Sahel atlas of changing landscapes

tracing trends and variations in vegetation cover and soil condition

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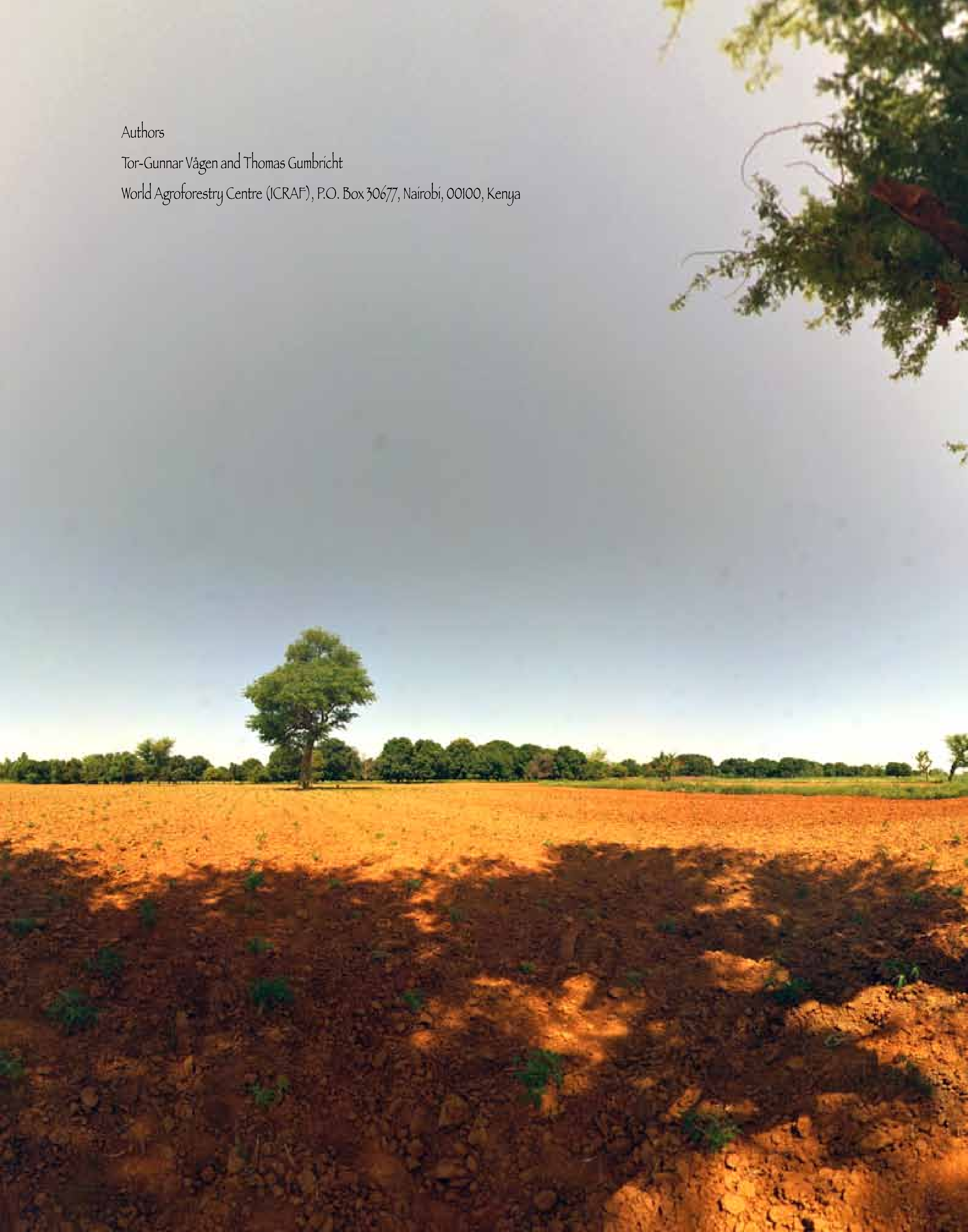

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Foreword

Developing countries, especially dryland countries in sub-Saharan Africa, depend strongly on ecosystem services generated by natural resources. However, as documented in UNEP's Global Environment Outlook (GEO-5), unprecedented land use changes resulting from the needs of a burgeoning population, economic development and global markets, and exacerbated by land governance issues locally, continue to cause depletion and degradation on an unprecedented scale. For example there is evidence of decline in the capacity of forest and dryland ecosystems to provide services on a regional basis. There are signs of larger scale feedbacks on regional climate change from desertification and deforestation. Competing demands for food, feed, fuel, fibre and raw materials will further intensify pressures on land over the next several decades.

