has been cleared gradually by local peoples over the centuries for traditional subsistence agriculture, and in recent decades, for vast hydro-agricultural projects designed to make Senegal self-sufficient in food production and to boost cash crop production for export (rice and sugarcane). Flood recession agriculture is practiced on the heavy alluvial soils on the banks of the river and its numerous channels. Vast expanses of the alluvial plain remain relatively barren.

Owing to the unique and highly threatened status of the riverine woodlands, we produced time-series maps of the entire length of the middle valley from Dagana to Bakel (Fig. 7). The general land use trends based on a limited area frame sample indicate a decrease in agriculture from 1965 to 1999 (Fig. 2). In this case, the trend is misleading, because the Landsat images were acquired in October during the high

Fig. 6. Aerial view of one of the few remaining the riverine *acacia* woodlands along the Senegal River.

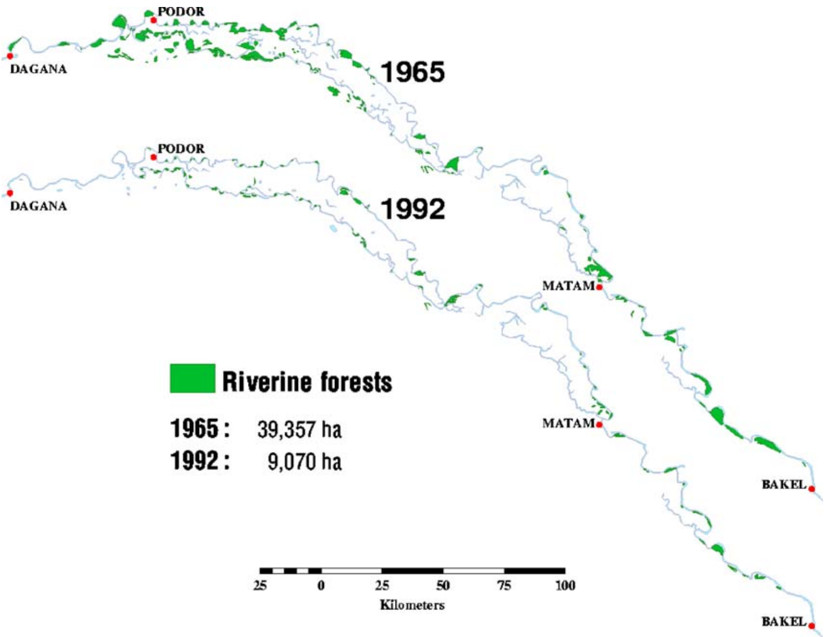

Fig. 7. A comparison of the extent of riverine acacia forests along the middle Senegal River, showing the rapid decline between 1965 and 1992.

river stage and maximum time of flood. Virtually all of the flood recessional fields would be under the floodwaters at that time. Second, October is not the season of peak irrigated agricultural production. The Corona photographs were acquired in December and May, when both flood recessional and irrigated agriculture is more readily visible. In contrast, the trend for the 'forest' or riverine woodlands is reliable for the sample areas, because these woodlands are readily identifiable year-round. Both analyses show a sharp decrease in the area of woodlands, despite the numerous reserves that 'protect' them from cutting. The time-series maps prepared from Corona and Landsat imagery show that the woodlands have declined from 39,357 ha in 1965 to 9070 ha in 1992. Particularly revealing are the time-series images taken just west of Podor in 1965 and 1994, shown in Figs. 8a and b. These historical photographs provide clear evidence of the devastation that has resulted from charcoal production and clearing for irrigation agriculture. The loss of the riverine forests has destroyed a rich and diverse habitat for wildlife, food for livestock (the pods provide valuable browse material), and termite-resistant wood used in construction.

3.3. Northern sandy pastoral ecoregion

This region, also known as the sandy Ferlo, constitutes the heart of Senegal's sylvo-pastoral zone. It has the typical characteristics of the central Sahelian climatic

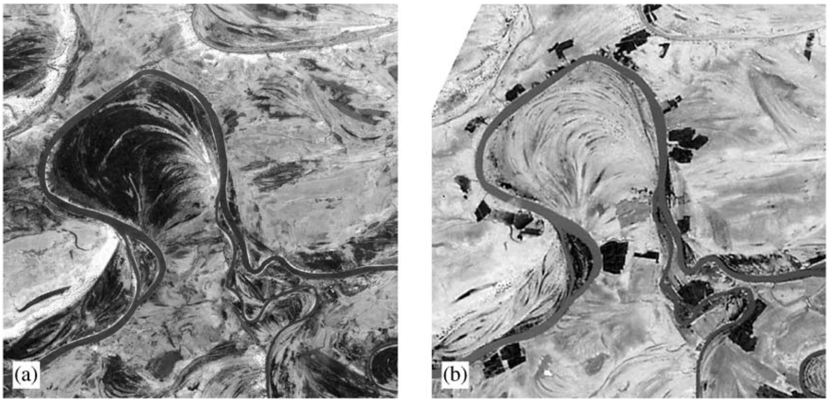

Fig. 8. (a and b). Left: Corona photograph, December 1965; right: TM image, January 1994. This pair of satellite images shows the total loss of riverine acacia forests at a loop in the Senegal River just west of Podor. Note the large, irrigated fields in the photo at right.

zone: a short, irregular rainy season, open grasslands with scattered shrubs and trees, a relatively limited number of woody species, and a predominance of the genus *acacia*. Generally too dry for crop production, the region is primarily used for grazing. The gently undulating to flat eolian sands are remnants of an erg deposited during the middle to recent Quaternary.

During the course of the 20th century, drought has had a moderate but not a severe impact on the woody cover. The deep, sandy soils, with their large water storage capacity, have helped temper the effects of drought on the woody vegetation. Nevertheless, the woody cover has declined over the past half century. Today, annual grasses flourish during a short 2–3 month rainy season, while the woody vegetation cover has become quite open and floristically poor. Our analyses of aerial photographs from 1942 (Fig. 9) and a high-resolution Corona satellite photograph from 1965 (Fig. 10) show a shrub savanna somewhat denser than the open shrub savanna found today. In 1965, before the severe droughts that followed, the woody cover in the central sandy Ferlo typically ranged from 10 to 15 percent. This range does not appear to have changed significantly since 1942, according to comparisons with the early aerial photographs. Analysis of aerial videography we collected in 1994 found the woody cover to range from less than 1–5 percent, except within the small interdune depressions where the density is often 10–40 percent. A study by CSE (1998) found the mean woody cover to be 5 percent at their field sites. A 10-year photographic comparison of a typical landscape at a monitoring site is shown in Figs. 11a and b, depicting the relative stability of the woody cover despite the decline in rainfall. Tree mortality is present, but not particularly high.

We analysed the land use and land cover in 12 area frame sample blocks to derive surface area trends from 1965 to 2000 (Fig. 14). The primary change is the significant incursion of rain-fed agriculture (mainly millet and peanuts). In 1965, cultivated area was limited to about 1 percent; in 1984, cultivation had increased to over 13 percent,

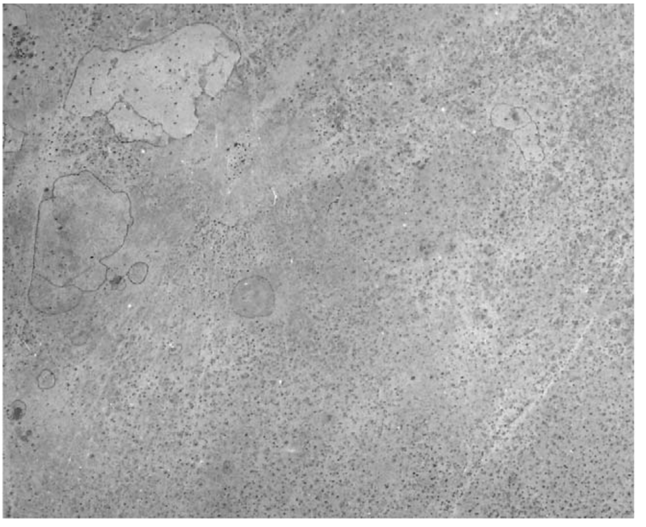

Fig. 9. An aerial photograph taken on April 4, 1942, in a pastoral area west of Lac de Guiers. The woody cover is 10 percent, typical of the region at that time. Note the brush hedges (dark linear features) enclosing millet fields cultivated by the Fulbe.

