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The social context of carbon sequestration: considerations from a multi-scale environmental history of the Old Peanut Basin of Senegal

P. Tschakert[a,*,1], G. Tappan[b]

[a] Arid Lands Resource Sciences, University of Arizona, 1955 E. 6th St., Tucson, AZ 85719, USA

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

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Abstract

This paper presents the results of a multi-scale investigation of environmental change in the Old Peanut Basin of Senegal throughout the 20th century. Based on historical accounts, ethnographies, aerial photos, satellite images, field and household surveys as well as various participatory research activities with farmers in selected villages, the study attempts to make explicit layered scales of analysis, both temporally and spatially. It shows that, despite some general trends of resource degradation in the Old Peanut Basin, local farming systems have embarked on different pathways of change to adapt to their evolving environment. It also illustrates that high diversity with respect to soil fertility management exists at the farm and household level. Finally, the paper proposes a farmer-oriented approach to carbon sequestration in order to integrate recommended technical options more efficiently into the complex and dynamic livelihoods of smallholders in dryland environments. This approach includes pathway-specific land use and management options at the level of farming systems and, at the level of individual households, a basket of possible practices from which farmers can choose depending on their multiple needs, capacities, and adaptive strategies to cope with risk and uncertainty.

Keywords: Environmental change; Soil fertility management; Remote sensing; Carbon sequestration; Rural livelihoods; Senegal

*Corresponding author. Tel.: +1-514-629-6726; fax: +1-514-398-5069.

E-mail address: petra.tschakert@mail.mcgill.ca (P. Tschakert).

[1] Current address: Department of Biology, McGill University, 1205 Ave. Dr. Penfield, Montreal, PQ H3A 1B1, Canada.

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1. Introduction

Recent historical analyses of African landscapes increasingly challenge the neo-Malthusian 'nexus' argument that portrays population growth, poor agricultural practices, and insecure land tenure as a fated causal chain, perpetuating the 'downward spiral' of land degradation and rural poverty (Leach and Mearns, 1996; Niemeijer, 1996; Sullivan, 1996; Scoones, 2001). Based on 'hybrid' interdisciplinary approaches (Batterbury and Bebbington, 1999), new insights have been emerging that link contemporary social and ecological processes through an historical context. Multi-scale environmental histories now offer new ways of interpreting much of environmental change in Africa by focusing on the intersection of social, institutional, political, economic, and ecological processes (Gray, 1999).

Central to this new framework for addressing environmental change, largely rooted in political ecology and new ecology thinking, are the notions of diversity, complexity, non-linear dynamics, uncertainty, and surprise. These differ greatly from the balance-of-nature perspective that is inherent to the static, equilibrium view of ecological systems. As expressed by Holling (1986), "not only is the science incomplete, the system itself is a moving target". As a consequence, prediction and control in such constantly transforming but nonetheless persistent systems are perceived as highly unlikely, if not impossible (Leach et al., 1999; Scoones, 1999).

At the same time, advances in agrodiversity[2] and livelihood studies provide a holistic perspective on how people in various agro-ecosystems, including complex, diverse and risk-prone environments such as African drylands, manage their resources and adapt to chances, shocks, and crises (Chambers and Toulmin, 1991; Brookfield and Stocking, 1999; Mortimore and Adams, 1999; Brookfield, 2001). Such a "people in places" emphasis (Scoones, 1999), explicitly addresses spatial and temporal dynamics through detailed, in situ assessments and provides new ways of explaining environmental change across time and space.

These approaches and insights are now increasingly incorporated in new research initiatives that assess opportunities and constraints with respect to resource management in drylands (Mazzucato and Niemeijer, 2000; Scoones, 2001). Carbon sequestration in soils has been discussed as one possible option for restoring degraded agro-ecosystems in semi-arid lands. It is argued that it has the potential to simultaneously improve local soil fertility, enhance crops yields, local food and livelihoods security, reduce poverty, and increase the global carbon uptake through terrestrial sinks and, thus, contribute to climate change mitigation (Rosenberg et al., 1999; Lal, 2002a, b; Olsson and Ardö, 2002). It is no surprise that carbon sequestration in soils has been advocated as a win-win strategy (Lal et al., 1999; Batjes, 2001; Ringius, 2002; FAO, 2001).

[2] Agro-diversity is defined as "the dynamic variation in cropping systems, output and management practice that occurs within and between agro-ecosystems. It arises from bio-physical differences, and from the many and changing ways in which farmers manage diverse genetic resources and natural variability, and organize their management in dynamic social and economic contexts" (Brookfield, 2001).

So far, the main focus of this new research domain has been on biophysical and technological aspects. Much progress has been made in estimating current and past soil carbon levels, evaluating most promising management practices to increase carbon stocks, and predicting potential sequestration rates (Parton et al., 2004). However, within the broader context of these 'carbon strategies', the dynamics of local farming systems and the role of social actors and ultimate beneficiaries of anticipated programs, small-scale farmers, have received only limited attention. Notable exceptions are provided, inter alia, by Bass et al. (2000), FAO (2002), and Nelson and de Jong (2003).

We argue that understanding the complexity of environmental change, diversity and dynamics of farming systems, and adoptability and flexibility of individual land users constitutes an essential first step for identifying and designing carbon sequestration activities that are both beneficial to local farmers and the global society. Such an approach focuses on the type and arrangement of activities that make most sense to key local resource managers, from the level of ecoregions down to the individual plot. Thus, our multi-scale assessment of environmental change should be perceived as an attempt to broaden the debate on the potential of carbon sequestration in drylands. It stresses the need to go beyond technical feasibility studies and to incorporate spatial and temporal variation, complexity, risk, and dynamics that are not always predictable.

The paper is divided in two major parts. The first part describes landscape and farming system dynamics in the Old Peanut Basin of Senegal. We use historic accounts to provide a broad-scale overview of changes in land use/land cover and farming systems as they have occurred in the Old Peanut Basin in Senegal over the last century. On a more detailed scale, we rely on remotely sensed imagery and change assessments with local farmers to illustrate specific pathways of change. Finally, at a household and field scale, actual land and soil management practices are assessed in two case study villages to investigate temporal and spatial variation at the level of individual farmers. The second major part of this paper discusses possible ways of integrating insights from such environmental histories and current management patterns into a more flexible community-oriented design of carbon sequestration programs for dryland environments.

2. Research setting

2.1. Description of the research area

This study, part of the SOCSOM (Sequestration of Carbon in Soil Organic Matter) project, was conducted in the West-Central Agricultural Region of Senegal, also known as the 'Old Peanut Basin'[3] (Fig. 1). This region is centered on the former, predominantly Wolof kingdoms of the Kayor and the Baol, but it also includes Serer

[3] The name goes back to the introduction of peanuts (groundnuts) by the French colonial power at the end of the 19th century in an area initially overlapping with today's administrative regions of Diourbel,

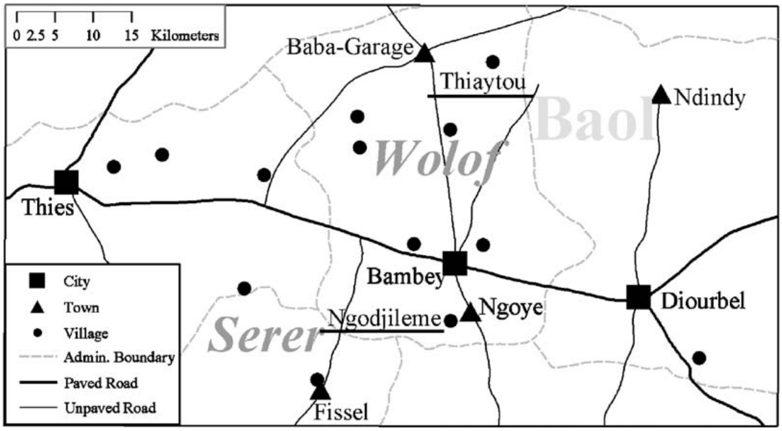

Fig. 1. Map of research area with main research locations, Old Peanut Basin. Source: Tschakert.

communities that extend as far south as the Saloum River. The Peanut Basin's sandy soils can be traced back to an ancient erg or dune field. Several periods of dune formation occurred during arid phases, beginning in the lower Quaternary, resulting in today's flat to gently rolling landscape of undulating dunes (Le Houérou, 1989). Generally, sandy, well-drained tropical ferruginous soils occur on plains and stabilized dunes. They are known locally as *dior* soils, occupying most of the Peanut Basin. These soils are deep, with little variation in characteristics. They are mostly brown and typically structureless. Bulk densities are generally high and the total porosity low (Seyler, 1993). Textures of *dior* soils are sandy or loamy sand. Organic matter content is typically less than 1%. Former dunes are dominated by red-brown soils, known as *tund*. These, too, tend to be sandy or loamy sand, with similar characteristics to the *dior* soils. A third type of soils is the colluvial brown and hydromorphic *dek* (or *xur*). These soils occupy the shallow interdunal clay depressions and valleys (Stancioff et al., 1986). They are thought to be formed by the lateral translocation of clays from the surrounding *dior* soils (Rodale, 1989). The organic matter content and clay content are relatively high, ranging from 3% to 4% and 8% to 12%, respectively (Seyler, 1993).