The billion poorest people in the world are disproportionately affected by land degradation because they mostly live in rural areas and are directly dependent on forests, croplands and rangelands for their livelihoods. Agriculture and the land resource base form the foundation for economic development of poorer countries, especially in the Sahel. Land degradation leaves populations vulnerable and decreases adaptive capacity to global change, especially climate change.

The Rio+20 outcome document The Future We Want called for urgent action "to reverse land degradation and to strive to achieve a land degradation neutral world in the context of sustainable development." Strategies for improved land management, such as those included in a Green Economy, emphasize the need for incorporating monitoring, valuation and protection of natural resources into economic decision making.

This Atlas illustrates the potential for harnessing new science and technology to provide accurate and cost-effective methods for assessing and monitoring land health at different scales. Better location specific information on land resource status and trends will improve evidence-based targeting of interventions and promote more rigorous impact assessment.

The Atlas shows how advances in remote sensing from satellites in space to spectrometers on the laboratory bench and systematic field survey can be integrated to provide a basis for operationalizing evidence-based land management. Finally, this report provides rich and valuable insights into the climate and vegetation dynamics of the Sahel, putting recent drought and land use changes in the context of longer-term historic changes.

Achim Steiner
United Nations Under-Secretary-General and Executive Director
United Nations Environment Programme

Tony Simons
Director General
World Agroforestry Centre (ICRAF)

Preface

Land degradation is widely recognized as an important global environmental problem threatening human development, especially in the world's poorest countries, not least the Sahelian region in West Africa. However, policy action is being hampered by the fact that land degradation remains a controversial and poorly quantified problem in the Sahel. There has been insufficient investment in the consistent application of science-based methods for assessing and monitoring land degradation. Without such efforts it will be difficult to guide policy and learn from past actions.

Land health surveillance is a scientific approach to land health assessment that is closely modelled on evidence-based approaches used in the public health sector – where surveillance is the main mechanism for determining public health policy and practice. The surveillance framework addresses the critical need to generate relevant and specific information on land health and degradation as an integral part of national planning processes aimed at better ecosystem and climate management and improved human well-being. Land health surveillance tells us where land problems exist; whom they affect; where programmatic and prevention activities should be directed; and how well they are working.

The Atlas provides a pictorial overview of the application of land health surveillance science in the Sahel at multiple scales from regional to local levels. It illustrates unprecedented advances in earth observation using remote sensing from space, in the field and on the laboratory bench, combined with geographical information systems, and hierarchical statistical methods. The landscapes, climate, vegetation and trends in vegetation and soil health in the Sahel are described.

The Atlas gives a detailed account of the historic, current and projected climate systems that principally determine Sahelian vegetation growth. Coarse resolution remote sensing and rainfall data are presented to provide a regional overview of recent time in trends vegetation growth over the West Africa Sahel. More detailed analyses of the indicative trends of vegetation degradation (land degradation hot spots) or improvement (greening-up) are investigated further using moderate resolution satellite data for a number of locations across the region. The results demonstrate the complexity of spatial and temporal landscape dynamics at local scales and the challenges they present for interpreting trends from broad scale remote sensing data.

Finally a ground-based surveillance scheme, including novel low-cost soil analytical methods, is illustrated with an application in Segou District in Mali. These results illustrate the feasibility of integrating consistent ground-based data with remote sensing in an efficient manner.

Consistent application of the new land health surveillance methods across the region would provide a sound basis for the future management of the Sahelian land resource base. There is need for a major capacity strengthening initiative to harness the new science approaches and tools to provide evidence-informed decision making as part of everyday policy and practice.