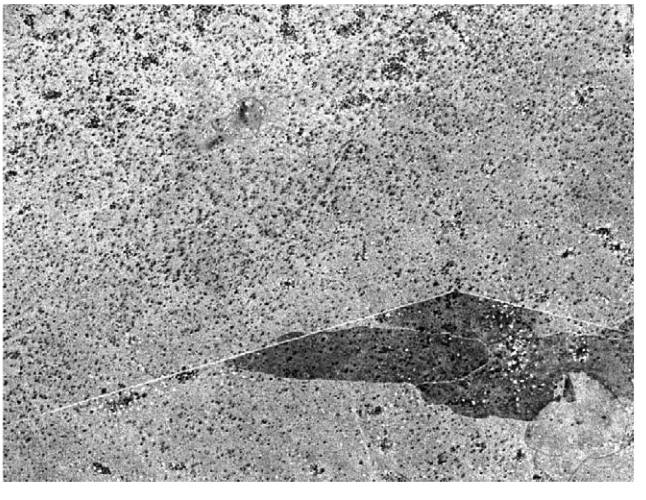

Fig. 10. An enlargement of a small part of a Corona photograph from December 1965, showing the extent of woody cover (14 percent) in the Réserve Sylvo-Pastorale des Six Forages (in the Northern Sandy Pastoral Region). Note the burned area that was prevented from further spreading by a firebreak.

and in 1999 it grew to over 16 percent. Reasons for the expansion into this climatically marginal region are complex, but some of the driving factors include mounting land pressure, soils that are deep, light, and workable, and national policies on land laws that encourage *mise en valeur*—maintaining land in production,

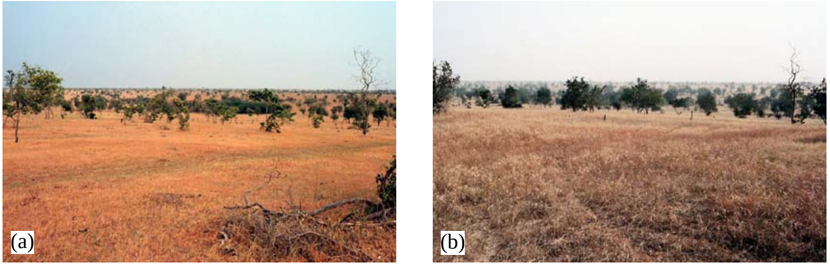

Fig. 11. (a and b). A 10-year comparison of a typical landscape near the Réserve Sylvo-Pastorale des Six Forages. The photographs show relative stability in the woody cover, despite a severe drought in 1982–84. Left: October 1983; right: January 1994.

which strengthens farmers' claims to the land. Traditional subsistence crops cultivated by the semi-nomadic Fulbe pastoralists have not significantly contributed to rise in cultivated area. The trend of agricultural expansion in the Ferlo is expected to continue as population pressure and the demand for land increases in the Senegal's western and southern regions.

3.4. Ferruginous pastoral ecoregion (or Lateritic Ferlo)

The shallow, loamy, gravelly soils of the 'Lateritic Ferlo' set this Sahelian and Sahelo–Sudanian region apart from the sandy pastoral regions to the west. Underlying the shallow plateau soils is an often-impenetrable laterite crust. The local relief is also more pronounced between plateaus and valleys. At fewer than 5 people km^{-2}, it is the least populated ecological region of Senegal, because of its poor agricultural potential and difficult access to water. The region constitutes a vast grazing land, with scattered settlements and temporary camps of the Fulbe semi-nomadic pastoralists, primarily along the fossil valleys. Aubréville (1949) described the vegetation as a 'dry bush formation.' Our 1994 aerial videography survey found that woody cover typically ranges between 5 and 15 percent. Detailed historical aerial photographs from 1943 and Corona satellite photographs from 1965 indicate a woody vegetation cover range of 10–20 percent, somewhat higher than the present levels.

Drought has more impact on the Lateritic Ferlo than any other region (Tappan et al., 2000b). Repeat visits to 33 field monitoring sites between 1983 and 1997 showed significant levels of mortality among woody species. Mortality is highest on the gravelly, lateritic plateaus. These soils have poor infiltration and low water storage capacity. Mortality is widespread and produced graveyards of standing dead bushes and trees for years following the major droughts of the 1970s and 1980s. A pair of photographs taken at one of our monitoring sites near Loumbol (Figs. 12a and b) shows stressed and dead woody vegetation, and the resulting reduced ground cover. We think these effects are temporary, however, as we found considerable evidence of regeneration of young trees and shrubs during the wetter years of the late 1990s.

As shown in the land use and land cover trends graph (Fig. 14), the land cover of the region has been very stable over the past 35 years. Agricultural expansion has been minimal. The main trend, and one that causes some concern, is the nearly nine-fold expansion of bare soils, representing barren, degraded land, from 0.3 percent in 1965 to about 4.5 percent in 1999. These unproductive surfaces have evolved rapidly as woody cover disappeared in the wake of drought, and at numerous specific locales, from the heavy concentration of livestock around boreholes and along fossil valleys. Overgrazing, browsing, and trampling led to loss of herbaceous and woody cover and soil compaction. Exposed soils became susceptible to water erosion, and the upper horizon was washed into the valley bottoms. A badland effect has spread quickly over recent decades, and can be monitored nationally using time-series satellite images. In a comparison of a 1965 Corona photograph and a 1999 Landsat image, Figs. 13a and b show the spread of badlands in the vicinity of Revane. Budde et al. (2004) further discuss these land surface anomalies.

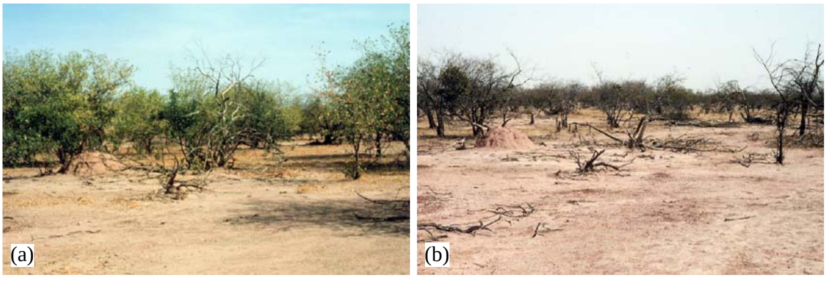

Fig. 12. (a and b). Drought in the 1970s and mid-1980s took a heavy toll on the woody vegetation of the Ferruginous Pastoral Region. This photograph pair taken 13 years apart shows mortality among *Pterocarpus lucens* bushes. Left: November 1983; right: February 1996.

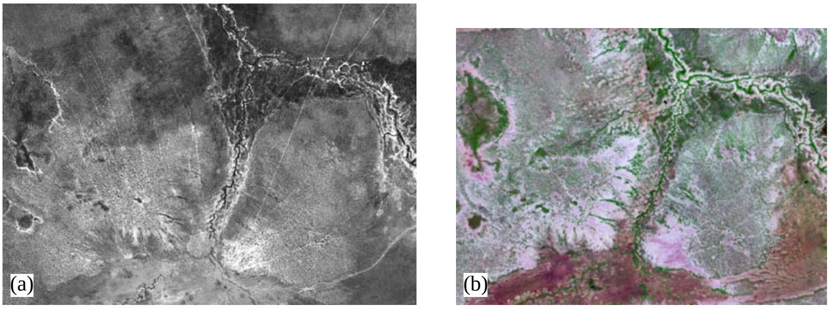

Fig. 13. (a and b). This pair of satellite images shows the rapid spread of barren, unproductive, degraded surfaces (bright areas) in proximity to the Revane borehole (Ferruginous Pastoral Region). Left: Corona, December 1965; right: ETM+, October 1999.

3.5. Southern Sandy Pastoral Ecoregion

This region shares many of the geomorphological and pedological characteristics of the Northern Sandy Pastoral Region but is distinguished from it by significantly higher rainfall (Table 1). Human settlement has been limited, mainly because the soils are shallower and less workable than those in the Peanut Basin, and because ground-water is generally much deeper. The Southern Sandy Pastoral Region is part of Senegal's extensive sylvo-pastoral region, with more reliable and more productive grasslands than ecoregions to the north and east. Large sylvo-pastoral reserves and forest reserves were established in the 1930s by the colonial authorities (Pélissier, 1966). Trochain (1940) considered the vegetation to be a 'fire-climax,' its woody cover kept open by centuries of burning. The predominant formation today is that of a shrub and tree savanna, with floristic composition characteristic of the transition from Sahelian to Sudanian types. Trees are taller than they are in the Sahelian zone (6–8 m), with fewer *acacia* species and a predominance of the *combretaceae* family. Despite the higher rainfall, the woody cover remains very open, typically ranging from 5–15 percent (mainly bushes) in continuous grassland, as estimated from the 1994 aerial videography. Estimates made from the high-resolution 1965 Corona photographs, taken before the major droughts of the 1970s and 1980s, indicate a woody cover range of 15–20 percent, somewhat higher than the estimates from the 1994 video survey. Interviews with local Fulbe pastoralists consistently indicate a progressive loss of woody vegetation over the past four to five decades. Between 1994 and 1997, we visited 24 land-resource monitoring sites and found that drought impact on the woody vegetation was minor to moderate, based on the relatively low occurrence of dead shrubs and trees (Tappan et al., 2000b).

