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Desertification and a shift of forest species in the West African Sahel

Patrick Gonzalez*

Earth Resources Observation Systems Data Center, US Geological Survey, Washington, DC 20523-4600, USA

ABSTRACT: Original field data show that forest species richness and tree density in the West African Sahel declined in the last half of the 20th century. Average forest species richness of areas of 4 km^2 in Northwest Senegal fell from 64 ± 2 species ca 1945 to 43 ± 2 species in 1993, a decrease significant at $p < 0.001$. Densities of trees of height ≥3 m declined from 10 ± 0.3 trees ha^{-1} in 1954 to 7.8 ± 0.3 trees ha^{-1} in 1989, also significant at $p < 0.001$. Standing wood biomass fell 2.1 t ha^{-1} in the period 1956–1993, releasing CO_2 at a rate of 60 kgC person^{-1} yr^{-1}. These changes have shifted vegetation zones toward areas of higher rainfall at an average rate of 500 to 600 m yr^{-1}. Arid Sahel species have expanded in the north, tracking a concomitant retraction of mesic Sudan and Guinean species to the south. Multivariate analyses identify latitude and longitude, proxies for rainfall and temperature, as the most significant factors explaining tree and shrub distribution. The changes also decreased human carrying capacity to below actual population densities. The rural population of 45 people km^{-2} exceeded the 1993 carrying capacity, for firewood from shrubs, of 13 people km^{-2} (range 1 to 21 people km^{-2}). As an adaptation strategy, ecological and socioeconomic factors favor the natural regeneration of local species over the massive plantation of exotic species. Natural regeneration is a traditional practice in which farmers select small field trees that they wish to raise to maturity, protect them, and prune them to promote rapid growth of the apical meristem. The results of this research provide evidence for desertification in the West African Sahel. These documented impacts of desertification foreshadow possible future effects of climate change.

KEY WORDS: Desertification · Forest biodiversity · Land cover change · Natural regeneration of forest species · Senegal · Vegetation zone shift · West African Sahel

1. INTRODUCTION

Environmental change and evolving patterns of human activity have produced a precarious situation in the West African Sahel. Today, a growing population can provide for its subsistence needs only with difficulty on a land whose productivity has degraded markedly since the mid-20th century (UNDP 1997, UNEP 1997). Formerly productive land has declined through the process of desertification, defined by the United Nations Convention to Combat Desertification (UNCCD) as ‘land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors, including climatic variations and human activities’ (UNCCD 1994). Desertification in West Africa culminated in the Sahel drought of 1968–1973, a tragedy that witnessed famine and the death of up to a quarter of a million people (CDC 1973, UNCOD 1977).

Feedbacks between land degradation and precipitation link desertification and climate change. Desertification aggravates climate change through the release of CO_2 from cleared and dead vegetation and through the reduction of the carbon sequestration potential of desertified land. Conversely, climate change exacerbates desertification through the alteration of spatial

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*E-mail: pgonzalez@usgs.gov

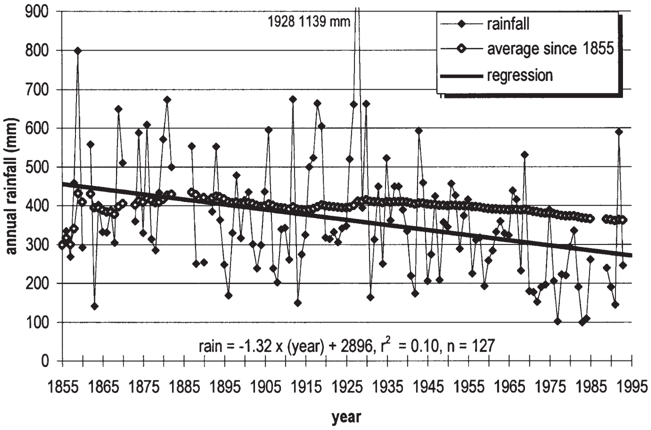

Fig. 1. Annual rainfall (mm) at St. Louis (Ndar), Senegal, 1855–1993. Data from Aubréville (1938) and from the Direction de la Méteorologie Nationale, Dakar, Senegal

and temporal patterns of temperature, precipitation, solar insolation, and winds.

Forest species guard against desertification and climate change through the provision of multiple ecosystem services, including soil erosion control, storage and transpiration of the water required for precipitation, carbon sequestration, and the formation of habitats for a diverse array of plant and animal species. Not only do trees and shrubs provide these ecosystem services, but they also provide firewood, structural timber, traditional medicines, staple foods, and drought emergency foods.

This report presents the results of ecological and socioeconomic field research (Gonzalez 1997) that documents a large-scale decline in forest species richness and tree densities in the Sahel. These results provide evidence for desertification in the West African Sahel. The research also analyzed human carrying capacity, the number of people that an ecosystem can support indefinitely under specified social circumstances (Gonzalez 1997). Finally, the research examined the natural regeneration of local species as the possible key to sustainable natural resource management.

The research addresses a lack of field documentation of the changes in forest biodiversity, tree density, and human carrying capacity in the Sahel. Limited studies (Shantz & Turner 1958, Poupon 1980, Olsson 1984, Lericollais 1988, Frankenberg & Anhuf 1989) have issued only anecdotal reports on changes in forest biodiversity and tree densities. Past estimates of carrying capacity (Gorse 1985, Kessler 1994) lacked field data. Finally, the examination of the practice of natural regeneration seeks to address the neglect of this practice, due, in part, to donor emphasis on the plantation of exotic species (World Bank 1988, FAO 1999).