Gemma Shepherd
Environmental Affairs Office and Project Manager
United Nations Environment Programme

Overview and Summary

During the 1970s and 1980s the Sahel, a semi-arid savannah between the Sahara Desert and the Guinea moist savannah, experienced severe droughts. The droughts had devastating consequences for this ecologically vulnerable transition region. Since the mid 1980s, however, rainfall and vegetation has largely recovered. The driving forces of the climate variations and the droughts are not fully understood. The views range from those blaming human caused land degradation driven by overgrazing and deforestation as the underlying forces, to those emphasizing the global climate system driven by annual to decadal changes in sea surface temperatures. The future of the Sahel ecosystem and the livelihoods of the farmers and herders depend on both the climate, and the ecosystem services that can be sustained by the soil and vegetation.

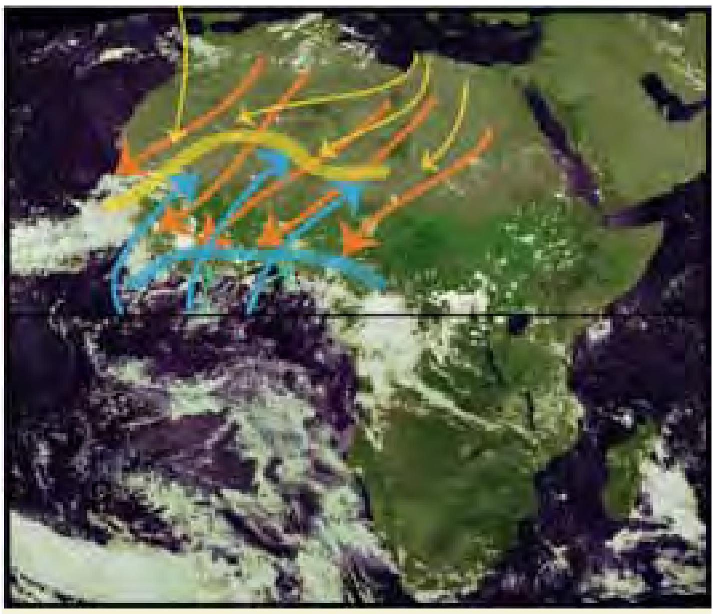
Knowledge about both soil and vegetation processes and future climate is needed in combating land degradation in the Sahel, and for proper planning of agricultural and economic development. This atlas aims to illustrate a rigorous scientific basis for understanding processes of landscape change in the Sahel.

Landscapes

The Sahel is a mainly flat savannah and grassland region with a few scattered plateaus and mountain ranges. The Sahel is not a strictly defined geographical region, but rather the transition between woodlands in the south and the Sahara Desert in the north. These vegetation boundaries are largely defined by annual rainfall, from approximately 100 mm in the north to 600 to 1000 mm in the south. The more rainy southern parts have a denser tree cover, which continuously decreases towards the drier north where thorny species of *Acacia* dominate. Towards the south the Sahel transitions into the woodlands of the Guinea moist savannah. The central region is characterized by parkland ecosystems – savannah converted into agricultural fields with economically valuable tree species preserved. Further north grasslands dominate with thorny shrubs interspersed as a result of grazing pressure and land clearing. Man has used these landscapes for over 5000 years. Bush burning, tree clearing and a high grazing pressure have converted large parts of the originally wooded savannah to agricultural fields and extensive grass and shrub land. Man has also expanded the more typical savannah landscapes southwards, by conversion of woodlands to more open landscapes.