The land use and land cover trends analysis revealed the beginning of a recent and rapid phase of agricultural encroachment into the region, with cultivated land increasing from only 1.2 percent in 1965 to 16.5 percent in 1999 (Fig. 14). Recent Landsat imagery indicates that the encroachment is occurring in the corridors between the reserves, with the exception of Mbégue, where agricultural expansion has continued throughout the 1990s.

3.6. The Niayes or long coast

A narrow strip of land along Senegal's northern coast forms a unique ecological region owing to the combined influences of a humid maritime air mass, a Sahelian rainfall regime, and a geomorphology of active littoral and stabilized continental sand dunes that create special microenvironments. The microenvironments consist of inter-dune depressions, called *niayes*. The *niayes* are a biological crossroads, harboring a complex and rich flora, with many relic species of the Sudanian and Guinean regions. The region includes a wide range of humid to arid habitats, ranging from hydromorphic depressions to the sandy soils of the sand dune formations. Many species of plants from the higher rainfall zones to the south are able to survive by tapping into the near-surface ground-water. Temporary lakes can form during the rainy season, especially during the wetter periods. Trochain (1940) considered these vegetation formations to be relics of a subguinean forest. Since the 1970s, drought and human pressure have taken their toll on this unique ecological zone. Many species of Guinean affinity, including the oil palms, have succumbed to the effects of drought. The moist, fertile soils of the *niayes* are good for market gardening. The

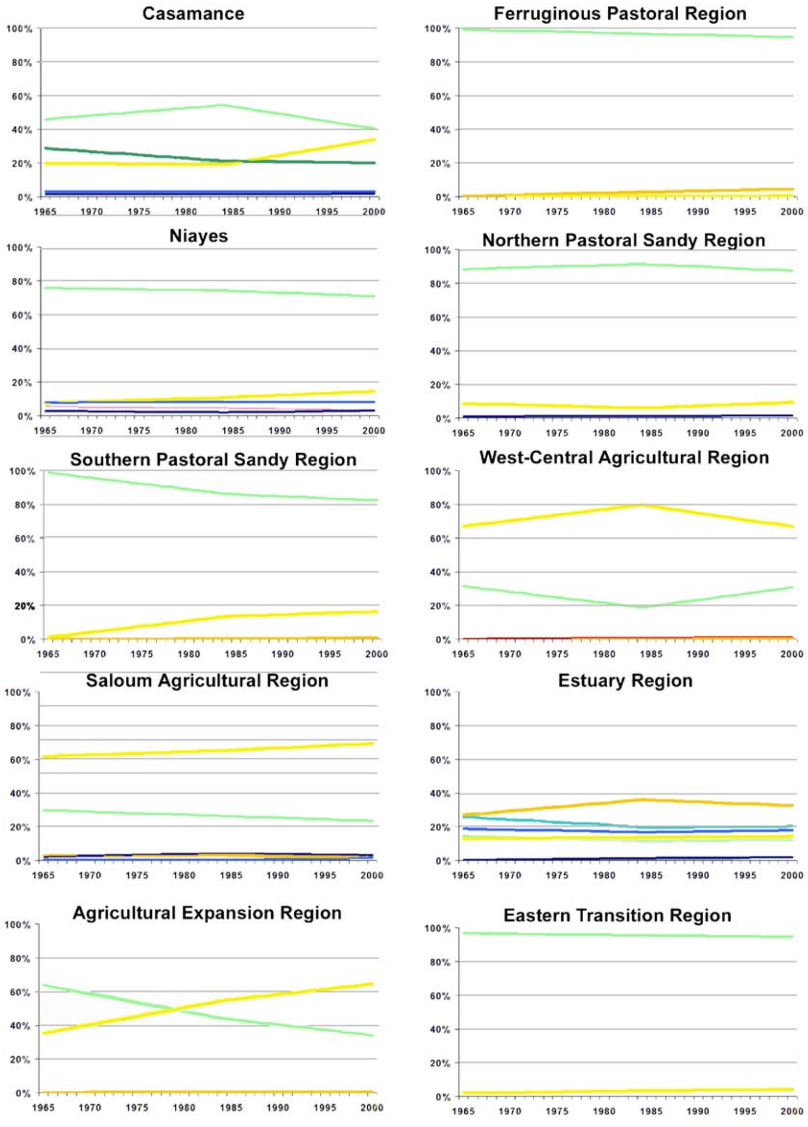

Fig. 14. Graphs of land use and land cover trends, by ecoregion. The legend for these graphs is on the following page.

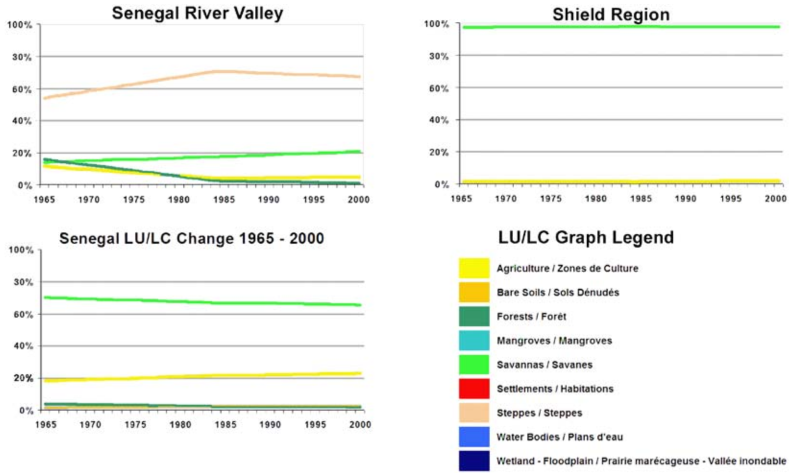

Fig. 14 (*continued*).

surrounding red-colored continental sand dunes support a shrub savanna, used for centuries by Fulbe pastoralists as important grazing lands.

The two area sample frames analysed for this small ecoregion show significant agricultural incursions onto the sandy grazing lands, from about 7 percent area under cultivation in 1968 to more than 14 percent in 2000 (Fig. 14). The area of the special *niaye* habitats appears to be stable, but the Landsat imagery was too coarse to quantify the replacement of wetland vegetation by market gardening. Photographs and field notes taken by the authors in 1983 and 1998 show a decline in the density and diversity of Sudanian and Guinean species of vegetation in the *niayes*. On a positive note, coastal sand dune stabilization projects, using the drought-tolerant Whispering Pine tree (*Casuarina equisetifolia* J.R. & G. Forst), have been very successful. Nearly the entire coastal zone, from Dakar to St. Louis, is now covered with young and old stands of these trees.

3.7. Saloum agricultural ecoregion

The land use and land cover of the Saloum Agricultural Region was dominated by an agricultural parkland until recently when it was nearly completely transformed by agriculture. Although generally included by many authors in the ‘Peanut Basin,’ it can be distinguished from the latter by its higher rainfall and greater floristic and agricultural diversity. Before the rapid changes of the 20th century, the climax vegetation was a biologically diverse, deciduous Sudanian woodland (Pélissier, 1966). Lawesson (1995) found a total of 89 woody species from numerous sites in the protected Fathala Forest. Aerial photographs from 1943 (Fig. 15) provide a glimpse of the last vestiges of the woodland that once blanketed the region. Tree cover, as shown in these historical photos, ranges from 40 to 70 percent. Today, most tree

Fig. 15. A part of an aerial photograph taken in October 1943 just west of the Koular Bolon (Saloum Agricultural Region). Small agricultural clearings were carved out of a Sudanian woodland, whose woody cover ranged from 40 to 70 percent.

species found in farmers' fields are relics of the ancient woodland. Today, only a few protected wooded savannas remain, and tree cover in these areas has fallen to 10–20 percent.

The agricultural expansion into the former woodlands is quite recent. Peanut production began to make inroads between 1900 and 1940, but the area under cultivation was small and scattered. Expansion increased dramatically in the 1950s and 1960s. By the 1990s, the transformation was complete, leaving only a few patches of protected woodlands. The analysis of Argon and Corona satellite photographs from the 1960s and Landsat TM images from the 1990s provides clear evidence of the more recent land use and land cover changes (Tappan et al., 2000a). The pair of maps in Fig. 16 depicts the stark contrast in land resources that results from the analysis of the time-series imagery. Mounting population pressures, drought, and national policies that encouraged peanut production have resulted in the demise of the centuries-old bushland–fallow agricultural system. By the 1990s, virtually all arable land was under cultivation, with little use of fallow or other soil conservation practices (Tappan et al., 2000a). The 1994 airborne video survey (Wood et al., 1995) found that tree cover had declined to less than 2 percent over most of the region. Furthermore, most rural people are no longer within walking distance of the few remaining woodlands—traditional sources of food, fiber, firewood, and medicine.