2. RESEARCH AREA AND METHODS

The research area covers the 7600 km^2 of land between 15° 00′ and 16° 01′ N and between 16° 00′ and 16° 42′ W in the Republic of Senegal on the west coast of Africa. In 1988, it was home to 485 000 people living at an average density of 45 people km^{-2} in rural areas and 64 people km^{-2} overall (République du Sénégal 1988). The Wolof ethnic group constitutes the majority, with 84% of the population (Gonzalez 1997). Three-quarters of the population engage in rain-fed agriculture on three-quarters of the land, with the remaining space left to semi-nomadic pastoralism (Gonzalez 1997).

Fixed sand dunes oriented NNE-SSW dominate the area, with the most pronounced dunes of up to 10 m height reaching across its north-central portion. Elsewhere, lesser dunes grade down to level plains. Entisols with sand fractions >0.85 cover almost all of the area (Maignien 1965, Zanté 1984, Stancioff et al. 1986).

Aridity marks the area's climate. At St. Louis (Ndar) (16° 3′ N, 16° 27′ W), the 1855–1993 mean rainfall was 360 ± 160 mm yr^{-1} (Aubréville 1938; data from the Direction de la Méteorologie Nationale, Dakar, Sénégal) (Fig. 1). At Louga (15° 37′ N, 16° 14′ W), the 1919–1993 mean precipitation was 400 ± 160 mm yr^{-1} (République Française 1925; data from the Direction de la Méteorologie Nationale, Dakar, Senegal). Le Houérou (1989) estimated a Penman potential evapotranspiration at Louga of 2000 mm yr^{-1}. Serious droughts have hit the area in the periods 1910–1914, 1942–1949, and 1968–1973.

A north-south latitudinal gradient of increasing rainfall derives from distance to the Equator; an east-west maritime gradient of decreasing temperature derives from distance to the Atlantic Ocean. Starting in the research area and extending across West Africa, the increasing rainfall and decreasing evapotranspiration toward the Equator differentiate vegetation into 3 latitudinal bands of increasingly mesic species: the vegetation zones of the Sahel, the Sudan, and Guinea (Aubrevillé 1950, White 1983).

Thorny tree species with small, deciduous, sclerophyllous, and bi-pinnately compound leaves characterize the Sahel. Trees occur singly and widely spaced, with small groves occurring in some cemeteries and interdunal valleys. In the Sudan, trees collect in small groves and form dense thickets in low-lying seasonal ponds and fossil valleys. Trees form an open layer 8 to 20 m in height. Most Sudanian tree species possess pinnately compound leaves with leaflets larger than Sahelian species and produce dense, slightly sweet fruits. In the Guinean zone, mesic species form a closed-canopy, broad-leaved evergreen forest. High precipitation and insolation bestow Guinean vegetation with an energy surplus that many forest species allocate to the production of dense timber or succulent fruit.

A decline in rainfall and an increase in human population have occurred at the same time throughout this century. Linear regression of the 1919–1993 Louga rainfall data yields a negative slope ($r^2 = 0.10$, $p < 0.001$), while the population of Senegal doubled in the period 1945–1988, growing at a rate of 0.025 yr^{-1} (République Française 1950, République du Sénégal 1992). The trends in both rainfall and population remain consistent with trends across the Sahel (Hulme 1992, UN 1999, Nicholson 2000).

I defined a grid of squares 7.5 km × 7.5 km that divides the research area into 135 cells. From August 1993 to June 1994, I hiked 1900 km and spent a day and night in each of 135 villages to conduct forest inventories and semistructured interviews. The research followed the principles of Participatory Rural Appraisal (Carruthers & Chambers 1981, Chambers et al. 1989).

At the geographic center of each cell, I took an inventory of all trees and shrubs in a 1 ha quadrat. Centric systematic area sampling such as this produces a random sample (Milne 1959). Maps at 1:50 000 scale (République du Sénégal 1991) and 1989 aerial photos at 1:60 000 scale (described later in this section) permitted establishment of the geographic center of each cell. I counted every tree and shrub in each quadrat and measured, for all trees of height ≥40 cm, height (h), diameter at $h = 40$ cm, and, for trees of $h \geq 1.3$ m, diameter at $h = 1.3$ m. For *Acacia raddiana* of $h \geq 40$ cm, I also measured the diameter at the ground (Coughenour et al. 1990). From trees of $h \geq 3$ m near the quadrat centers, I extracted 137 wood cores using a 4.3 mm diameter 2-thread increment borer, measured heights and diameters, and photographed each tree.

The height and diameter measurements and wood cores permitted quantification of standing wood biomass and wood growth, using allometric equations (Poupon 1980, Coughenour et al. 1990) and growth rates (Catinot 1967, Giffard 1967, Cazet 1989, CTFT 1989) for West African species. Normalized difference vegetation index (NDVI) (Tucker 1979) data for the research area at 1.1 km resolution (CSE 1993), integrated over calendar year 1993 and correlated to biomass measurements across Senegal by the Centre de Suivi Écologique, permitted quantification of green biomass, the other component of total standing biomass. To calculate wood biomass of *Boscia senegalensis*, *Combretum glutinosum*, and *Guiera senegalensis*, the 3 shrubs that local people coppice for firewood, I measured branch volumes on 2 uncut 1 ha quadrats in the 'Arrondissement de Sakal' near the center of the research area and measured densities from wood samples gathered in the same area.

At the village on whose land the 1 ha quadrat lay or at the village closest to the quadrat, I spoke with 2 elders, 1 man and 1 woman, concerning their perceptions of environmental change. Each village chose the 2 elders to speak according to 3 criteria determined by the author: age ~65 yr in order to check the ranges of species at the time of the 1940s drought, knowledge of local flora, and continuous residence in the village. Semistructured interviews centered on a set of 10 precisely worded questions, although flexible discussions ranged over many topics. The first question consisted of a systematic check of the presence or absence of the 126 tree and shrub species in the research area (Table 1) ca 1945 and in 1993. To fix the time period of the historic species ranges, I specified that I was asking about the time period of the 1942–1949 drought. Therefore, the results on historic species ranges apply to a time around 1945.

