Global Change Biology (1996) 2, 137–141

Archival photographs show no climate-induced changes in woody vegetation in the Sudan, 1943–1994*

WILLIAM H. SCHLESINGER† and NICHOLAS GRAMENOPOULOS‡
†Departments of Botany and Geology, Duke University, Durham, NC 27708, ‡The MITRE Corporation, 7525 Colshire Drive, McLean, VA 22102, USA

Abstract

An archive of satellite and aircraft photographs of the western Sudan showed no long-term (1943–1994) trends in the abundance of trees despite several decades of recent drought in this region. These data extend the extant historical record of vegetation change in the African Sahel, where recent fluctuations in vegetation greenness have been monitored with the NOAA Advanced Very High Resolution Radiometer since 1980. Despite substantial population turnover, woody vegetation is not yet indicative of the recent climate changes in this region.

Keywords: climate change, desertification, remote sensing, sahel, sudan, vegetation change

Received 3 July 1995; revision accepted 24 October 1995; accepted 10 November 1995

Introduction

Global warming, induced by increasing concentrations of greenhouse gases in the atmosphere, has the potential to produce worldwide changes in precipitation as well as temperature (Rind *et al.* 1990). These climatic changes are expected to produce shifts in the natural boundaries of vegetation, especially at the borders of deserts (Emanuel *et al.* 1985; Schlesinger *et al.* 1990). Recently, Tucker *et al.* (1991, 1994) analysed the normalized difference vegetation index (NDVI) of vegetation greenness, derived from the NOAA Advanced Very High Resolution Radiometer (AVHRR) to suggest cyclic changes in the extent of the Sahara desert that were correlated to variations in precipitation along its southern border during the 1980s. There was little evidence for an overall increase in the area of desert, which might indicate desertification of the Sahelian grasslands along its southern border.

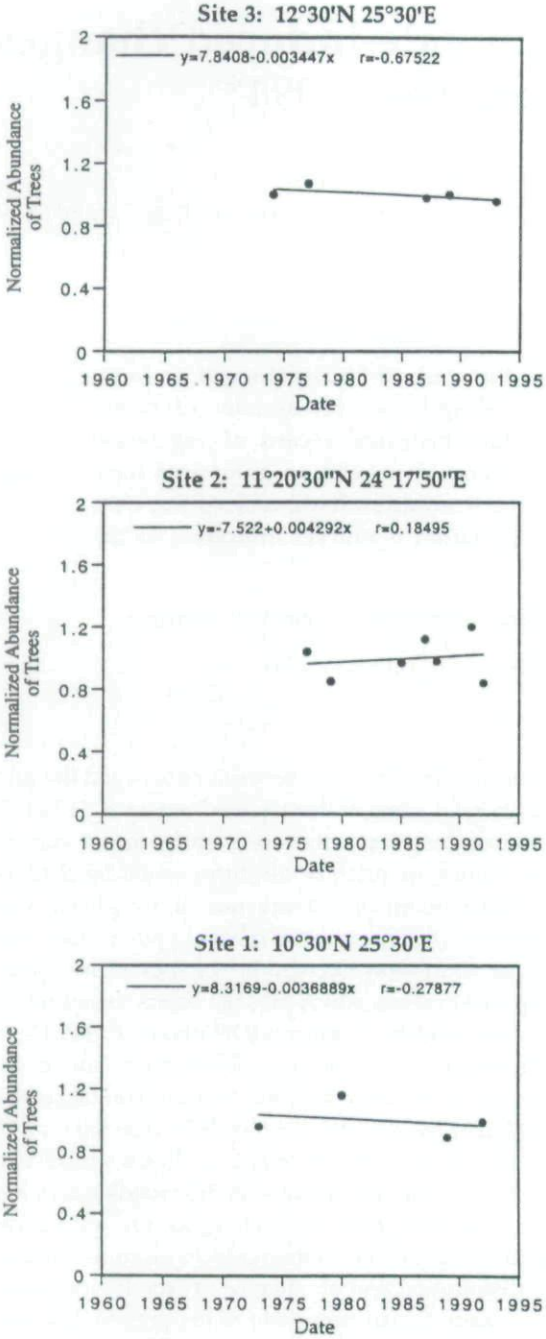
Grasses comprise a large fraction of the vegetative cover in the Sahel, accounting for rapid annual and seasonal fluctuations in vegetation in response to precipitation and the direct link between rainfall and the success of pastoral grazing in this region (Breman & de Wit 1983). However, long-term directional shifts in the climate of arid regions are often better documented by changes in the distribution and abundance of long-lived woody vegetation (Peters *et al.* 1993). Woody plants are buffered against short-term fluctuations in rainfall by virtue of deep root systems which provide access to soil moisture that is unavailable to grasses (DeLucia *et al.* 1988; Dawson & Ehleringer 1991). For example, the abundance of *Larrea tridentata* is directly correlated to mean annual rainfall in the Mojave Desert, USA (Beatley 1974; Woodell *et al.* 1969), and the cover of woody plants is directly correlated to the mean annual precipitation in dry woodlands of Kenya (Coughenour & Ellis 1993). Here, we use an archive of satellite and aircraft photographs to examine changes in the distribution and abundance of woody vegetation in the western Sudan from 1940 to the present. The results of our study do not show a statistically significant trend, corroborating the conclusions of Tucker *et al.* (1994) and Hellden (1990).