Climate

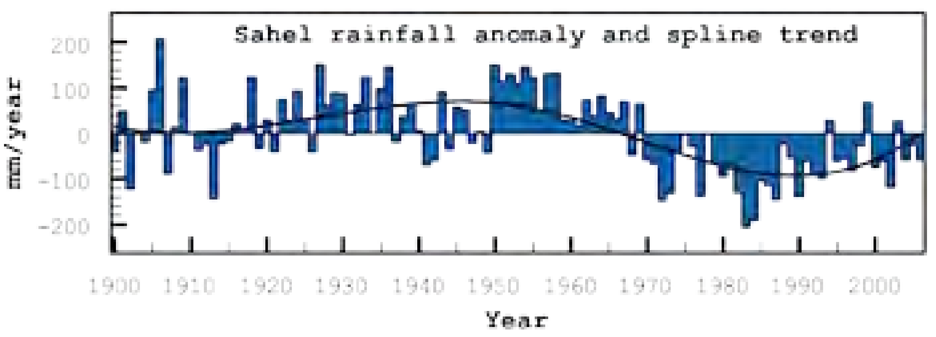
The climate of the Sahel is warm and arid, with a short summer monsoon lasting two to four months. The annual rainfall cycle is a result of the interplay between dry Harmattan trade winds blowing from the Sahara in the north and moist monsoon trade winds blowing from the Atlantic Ocean in the west and south of the Sahel. The monsoon winds give off their moisture as rainfall when travelling north, hence creating the rainfall gradient typical for the Sahel. Remaining moisture is released as rainfall where the monsoon and the Harmattan trade winds meet, causing the moist air to rise and form clouds and rainfall. The latter process is a result of the formation of a low pressure zone, which migrates with the sun, also referred to as the tropical rain belt or the Inter-Tropical Convergence Zone (ITCZ). During summer in the northern hemisphere, the tropical rain belt reaches about 10ºN, attracting moist monsoon winds from the Atlantic Ocean which move north into the Sahel. Further south, the oscillating rain belt passes twice every year, when the sun migrates northwards in spring and then again when the sun migrates southwards in autumn.



During the summer the tropical rain belt (yellow belt) attracts rain bearing monsoon trade winds (blue arrows). The dry Harmattan winds (orange arrows) dominate the Sahelian climate during winter when the rain belt is positioned around the equator (blue belt).

Sea surface temperatures in the Indian and Atlantic oceans control the strength and position of the tropical rain belt and the summer monsoon. Colder surface temperatures in the Indian Ocean generate more rainfall over West Africa, as does a stronger northward flow of the warm Atlantic Gulf Current. During wetter periods in the Sahel, denser vegetation can assist in further strengthening the monsoon rainfall and more vegetation growth through positive feedback. Dense vegetation cover both leads to soils with better water holding capacity and can deliver more moisture to the atmosphere. Water is trapped in a local vertical cycle of evapotranspiration going up and rainfall coming down. When the soil is exposed in a drying cycle, vegetation loses this capability, exacerbating the drying and further decreasing vegetation growth.

During the ice age, over 12,000 years ago, sea surface temperatures were lower and the warm north-flowing current of the Atlantic was shut off. Rainfall over West Africa and the Sahel was therefore much lower than at present. The Sahara Desert reached into the Sahel, which was covered by sand dunes that now remain as rolling hills. The dry ice age was followed by the African Humid Period, when the Sahel was much greener. This wetter period was caused by a combination of shifts in sea surface temperatures and self-generating rainfall by the denser vegetation. When sea surface temperatures became less favorable (colder) – about 5,000 years ago, vegetation decline resulted, which again led to lower rainfall as a result of feedback between vegetation and climate. Since then the Sahel has been the transition zone it is today. Annual to decadal variations in rainfall over the Sahel are large, with a quasi 80–year cycle of wetter and drier periods. The 1950s and early 1960s was a wet period, followed by a decline in rainfall that culminated in the droughts of the early 1970s and 1980s. Since the droughts, rainfall has been increasing. Until the 1970s man's use of the landscape was seen as the major agent causing “desertification”. The Sahel droughts in the 1970s and 1980s were consequently blamed on overgrazing and deforestation. A better understanding of the global climate system, the return of more plentiful rains and the availability of satellite images showing increases in vegetation, changed this view. Humans became regarded as successful land managers optimizing food production by adaptation to environmental changes. There is still controversy over the degree to which the droughts are a result of externally forced changes due to variations in sea surface temperatures or whether they are caused by losses in vegetation cover due to human activity.