The results of the land use and land cover trend analysis using time-series imagery from 1968, 1984, and 1999 are shown in the graph in Fig. 14. This period covers the final stage of the region's complete facelift from woodland to agriculture. Although the numbers show only a moderate increase in agricultural area (61 percent in 1968 and 69 percent in 1999), they do not reflect the sharp decline in the use of traditional

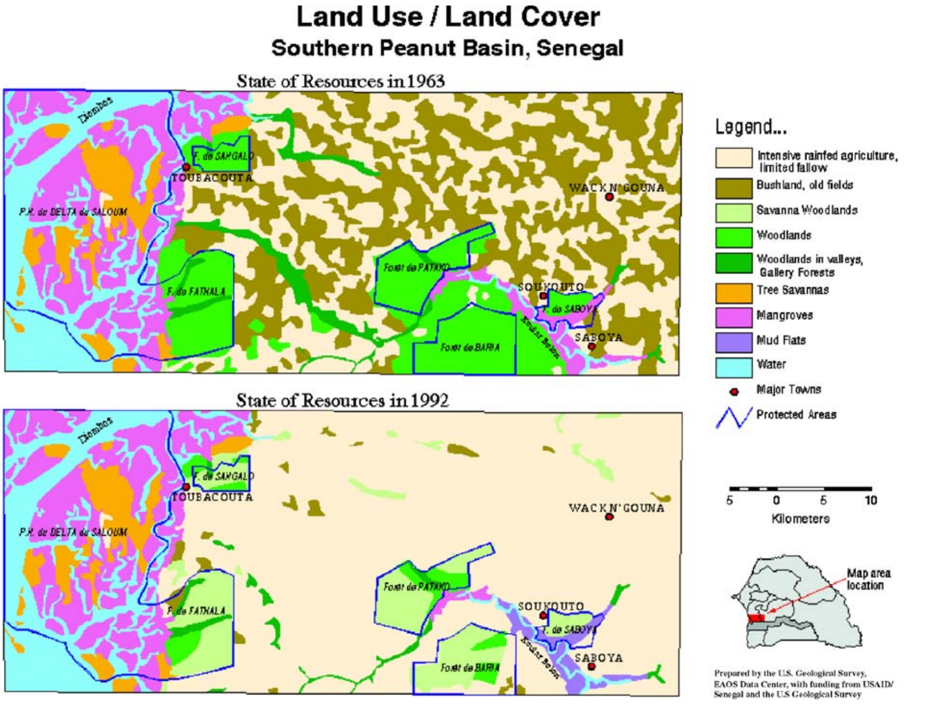

Fig. 16. A pair of maps depicting the final stage of agricultural transformation that has swept across the Saloum Agricultural Region. The maps were produced from interpretations of an Argon satellite photograph and a Landsat image.

bush fallow, because fallow was included as a component of the agricultural landscape in the area measurements taken from the imagery.

3.8. Agricultural expansion ecoregion

In the past half-century, winds of change have swept across this ecoregion, driven almost exclusively by human activity. In the deeper soils of the broad valleys, its wooded savannas have been replaced by agriculture, and the thin soil uplands have been transformed into a degraded shub and tree savanna. As land constraints and declining soil fertility in the Peanut Basin became more acute, the most logical direction for expanding production was to the south-east. Wedged between The Gambia to the south and the sylvo-pastoral regions to the north, the Agricultural Expansion Region has higher rainfall and a longer rainy season than most of the Peanut Basin. Its broad valleys with deep, sandy to loamy soils are suitable for many crop varieties.

Wolof and Serer farmers from the Peanut Basin, driven by harsh economic and environmental conditions, settled in the region, and by the 1980s, most of the wide valleys were under cultivation (Fig. 17). However, unlike the Peanut Basin, more

Fig. 17. A view from a 1994 aerial survey of Senegal, showing a patchwork of cultivation and degraded upland wooded savannas in the Agricultural Expansion Region. Severely eroded surfaces are beginning to form along valley slopes (bright areas).

than half of the region is composed of low, lateritic plateaus, with a thin veneer of gravelly and loamy soils. Far less suited to agriculture than the valleys, the plateaus have remained mostly unfarmed. Wooded savannas with flora characteristic of the northern Sudanian bioclimatic region remained relatively intact until a wave of charcoal production swept across the region from the 1960s to about 1990. Tree mortality from drought in the 1970s and 1980s also exacerbated the situation (Tappan et al., 2000a). Today, patches of degraded, biologically poor shrub and tree savannas are all that remain.

Agriculture has clearly been the primary agent of change, expanding from 35.4 percent of the area to 64.6 percent from 1965 to 2000 (Fig. 14). The rate of expansion will slow considerably, because most of the soils suitable for cultivation have been used (Moore et al., 1991).

The land use and land cover trends analysis provides figures on land surface change, but it does not reflect the qualitative and quantitative modification of the vegetation cover. Corona satellite photographs from 1965 show that the predominant vegetation in the broad valleys and uplands was a wooded savanna, with a woody cover of 20–30 percent. In the aftermath of the wave of charcoal production, our airborne videography from 1994 indicates a typical woody cover range of 6–10 percent, whereas cultivated areas show woody cover to be less than 3 percent. Consequently, the predominant vegetation cover has changed from a wooded savanna to a shrub and tree savanna.

3.9. Eastern Transition Ecoregion

Biophysically, the Eastern Transition Region is similar to the Agricultural Expansion Region. However, its distance from Senegal's densely populated agricultural region, and the predominance of lateritic plateaus have spared the region from the anthropogenic pressures of the western regions. Spared, that is, until the 1980s when the wave of charcoal production began to sweep through its wooded savannas and forest reserves. This region has become Senegal's primary source for fuelwood, mainly in the form of charcoal. Aerial photographs from the mid-1950s and Corona photographs from 1965 show that woody cover typically ranged from 15 to 20 percent over much of the region. By 1994 when EDC and CSE conducted an airborne video survey, approximately half of the wooded savannas had been degraded by charcoal production, leaving behind a biologically poor tree savanna and woody cover typically ranging from 5 to 20 percent. Thus, the woody cover is significantly reduced following logging for charcoal production; the impact on the biology and habitat quality may be much greater. Figs. 18a and b show the thinning of the wooded savanna over time at a ground-monitoring site and the impact on the biological diversity of the woody flora. The eastern third of the region still maintains its wooded savannas, which double as important grazing lands. Fragments of gallery forest also remain along some of the region's fossil valleys.

Agricultural expansion, driven by Wolof and Serer settlers from the west, is a secondary force of change. It is beginning to nibble away at the wooded savannas and grazing lands. Cotton and peanuts have become significant cash crops. Farmers carve new fields out of the wooded savannas and systematically clear stumps, shrubs, and trees to facilitate animal traction (Figs. 19a and b). The authors have revisited many sites since 1983 and have documented the process of agricultural expansion. The transformation is equally dramatic when viewed from space. The image pair (Figs. 20a and b) shows the changing land use and land cover of an area north-east of the bridge over the Nieri Ko River. Tragically, this example shows the loss of one of the largest and densest gallery forests in the region. Gallery forests are unique niches that preserve rich communities of Guinean and Sudanian flora and fauna.

The land use and land cover trends analysis (Fig. 14) shows the slow but significant expansion of agriculture into the region. In 1965, 2.1 percent of the region was cultivated, compared with 4.0 percent in 2000. This analysis, however, is not particularly sensitive to the modification of vegetation cover by the region's primary external pressure, charcoal production, because selective harvesting of trees in the process is not readily identified on Landsat images. Note also that bare, degraded

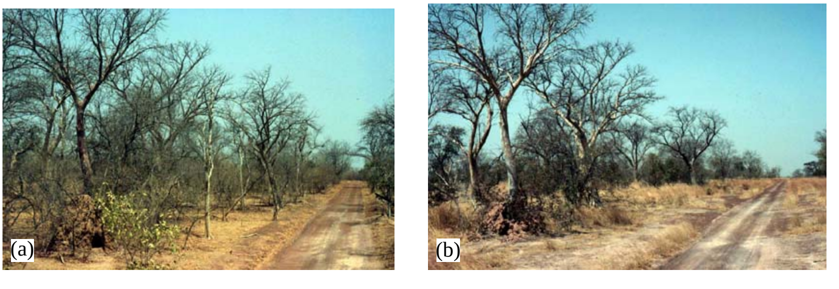

Fig. 18. (a and b). An 11-year comparison of a Sudanian wooded savanna 10 km north of the Forêt Classée de Goudiri. The tree cover has been thinned out from logging for charcoal production, creating a negative impact on the biological diversity. Left: March 1983; right: February 1994.