Recollections of the historical presence or absence of species served as a proxy for non-existent data on historical distributions. Although recollections are inexact, the research required only 1 point of binary information: presence = 1, absence = 0. Restricting species richness data to this 1 point avoided the errors that more extensive questions would have introduced. In order to quantify the error of recollection of the male elders, the author recorded corrections made to ca 1945 recollections by male peers in group discussions or in individual conversations separate from the semistructured interviews, corrections to ca 1945 and 1993 data made by female elders, and corrections made from my observations of 1993 species distributions. Corrections to data from male elders amounted to only 1% of 34 020 data points.

The conviction with which most elders identified the presence or absence of species and the cogent manner in which they discussed the local flora demonstrated their thorough knowledge of natural history. Indeed, elders often identified the exact location of the last individual of a species that had disappeared from village lands. Countless times, farmers sat down in their compounds and provided running narrations of the layout of their fields, complete with the locations of individual trees. Vansina (1961) has examined African oral traditions and validated their general historical accuracy.

Examination of 137 aerial photos taken by the Institut Géographique National (IGN) of France and 83 aerial photos taken by the Japanese International Cooperation Agency (JICA) permitted quantification of total tree densities. IGN photographed the research area in February 1954 during Missions AOF 083 ND-28-XX and AOF 087 NE-28-II. IGN photos at 1:52 500 scale

Table 1. Flora of northwest Senegal (Gonzalez 1997). Vegetation zone affiliations for 106 species from Aubréville (1950) and Trochain (1940). Affiliations of other species are based on climate requirements and botanical characteristics. For the Wolof names, [text] indicates alternative names, (text) indicates the reason for an alternative name. S = southern part of the research area

Species	Wolof name	Botanist	Family	Vegetation zone
Acacia albida	Kàdd	Del.	Mimosaceae	Sudan
Acacia ataxacantha	Déd	DC.	Mimosaceae	Sudan
Acacia macrostachya	Sam, Cam (South)	Reichenb. ex Benth.	Mimosaceae	Sudan
Acacia nilotica adansonii	Neb Neb	(Guill. et Perrott.) O. Ktze.	Mimosaceae	Sahel
Acacia nilotica tomentosa	Gonake	(Benth.) A.F. Hill.	Mimosaceae	Sahel
Acacia raddiana	Séng	Savi	Mimosaceae	Sahel
Acacia senegal	Verek	(L.) Willd.	Mimosaceae	Sahel
Acacia seyal	Fonax (green), Surur (red)	Del.	Mimosaceae	Sahel
Acacia sieberiana	Sandandur	DC.	Mimosaceae	Guinea
Achras sapota	Sàppóoti	L.	Sapotaceae	Guinea
Adansonia digitata	Guy	L.	Bombacaceae	Sudan
Adenium obesium	Liisugaar	(Forsk.) Roem. et Schult.	Apocynaceae	Sudan
Afrægle paniculata	Kunsay, Ngunsay	(Schum.) Engl.	Rutaceae	Guinea
Afrormosia laxiflora	Kulukulu	Harms.	Fabaceae	Guinea
Agave sisalana	Yoos, Bissaw (South)	L.	Agavaceae	Sudan
Anacardium occidentale	Darkase	L.	Anacardiaceae	Sudan
Annona glauca	Dugor Yunoori	Thonn.	Annonaceae	Guinea
Annona senegalensis	Dugor Mer	Pers.	Annonaceae	Guinea
Anogeissus leiocarpus	Ngejan, Gejj (South)	(DC.) Guill. et Perrott.	Combretaceae	Guinea
Aphania senegalensis	Xewar	Radlk.	Sapindaceae	Guinea
Avicennia africana	Sanaar	P. Beauv.	Avicenniaceae	Guinea
Balanites ægyptiaca	Sump	(L.) Del.	Balanitaceae	Sahel
Bauhinia rufescens	Rand	Lam.	Caesalpiniaceae	Sudan
Bombax costatum	Garabu Lawbe, Dundul, Guy Jeeri	Pellegr. et Vuillet	Bombacaceae	Guinea
Borassus æthiopium	Ron, Xadin (small)	Mart.	Palmae	Sudan
Boscia angustifolia	Nus	A. Rich.	Capparidaceae	Sahel
Boscia senegalensis	Njandam	(Pers.) Lam. ex Poir.	Capparidaceae	Sahel
Cadaba farinosa	Ndeybarga, Ndeymarga (S)	Forsk.	Capparidaceae	Sahel
Calotropis procera	Paftan, Faftan (South)	(Ait.) Ait. F.	Asclepiadaceae	Sahel
Capparis tomentosa	Xareñ	Lam.	Capparidaceae	Sudan
Cassia occidentalis	Bànta[e(S)]mare, Mbànta[e(S)]	L.	Caesalpiniaceae	Sudan
Cassia sieberiana	Senjeñ	DC.	Caesalpiniaceae	Guinea
Ceiba pentandra	Béntéñe	(L.) Gaertn.	Bombacaceae	Guinea
Celtis integrifolia	Mbul	Lam.	Ulmaceae	Guinea
Chrysobalanus orbicularis	[Wo]rajj	Schum. et Thonn.	Rosaceae	Guinea
Cocculus pendulus	Sangool	(Forsk.) Diels	Menispermaceae	Sahel
Cocos nucifera	Koko	L.	Palmae	Guinea
Combretum aculeatum	Sawet	Vent.	Combretaceae	Sahel
Combretum glutinosum	Rat, Rat bu Goor (resprout)	Perrott. ex DC.	Combretaceae	Sudan
Combretum micranthum	Sexaw	G. Don	Combretaceae	Sudan
Combretum nigricans	Taap	Lepr. ex Guill. et Perrott.	Combretaceae	Guinea
Commiphora africana	Ngutoot	(A. Rich.) Engl.	Burseraceae	Sahel
Cordia senegalensis	Bee Gile	Juss.	Cordiaceae	Guinea
Cordyla pinnata	Dimb, Dimbu	(Lepr. ex A. Rich.) Milne-Redh.	Caesalpiniaceae	Guinea
Crateva adansonii	Xoril, Xoritt (South)	DC.	Capparidaceae	Guinea
Dalbergia melanoxylon	Jalamban	Guill. et Perrott.	Fabaceae	Sudan
Detarium microcarpum	Dànq	Guill. et Perrott.	Caesalpiniaceae	Guinea
Detarium senegalensis	Ditax	Gmel.	Caesalpiniaceae	Guinea
Dialium guineense	Solum	Willd.	Caesalpiniaceae	Guinea
Dichrostachys cinerea	Sinc	(L.) Wight et Arn.	Mimosaceae	Sudan
Diospyros ferrea	Selax	(Willd.) Bak.	Ebenaceae	Guinea
Diospyros mespiliformis	Alom	Hochst. ex A. DC.	Ebenaceae	Guinea
Ekebergia capensis	Farxañ	Sparrm.	Meliaceae	Guinea
Ekebergia senegalensis	Xak Cooy	A. Juss.	Meliaceae	Guinea
Elæis guineensis	Tiir	Jacq.	Palmae	Guinea
Entada africana	[Samba] Sayer	Guill. et Perrott.	Mimosaceae	Guinea
Erythrina senegalensis	Xunjël [Fall]	DC.	Fabaceae	Guinea