The contemporary climate is tropical semi-arid, with high annual temperatures and a stark contrast between a short wet season and a long dry season. A single annual rainy season occurs between June and October. Rainfall amounts and the length of the rainy season decrease from south to north. Furthermore, average annual rainfall has decreased in recent decades, and there is evidence of a longer-term decline based on the St. Louis rainfall records going back to 1855 (Gonzalez, 1997). Scientists at the US Geological Survey (USGS)/Earth Resources Observation Systems (EROS) Data Center used climate records and a surface-generating

(*footnote continued*)
Louga, and Thiès (Pélissier and Laclavère, 1980). Nowadays, the term "Peanut Basin or "Bassin Arachidier" reflects a certain socio-economic entity in Senegal (Stomal-Weigel, 1988).

algorithm to prepare a time-series of ten-year average rainfall maps from the 1930s to the late 1990s. These show a marked decline in rainfall over the Peanut Basin in the last 30 years. In the 1960s, the average annual rainfall ranged from approximately 400 mm in the north to 800 mm in the south. These amounts had declined in the 1980s and 1990s to approximately 280 mm in the north and 650 mm in the south. As is common with most areas of the Sahel, the primary characteristic of the rainfall is its variability, both spatially and temporally (Fig. 2). Recurrent and periodic drought is the major impediment to agricultural production. In addition, the high temperatures result in high evapo-transpiration rates and rapid desiccation of the soils, particularly the sandy soils with low organic matter content.

As for vegetation in the Peanut Basin, the agricultural transformations of the 20th century have left few remnants of its natural state. Most of the original wooded savannas and open woodlands have disappeared. The last vestiges of the original vegetation were cleared in the early 1900s, leaving in its place an agricultural parkland dominated by two acacias—the *Acacia raddiana* (Savi) Brenan in the north and *Faidherbia albida* (former name: *Acacia albida*) (Del) Chev. in the center and south (Pélissier, 1966). Although these two tree species form a quasi-monoculture, numerous other tree species can still be found, including *Adansonia digitata* L., *Tamarindus indica* L., *Balanites aegyptiaca*, (L.) Del., *Diospyros mespiliformis* Hochst.ex A. Rich., *Celtis integrifolia* Lam., and *Neocarya macrophylla* (Sabine) Prance. Many other species from the former Sudano-Sahelian woodland survive as isolated specimens in the fields and grazing lands of the village *terroirs*. At least 69

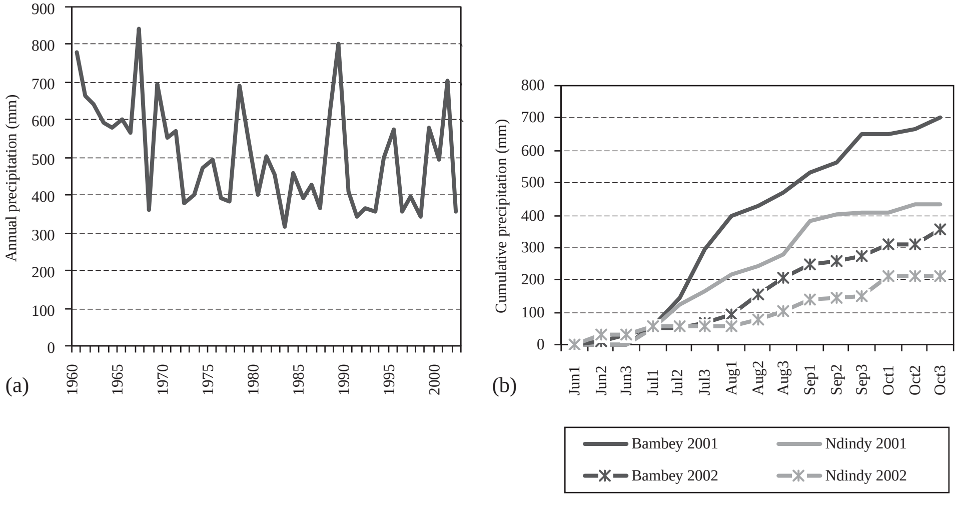

Fig. 2. Spatial and temporal variation in precipitation. (a) Annual precipitation (mm) for Bambey, located in the center of the Old Peanut Basin, 1960–2002. Data source: Direction de la Météorologie, Dakar, Senegal. (b) Cumulative precipitation (mm) during the cropping seasons 2001 and 2002 (June–October) for two selected locations (Bambey and Ndindy), expressed in decades (10-day periods). Data source: Direction de la Météorologie, Dakar, Senegal.

woody species can still be found in the central Peanut Basin (Seyler, 1993), some of which farmers effectively protect and maintain.

The average height of the tree stratum in the northern portion of the Peanut Basin is 6–8 m, increasing to 10–12 m in the south. Percent ground cover by woody vegetation ranges between 1% and 5%, with most areas in the 1–2% range (Stancioff et al., 1986). In a few local areas, cover can reach 6–10%.

Finally, the Old Peanut Basin is also known for its high population densities. Today, population varies between 120 and 225 inhabitants/km^2 (CSE, 2000). This level is the highest of any region in the Sahel, including the heavily farmed Central Plateau in Burkina and the cotton regions of southern Mali. Over 80% of the people living in this part of Senegal identify themselves as either Serer or Wolof, the two main ethnic groups (CSE, 2000).

2.2. *Methodology*

Research was conducted in several villages of the Old Peanut Basin (Fig. 1). The major components were a study of local farming systems, an assessment of management practices at the household level, and the monitoring of vegetation and land use change through remotely sensed imagery. Also, agricultural statistics (1960–2002) and existing geographical ethnographies were reviewed to complement the historical assessment. The methodological steps of the main research pieces are explained below.

2.2.1. *Farming systems, management practices, and research villages*

Thirteen villages were selected for the farming system assessment. A stratified sampling technique was used to capture the existing variation in terms of soil types, village size, ethnic groups, location, agricultural activities, and land use/land cover change as reconstructed from remotely sensed time-series. Research was conducted between December 2000 and January 2002, using highly participatory methods. These included the elaboration of village and natural resource maps, focus groups, large group discussions, change matrices with pebbles, Venn diagrams, and agricultural calendars, as well as environmental education through a theatrical performance with elementary school children. Three out of the total villages were selected for the assessment of management practices. A participatory wealth ranking technique was used to stratify all village compounds according to locally defined criteria of resource endowment. Out of three distinct wealth groups, 12 compounds per village were chosen at random and their fields and management strategies evaluated through field visits, household resource maps, semi-structured interviews, and field and household surveys.

The villages of Ngodjilème and Thiaytou, described in the case studies of this paper, are typical, though unlike examples for the rural communities in the research area (Table 1). Ngodjilème, a Serer village, is characterized primarily by a high people to land ratio, resulting in small total land holdings per compound, the main decision-making unit with respect to land use and allocation. In contrast, Thiaytou, a large Wolof village, has roughly five times as much village territory (*terroir*

Table 1
Basic characteristics of the two case study villages

Village characteristics	Expansion pathway	Intensification pathway
Name	Thiaytou	Ngodjilème
Location	N14°56′02.7″ W16°24′33.6″	N14°37′36.5″ W16°27′20.6″
Communauté Rurale (Arrondissement)	Dinguiraye (Baba Garage)	Ngoye (Ngoye)
Average precipitation 2000–2002 (mm)	351	520
Population	827	573
Village territory (ha)	1393	179
Compounds	90	56
Land/compound (ha)	15.5	3.2
Ethnic group (s)	Wolof, Fulani	Serer
Major sources of income	Trading, crops, animal fattening, livestock, remittances	Animal fattening, petty trade, seasonal migration, remittances

villageois) and five times more land per compound than Ngodjilème. Average field sizes also tend to be larger in the Wolof village (2.5 ha) compared to 0.6 ha in the Serer community.