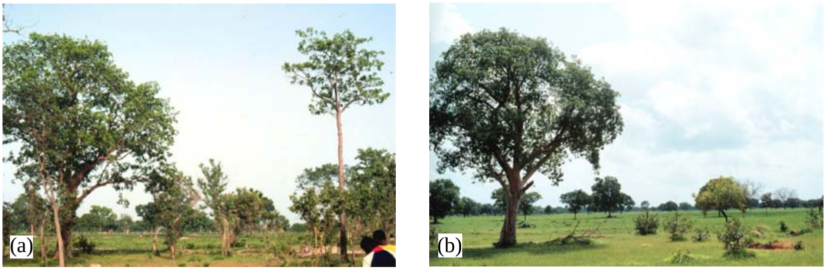

Fig. 19. (a and b). This time-series pair taken near Maka in the Eastern Transition Region shows the initial process of clearing a wooded savanna for cultivation (left, August 1983), and the transformation into an area of permanent cultivation (right, August 1998). All paired landscape photographs in this article use a technique known as rephotography, in which successive photographs are taken from a single location.

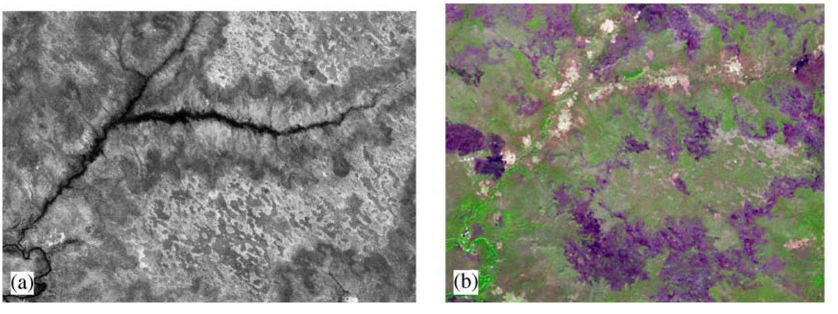

Fig. 20. (a and b). A comparison of a 1965 Corona photograph (left) and a 1999 Landsat ETM+ image (right). The dark strip along the main valley is a dense, biologically diverse gallery forest (left). By 1999, the gallery forest had been cleared for cultivation (light patches). The dark patches in the Landsat image are ash from recent bushfires.

soils have begun to appear in the past several decades. The images quite clearly record the spread of a 'badlands effect' in the eastern ecoregions of Senegal. Preliminary ground studies indicate that a combination of factors is responsible, including drought, overgrazing, topography, and the erosion force of torrential rain. These badland areas have lost virtually all productivity. Successes in Burkina Faso show that they can be reclaimed for agriculture when treated with soil and water conservation practices (Reij and Thiombiano, 2003).

3.10. Shield ecoregion

Geology is the primary feature that sets this region apart. Ophiolitic, granitized, and tightly folded volcanic and sedimentary rocks make up a Precambrian shield (Stancioff et al., 1986). The surface geomorphology of low plateaus and hills, terraces, and valleys only hints at the complexity of the underlying geology. Until recently, the great distance from Senegal's population centers and the very limited agricultural potential of the region has deterred migration to the region. Population and human pressure have been low (4 people km^{-2}), with widely scattered villages lining up along the fossil valleys.

A Sudanian deciduous wooded savanna constitutes the main vegetation type of the region. Based on his detailed field observations the 1930s, Trochain (1940) found that the dry woody formations that cover the region form heterogeneous communities, with no one tree species dominating the floristic composition. The communities are floristically rich. We found more than 150 woody species at 57 monitoring sites that we revisited in 1994–97.

A mosaic of several other vegetation formations occurs as a function of the geomorphology, soils, rainfall, fire, and to a smaller degree, grazing and shifting cultivation. Annual fires that sweep across most of the region are such an important component of the ecosystem that these wooded savannas are referred to as fire-climax formations. The wide range of habitats explains the rich flora, with species from both the Sudanian and the Guinean bioclimatic zones. A unique but common formation is the grassy *bowé*, which are marked by outcrops of impermeable laterite that restricts root penetration and results in open, often treeless meadows (Fig. 21). Evergreen, closed-canopy gallery forests still occur along some fossil valleys, but they are being fragmented and destroyed by agricultural expansion.

A large part of this region falls under the protection of the Niokolo-Koba National Park. The park covers some 913,000 ha and contains some of the most pristine Sudanian-type flora and fauna left in Africa. The floristic diversity remains high, preserving many of the genetic resources that are being lost in other parts of Senegal.

Agriculture in the region enjoys relatively high rainfall, and farmers grow responsive crops, such as maize, sorghum, peanuts, cotton and, even rice. Bush fallows of up to 5 years are still practiced. When the fragile soils are laid bare by

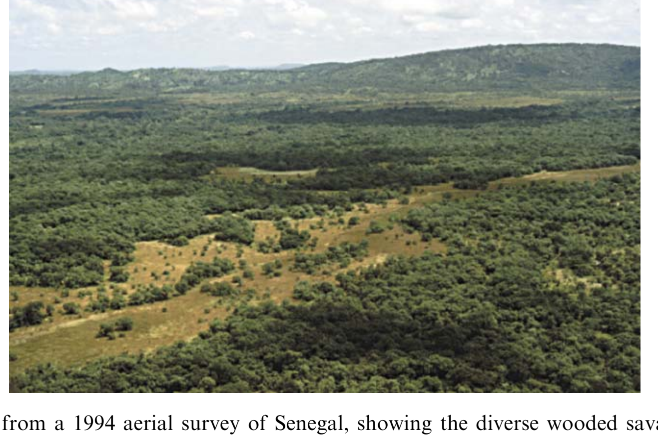

Fig. 21. A view from a 1994 aerial survey of Senegal, showing the diverse wooded savannas and *bowé* (open grassy, often treeless meadows) of the Shield Region. Human population is very low, and much of the area is protected under the Niokolo-Koba National Park.

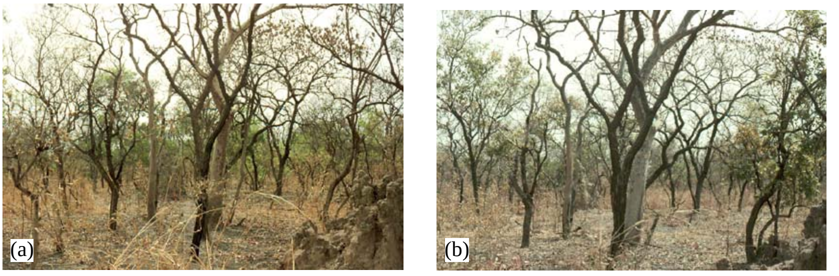

Fig 22. (a and b). A 10-year comparison of an upland wooded savanna in the Niokolo-Koba National Park. Note the stability of the woody cover and the very slow rate of growth, judging from the thickness of the branches and trunks. Left: April 1984; right: February 1994.

cultivation, however, they are quite vulnerable to water erosion. The vast areas of non-tillable terraces and plateaus ensure the availability of extensive rangelands for cattle and a corresponding potential for internal transport of nutrients to fields (Grosenick et al., 1990).

Results from the land use and land cover trends analysis (Fig. 14) show a relatively stable situation. In 2000, 98 percent of the region was still blanketed by diverse natural vegetation types. The agricultural area has only increased from 1.6 to 2.0 percent in 35 years. Our 1994 airborne video survey showed little pressure on the natural vegetation, including virtually no charcoal production. Woody cover generally ranged from 10 to 30 percent. In the Niokolo-Koba National Park, the percentage of cover range was generally higher than in other areas, occasionally reaching 40 percent. Our field surveys in 1984 and 1994–97 confirmed the physical and biological stability of the woody vegetation throughout the region (Figs. 22a and b). Exceptions to this are found around the fast-growing mining towns and in areas of expansion where gallery forest is being converted to agriculture (0.9 percent in 1965, 0.4 percent in 2000). In short, the region has great potential in terms of its biological richness, minerals, and fuelwood. These riches bring vulnerabilities that will need to be carefully managed in the near future.