*Many of the data for this paper are in classified intelligence archives. As a consequence, the options for evaluating the paper and for ensuring that other scientists can reproduce the analysis are constrained. Publication of this paper in *Global Change Biology* is intended to illustrate the potential use of, and stimulate discussion on the role of, classified data in the open scientific literature. Limitations on access to the data make it impossible for the journal's usual review process to assess all aspects of data quality, selection, or interpretation

Correspondence: William H. Schlesinger, fax +1-919-660-7425, e-mail schlesin@acpub.duke.edu

Methods

Lamprey (1975) reported that the Sahara was expanding southward at a rate of 5.5 km y^{-1} in the central Sudan. We used the archive of remotely sensed photography from aircraft and satellites operated by the Intelligence Community and Department of Defense to provide a record of the abundance of woody vegetation in Darfur



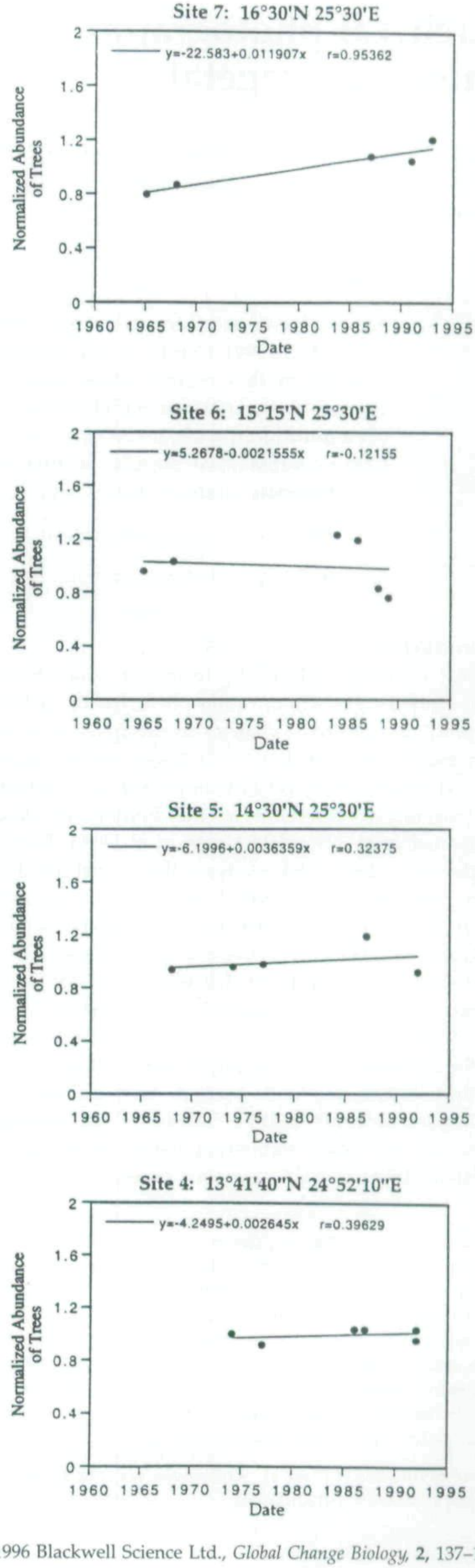


Fig. 1. Normalized abundance of woody vegetation, 1965–93, at 7 sites along a transect from 10° 30′ N (site 1) to 16° 30′ N (site 7) at 25° 30′ E. longitude (unless otherwise noted) in the western Sudan.