In both villages, rain-fed agriculture, primarily on the basis of millet (*Pennisetum typhoideum* (L.) R. Br.), peanuts (*Arachis hypogaea* L.), sorghum (*Sorghum bicolor* (L.) Moench), and cowpeas (*Vigna unguiculata* (L.) Walp. ssp. unguiculata), constitutes an important source of income. Crop yields and area under cultivation might vary considerably from year to year and from household to household. At the same time, however, most farmers are also involved with animal husbandry and off-farm activities—trading, crafts, seasonal, and long-term migration. Such 'multi-enterprise rural household or production units' (Hunt, 1991) are fairly typical in rural areas throughout the Sahel. Their main purpose is to diversify the resource endowment in order to spread and, hence, reduce risks.

2.2.2. *Vegetation monitoring through time-series remote sensing data*

In order to gain a historical perspective on landscape dynamics, we assembled four sources of remotely sensed imagery; high resolution was emphasized. In all cases, the time-series data were taken during the dry season. We attempted to compare and quantify the surface resources over time using standard photo-interpretation techniques. Summaries of imagery sources that were used were as follows:

- *1968 Corona satellite photography*: small portions of two Corona frames, part of a world-wide archive from the 1960s and declassified in 1995, provided coverage of the study villages. The ground resolution of film positives is approximately 2 m. The cameras on the Corona satellites took panchromatic film-based photographs with each frame providing nominal ground coverage of 19.6 × 266 km (McDonald, 1995). For Senegal, 100% coverage is available.

- *1989 JICA aerial photography*: two black and white, 1:50,000 scale aerial photographs were used. The images, from a Japanese aerial mission over western Senegal for topographic mapping, provided good quality coverage of the study sites. The photographs were enlarged to approximately 1:10,000 for the present analysis.
- *1999 Landsat ETM+Image*: a Landsat Enhanced Thematic Mapper Image acquired on November 4, 1999 (Path 205, Row 50) was selected for a general, recent assessment of land use and land cover of the study sites. It provided a 30-m multispectral and 15-m resolution panchromatic coverage.
- *2001 Color aerial photography*: the authors collected vertical format 35-mm color aerial photographs over several sites in the Old Peanut Basin, including Ngodjilème and Thiaytou. The system, developed for a variety of land resource mapping and monitoring applications (Slaymaker, 1999), consisted of a portable aerial camera mount that was clamped to the doorframe of a low-wing single-engine airplane. The mount housed one 35 mm and two digital-color video cameras. A GPS receiver provided co-ordinate data for navigation and geographic reference for the imagery.

One of the pitfalls of working with several types of remotely sensed data over time is that, if care is not taken, the results can reflect differences in the image characteristics rather than actual changes taking place on the ground (Reid et al., 2000). We minimized the problem in several ways. First, we used a manual photographic interpretation method, which is useful when working with analog, film-based photographs. It provided more reliable results than scanning the photographs and using a digital image classification approach. It was also effective for integrating the photographic elements of tone, hue, texture, shape, size, pattern, shadow, and geographic context. Second, we analysed a limited number of local landscape features that could be easily recognized on the Corona and aerial photographs. These included shrubs and trees, grassy fallow and grazing land, hedges and woodlots, cultivated fields, bare soil, paths and roads, and traditional and modern village housing. We used the Landsat image to assess the area of cultivated and fallow land in 1999. Third, the authors are very familiar with the land resources, after spending considerable time in the field.

The analysis of the aerial photographs focused on three elements: shrub/tree density, area under cultivation, and area under fallow. Rather than producing time-series maps of the study sites, we quantified the tree density and area of cultivation and fallow directly from the photographs. Since the *terroirs* were limited in size, we counted every shrub and tree and calculated the densities by looking at the whole population, not a sample. The same applies for fallow areas. Thus, the numbers closely reflect reality, not a statistical inference. For this purpose of quantification, the following steps were taken.

First, the scale of each photograph was precisely determined. Next, the boundaries of the two *terroirs*, taken from field-based GPS surveys, were superimposed on each photograph. In order to examine the elements as a function of distance from the central village, concentric circles were superimposed on the photographs, representing distances of 500, 1000 and 2000 m from the centers of the two villages. Next, a systematic dot grid was randomly placed over the photographs. The dots falling within each concentric ring were counted to quantify the percent area of cultivated land and fallow. The area of compounds and land beyond the *terroir* boundaries were excluded from the analysis.

The tree density trend analysis was done using a regular grid, placed randomly over the photographs. The ground area represented by each grid cell was calculated in hectares from the photo scale. Trees were counted in all grid cells, tallied within the various concentric rings, and density/ha was computed. In counting, we used an approximate tree canopy diameter of 2 m as a minimum threshold, thus eliminating shrubs and very small trees. Also excluded were trees within the area of village compounds.

3. Landscape and farming systems dynamics

Both landscapes and farming systems in the Old Peanut Basin have undergone several changes since colonial times, which roughly overlap with the beginning of written historical records. The most significant ones are: (1) the conversion of traditional food crop systems into a market economy through the introduction of peanuts as a cash crop, (2) an overall decline in precipitation coupled with several periods of drought, (3) population growth, and (4) changes in land use and management as a consequence of state-led agricultural transformation programs. They all influence what decisions individual farmers make with respect to the distribution and allocation of labor, land, crops, livestock, forage, and trees between the various components of specific farming systems.

3.1. Major drivers of change

The first factor that radically transformed both landscapes and farming systems in the Peanut Basin was the introduction of peanuts. In the 1840s, the French colonial power in St. Louis began to push the cultivation of peanuts, from which they extracted oil for food and industry (Giffard, 1974). The colonial government impelled the local people to cultivate peanuts, resulting in a more or less continuous expansion of the crop into the sandy soils of west-central Senegal. Growing peanuts for commercial purposes began in the coastal areas of northern Senegal soon after the colonial conquest. By 1885, the production had reached 25,000 tons and grew to 500,000 tons in 1930. In the early 1900s, the French empire promoted economic policies that included a plan to promote peanut production for the European metropole. Through the early 1900s, cultivation of peanuts was expanded into what became the Old Peanut Basin. Expansion continued through the century, facilitated by the construction of railroad and road infrastructure, and the establishment of collection and processing centers in towns across western Senegal.

The extension of the agricultural domain along the eastern flank of the Peanut Basin was the result of the convergence of three factors (Pélissier, 1966): (1) the introduction of the *Mouride* (a major Islamic brotherhood in Senegal) communities along the margins of the former States and their propensity for colonizing new agricultural lands; (2) the success of peanut farming in Senegal and the efforts of the administration and agribusiness to encourage its expansion; and (3) the penetration of transportation routes eastward, particularly the construction of the Dakar-Bamako railroad. These factors interplayed to quickly drive the agricultural expansion, often at the expense of food crops, fallowing, and set-aside wooded areas. The railroad helped open new lands, starting in 1908 as it progressively made its way through the ''Agricultural Extension Region'' (Fig. 1) and on to south-eastern corner of the country.

By the late 1930s, peanut production was well established throughout the sandy soils of the 'Peanut Basin', well east of a north–south line projected through Diourbel. Production centers were also established in the Casamance. By 1950, peanut cultivation had spread into the heavier loamy and clayey soils of the Saloum, making inroads to Tambacounda, and into the Casamance.

Peanuts came to dominate the Senegalese economy. Peanut exports from Senegal far surpassed those of other West African regions. At independence in 1960, Senegal had inherited a dependence on export crops, with peanuts accounting for 80% of the monetary value of exports. The new government continued to promote expansion of Senegal's peanut production, from the core Peanut Basin into new lands to the east and south. Agricultural extension programs introduced new techniques and tools that would facilitate cultivation, including plows and animal traction. As a result, more land went into production, and the natural vegetation was removed.

The second major driving force behind the changes in local landscapes and farming systems in the Peanut Basin was and still is drought. Senegal experienced four major droughts during the 20th century (1910–1914, 1942–1949, 1968–1973, and 1982–1984). Between 1994 and 1998, an EROS/CSE field team revisited many of the sites originally established and studied in the early 1980s, including 136 sites located in the Peanut Basin. They found that the impact of the two recent droughts on woody vegetation was considerable over the northern two-thirds of Senegal, and that the phenomenon was uniformly present in both agricultural lands and non-agricultural regions (Tappan et al., 2000). Time-series landscape photographs taken at the ground sites show that while some mortality occurred following the 1982–1984 drought, tree cover in the Peanut Basin has been relatively stable since then.