3.11. The Casamance

'*La Verte Casamance*,' as it is fondly referred to, is well known for its tropical greenery, lush forested landscapes, valleys fringed with oil palm groves, and rice paddies. These traits give it a unique personality, markedly different from the semi-arid regions to the north. Geographically, the region can be distinguished from other regions by the combination of high seasonal rainfall, a well-developed drainage system, ferralitic soils, relatively dense and floristically rich Sudanian and Guinean vegetation types, diverse agrarian ethnic groups, and its relative isolation from the rest of Senegal.

The Casamance is showing signs of a major, potentially irreversible transformation in land use and land cover, comparable to the dramatic evolution that

Fig. 23. A 1994 aerial view of a small farming community in the upper Casamance Region. These communities are often separated by large tracts of woodlands that represent some of the densest and most diverse vegetation formations in Senegal.

reconfigured the Saloum Agricultural Region from the 1930s to the 1990s. Senegalese ecologists are already referring to parts of eastern and central Casamance as '*la région compromise,*' whose biological resources are quickly succumbing to the extreme pressures of expanding cultivation and charcoal production. Today tracts of agricultural parkland closely resemble the open, degraded landscapes of the Saloum Agricultural Region.

As in the Shield Region to the east, annual rainfall amounts of over 1000 mm support a Sudanian-type deciduous wooded savanna and woodland over much of the region (Fig. 23). In the numerous forest reserves and areas of minimal human activity, these floristically rich and heterogeneous formations maintain woody cover levels of 20–50 percent. The highest woody densities occur in the extreme east (Department of Velingara) and extreme west (Department of Ziguinchor).

Natural conditions are favorable to diverse agricultural activities, including rice, millet, corn, peanuts, and cotton, as well as animal rearing and tree crops, particularly mango and cashew. Agricultural production has been boosted in recent years by the expansion of cotton production in the Kolda Region and rice growing in the Anambé Basin.

Corona photographs from 1965 were compared qualitatively with aerial photographs and videography taken in 1994 by the EDC/CSE team. No noticeable change was found in the land cover and tree density where human activity has been limited, especially on some of the remote plateaus of the southeast. However, tree cover and diversity are declining fast in parts of the eastern half of the Casamance ecoregion, because of charcoal production and agricultural expansion. Field surveys conducted in 1984, 1997, and 2001 confirm this. Farmers from the Saloum region are settling in the forest reserves of Guimara and Pata. Figs. 24a–c portray the clear-cutting of the woodlands in these forest reserves. By 1999, 4.6 percent of the Forêt Classée de Guimara and 28.8 percent of the Forêt Classée de Pata had been

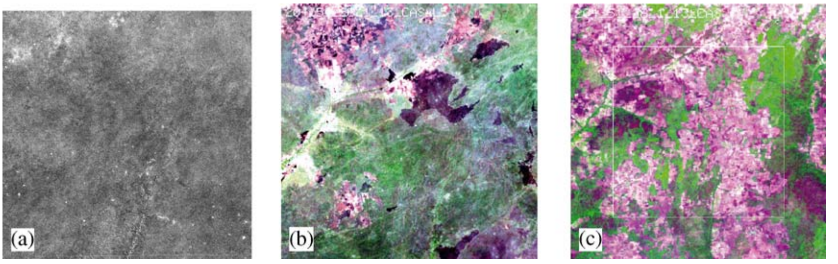

Fig 24. (a, b, and c). This time-series of satellite images represents one of the $10 \times 10\,km^2$ area frame samples used to monitor and quantify land use and land cover trends in the Casamance Region. This example shows deforestation and rapid expansion of agriculture in the Pata Forest Reserve. Left: Corona, January 1968; center: Landsat, November 1985; right: Landsat, December 1999.

converted to agriculture, which fueled tensions between local agro-pastoralists and the recent migrants.

The area frame trends analysis of Corona and Landsat imagery was based on 10 sample blocks for this region. The agricultural area was stable overall from 1965 to 1985, then began to expand rapidly from about 19–34 percent of the total area (Fig. 14). Agricultural production in the Casamance continues to increase through extensification, rather than intensification. The natural landscapes are being increasingly fragmented. The rapid change driven by agricultural extensification, and more recently, charcoal production, is alarming if conservation of the Casamance forest resources and diverse genetic material is a priority. For a more in-depth look at changing land use patterns and carbon sequestration potential in the eastern Casamance, refer to the articles in this issue by Wood et al. and Liu et al. (2004).

3.12. The estuaries

Two major complexes of low tidal flats and estuaries produce another distinct ecoregion (aerial view, Fig. 25). These coastal wetlands are flooded twice daily by the ocean tide and have historically been occupied by mangroves of the genus *rhizophora* and *avicennia*. The mangrove forest cover is quite dense, ranging from 50 to 100 percent. Ancient mud flats called *tannes* occur on slightly higher ground between the channels. The Saloum and Casamance Rivers, which constitute the main arteries of the two estuary regions, receive only minimal water flow from upstream, and only in the rainy season (3–4 $m^3\,s^{-1}$ at Kolda (MEPN, 1998)). Consequently, the water remains brackish from the intrusion of seawater.

Since the 1970s and 1980s, some of the mangrove forest has perished, particularly in the northern third of the Saloum estuary complex, as well as along the Casamance River. We see direct evidence of the loss of mangrove forest from comparisons of Corona, Landsat, and aerial images (Figs. 26a and b).

The disappearance of the mangrove is related to a modification of physical–chemical conditions of the river water and ground-water (increased salinity and

Fig. 25. A view from the 1994 aerial survey of the mangrove swamps and tidal flats of the coastal Estuaries Region.

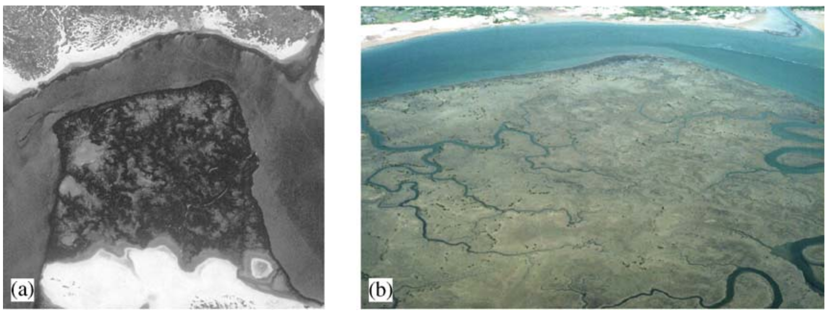

Fig 26. (a and b). A comparison of a Corona satellite photograph from January 1968 (left) and an oblique-looking aerial view from October 1994 (right), showing the virtual disappearance of a mangrove forest along the Saloum River 5 km east of Foundiougne. The mangrove forest is represented by the very dark tones (left); the photograph at right covers much of the area seen in the center of the Corona photograph.

acidity) because of the decline in rainfall in recent decades. Drought is cited as the primary cause (MEPN, 1998). Marius (1985) found considerable increases in salinity levels in the ground-water and in the soils in a channel near Bignona from 1974 to 1978. Salinity reached three to five times that of seawater. On a positive note, the villagers of Faoye (south of Fatick) have noticed regeneration of mangrove plants in the mud flats since 1994. They attribute this to somewhat higher rainfall. Regeneration is also occurring along the lower Casamance River.

Our trends analysis shows that mangrove vegetation decreased from 25.9 percent in 1968 to 20.0 percent in 1984, followed by a modest increase to 20.4 percent in 2000. The timing of this trend would seem to confirm the impact of drought on the mangrove forests. Bare soil, much of it represented by the naturally occurring *tannes*, has increased as mangrove declines, but the area of these *tannes* is also influenced by the daily tide. A more accurate time-series analysis would need to account for the daily fluctuation between tidal water and exposed tidal flats.

4. National trends

The overall land use and land cover trends from 1965 to 2000 show slight to moderate change over the 35-year period, depending upon the class (Figs. 14 and 27). These data are summaries from all area frame analyses and all ecoregions, reflecting the conversions of one land use and land cover to another.

It is apparent from the results that agricultural expansion has been the main source of change. In 1965, cultivated land covered 17 percent of the country; in 1985, the area expanded to 19.8 percent, and in 2000 it reached 21.4 percent. The rate of expansion was slower in the more recent 1985–2000 timeframe than in the 1965–85 period. If we annualize the expansion, we find that cropland expanded at a rate of 27,715 ha year^{-1} from 1965 to 1985, and 20,573 ha year^{-1} from 1985 to 2000.