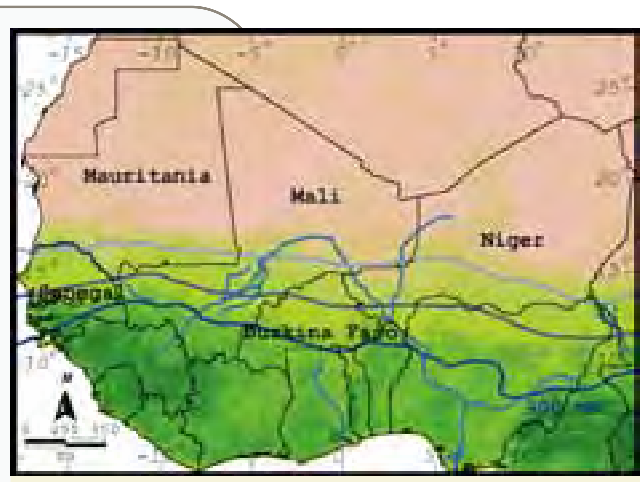
Vegetation

In general, climatic factors such as rainfall and relative humidity have a dominant influence on vegetation growth and composition. The Sahel vegetation is therefore a reflection of the steep south to north decline in rainfall. However, local factors such as soil and water availability are important, especially near climatic margins and where hardened (lateritic) crusts, saline or water logged soils occur. Grass cover is fairly continuous across the region, dominated by annual grass species. Plant species variations are larger towards the wetter south, with *Acacia* species becoming more dominant further north. In the northern fringes of the Sahel, areas of desert shrub alternate with areas of grassland and savannah. During the long dry season the predominantly annual grasses die and many trees lose their leaves. The large variation in rainfall also causes annual to decadal changes in species compositions, especially in annual grasses.

Grass- and shrub lands have become more prominent from frequent burning and high grazing pressure. The extent of the woodlands in the south has decreased as a result of logging for timber and fuel wood, and conversion to agroforestry, farmland and grazing land. These processes have been ongoing since the end of the African Humid Period, 5,000 years ago, but have accelerated in the last century.

The growing archives of satellite imagery have become a major source for screening and exploring regional and global vegetation change. The longest available vegetation time-series is from 1981 to present, and comes from the AVHRR (Advanced Very High Resolution Radiometer) sensor. This data has a spatial resolution of eight km. The more recent MODIS (Moderate Resolution SpectroRadiometer) sensor is a much more accurate sensor with automatic calibration, and provides vegetation data at 250 m resolution. MODIS has been producing global vegetation data since 2000. Both sensors produce daily global satellite images. Using cloud free images for mapping annual vegetation production, these sensors show that vegetation growth in the Sahel has increased since the droughts in the 1980s. The recovery in vegetation has, however, not been as strong as the rainfall recovery. While rainfall has moved north at a pace of around nine km per year over the period 1982 to 2006, vegetation has responded by moving only a third to half this distance northwards.

Vegetation growth alone cannot be used for mapping land degradation in drylands with large fluctuations in rainfall like the Sahel. A simple way to separate rainfall driven vegetation growth from other factors is to normalize the annual vegetation production by annual rainfall. The ratio of vegetation growth over rainfall is a measure of the vegetation's capacity to turn available rainfall into green biomass, and hence a way of comparing the effectiveness of vegetation growth between years with varying rainfall.

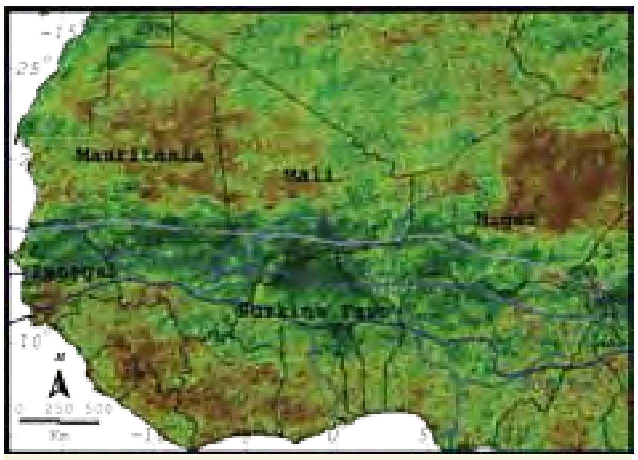


Average vegetation cover 1982–2006 derived from AVHRR satellite data at eight km resolution. Denser vegetation cover is shown as dark green.