The combined effects of the introduction and then dominance of peanuts and recurrent periods of droughts on natural resources of the Old Peanut Basin are multiple. The two greatest negative impacts since the 1950s are most likely the apparent breakdown of the traditional practice of fallowing in the rain-fed agricultural system and the decline in tree species and densities. Traditionally, when land availability was not a limiting factor, parts of the land in a village territory lay idle in bush fallow, an integral component of the traditional crop rotation cycle. This system maintained soil fertility, soil structure, and relatively high levels of organic matter content. It also helped maintain good crop yields. With the steady decline of the fallow system, Peanut Basin soils have become more degraded and vulnerable to wind erosion due to the loss of nutrients contributed by soil organic matter (Grosenick et al., 1990). However, farmers continue to produce low-yield crops on these soils. Whether or not yields have in fact decreased as a consequence of general degradation will be discussed later.

The impacts of these transforming processes on woody biomass have been discussed in several studies. Seyler (1993), for instance, conducted an extensive analysis of the *F. albida* agro-forestry system[4] in the Peanut Basin. One of the parameters he examined was farmers' perception of the reasons for decrease in cover of *F. albida* and other tree species. The leading reason cited by 129 informants was drought (39% of informers relative to *F. albida*, 33% relative to other species). He highlighted that the survival of *F. albida* was highly correlated with water-table depth, i.e. tree survival was poor when the water-table dropped as a result of drought. Dead *F. albida* trees tended to occur on higher ground while trees of lower elevations were usually not affected.

Lericollais (1987) monitored tree densities and species in the fields surrounding the Serer village of Sob in 1965 and 1985. He found an overall decrease of 23%, which he attributed the decline to human population pressures, animal traction, shortage of land, and the clearing of *F. albida*, and not to the direct effects of drought. He noted a drop in the water-table from 6 to 14 m that negatively affected tree survival.

Gonzalez (1997, 2001) investigated tree densities, biodiversity, and human carrying capacity for the past half century in north-western Senegal, including much of the northern Peanut Basin. Using various methodological tools, he showed quantitatively that tree density and biodiversity have decreased in north-western Senegal since the 1950s, resulting in a retraction of the Guinean and the Sudanian vegetation zones to the south, and a shift of Sahelian characteristics from the north. He found that mean tree density had declined from 10.1 trees/ha in 1954 to 7.8 trees/ha in 1989. He also reported that species richness declined by about 33% between 1945 and 1993, constraining local people's need for wood, habitation, medicine, and nutrition.

[4]The *F. albida* tree, often referred to by its local names (*kad* in Wolof, *sas* in Serer), stands out in the agricultural parklands of the Old Peanut Basin. This species did not belong to the original woodland (Pélissier, 1966), but is associated with all the old agrarian civilizations of the Sahel and parts of Sudan and Ethiopia. This leguminous tree is an integral component of an old traditional agroforestry system, often associated with millet and sorghum subsistence crops. It has many ecological and economic advantages. The trees lose their leaves in the rainy season, eliminating light or nutrient competition with crops (Seyler, 1993). The tree's abundant litter fall, its ability to fix atmospheric nitrogen and recycle nutrients via its deep tap root provides many Sahelian farming systems with their major source of nutrients while helping to maintain or increase soil organic matter content (Charreau, 1974). During the dry season, the tree parkland makes an effective windbreak thus reducing soil erosion (McGahuey, 1986). Economically, it has been determined that this system can increase millet yields by 30–50% while providing an important source of on-farm fuelwood, poles, and fodder (Seyler, 1993).

3.2. Assessing land use and land cover dynamics through remote sensing

Whether or not these overall dynamics can be substantiated through time-series of remotely sensed imagery was tested in the second major component of our multi-scale environmental histories approach. One of the best indicators for monitoring and assessing changes in landscapes and farming systems is to examine changes in the land use and land cover, particularly through the vegetation. Vegetation is a convenient proxy of the state of natural resources because it can be more easily observed and measured than changes in soils. For example, vegetation loss often represents the beginning of a chain of events ultimately leading to the loss of productivity and even desert-like conditions, since it can lead to feedbacks such as declining soil fertility (Breman and de Wit, 1983). Vegetation cover and diversity are thus barometers of change, both short- and long-term as well as natural or human induced. This section presents the results from the time-series remote-sensing analysis based on changes in tree density and fallow land as observed for the two study villages. Figs. 3 and 4 show images of these villages at three different time periods.

As for changes in tree density, the two village 'stories' reveal interesting differences (Table 2). On the Thiaytou *terroir*, two trends are readily apparent. First, tree density decreased dramatically with distance from the village, from approximately 4.5 to 0.46 trees/ha in 1989. Second, the time-series analysis confirms that tree densities have declined overall since 1968, falling precipitously in the outer areas of the *terroir* (from 1.4 trees/ha in 1968 to 0.46 trees/ha in 1989), while showing remarkable stability within the inner 500 m circle. In the 500–1000 m ring, tree density has in fact increased over the last decade, amounting to 5.3 trees/ha compared to 3.8 trees/ha in 1989. In Ngodjilème, the overall tree density has also decreased through time, though only slightly. In contrast to Thiaytou, tree densities actually increased with distance from the central village (from 3 to 4.5 trees/ha in 1989). The distance to village relationship appears not to be a factor in the Serer village. This village trend is also confirmed in other Serer *terroirs* in this part of the research area (Fig. 5).

The results on the use of fallow (Table 3) show an even more stark contrast between the two villages. In Thiaytou, fields are placed in fallow throughout the *terroir*, although more so in the remote fields (see Fig. 3a, dark patches). A striking fact is that fallow has only decreased slightly between 1968 and 1989 (from 64% to 43%), with an overall increase since then. In 2003 it amounted to roughly half of the entire village territory. Fig. 6 depicts such a recent change from continuous cultivation to fallow. In Ngodjilème, the impact of population pressure on fallow land has been much stronger. In 1968, only one-fifth of the total *terroir* was used for fallowing and has decreased ever since.

It can be concluded that the remote-sensing time-series, rather than confirming general trends, indicates some striking differences between the two case studies in the Old Peanut Basin. The next section examines these differences through two distinct pathways of change. These pathways are then used to estimate future changes in agricultural systems as they are likely to impact the potential of carbon sequestration.