We know from the time-series images that agriculture is primarily encroaching upon Senegal's diverse savannas and forests. The broadly defined 'savanna' class

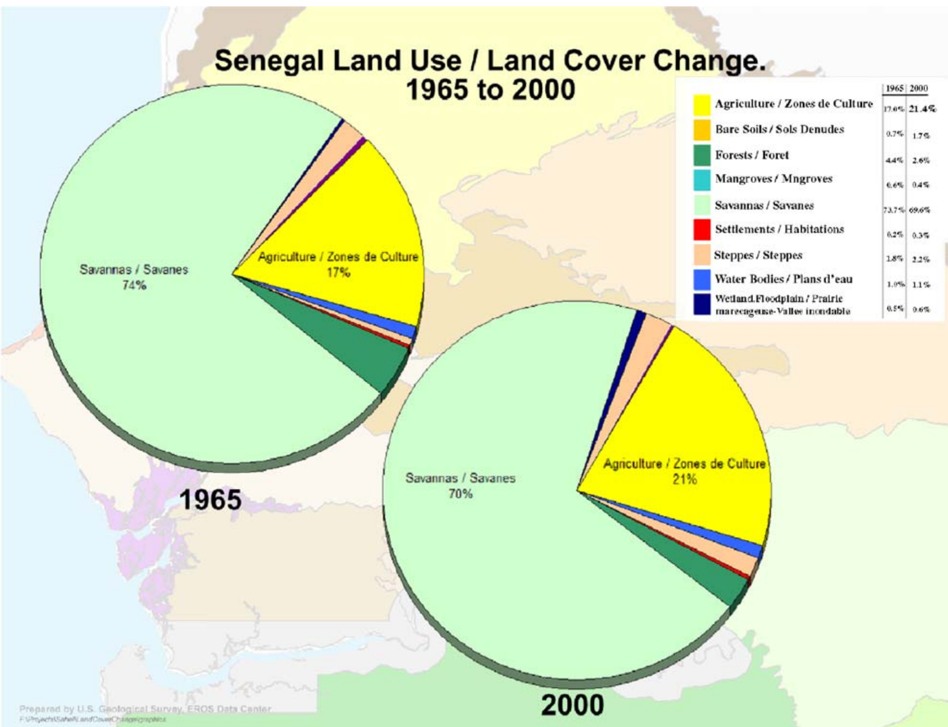

Fig. 27. National land use and land cover trends for Senegal, comparing the 1965 and 2000 situations.

declined from 73.7 to 69.6 percent. This is a moderate decline in contrast to the relatively big bite that Senegal's forests have taken, decreasing from 4.4 percent in 1965 to 2.6 percent in 2000. The forests include the unique riverine woodlands of the Senegal River, biologically diverse gallery forests, and Sudano-Guinean forests in the lower Casamance. Lumped together into an all-encompassing class, Senegal's shrub savannas, tree savannas, wooded savannas, and forests have declined from 78.1 percent in 1965 to 72.2 percent in 2000. Assuming a linear decline through this period, the annual rate of decline amounted to 333 km^2 $year^{-1}$, or 33,000 ha $year^{-1}$. Although significant, these figures are somewhat less than figures found in the literature. The Food and Agriculture Organization (FAO, 1995) estimated deforestation at 520 km^2 $year^{-1}$. The NEAP cited similar figures (MEPN/CONSERE, 1997). Our trends for Senegal differ considerably from the results obtained by Stephenne and Lambin (2001) using a dynamic simulation model. They attempted to reconstruct land use and land cover change over approximately the same period. Their model showed approximately 300 percent expansion of cropland from 1965 to 1997, and a 200 percent increase in fallow land, with similarly huge reductions in pastoral land and 'fuelwood extraction areas' (equivalent to our savannas and forests).

Several other transitions are worth noting. Our figures show that steppes have increased from 1.8 to 2.2 percent. In Senegal, steppes (discontinous or sparse herbaceous ground cover, often with scattered shrubs) primarily occur in the Senegal River Valley. Steppes are the primary land cover type that has replaced the once-extensive riverine woodlands. Wetlands (in floodplains and natural depressions) have increased slightly. The increase can be explained by the 1999 growing season, which was particularly wet. Water remained in depressions well into the 1999–2000 dry season and temporarily increased the wetlands area. The bare (degraded) soil class grew significantly from 0.7 to 1.7 percent. This cover type does not include the natural exposure of bare soil during the dry season. Rather, it reflects soil surfaces that have lost most or all productivity owing to problems of erosion and compaction. The expansion of a 'badland' type landscape has become quite apparent in several ecoregions. These areas will require special attention if the trend is to be arrested. Finally, the settlements class shows only modest expansion. Only rarely did our area frames fall over a major town; thus, this trend does not reflect the rapid urban expansion rates found in Senegal.

5. Discussion

The results of our time-series analysis portray a picture of moderate change in the land use and land cover of Senegal over the past 35 years. When examined at the ecoregion level, it becomes clear that some ecoregions are undergoing fundamental transformations, while others remain fairly stable. The changes we have seen result from declines in the area of the country's diverse vegetation types, both through outright conversion to agriculture and through reduction (modification) of woody cover. These changes, while significant, are not entirely consistent with the presentations of doom and gloom that can be found in a long string of environmental-crisis reports on Senegal. In 2000, Senegal is still largely a country dominated by a great diversity of land cover types, while less than a quarter of its land area is devoted to food production. Even within Senegal's agricultural landscapes, farmers usually preserve a diversity of trees that represent a great source of natural wealth.

The trends highlight several areas of concern. One is the clear loss of more than half of Senegal's forests (cover types with over 80 percent canopy closure) in just 35 years. Most of these represent biodiverse 'hotspots,'—habitats for a great variety of flora and fauna. A second trend, not reflected directly in land cover change, is the decline in woody cover throughout Senegal. Although a discussion of the driving factors of change is beyond the scope of this paper, a complex set of causes is emerging. The causes vary in intensity from place to place, as do the local circumstances that determine specific vulnerabilities. Many of the major causes are physical ones, often occurring in combination—drought, livestock concentrations at local scales, sloping surfaces, and soils that are susceptible to water and wind erosion. Humans are probably the most important agent of change, responsible not only for the agricultural transformations but also the great modifications occurring in Senegal wooded savannas and woodlands. An unrelenting demand for fuel, particularly in the form of charcoal, is driving an ever-growing wave of selective logging in all regions with significant woody resources. From our 1994 systematic aerial videography survey, we found that 28 percent of Senegal's wooded savannas and woodlands were moderately to severely degraded by charcoal production (Tappan et al., 2000b).

This study would not have been possible without the high-quality, blanket coverage available through the Corona and Landsat Earth-observing programs. The additional use of aerial photographs from 1942 to 1943 provided selected windows even further into the past. Interpretation and quantification of land use and land cover types was straightforward and reliable, owing in part to the high quality of the image data, the use of broadly defined land use and cover classes, the extensive aerial surveys conducted by the authors, and considerable field experience. Many of the area frame interpretations were validated using low-altitude aerial photographs taken during our 1994 aerial survey, lending confidence to the analysis. Through years of experimentation, we found that manual interpretation of Landsat imagery provides high-quality results, particularly when time-series land resource change is the goal. We found automated spectral classification techniques to be problematic in the West African context.

Senegal is but one of 15 countries that are participating in this effort to characterize land use and land cover changes in West Africa. The project is being coordinated by the Regional AGRHYMET Center, the USGS/EDC, and the Institut du Sahel. Results for the Sahelian countries extending from Mauritania to Chad will be published soon. It is our hope that this effort will contribute to an improved understanding of the spatial and temporal dimension of land use and land cover change across West Africa.

Acknowledgements

This study is part of the West Africa land use and land cover trends project, funded by the US Agency for International Development (USAID)/West Africa Regional Program. We would particularly like to acknowledge the interest and support of C. Dei and R. Anderson in this endeavor. A special thanks goes to our colleagues M. McGahuey and P. Bartel at USAID in Washington, who have encouraged and supported development and practical application of environmental-monitoring tools we use in Africa. We would like to thank our colleagues at the Regional AGRHYMET Center and at the Institut du Sahel for the strong collaboration we have enjoyed in recent years. For our work in Senegal, we would like to extend a special thanks to our colleagues at the *Centre de Suivi Ecologique*, especially A. Touré and M. Ba, for the many years of close collaboration and support. CSE's Director, M. Niang, has been particularly supportive over the years, providing valuable direction and vision for our collaboration. For his unfailing positive support, great depth of knowledge in both the natural and social sciences, and long-term friendship, we extend a special thanks to A. Hadj. We would like to give special recognition to three individuals at the EDC: L. Tieszen, for his encouragement in preparing this manuscript and for the opportunity to participate in carbon sequestration research in Senegal; T. Albright, for his tireless and enthusiastic support to the overall land use change project in West Africa; and J. Smith, for proofing and formatting the manuscript. Finally, we would like to pay special tribute to the late A. Bodian from the Casamance, one of Senegal's greatest plant ecologists, who provided us with tremendous support and friendship in the field for nearly 20 years until his untimely passing in September 2001.