Province, western Sudan — a region of suspected, potential desertification (Rapp 1976; Holcombe 1987; El Moghraby 1987). First, we selected 7 sites extending from 10° 30′ N to 16° 30′ N along the 25° 30′ E longitudinal meridian to provide a transect extending from the Sahara desert through the Sahel zone. All available, usable photographs of these sites, spanning the period from 1940 to the present, were obtained from the archive. Second, 4 additional sites were selected along the transect in the area east of Jebel Marra, which Lamprey (1975) indicates as especially vulnerable to desertification. In each area, we chose sites that showed no apparent human impact (e.g. clearing for agriculture or firewood) at any point in the repetitive sequence.

We used geological features to delineate a specific study area that could be relocated in each photograph of each site. The census area in each of the 7 sites of the initial transect was variable from site-to-site, but it always contained between 100 and 1000 trees. The area examined in each of the 4 sites near Jebel Marra was ≈170 m × 170 m, and it typically contained 100–500 trees or shrubs greater than 4 m diameter. Each area was selected to avoid riparian areas that often support unusually dense vegetation in arid regions (Schlesinger & Jones 1984; Coughenour & Ellis 1993).

The woody vegetation in western Sudan is dominated by *Anogeissus leiocarpus*, various species of *Acacia*, and other desert trees (Wickens 1976; Ahmed 1982). Individual plants greater than 4 m diameter were counted in the census area delineated in each photograph. The count of trees in each photograph recognized new individuals that entered this minimum size class since the previous photograph of the site, as well as trees that had disappeared from the site. A rate of population turnover was calculated from these data, but it is important to remember that the 'birth' or 'death' of trees between consecutive censuses reflects the appearance or disappearance of individuals from the minimum size class, rather than the confirmed birth or death of individuals. The final count of trees in each photograph was normalized against the mean of counts from all repetitive photographs of the site to give an index of temporal fluctuations in vegetation. When sufficient data were available, we examined the trends in vegetation in photographs taken at the end of the wet season (September to November), as a subset of the entire photographic record of each site. In Senegal, Tappan *et al.* (1992) found that the NDVI peaked during the autumn rains.

Results

Figure 1 shows the normalized abundance of woody plants at the 7 sites comprising the transect from 10° 30′ N to 16° 30′ N in the western Sudan. This transect extends from deciduous savanna woodland (site 1) in the south, through thorn savanna and semi-desert scrub, to true desert (site 7) in the north (Wickens 1976). Owing to the small number of repetitive photographs at each site, the trends at sites 1–6 are not statistically significant. At these sites, the long- term average rate of population turnover ranges from 1.0 to 2.0% per year (Table 1) — not unlike that recorded in physiognomically similar woodlands in North America, including pinyon (*Pinus monophylla*)–juniper (*Juniperus osteosperma*) woodlands of the Great Basin desert of Nevada and Utah (Blackburn & Tueller 1970; Beatley 1980). No directional shifts in vegetation are evident as a function of latitude; however, there is an increase in the abundance of woody vegetation at the northernmost site, located in the Sahara desert. Here, the count of woody plants showed a significant ($P < 0.05$) increase of 1.5% per year between 1965 and 1993.