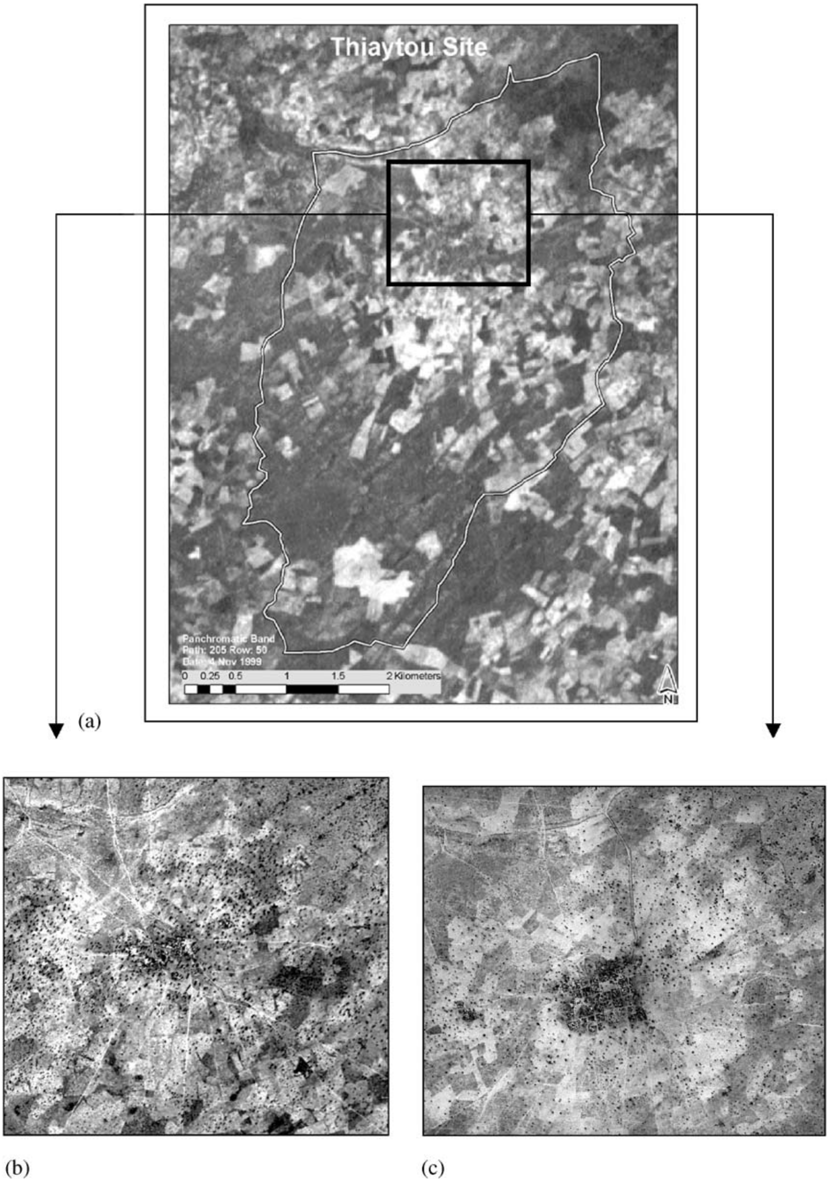

Fig. 3. Time-series views of the Thiaytou *terroir*, including the central village. (a) Landsat ETM+ (1999); (b) Corona satellite photograph (1968); and (c) JICA aerial photograph (1989).

3.3. Specific pathways of change

Although the two sample villages are part of the same biophysical environment and a very similar farming system based on rain-fed agriculture, they have reacted

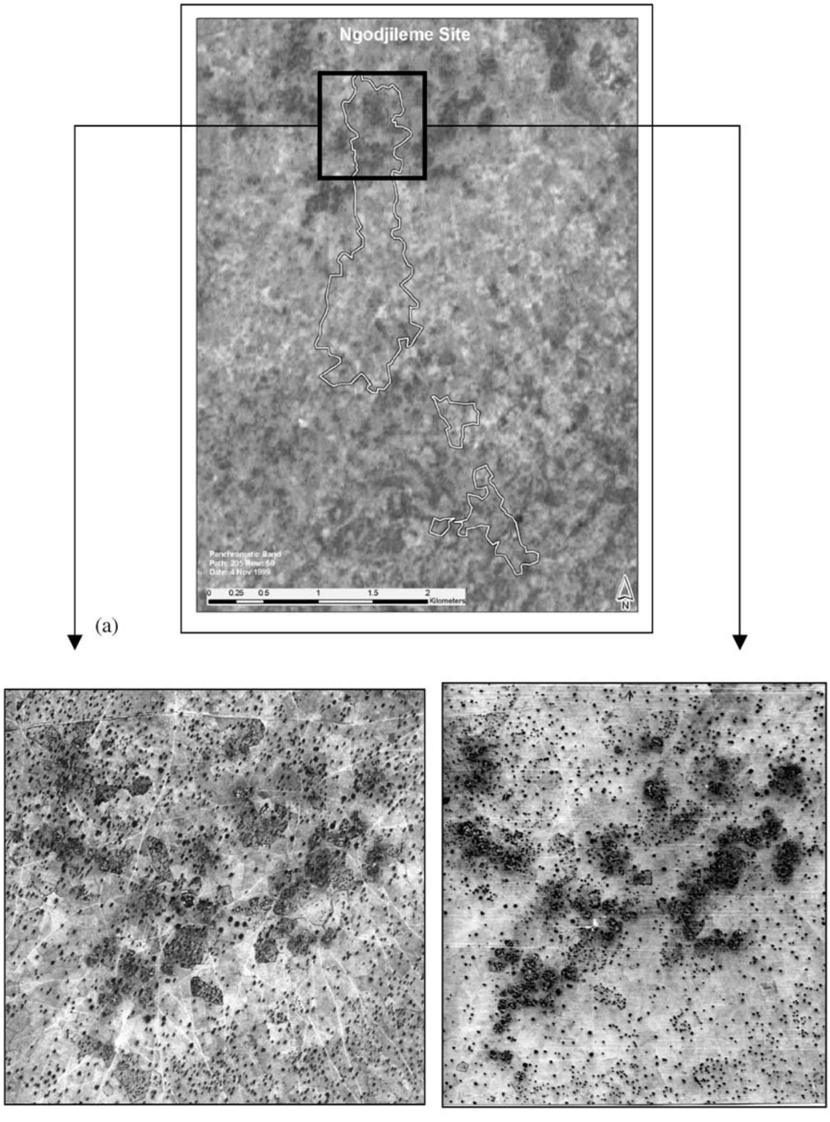

Fig. 4. Time-series views of the Ngodjilème *terroir*, including the central village. (a) Landsat ETM+ (1999); and (b) Corona satellite photograph (1968); and (c) JICA aerial photograph (1989).

and adapted very differently to the major drives of changes, as described above. While the Wolof village of Thiaytou represents an extensification 'pathway of change' (Scoones, 2001), the Serer village of Ngodjilème demonstrates an intensification pathway.

Table 2
Tree density trends (in trees/ha)

Distance from village center (m)	Thiaytou			Ngodjilème		
	1968	1989	2001	1968	1989	2001
0–500	4.57	4.68	4.45	3.05	2.95	2.80
500–1000	4.19	3.82	5.30	3.58	3.27	3.21
1000–2000	2.63	1.87	—	4.90	4.00	—
> 2000	1.40	0.46	—	4.70	4.48	—

Note: The 0–500 m tree count excludes village trees and compound trees.

Participants in both villages were asked to assess changes in land use, land cover, and management practices for three time periods since independence. The results, presented in Figs. 7 and 8, shed light on the specific pathways of change these two rural communities have been taking. With some exceptions, they are representative for the large majority of Serer and Wolof communities in the study area.

Farmers in Thiaytou recalled the period of peanut expansion, particularly in the 1960s, and the beginning of the 'Agricultural Modernization Program', introduced by the newly independent state. This program was clearly keyed toward increased production and yields of peanuts, the country's most lucrative remnant of the colonial time. It also included governmental credits for animal traction, improved seeds, and chemical fertilizer. Wolof farmers signed up eagerly for the program, thus accelerating agricultural development through technical process and individual indebtedness (Couty, 1972; Roch, 1972). As a result, many fields were under continuous cultivation with annual millet–peanut rotation and this despite population densities not higher than 51 in/km^2 (Pélissier, 1966). A pair of oxen and a plough, made available through agricultural credits, enabled more intensive cultivation. Yields were sustained through mineral fertilizer which was also distributed by the government. To maintain soil fertility, farmers relied primarily on mulching with millet stalks and, to a certain extent, on fallowing. According to smallholders in Thiaytou, livestock raising, manure production, and tree protection played only a very limited role during this time. This corresponds well with Pélissier's (1966) observation that animals were most often entrusted to Fulani (*peulh*) herders, which precluded an efficient integration of crops and organic matter inputs.

Significant changes occurred at the beginning of the 1980s, triggered by a mix of declining soil fertility, a drop in world market prices for peanuts, a severe drought, and a shift in governmental policies. With the removal of all state subsidies for agricultural inputs under the '*Nouvelle Politique Agricole*', farmers were forced to switch strategies. Many individual farmers and even entire families left the Baol, searching for new livelihoods in Senegal's urban areas as well as abroad. On the one hand, this most recent form of Wolof mobility gave rise to a new economic force of small-scale merchants, the *Móodu-Móodu*, who have been infiltrating urban markets from Dakar to Marseille and New York to Singapore (Ebin, 1993; Copans, 2000). On the other hand, it resulted in a heavily reduced agricultural labor force, making