Table 1 (continued)

Species	Wolof name	Botanist	Family	Vegetation zone
Euphorbia balsamifera	Salan	Ait.	Euphorbiaceae	Sahel
Fagara xanthoxyloides	Dungidik, dun	Lam.	Rutaceae	
Guinea*Feretia apodanthera*	Sanceer	Del.	Rubiaceae	Sudan
Ficus congensis	Xël Baroom	Engl.	Moraceae	Guinea
Ficus gnaphalocarpa	Gang	(Miq.) Steud. ex A. Rich.	Moraceae	Guinea
Ficus ingens	Sanxay	(Miq.) Miq.	Moraceae	Sahel
Ficus iteophylla	Loro, Tat	Miq.	Moraceae	Sudan
Ficus platyphylla	Xël Mbap, Xaafor (resprout)	Del.	Moraceae	Guinea
Ficus polita	Xameful, Xamesul (South)	Vahl.	Moraceae	Guinea
Ficus sp.	Gojji		Moraceae	Guinea
Ficus sp.	Sàkkar		Moraceae	Guinea
Ficus sp.	Sasum		Moraceae	Guinea
Ficus thonningii	Dóobale	Blume	Moraceae	Guinea
Gardenia erubescens	Dibuton, Ñasel	Stapf et Hutch.	Rubiaceae	Guinea
Grewia bicolor	Kel	Juss.	Tiliaceae	Sahel
Grewia flavescens	Xorom Sap bu Jigéen	Juss.	Tiliaceae	Sahel
Grewia villosa	Xorom Sap	Willd.	Tiliaceae	Sahel
Guiera senegalensis	Nger	J.F. Gmel.	Combretaceae	Sudan
Heeria insignis	Waswasor	(Del.) O. Ktze.	Anacardiaceae	Guinea
Hexalobus monopetalus	Xaasew (North), Xaasaw	Engl. et Diels	Annonaceae	Guinea
Holarrhena floribunda	Selali	H. Huber	Apocynaceae	Guinea
Hymenocardia acida	Enkeleñ	Tul.	Euphorbiaceae	Guinea
Jatropha chevalieri	Wëttéenu Bët	Beille.	Euphorbiaceae	Sudan
Jatropha curcas	Tabanani	Linn.	Euphorbiaceae	Sudan
Khaya senegalensis	Xaay	(Desr.) A. Juss.	Meliaceae	Guinea
Kigelia africana	Ndambal	Benth.	Bignoniaceae	Guinea
Landolphia heudelotii	Tol	A. DC.	Apocynaceae	Guinea
Lannea acida	Son	A. Rich.	Anacardiaceae	Guinea
Lannea velutina	Songa Bay	Engl. et K. Krause	Anacardiaceae	Guinea
Lawsonia inermis	Fuddën	L.	Lythraceae	Sudan
Leptadenia pyrotechnica	Ceexaatu [Maam] Yàlla	(Forsk.) Dec.	Asclepiadaceae	Sahel
Macrosphyra longistyla	Telteliman	Hook. f.	Rubiaceae	Guinea
Maerua angolensis	Tocc [Ñaan]	DC.	Capparidaceae	Sudan
Maerua crassifolia	Xed	Forsk.	Capparidaceae	Sahel
Mangifera indica	Mango	L.	Anacardiaceae	Sudan
Maytenus senegalensis	Ndori, Ngandik, Genamdik	(Lam.) Exell.	Celastraceae	Sudan
Mitragyna inermis	Xos	(Willd.) O. Ktze.	Rubiaceae	Sudan
Moringa oleifera	Sap Sap	Lam.	Moringaceae	Sudan
Morus mesozygia	Sànd	Stapf.	Moraceae	Guinea
Nauclea latifolia	Nandoob	Sm.	Naucleaceae	Guinea
Opuntia linguiformis	Sol	Griff.	Cactaceae	Sudan
Opuntia tuna	Gargamboose	(L.) Mill.	Cactaceae	Sudan
Parinari marophylla	New	Sabine.	Rosaceae	Sudan
Parkia biglobosa	Wul	(Jacq.) Benth.	Mimosaceae	Guinea
Phœnix dactylifera	Tàndarma	L.	Palmae	Sahel
Phœnix reclinata	Coor, Soor	Jacq.	Palmae	Guinea
Piliostigma reticulatum	Ngiigiis	(DC.) Hochst.	Caesalpiniaceae	Sudan
Prosopis africana	Yir	(Guill., Perrott., et Rich.) Taub.	Mimosaceae	Guinea
Pterocarpus erinaceus	Win	Poir.	Fabaceae	Guinea
Pterocarpus lucens	Mbey Mbey, Beey Beey	Lepr. ex Guill. et Perrott.	Fabaceae	Sudan
Rhizophora racemosa	Xeex	G.F.W. Mey	Rhizophoraceae	Guinea
Ricinus communis	Xeymag, Xexam	L.	Euphorbiaceae	Sudan
Salvadora persica	Ngaw	L.	Salvadoraceae	Sahel
Sapindus saponaria	Soobaan	L.	Sapindaceae	Guinea
Sclerocarya birrea	Bér	(A. Rich.) Hochst.	Anacardiaceae	Sudan
Securidaca longipedunculata	Fuuf	Fres.	Polygalaceae	Guinea
Securinega virosa	Keng	(Roxb. ex Willd.) Baill.	Euphorbiaceae	Sudan
Sterculia setigera	Mbép	Del.	Sterculiaceae	Sudan
Stereospermum kunthianum	Feex, Yetu Dëmm, Peex	Cham.	Bignoniaceae	Sudan
Strophanthus sarmentosus	Coox, Soox	DC.	Apocynaceae	Sudan
Strychnos spinosa	Tëmb	Lam.	Loganiaceae	Guinea