Figure 2 shows changes in the normalized abundance

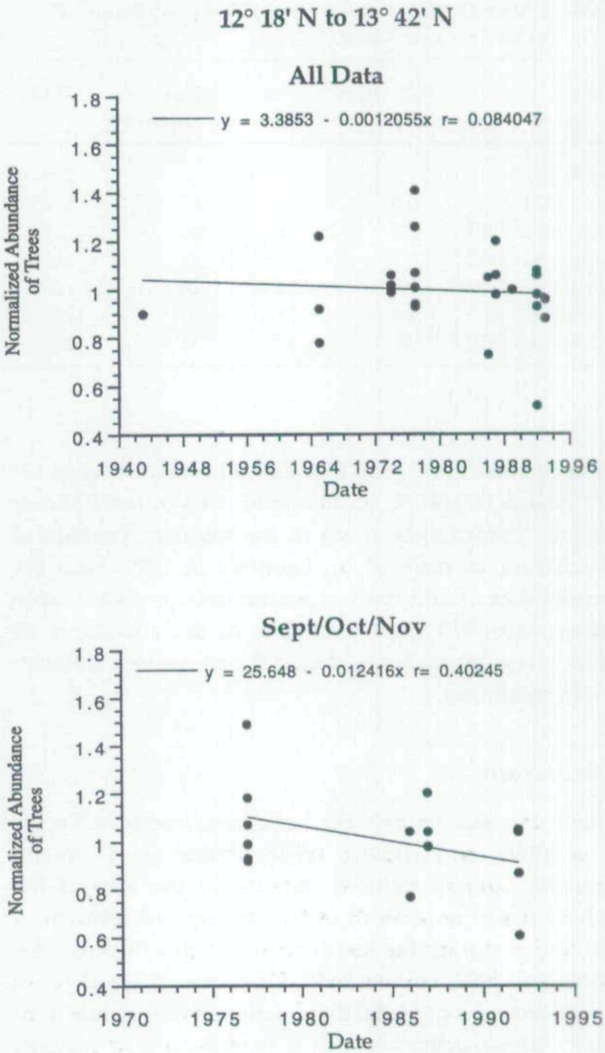


Fig. 2 Normalized abundance of woody vegetation at 6 sites just east of Jebel Marra in western Sudan. (We combined the data from the 4 sites east of Jebel Marra with 2 sites of the original transect that were located in the same area). The upper panel shows the entire dataset, whereas the lower panel includes data from recent photographs taken at the end of the wet season (September–November).

Table 1 Abundance of trees at site 4 (13° 41′ 40″ N; 24° 52′ 10″ E) in Darfur Province, Sudan

Date	Old trees expected	Trees lost	New trees appearing	Total
April 1943				228
June 1974	228	58	87	257
November 1977	257	66	46	237
September 1987	237	0	29	266
November 1987	266	14	16	268
April 1992	268	31	10	247
November 1992	247	17	38	268

of vegetation in a group of six sites located between 12° 18′ N and 13° 14′ N, on the plains east of Jebel Marra, an area immediately south of the southern position of the Sahara as mapped by Lamprey in 1975. Both the overall dataset and the wet season data in photographs taken since 1975 show a decline in the abundance of woody vegetation, but neither of the regressions is statistically significant.

Discussion

These data substantiate the basic conclusions of Tucker *et al.* (1994) and Hellden (1990), indicating no recent, dramatic, climate-induced increase in the area of the Sahara desert as a result of the widespread drought in the Sudan during the last several decades (Eltahir 1988; Nicholson 1989; Hulme 1990). Of course, these data do not address the potential degradation of woodlands from direct human activities, such as land clearing or grazing, and the trend pictured in Fig. 2 might become significant with a longer or larger data set. Significantly, access to this archive* has extended the period of record for several decades before the earliest AVHRR data are available, and it allows an explicit examination of that component of vegetation – woody plants – that is most indicative of long-term climatic trends. Although our analysis applies only to the western Sudan, the photographic archive for other regions of the Sahel might be used to extend this analysis across all of Africa.

Acknowledgements

We thank the U.S. Intelligence Community and the Department of Defense for help in accessing the photographic archive and for reproduction of the photographs. Jonathan Doughty helped with the development of calibrated grids. We also thank Regis Cardillo, Nadine White, and Sharon Schloe of MITRE for help in photographic interpretation, and Jane Raikes and Jim Clark of Duke University for statistical analysis of the data. This effort was funded by the Environmental Task Force (ETF) of the U.S. Intelligence Community and the Strategic Environmental Research and Development Program, managed by the Department of Defense, the Department of Energy, and the Environmental Protection Agency.

*On 23 February 1995, President Clinton signed Executive Order # 12951, declassifying the Corona satellite archive through May 1972, which will be available through the USGS EROS Data Centre, Sioux Falls, South Dakota.

References

Ahmed AA (1982) Land use history of Jebel Marra, Sudan, as related to the present distribution of woody vegetation. *Geojournal*, **6**, 5–14.

Beatley JC (1974) Effects of rainfall and temperature on the distribution and behavior of *Larrea tridentata* (creosotebush) in the Mojave Desert of Nevada. *Ecology*, **55**, 245–261.