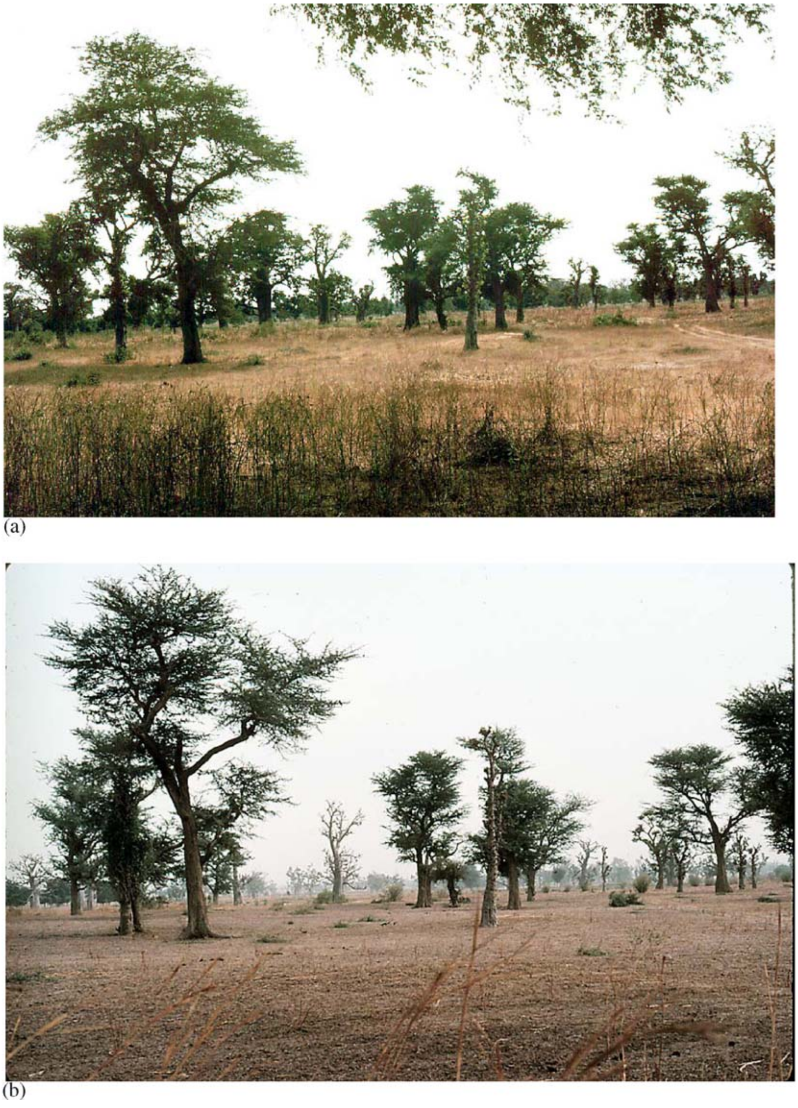

Fig. 5. A pair of field photographs taken in 1982 and in 2003 of a typical *F. albida* parkland in a Serer *terroir* about 15 km south of Ngodjilème. (a) 1982 and (b) 2003. Note: As in Ngodjilème, the photo pair shows remarkable stability of the agricultural tree parkland. Note also the very slow nature of tree growth and the fact that some pruning has occurred. Source: Tappan (1982, 2003).

this part of the Peanut Basin the ''epicenter of rural exodus'' (Badiane et al., 2000). Against the backdrop of this new pathway, those who stayed shifted from mulching to the application of manure, stubble grazing, and, for the first time, household waste to maintain soil fertility. The increase in fallowing has been interpreted as a

Table 3
Trends in the use of fallow (in % of village territory)

Distance from village center (m)	Thiaytou				Ngodjilème			
	1968	1989	1999	2001	1968	1989	1999	2001
0–500	32	32	—	27	13	0	—	0
500–1000	35	29	—	43	13	0	—	—
1000–2000	63	31	—	—	25	0	—	—
>2000	69	53	—	—	N/A	N/A	N/A	N/A
Entire territory	64	43	50	—	21	0	2	—

Note: Land that is not in fallow is cultivated, except for minor areas occupied by village compounds. N/A = Not applicable.

consequence of lacking seeds and the beginning of out-migration rather than a conscious and well-designed management strategy.

Most recently, another pathway of change has become apparent, not only in Thiaytou but also in several other rural communities in the north/eastern part of the Old Peanut Basin. The most striking element is the recent increase in grassy fallow, also apparent in the 1999 Landsat image. It underlines the most recent trends in outmigration. Several households in Thiaytou and surrounding villages have moved to Touba, the religious center of the *Mouride* brotherhood. Touba has seen an economic boom in recent decades, and it now ranks as Senegal's second largest city, offering important economic alternatives to agriculture. These new possibilities are particularly appealing to Wolof farmers who, according to Pélissier (1966), have always been less attached to their lands. Those who stayed now benefit from unused land, which has resulted in a rotational fallow scheme between farmers in Thiaytou and six surrounding villages. It allows them to leave some of their own land in fallow while cultivating fields left behind by relatives, despite the restrictive regulations of the law on land tenure (*Loi sur le Domaine National*)[5]. In addition, there are large blocks of fallow in the southern half of the *terroir* that belong to the village's *marabout*, an important religious leader, who himself has moved closer to Touba. All in all, smallholders in Thiaytou have followed an 'extensification' pathway, possible because of both the abundance of land within territory boundaries (Table 1) and the easy accessibility of land outside these boundaries. Today, every household in this village enjoys the luxury of having at least one field in fallow, which, a decade ago, would have been impossible.

In terms of management practices (Fig. 7), farmers in Thiaytou now increasingly rely on manure, household waste, organic matter inputs through stubble grazing,

[5] *Loi sur le Domaine National*, officially introduced in 1964 and complemented by other laws and decrees later. It encourages, *inter alia*, the use of all arable land while prohibiting land transactions and fallow periods longer than one year (Lo and Dione, 2000). In areas with high population pressure, like in many Serer villages, the law is enforced rather strictly. In contrast, in villages like Thiaytou, where land is abundant and conflicts over land less common, it is barely noticeable.

(a)

(b)

Fig. 6. A pair of field photographs/before and after (1983 and 1996); 18 km northeast of Bambey ground photo pair showing a site that was cultivated in 1983 (a) and became a grassy fallow area in 1996 (b). Source: Tappan (1983, 1996).

and fallowing in order to maintain soil fertility. Mulching has also increased in recent years. The clustering of trees around village's compounds, as illustrated in Table 2, is common among Wolof communities in the Peanut Basin. With local unwritten codes that extend protection to field trees, particularly *F. albida*, locals as well as outsiders are not likely to fell trees within sight of a village. However, trees in the outer reaches of the *terroir* are more vulnerable to exploitation. The increase in field trees in the 500–1000 m circle is most likely related to a mix of slowly growing environmental consciousness with respect to trees (Fig. 7 indicates timid tree

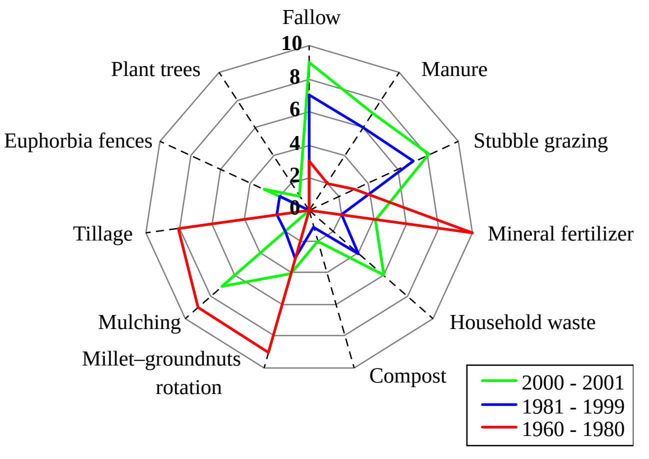

Fig. 7. Changes in land use and soil fertility management over time in Thiaytou, expressed in weighted points of importance/extent (1–10), as perceived by farmers. Source: Tschakert (fieldwork 2001).

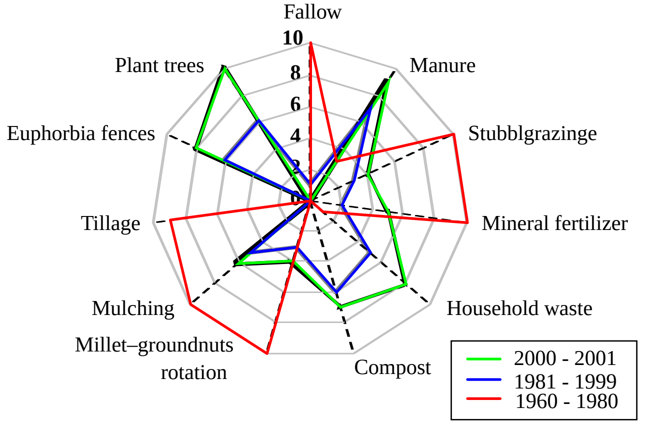

Fig. 8. Changes in land use and soil fertility management over time in Ngodjilème, expressed in weighted points of importance/extent (1–10), as perceived by farmers. Source: Tschakert (fieldwork 2001).

planting initiatives), the release in population pressure, and the regeneration of trees after the 1982–1984 drought.