References

Aubréville, A., 1949. Climats, Forêts, et désertification de l'Afrique tropicale. Société d'Editions Géographiques, Maritimes, et Coloniales, Paris.

Bucknall, J., Livingston, G., Kagbo, R., Brown, D., 1997. Senegal Agriculture Sector Analysis Update. International Science and Technology Institute, Inc. (ISTI), Arlington, VA. Report prepared for USAID, 154pp.

Budde, M., Tappan, G., Rowland, J., Tieszen, L., Lewis, J., 2004. Assessing land cover performance in Senegal, West Africa using 1-km integrated NDVI, local variance analysis, and high resolution satellite imagery. Journal of Arid Environments, this issue.

CSE, 1998. La Végétation Ligneuse du Sénégal: Distribution, Dynamique et Fonction. Centre de Suivi Ecologique, Study No. 98/002, 52pp.

DAT, PNUD, DTCD, 1984. Schéma national d'aménagement du territoire, version préliminaire. SEN 82.016, 749pp.

FAO, 1995. Forest Resources Assessment 1990: Global Syntheses. Food and Agriculture Organization, Rome, Italy.

Giffard, P., 1974. L'Arbre dans le paysage sénégalais, Dakar, 431pp.

Gonzalez, P., 1997. Dynamics of biodiversity and human carrying capacity in the Senegal Sahel. Ph.D. Dissertation, University of California, Berkeley, 427pp.

Gonzalez, P., 2001. Desertification and a shift in forest species in the West African Sahel. Climate Research 17, 217–228.

Grosenick, G., Djegal, A., King, J., Karsh, E., Warshall, P., 1990. Senegal Natural Resource Management Assessment. Final Report, Development Economics Group/Louis Berger International, Inc. and the Institute for Development Anthropology, Washington, DC, 187pp.

Hulme, M., 1996. Recent climatic changes in the world's drylands. Geophysical Research Letters 1, 61–64.

Lal, R., 2002. Carbon sequestration in dryland ecosystems of West Asia and North Africa. Land Degradation & Development 13, 45–59.

Lawesson, J.E., 1995. Studies of woody flora and vegetation in Senegal. Opera Botanica, Copenhagen No. 125, 172pp.

Lericollais, A., 1987. La mort des arbres à Sob, en pays sereer (Sénégal). ORSTOM, Dakar, 16pp.

Liu, S., Kaire, M., Wood, E., Diallo, O., Tieszen, L., 2004. Impacts of land use and climate change on carbon dynamics in south-central Senegal. Journal of Arid Environments, this issue.

Loveland, T., Sohl, T., Stehman, S., Gallant, A., Sayler, K., Napton, D., 2002. A strategy for estimating the rates of recent United States land-cover changes. Photogrammetric Engineering and Remote Sensing 68 (10), 1091–1099.

Maignen, R., 1965. Notice Explicative, Carte Pédologique du Sénégal au 1/1.000.000. *Publication ORSTOM*, Dakar, 63pp., 1 carte couleur h.t.

Marius, C., 1985. Mangroves du Sénégal et de la Gambie. Ecologie–Pédologie–Géochimie, Mise en Valeur et Aménagement. Thése d'Etat, Strasbourg (1984), Trav. Et Doc. ORSTOM no. 193, Paris, 357pp.

McDonald, R.A., 1995. Corona: success for space reconnaissance, a look into the cold war, and a revolution for intelligence. Photogrammetric Engineering and Remote Sensing 61 (6), 689–720.

MEPN, 1998. Monographie National sur la Biodiversité au Sénégal, Bldg. Administratif, Ministère de l'Environnement et de la Protection de la Nature, Dakar, 81pp.

MEPN/CONSERE, 1997. Plan National d'Action pour l'Environnement, Ministère de l'Environnement et de la Protection de la Nature, Conseil Supérieur des Ressources Naturelles et de l'Environnement, Dakar, 158pp.

MEPN/CONSERE, 1998. Programme d'Action National de Lutte Contre la Désertification, Ministére de l'Environnement et de la Protection de la Nature, Conseil Supérieur des Ressources Naturelles et de l'Environnement, Dakar, 166pp.

Moore, D.G., Tappan, G., Howard, S., Lietzow, R., Nadeau, A., Renison, W., Olsson, J., Kite, R., 1991. Geographic Modeling of Human Carrying Capacity from Rainfed Agriculture: Senegal Case Study. USGS EROS Data Center, Sioux Falls, SD, USA.

Nicholson, S., 1989. Long-term changes in African rainfall. Weather 44 (2), 46–56.

Nicholson, S., 2000. Land surface processes and Sahel climate. Reviews of Geophysics 38, 117–139.

Omernik, J., 1987. Ecoregions of the conterminous United States. Annals of the Association of American Geographers 77, 118–125.

Omernik, J., 1995. Ecoregions: a spatial framework for environmental management. In: Davis, W., Simon, T. (Eds.), Biological Assessment and Criteria: Tools for Water Resource Planning and Decision Making. Lewis Publishers, CRC Press, Boca Raton.

Parton, W., Tappan, G., Ojima, D., Tschakert, P., 2004. Ecological impact of historical and future land use patterns in Senegal. Journal of Arid Environments, this issue.

Pélissier, P., 1966. Les Paysans du Sénégal: Les civilisations agraires du Cayor à la Casamance, Impriméric Fabrègue. Saint-Yrieix, France, 939pp.

Reij, C., Thiombiano, T., 2003. Développement Rural et Environnement au Burkina Faso: La réhabilitation de la capacité productive des terroirs sur la partie nord du Plateau Central entre 1980 et 2001. Rapport de synthèse, GTZ/PATECORE, Burkina Faso, 82 pp.

Roberty, G., 1962. Carte de la Végétation Tropical Occidental à 1/1 000 000e.

Stancioff, A., Staljanssens, M., Tappan, G., 1986. Mapping and Remote Sensing of the Resources of the Republic of Senegal: A study of the geology, hydrology, soils, vegetation and land use potential. SDSU, Remote Sensing Institute, SDSU-RSI-86-01, 655pp.

Stephenne, N., Lambin, E., 2001. Backward land-cover change projections for the Sudano-Sahelian countries of Africa with a dynamic simulation model of land-use change (SALU). In: Matsuno, T., Kida, H. (Eds.), Present and Future of Modeling Global Environmental Change: Toward Integrated Modeling, Terrapub, Tokyo. pp. 255–270.

Tappan, G., Wood, E., Hadj, A., Bodian, A., 1994. Monitoring Natural Resource Changes in Senegal: Preliminary Evidence from Field Sites. USGS EROS Data Center, Sioux Falls, SD.

Tappan, G., Hadj, A., Wood, E., Lietzow, R., 2000a. Use of argon, corona, and landsat imagery to assess 30 years of land resource changes in west–central Senegal. Photogrammetric Engineering and Remote Sensing 66 (6), 727–735.

Tappan, G., Wood, E., Hadj, A., Lietzow, R., Sall, M., 2000b. Monitoring climate and human impacts on the vegetation resources of Senegal: drought, agricultural expansion, and natural resource management. USGS EROS Data Center, Sioux Falls, SD, Unpublished Report submitted to the US Agency for International Development, Dakar, Senegal.

Tschakert, P., Tappan, G., 2004. Environmental histories and carbon visions: a multi-scale assessment in the old peanut basin of Senegal. Journal of Arid Environments, this issue.

Tiessen, H., Felle, C., Sampaio, E.V.S.B., Garin, P., 1998. Carbon sequestration and turnover in semiarid savannas and dry forest. Climate Change 40, 105–117.

Trochain, J., 1940. Contribution à l'étude de la végétation du Sénégal. Mémoire de l'IFAN, Paris, 433pp.

Trochain, J., 1957. Accord interafricain sur la définition des types de végétation de l'Afrique tropicale. Bull. Inst. Et. Centrafri., Nouv. Sér. p. 55–93.

Wood, E., 2002. Modeling and characterizing agricultural expansion: a case study in Senegal. Ph.D. Dissertation, University of Wisconsin, Madison.

Wood, E., Tappan, G., Jacobs, D., 1995. Monitoring Senegal's natural resources using airborne videography. Proceedings, 15th Biennial Workshop on Color Photography and Videography in Resource Assessment. Terre Haute, Indiana, pp. 315–325.

Wood, E., Tappan, G., Lietzow, R., Albright, T., 1998. The impact of agricultural production systems on land use / land cover change: Senegal, West Africa. Raytheon Center for Global Change 5 (2), 2–16.

Wood, E., Tappan, G., Hadj, A., 2004. Understanding the drivers of agricultural land use change in south–central Senegal. Journal of Arid Environments, this issue.