(Table continued on next page)

Table 1 (continued)

Species	Wolof name	Botanist	Family	Vegetation zone
Swartzia madagascariensis	Dimbeli	Desv.	Fabaceae	Guinea
Tamarindus indica	Dakkar	L.	Caesalpiniaceae	Sudan
Tamarix senegalensis	Ngejji, Mbundu	DC.	Tamaricaceae	Sahel
Terminalia avicennoides	Reb Reb	Guill. et Perrott.	Combretaceae	Sudan
Vitex doniana	Lëng	Sweet	Verbenaceae	Guinea
Ximenia americana	Ngoloñ	L.	Olacaceae	Guinea
Zizyphus mauritiana	Sidéem	Lam.	Rhamnaceae	Sahel
Zizyphus mucronata	Sidéemu Bukki	Willd.	Rhamnaceae	Sudan

covered 60% of the research area while IGN photos at 1:51 700 scale covered 40%. JICA photographed the research area in March 1989, producing photos at a scale of 1:60 000. The JICA photos show superior clarity and resolution. I converted data from the IGN photos at 1:52 500 and 1:51 700 to data corresponding to 1:60 000 by using a set of IGN 1954 photos at 1:62 687 scale covering 24% of the research area. Each 1:62 687 photo matched a 1:52 500 photo.

Using an 8× aplantic lens magnifier, the author counted, for each cell, the trees in a grid of nine 12.5 ha circles spaced at 1.5 km and centered on the cell center. These counts covered 1209 circles totaling 151 km^2. Ground-truthing of the 1989 photos indicated that, in general, only trees of $h \geq 3$ m show under 8× magnification. The inventory of field trees verified this resolution. A heteroscedastic t-test showed no significant difference ($p = 0.30$) between the density of trees $h \geq 3$ m counted in the 135 1-ha quadrats (7.2 ± 0.9 trees ha^{-1}) and the density of trees counted on the 1989 aerial photos in 1209 12.5-ha quadrats (7.8 ± 0.3 trees ha^{-1}).

An original survey of well depths provided data on the depth of the surface water table across the research area. In addition, a published soil and water survey (Stancioff et al. 1986) provided maps of confined aquifer depths, soil types, and geological formations.

Original surveys of ethnic groups, Islamic brotherhood affiliations, infrastructure, and development activities in the 2600 villages in the research area provided fundamental data on the area's population. In addition, government census results (République Française 1938, République du Sénégal 1964, 1982, 1988) provided population by village over time.

3. RESULTS

From ca 1945 to 1993, the average species richness of areas of 4 km^2 declined from 64 ± 2 to 43 ± 2 species, a difference significant at $p < 0.001$ (Gonzalez 1997). Species richness of Guinean trees and shrubs, the most mesic species, fell by 52 ± 9%; Sudan species richness fell 29 ± 4%; the most xeric species, Sahel species, fell by 14 ± 4%. Aubréville (1950) and Trochain (1940) list the vegetation zones of West African tree and shrub species. The original range maps of the area's 126 tree and shrub species are consistent with the range limits for 67 species drawn by Aubréville (1950) and the limits for 20 species drawn by Trochain (1940).

From 1954 to 1989, densities of trees of $h \geq 3$ m decreased from 10 ± 0.3 trees ha^{-1} to 7.8 ± 0.3 trees ha^{-1}, a difference significant at $p < 0.001$ (Fig. 2). Both the fall in species richness of 33 ± 5% over 48 yr and the decrease in tree densities of 23 ± 5% over 35 yr translate to a rate of –0.008 yr^{-1}.

Research results clearly show a retraction of the Guinea and the Sudan vegetation zones to the southwest, tracking a concomitant shift of the Sahel from the northeast (Fig. 3). Vegetation zones shifted southwest 25 to 30 km in the period 1945–1993, an average rate of 500 to 600 m yr^{-1}. The historical change acted through a higher mortality among mesic species, leaving drought-resistant species to dominate the remaining tree cover.