The pathway of change observed in Ngodjilème, a typical Serer village, is indeed different from the one described for Thiaytou. Serer farmers in the entire area have been known as a highly egalitarian peasant population with strong attachment to their land and well-developed farming techniques (Pélissier, 1953, 1966). The key to their farming system in the pre- and post-independence period was a systematic integration of croplands, fallow, pasture land, village herds, and relatively dense *F.*

albida stands in form of 'farmed parklands'. This integration allowed Serer farmers to maintain their agricultural system despite population densities as high as 75–85 in/km^2 in the 1960s (Pélissier, 1966) and 130 in/km^2 in the 1980s (Garin et al., 1990). Although groundnuts have also penetrated the Serer farming system, the new cash crop did not jeopardize the role of millet, the primary food crop (Stomal-Weigel, 1988). Moreover, Serer farmers were more reluctant to go into debt during the 'Agricultural Modernization Program', at least initially. Fig. 8 depicts the central role of fallowing and stubble grazing during the 1960s and 1970s in combination with other practices also reported in Thiaytou. The main difference was the systematic use of fallowing and grazing animals, together with the careful maintenance of *F. albida* parklands, especially in more remote areas of the village territory (Table 3). This certainly contributed to higher organic matter inputs, which is important on the highly sandy soils of the Peanut Basin.

As in Thiaytou, the village of Ngodjilème experienced other significant changes in their farming system. The droughts of the early 1970s and 1980s combined with a new law on land tenure (*Loi sur le Domain National*) resulted in an increase in cultivated land that surpassed the extension reached through the state-led technical innovation. Given the small village territory of Ngodjilème (Table 1), it is not surprising that, as a consequence, fallow and pasture land declined considerably during the 1980s, forcing local herds to graze outside the village territory. *F. albida* parklands deteriorated, primarily because of the droughts (Lericollais, 1987; Lericollais and Waniez, 1993). Also, farmers stressed the lack of grazing animals for natural regeneration. Unlike many Wolof farmers, who have opted for outmigration during this difficult time, usually referred to as '*békor*', Serer farmers were much more reluctant to migrate (Couty, 1972), at least at this point. Instead, they embarked on a pathway of 'indigenous and adaptive intensification' (Mortimore and Adams, 1999), as observed in other parts of Africa with high population to land ratios (Boserup, 1965, 1981; Tiffen et al., 1994). Drawing from higher local labor inputs, locally available organic matter, and low-cost technologies, they seemed to successfully fight degradation (Garin et al., 1990). Fig. 8 illustrates this shift through composting, manuring, the application of household waste, and the establishment of euphorbia hedges around their fields; farmers in Ngodjilème tried to compensate for the cut in governmental subsidies.

In recent years, this trend has become even more pronounced, expressed in higher usage of organic matter input in combination with tree planting, including *F. albida*. Similar examples of such efficient integration of agriculture, animal husbandry, and tree protection are reported for other Serer villages in this area (Garin et al., 1990; Lericollais and Faye, 1994). An important element of this intensification process is the shift from herding to animal fattening, which allows compensating for the loss in fallow and pasture land (Table 3), as well as organic matter inputs from grazing animals. At the same time, it should be stressed that this intensification process would not have been possible with a parallel release in population pressure through seasonal and longer-term migration (Pontié and Lericollais, 1995; Lericollais et al., 1998). Today, people in rural Serer communities are increasingly mobile. In fact, farmers in Ngodjilème stated that not having at least one migrant per family would qualify a household as "poor."

3.4. Assessing farmers' management practices at the household and field level

The last element of our multi-scale assessment deals with individual households, the smallest unit of analysis used in this study. So far, historic accounts, remote-sensing time-series, ethnographies, and collaborative research with local farmers have shown that environmental histories are likely to be scale specific. In other words, although there are broad general trends that can be observed for an entire region, there are clear differences at the level of farming systems and their possibilities to manage land and soil resources. This section demonstrates that even within one and the same farming system, considerable variation exists both between and within individual households.

Table 4 illustrates the differences in organic matter input and the use of fertilizer in the 24 sample households. Overall amounts of inputs from manure and fertilizer are more than ten times higher in Ngodjilème than in Thiaytou, where stubble grazing and night corralling predominate (Fig. 9). This reflects the intensification versus extensification pathway. Nevertheless, the results from household surveys show large variation among the various households in the two research villages. These differences are more or less independent of the wealth categories (low, medium,

Table 4
Organic and inorganic inputs for all fields per household, 2001

Thiaytou						Ngodjilème				
Household	Wealth category	Fertilizer (kg/ha)	Manure (kg/ha)	Household waste (kg/ha)	Animals grazing (heads)	Wealth category	Fertilizer (kg/ha)	Manure (kg/ha)	Household waste (kg/ha)	Animals grazing (heads)
1	P	17	0	0	0	P	0	0	36	0
2	P	0	748	196	0	P	129	1926	147	0
3	P	0	0	0	0	P	431	568	0	0
4	P	0	0	0	0	P	245	742	57	0
5	M	0	183	0	24	P	135	2133	23	0
6	M	0	0	44	24	M	47	4444	0	0
7	M	0	0	0	90	M	68	0	0	0
8	M	0	0	0	18	M	300	524	10	0
9	R	0	0	0	0	M	176	0	0	0
10	R	28	0	0	32	R	124	2965	0	113
11	R	93	348	0	8	R	287	1695	0	0
12	R	35	0	78	35	R	0	2643	76	40
Mean		14	107	27	19		162	1470	29	13

P = poor household, M = medium household, R = rich household.
Source: Fieldwork (2001).

Fig. 9. Field used for night corralling and stubble grazing with cattle and sheep, Thiaytou. Source: Tschakert (fieldwork 2001).

and high resource endowment). Organic matter inputs among 24 households range from 0 to 4000 kg/ha. The use of mineral fertilizer, available again since 2000 through governmental credits, varies from 0 to 300 kg/ha. There is also significant variation in yields. While farmers in Ngodjilème report millet yields of 66–2180 kg/ha, those in Thiaytou are of 55–1460 kg/ha. Groundnut yields are also higher in the Serer village, amounting to 300–1760 kg/ha compared to 30–1200 kg/ha in the Wolof community.

Finally, our multi-scale assessment also reveals considerable variation within households, both temporally and spatially. As a strategy to spread risk among individual fields, farmers tend to manage their land on a patch-to-patch basis, which constitutes a key strategy of opportunistic farming (Mortimore and Adams, 1999). Farmers in both villages apply available, yet often scarce resources to certain fields and crops, but apparently not to others. Fig. 10 depicts such a patchy approach for one farmer in Ngodjilème. In 2001, in addition to organic matter input from grazing animals, this farmer added mineral fertilizer and manure from the homestead to his millet fields (Fig. 11). With annual crop rotation, peanuts will benefit from the previous year's inputs in 2002. In Thiaytou, where land is more abundant, rotational cycles usually also include fallow.

4. Implications for carbon sequestration programs

The results from our multi-scale assessment of environmental change in the Old Peanut Basin of Senegal can be summarized in the following five points: (1)

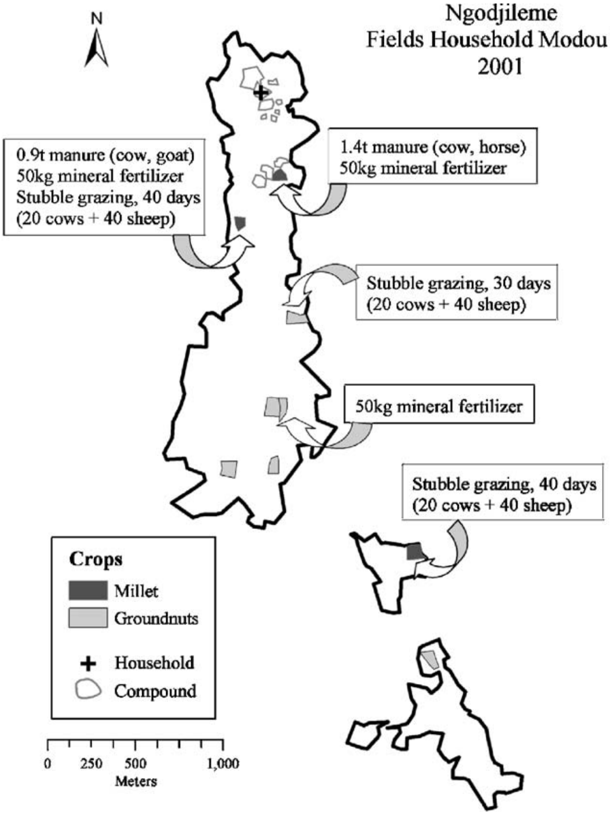

Fig. 10. Fields, crops, and management practices for a sample household in Ngodjilème, 2001. Source: Tschakert (fieldwork 2001: household surveys, soil, and biomass carbon measurements).

agricultural systems have changed significantly over time; (2) there are several different drivers of change. Some are apparent at a broad scale while others require investigation at much smaller scales; (3) rural communities have reacted and adapted very differently to these drivers of change, depending on geographical, social, cultural, and economic possibilities and constraints; (4) as a result of different types of adaptation, distinct pathways of change have emerged; and (5) the actual use of management practices depends on a farmer's perceptions, choices, and decisions and might vary considerably from one field to another and from one year to the next.