Beatley JC (1980) Fluctuations and stability in climax shrub and woodland vegetation of the Mojave, Great Basin and transition deserts of southern Nevada. *Israel Journal of Botany*, **28**, 149-168.

Blackburn WH, Tueller PT (1970) Pinyon and juniper invasion in black sagebrush communities in east-central Nevada. *Ecology*, **51**, 841–848.

Breman H, de Wit CT (1983) Rangeland productivity and exploitation in the Sahel. *Science*, **221**, 1341–1347.

Coughenour MB, Ellis JE (1993) Landscape and climatic control of woody vegetation in a dry tropical ecosystem: Turkana District, Kenya. *Journal of Biogeography*, **20**, 383–398.

Dawson, TE, Ehleringer JR (1991) Streamside trees that do not use stream water. *Nature*, **350**, 335–337.

DeLucia EH, Schlesinger WH, Billings WD (1988) Water relations and the maintenance of Sierran conifers on hydrothermally altered rock. *Ecology*, **69**, 303–311.

El Moghraby AI, Ali OMM, El Seed MT (1987) Desertification in western Sudan and strategies for rehabilitation. *Environmental Conservation*, **14**, 227–231.

Eltahir EAB (1988) Tests for the suspected trend in annual rainfall series in central and western Sudan. *The Sudan Engineering Society Journal*, **30**, 37–50.

Emanuel WR, Shugart HH, Stevenson MP (1985) Climatic change and the broad-scale distribution of terrestrial ecosystem complexes. *Climatic Change*, **7**, 29–43.

Hellden U (1990) Desertification – time for an assessment? *Ambio*, **20**, 372–383.

Holcombe A (1987) Reaching beyond famine relief: Planning a strategy for rehabilitation and development in Dar Fur Region, western Sudan. *Geojournal*, **14**, 11–18.

Hulme M (1990) The changing rainfall resources of Sudan. *Transactions of the Institute of British Geographers*, **15**, 21–34.

Lamprey HF (1975) *Report on the Desert Encroachment Reconnaissance in Northern Sudan.* Report to the United Nations Environment Program, UNEP, New York.

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

Peters AJ, Reed BC, Eve MD, Havstad KM (1993) Satellite assessment of drought impact on native plant communities of southeastern New Mexico, USA. *Journal of Arid Environments*, **24**, 305–319.

Rapp A (1976) Sudan. In: *Can Desert Encroachment be Stopped?* (eds Rapp A, Le Houerou HN, Lundholm B), pp. 155–164. Swedish Natural Science Research Council, Stockholm.

Rind D, Goldberg R, Hansen J, Rosenzweig C, Ruedy R (1990) Potential evapotranspiration and the likelihood of future drought. *Journal of Geophysical Research*, **95**, 9983–10,004.

Schlesinger WH, Jones CS (1984) The comparative importance of overland runoff and mean annual rainfall to shrub communities of the Mojave Desert. *Botanical Gazette*, **145**, 116–124.

Schlesinger WH, Reynolds JF, Cunningham GF, Huenneke LF, Jarrell WF, Virginia RA, Whitford WG (1990) Biological concepts in global desertification. *Science*, **247**, 1043-1048.

Tappan GG, Tyler, DJ, Wehde ME, Moore DG (1992) Monitoring rangeland dynamics in Senegal with Advanced Very High Resolution Radiometer data. *Geocarto International*, **7**, 87–98.

Tucker CJ, Dregne HE, Newcomb WW (1991) Expansion and contraction of the Sahara Desert from 1980 to 1990. *Science*, **253**, 299–301.

Tucker CJ, Newcomb WW, Dregne HE (1994) AVHRR data sets for determination of desert spatial extent. *International Journal of Remote Sensing*, **15**, 3547–3565.

Wickens GE (1976) *The Flora of Jebel Marra (Sudan Republic) and its geographical affinities*. Royal Botanic Gardens, Kew.

Woodell SRJ, Mooney HA, Hill AJ (1969) The behaviour of *Larrea tridentata* (creosote bush) in response to rainfall in California. *Journal of Ecology*, **57**, 37–44.

Appendix 1

The location of the study sites in Darfur Province, showing the initial transet of 7 (numbered) sites, and the additional (unnumbered) sites just east of Jebel Marra.