The decline in mesic species is consistent with pollen analysis of a sediment core from Lac de Guiers, 2 km northeast of the research area (Lézine 1988). The core yielded the following pollen grain percentages from 2000 yr BP: Sahel spp. 2%, Sudan spp. 10%, and Guinean spp. 3%. These changed to the following percentages in the 1980s: Sahel spp. 3%, Sudan spp. 1%, and Guinean spp. absent. Furthermore, species inventories in 1993 are consistent with pollen analysis of a soil core from the southeast corner of the research area (Lézine & Edorh 1991). The core yielded current pollen percentages of 3% for Sahel spp. and 5% for Sudan spp., consistent with the 33%:67% Sahel:Sudan ratio of trees $h \geq 3$ m in 2 southeast cells in 1993.

The species richness recorded for each cell refers to an area of approximately 4 km^2 around each research village. The average 1988 population of the 135

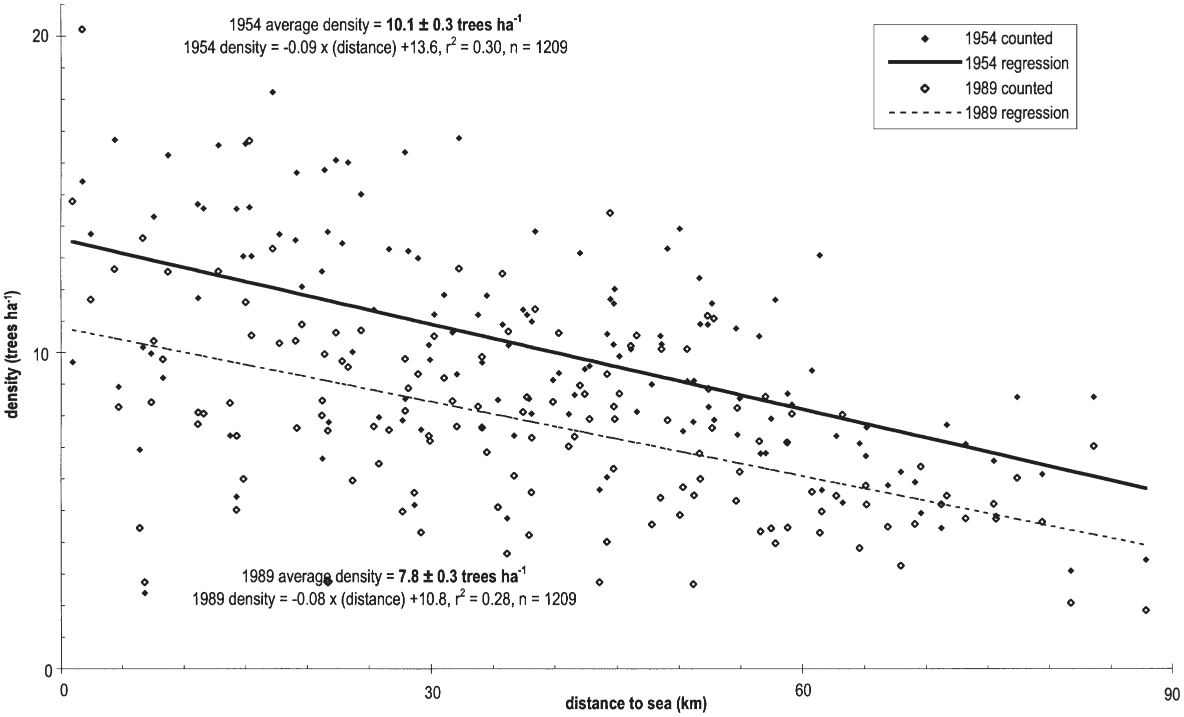

Fig. 2. Decrease in density of trees of height ≥ 3 m from 1954 to 1989, from aerial photos. Each point represents average density in 1 of 135 research cells

research villages was 242, with the populations of 97 out of 135 research villages between 100 and 600. A 1988 rural population density in the research area of 45 people km^{-2} yields an area of 2.2 ha person^{-1}. The product of a village's population and either the research area's average land area per person or the land area per person in each of the 57 cells with a rural population of >45 people km^{-2} produces an estimated average area of research village lands of 440 ha. Species richness ca 1945 and in 1993 showed very weak correlations with calculated area of village lands, r = 0.16 and r = 0.18 respectively, compared to correlations with longitude, described below, of r = –0.57 and r = –0.70.

Multivariate analysis using canonical correlations identifies latitude and longitude, proxies for rainfall and temperature, as the most significant factors, out of 215 ecological and socioeconomic variables, explaining the variance in the distribution, densities, and changes in trees and shrubs in the research area (Gonzalez 1997). For the 15 most significant factors identified by correlation coefficients, *t*-tests, ANOVA, gradient analyses, and principal components analyses, a final

Fig. 3. Shift of the Sahel and Guinean vegetation zones in Northwest Senegal (15° 00′ to 16° 01′ N, 16° 00′ to 16° 42′ W) from ca 1945 to 1993

canonical correlations analysis yielded rotated loadings of −0.91 for longitude on factor 1 and 0.97 for latitude on factor 2.

Standing biomass in the research area in 1993 averaged 15 t ha^{-1}, with wood comprising 12 t ha^{-1}. The standing biomass of trees across the research area decreased by 2.1 t ha^{-1} in the period 1956–1993, matching a cumulative firewood deficit in the same period of 2.1 t ha^{-1}. The 1956–1988 rate of reduction in standing biomass of 140 kg person^{-1} yr^{-1} released carbon into the atmosphere at a rate of 60 kgC person^{-1} yr^{-1} (Gonzalez 1997), somewhat less than the 100 kgC person^{-1} yr^{-1} released (World Bank 1996) from the burning of fossil fuels.