Our results closely match the ones Gray (1999) reported on landscape change and environmental degradation in Burkina Faso. She concluded that "… within a very small geographic area, there are different stories of environmental change" and that certain processes that can be detected at a larger scale have triggered distinct responses at much narrower scales. Focusing on smallholders as responsive agents within their farming systems reveals a variety of adaptive management practices. Many of these practices are an integral part of what Richards (1989) refers to as

Fig. 11. Farmer carrying manure from his homestead to an outfield, Ngodjilème. Source: Tschakert (fieldwork 2001).

“agricultural performance” or, as expressed by Scoones et al. (1996), “the result of improvisation, experimentation, innovation, and creativity”. The underlying rationale for such adaptive management is to flexibly respond to socioeconomic, environmental, political, and institutional changes while spreading risks as efficiently as possible, rather than to concentrate all efforts on maximizing agricultural output. We do not want to imply that all local initiatives are necessarily good and sustainable or one pathway of change better or more sustainable more than another. In fact, total system carbon values between the two villages (Tschakert et al., 2004) show no statistically significant difference. What we want to emphasize is that a more differentiated approach to long-term natural resource management, including soil fertility through carbon sequestration, could build on successful local examples that are most attractive and feasible from both a farming system and a livelihood perspective.

The complexity, dynamics, and variation that were made apparent through this multi-scale investigation suggest that predictable and controllable action through carbon sequestration schemes seems highly unlikely, if not impossible. In such dynamic and uncertain systems as African drylands, it seems futile to search for the ideal management or land use option that would both maximize carbon gains and local yields for the majority of farmers, and for a long period of time. Instead, it appears more beneficial to maximize farmers' flexibility and adaptability in the use of land use and land management strategies than to specialize too narrowly (Niemeijer, 1996; Bass et al., 2000). Encouraging flexibility will also enhance the resilience of the resource management systems in question (Brookfield, 2001).

The insights gained from this multi-scale environmental history for potential carbon sequestration programs in the Old Peanut Basin, and most likely other small-scale farming systems in dryland environments, are straightforward. We argue that it is imperative to understand the spatial and temporal variation as well as the heterogeneity among seemingly similar stakeholders since they determine which options make most sense to certain groups of smallholders. Without such a broader social context, all 'best management approaches' for the Old Peanut Basin, defined on the basis of their carbon storage potential, would seem equally realistic. These approaches include indigenous optimum agricultural intensification, the plantation of nitrogen-fixing *F. albida* (*kad*), long-term fallow-crop rotations, the conversion of cropland to grassland or pasture, and the application of 4–10 tons of manure, yielding 18.6–40.8 tons C/ha over 50 years (Tschakert et al., 2004). It then would be only too tempting to focus on a limited set of 'best practices' and apply them on a large scale. For the purpose of carbon contracts, monitoring, and verification, such "carbon monocultures" (Nelson and de Jong, 2003) constitute the most appealing option (Bass et al., 2000; FAO, 2002). The lessons from our environmental histories, however, suggest that such blanket applications risk undermining the very strength of the system that carbon programs intend to improve.

Applying the distinction used by Dixon et al. (1994), land that is "technically suitable" for carbon sequestration in the Old Peanut Basin may not necessarily be the one that is "socio-politically available". This is true for the level of farming systems and the level of individual households. In the case of farming systems, the differential pathways of change described in our case study demonstrate that, at this point, carbon sequestration practices based on the availability and accessibility of fallow lands, pastures, and converted croplands would make sense to farmers in Thiaytou but not to those in Ngodjilème. For the latter, much more constrained by land scarcity and the law on land tenure, practices related to continued agricultural intensification seem more feasible from a socio-political perspective. Such practices could involve increased amounts of manure, compost, green manure from small-scale agro-forestry, and short-term improved fallow, yielding as much as 32.2 tons C/ha over half a century (Tschakert et al., 2004).

Maximizing flexibility and diversity in carbon-offset projects is also key at the level of individual households. Instead of proposing a narrow set of carbon blueprints, we

Table 5
A farmer-centered approach to carbon sequestration: recommendations for drylands

Offer a basket of management choices from which farmers can choose
Measure carbon contents and soil fertility at the end of well-specified management periods
Identify strong local institutions to achieve an aggregate of participating farmers
Encourage a flexible and adaptive management and policy approach
Facilitate a shift in power and control from global to local ('principle of subsidiarity')
Stress equity issues through special emphasis on less influential groups ('late adopters')

recommend a program design built upon a basket of management options from which farmers can choose, depending on individual needs, capacities, and adaptive strategies to cope with risk and uncertainty. Such a design would fit best into the opportunistic management regime, as illustrated in Fig. 10. It would leave room for balancing scarce resources and including trade-offs and surprises. As in the case of *Fondo Bioclimatico*, a community-oriented carbon mitigation project in Mexico (Nelson and de Jong, 2003), farmers' individual management plans could be bundled and assessed for their carbon sequestration potential as well as anticipated costs and benefits. Economic assessments for specific management options and agro-ecoregions already exist (Woomer et al., 1998; De Jong et al., 2000; Tschakert, 2004) but more work needs to be done.

Such baskets of management choices are only one component of a flexible, community-oriented approach to carbon sequestration. Additional elements, listed in Table 5, include strong local institutions and a flexible, adaptive management and policy approach taken by national governments and international partner organizations. Without such complementary structures, individual actions pursued by farmers seem very difficult to sustain over the long run.

5. Conclusion

Carbon sequestration in soils is advocated as a potential win-win strategy to simultaneously address soil fertility decline and rural poverty in drylands of the developing world and global climate change mitigation. We argue that linking the biophysical potential for carbon-offset activities to social explanations of land use, land use change, and soil fertility management in specific agro-ecosystems is essential for the design of sustainable carbon mitigation projects. Understanding farmers' socio-political situation, the present state of farming systems, and the specific pathways of change over time provides a good starting point for long-term natural resource management projects that can be beneficial to smallholders in dryland regions, as well as to the global society.

A set of complementary tools from the social sciences, physical sciences, and remote sensing was used to better understand the complexities of environmental change, diverse farm and natural resource management strategies, and highly adaptive approaches at both household and community levels. The time-series satellite and aerial photographs added a unique historical perspective on land use and land cover, serving to triangulate information gathered from local stakeholder and other field data. The results from this multi-scale environmental history approach reveal high spatial and temporal diversity and variation that reflect distinct biophysical and socio-political dynamics.

To take into account such differential dynamics for the design of carbon-offset programs, we propose a farmer-oriented approach that integrates promising technical options more efficiently into the complex livelihoods of smallholders in dryland environments. This approach contains two major components. First, it includes a broad set of land use and management options that reflects the differential social dynamics within farming systems. Options that accommodate smallholders in systems following an 'extensification pathway' are likely to differ greatly from those useful under an intensification pathway. Second, it advocates a basket of possible management practices from which individual farmers can choose depending on their multiple needs, capacities, and adaptive strategies to cope with risk and uncertainty. Such a farmer-oriented management and project design implies that carbon is viewed as an additional element in people's livelihood portfolios rather than a technical venture detached from local social contexts.

Engaging in carbon mitigation activities in smallholder farming systems in drylands requires innovative ways of packaging both social and environmental goals and benefits that go beyond the measurable gains in the amount of carbon sequestered. Any attempt to prescribe a narrow set of presumably beneficial management strategies to a highly dynamic system will limit farmers' flexibility and adaptability to cope with risk and, thus, will increase rather than decrease their vulnerability.

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