Rain normalized vegetation production

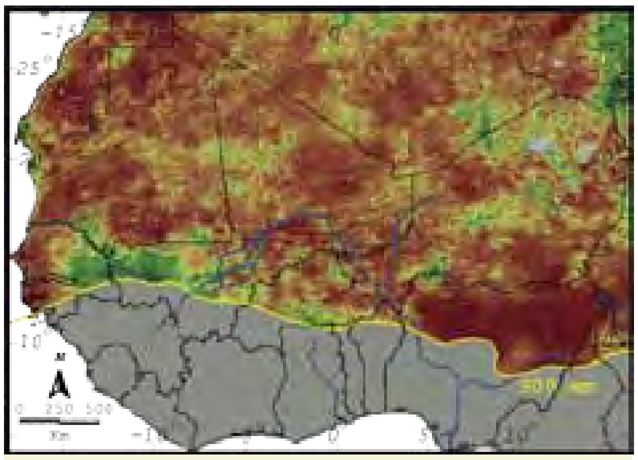
1982–2006 derived from the ratio of annual vegetation cover (AVHRR) to annual rainfall. Rain normalized vegetation production disentangles vegetation changes caused by rainfall variation from other factors. It is a method applied for screening regional vegetation data for potential areas affected by land degradation.

Rainfall normalized vegetation production 2001–2006 derived from the ratio of annual vegetation cover (MODIS) to annual rainfall.



Greening and browning trends in average vegetation cover 1982–2006. Absolute vegetation growth has increased (green) in the Sahel since the droughts in the 1980.

Vegetation recovery after the droughts in the 1970s and 1980s has been strong. The trends in rain normalized vegetation growth, however show that vegetation has not recovered to its full potential since the rainfall started to increase after the droughts. There are multiple explanations for this. One is that the vegetation composition has changed towards more drought resistant species during the long drought periods, and that this makes the vegetation less able to fully utilise more plentiful rain, causing a lag in the response to increased rainfall. Another cause could be land degradation, which reduces the soil's water holding capacity and also diminishes nutrient supply. A third explanation could be that farmers have adjusted their management practices to lower rainfall, and there may be a lag in adapting back to a situation with more rainfall.



Trends in rain normalized vegetation production 1982–2006. Trends are shown for areas with less than 900 mm rainfall per year. Strong negative trends (brown) indicate that the ability of the vegetation to utilize available rainfall has decreased in this time period.

Rainfall normalized vegetation production trends between 2001 and 2006. The MODIS EVI trends shown here, although from a shorter time-series, resemble those observed in the AVHRR data.