In 1993, total wood production was 190 kg ha^{-1} yr^{-1} out of a total net primary productivity (NPP) of 3.1 t ha^{-1} yr^{-1}. The rate of energy fixation in NPP averaged 1.7 kW ha^{-1}, of which humans directly used 210 W ha^{-1}, based on firewood use of 450 kg person^{-1} yr^{-1} by Wolof and 380 kg person^{-1} yr^{-1} by Fulbe (Berger 1989) and urban charcoal use of 95 kg person^{-1} yr^{-1} (CTFT 1989).

Analyses of forestry and population data show that rural firewood use exceeds firewood production from shrubs over 89% of the research area, affecting 95% of the rural population (Gonzalez 1997). The rural population density of 45 people km^{-2} exceeded the 1993 carrying capacity of firewood from shrubs of 13 people km^{-2} (range 1 to 21 people km^{-2}). Population data indicate that rural population density has exceeded carrying capacity since 1956. In addition, the sum of rural and urban charcoal use and urban firewood use exceeded the wood production of tree trunks. Conversely, wood production from trunks exceeded rural charcoal use alone, and the production of poles measuring 3 m × 0.15 m exceeded rural pole use.

4. DISCUSSION

The results of this research document a long-term change in forest vegetation in the Sahel. The 500 to 600 m yr^{-1} shift of forest species from ca 1945 to 1993 and the decline in tree densities from 1954 to 1989 constitute unique evidence for land degradation and desertification in the Sahel. Moreover, the 500 to 600 m yr^{-1} average rate of change foreshadows the projected rate of vegetation shifts in North America driven by climate change (Davis & Zabinski 1992, IPCC 1996).

This shift of xeric Sahel species into mesic Guinean areas in the Sahel is similar to a permanent 2000 m shift of xeric piñon-juniper woodland into mesic ponderosa pine forest in New Mexico, USA, caused by a 1954–1958 drought in which precipitation there fell to its lowest recorded levels (Allen & Breshears 1998).

The multivariate analyses of the data from northwest Senegal show that rainfall and temperature most explain the variance in the distribution, densities, and changes in forest species in the research area. Indeed, the shift in forest species follows a southward shift of isohyets, or lines of equal rainfall, in the Sahel during the same period. Analyses by the Centre Regional AGRHYMET, the institution that maintains the rainfall data archive for the Sahel countries, show that the 300 mm yr^{-1} isohyet shifted south 100 km between the periods 1950–1967 and 1968–1997 (CILSS 2000).

Since 1968, the Sahel has experienced the most substantial and sustained decline in rainfall recorded in the world within the period of instrumental measurements (Nicholson 2000). Linear regression of 1901–1990 rainfall data from 24 stations in the West African Sahel yields a negative slope amounting to a fall of 1.9 standard deviations in the period 1950–1985 (Nicholson & Palao 1993). Since 1971, the average of all stations fell below the 89 yr average and showed a persistent downward trend since 1951. Within the research area itself, linear regressions of 1855–1993 rainfall data at St. Louis (Ndar) (Fig. 1) and of 1919–1993 rainfall data at Louga also yield negative slopes.

The multivariate analyses seem to indicate that climatic factors override local anthropogenic factors in explaining the overall changes in vegetation. Examination of dead trees along the coast supports a predominance of climatic over local anthropogenic factors. Dead trees and stumps cluster along the coast such that 55% of the calculated dead woody biomass in all quadrats occurs within 12 km of the sea, compared to an average distance to the sea of 40 km for all 135 quadrats. Many dead trees along the coast still stand, but show no ax marks or any sign that humans directly caused their death. The sparsely populated coast offers a view of the state of the countryside before cultivation. For example, natural stands of *Euphorbia balsamifera* still occur there. In contrast, elsewhere in the Senegal Sahel, farmers have cut all natural stands of this species and replanted it along field boundaries. In the collective memory of local people, the vast areas along the coast have not been cultivated. The absence of intensive agriculture renders less likely a local anthropogenic cause for the death of the coastal trees. Nevertheless, anthropogenic factors on a regional scale, described below, may still have caused the decline in Sahel rainfall, and, therefore, in the changes in forest species in the Senegal Sahel.

Efforts to determine the relative importance of anthropogenic and climatic factors in explaining the long-term rainfall decline in the Sahel have produced evidence pointing both to changes in land cover (Charney 1975, Schlesinger et al. 1990, Xue & Shukla 1993, Wallace et al. 1994, Dirmeyer & Shukla 1996, Xue 1997, Claussen et al. 1999, Zeng et al. 1999, Wang & Eltahir 2000) and to changes in sea-surface temperatures (SST) (Lamb 1978, Folland et al. 1986, Street-Perrott & Perrott 1990, Rowell et al. 1995, Myneni et al. 1996, Nicholson & Kim 1997, Hulme et al. 1999).

A positive feedback mechanism between albedo, and therefore vegetation cover, and precipitation may help explain the Sahel drought (Charney 1975). Some research supports an albedo-precipitation feedback mechanism (Otterman 1974, Cunnington & Rowntree 1986, Xue et al. 1990, Diedhiou & Mahfouf 1996, Zheng & Eltahir 1997, Zeng et al. 1999), although other research disputes the importance of albedo (Jackson & Idso 1974, Ripley 1976, Wendler & Eaton 1983, Gornitz & NASA 1985, Nicholson et al. 1998).

Recent modeling and observations (Diedhiou & Mahfouf 1996, Xue 1997, Zeng et al. 1999, Wang & Eltahir 2000) demonstrate that a combination of factors, including vegetation cover, soil moisture, and SST, best explains the reduction of rainfall in the Sahel and that vegetation cover predominates among these factors. Diedhiou & Mahfouf (1996) modeled changes in albedo, soil moisture, land surface roughness, and SST and calculated a rainfall deficit over the Sahel similar to observed rainfall. Xue (1997) used coupled biosphere and general circulation models to show that observed rainfall and runoff declines in the Sahel result from reductions in moisture storage and availability caused by degradation of vegetation. Zeng et al. (1999) compared actual rainfall data from the period 1950–1998 with the output of a coupled atmosphere-land-vegetation model incorporating SST, soil moisture, and vegetative cover. Their results indicate that actual rainfall anomalies are only weakly correlated to SST by itself. Only when the model includes variations in vegetative cover and soil moisture does it come close to matching actual rainfall data. Another coupled surface-atmosphere model (Wang & Eltahir 2000) indicates that, whether anthropogenic factors or changes in SST initiated the Sahel drought of 1968–1973, permanent loss of Sahel savanna vegetation would permit the drought conditions to persist.

In effect, because evapotranspiration constitutes the only local input to the hydrologic cycle besides surface water, a reduction in vegetative cover leads to reduced precipitation, initiating a positive feedback cycle. Therefore, degradation of vegetation cover in moister areas south of the Sahel may have decreased continental evapotranspiration and reduced precipitation in the Sahel. The results of Xue (1997), Zeng et al. (1999), and Wang & Eltahir (2000) support a mechanism proposed by Aubréville (1949), namely, that deforestation of tropical rainforests in the Congo vegetation zone from the Republic of Guinea to Côte d'Ivoire may have reduced the evapotranspiration inputs essential to the maintenance of the southwest monsoon. Reduced rainfall over an extended period would reduce the vegetation cover in the Guinean zone to the north. This in turn would decrease rainfall and vegetation farther north in the Sudan, eventually reducing rainfall and vegetation in the Sahel. Human activities in the distant rainforests may initiate a concatenation of climatic changes that ultimately touch the Sahel.

The research results on human carrying capacity in Northwest Senegal show that not only do the quantitative uses of firewood and charcoal exceed the area's wood production, but that the fall in species richness has also reduced people's options qualitatively. For example, rural women depend on 2 particular shrub species for firewood because of the size of the branches, high wood density, and ease of collection. Beyond that, few fallback species remain. The fraction of women that reported shrub species as most prevalent in firewood use fell from 87 % ca 1945 to 50 % in 1993. With respect to traditional medicine, 25 useful species have diminished significantly. Furthermore, 8 species that provided fruit, leaves, and gum in past droughts have disappeared from as much as 53 % of their range. If a grave famine hit the area in its current condition, people would not be able to find the emergency foods that saved others in past episodes.

To restore the human carrying capacity of this arid land, ecological and socioeconomic factors favor the natural regeneration of local species over the massive plantation of exotic species. Because of a lack of water, massive plantations of *Eucalyptus camaldulensis* and other exotics by foreign aid projects in the region show a survival rate of only 18 %, leading to costs of up to $50 per surviving tree (Gonzalez 1997). The only successful exotic plantation efforts include $22 million of maritime dune plantations of *Casuarina equisetfolia* along the Atlantic coast, which the government keeps off-limits to rural villagers, and individual shade plantings of *Azadirachta indica* and *Prosopis juliflora* in villages and along roads. Nevertheless, plantations account for only 0.4 % of the standing biomass and 3 % of the wood production in the research area.

Farmers and herders in Africa have traditionally adapted to arid and semi-arid conditions by promoting the natural regeneration of trees and shrubs. Natural regeneration is a practice in which farmers and herders seek to reconstitute the vegetative cover either by setting aside parcels of land or by selecting small trees in their fields, protecting them, pruning them to promote rapid growth of the apical meristem, and raising them to maturity. The practice requires no special inputs and encourages the propagation of well-known, multiple-use trees. The Sereer in Senegal (Lericollais 1973) and the Mossi in Burkina Faso (Kessler 1992) have doubled tree densities in certain semi-arid areas with *Acacia albida* and *Butyrospermum parkii*, respectively.

In the research area, small trees (h < 40 cm) occur at a density of 160 ± 18 trees ha^{-1}, over 20× the density of adult trees ($h \geq 3$ m). Because drought-tolerant Sahel species account for 37% of small trees, natural regeneration under current climatic conditions could potentially reconstitute the vegetative cover. In the semi-structured interviews, 77% of local people favored natural regeneration of local species over plantation of exotics. In a survey of 27 forestry project directors and technical advisors across Senegal, 67% also favored natural regeneration (Gonzalez 1997).

According to local people, the browsing of livestock and the seasonal clearing of agricultural fields most threaten small trees. Traditional live fencing using *Euphorbia balsamifera* and thorny branches together with the social fencing of village agreements and surveillance would allow drought-tolerant trees to flourish, as demonstrated by stands of *Acacia albida* of $h \geq$ 3 m at up to 20 trees ha^{-1} in densely populated parts of the research area.

5. CONCLUSION

Original field data show that forest species richness in northwest Senegal fell 33% from ca 1945 to 1993. Densities of trees of $h \geq 3$ m declined 23% from 1954 to 1989. These changes shifted the Sahel, Sudan, and Guinean vegetation zones towards areas of higher rainfall at an average rate of 500 to 600 m yr^{-1}. The changes also decreased human carrying capacity below actual population densities. The possibility of future droughts in the Sahel raises the specter of another grave episode sometime in the 21st century. Yet, this research shows that the impoverished flora may have lost its capacity to provide aid to a substantial population ravaged in the future by famine. This renders imperative a sustainable system of resource management. Ultimately, only natural regeneration can cover an extensive surface area, a condition necessary not only to map a comprehensive system of natural resource management, but also to engage positive climatic effects. In the face of desertification and climate change, sustainable natural resource management in the Sahel depends on natural regeneration.

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