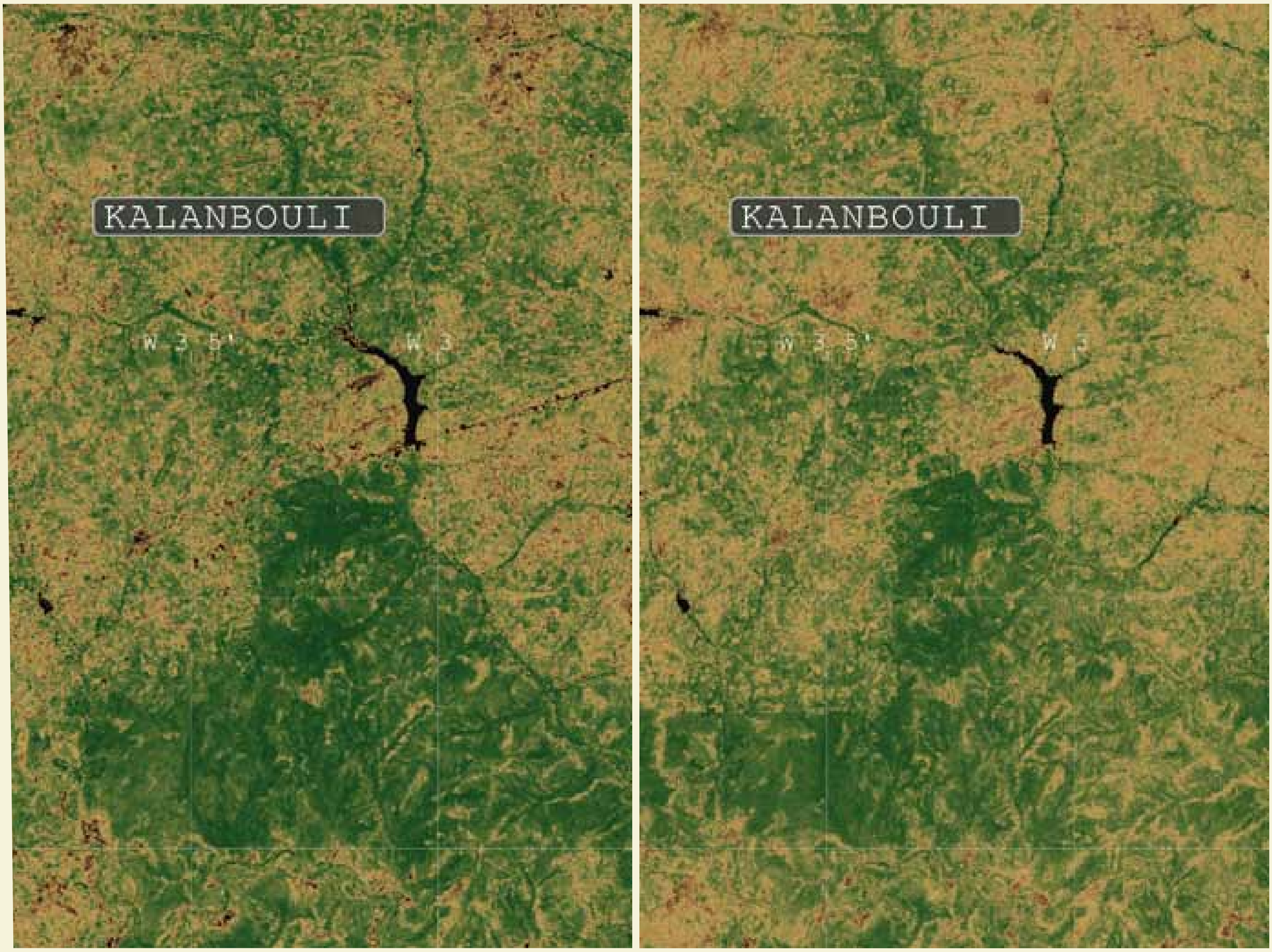
Land degradation* hotspots

Our analysis of trends in vegetation cover in the Sahel after normalizing for rainfall, indicates that vegetation recovery in this region is not as strong as increases in rainfall may suggest. Regional screening of the historical (1982 to 2006) AVHRR vegetation and rainfall data for potential areas of land degradation reveals wide areas of potentially degraded land in the Sahel. A more detailed analysis with better quality and higher resolution MODIS satellite vegetation data for the period 2001 to 2006 confirms these negative trends. These maps are starting points for selecting areas for more thorough analysis of land degradation processes on the ground.

A closer examination of areas showing greening–up or browning–down trends in AVHRR and/or MODIS vegetation maps using multi–date moderate resolution satellite imagery (e.g. Landsat TM and ETM+) shows the complexity of land cover change in the Sahel (facing page).

Land degradation hotspots (brown) identified as areas with a statistically significant negative trend in AVHRR derived rain normalized vegetation growth between 1982 and 2006.

Land degradation hotspots based on MODIS derived rain normalized vegetation growth 2001 to 2006.



Land cover change between 1988 and 1999 near Kalanbouli, Burkina Faso, from Landsat TM (left) and ETM+ (right).

*Defining desertification and land degradation

Despite a century of debate and research on desertification and land degradation, often focusing on the African Sahel, these concepts are difficult to define and identify. Hundreds of definitions have been suggested. One of the most widely used being that applied by the United Nations Convention to Combat Desertification (UNCCD);

"Land degradation in arid, semiarid and sub-humid areas resulting from various factors, including climate variations and human activities", where land degradation refers to the UN (1994) definition; "reduction or loss of the biological and economic productivity and complexity of terrestrial ecosystems, including soils, vegetation, other biota, and the ecological biogeochemical, and hydrological processes that operate therein".

The major bottleneck is a lack of scientific approaches applied consistently at local, national and regional scales. This means that managers and policy makers have little reliable information for assessing and managing land degradation.

Land Degradation Surveillance

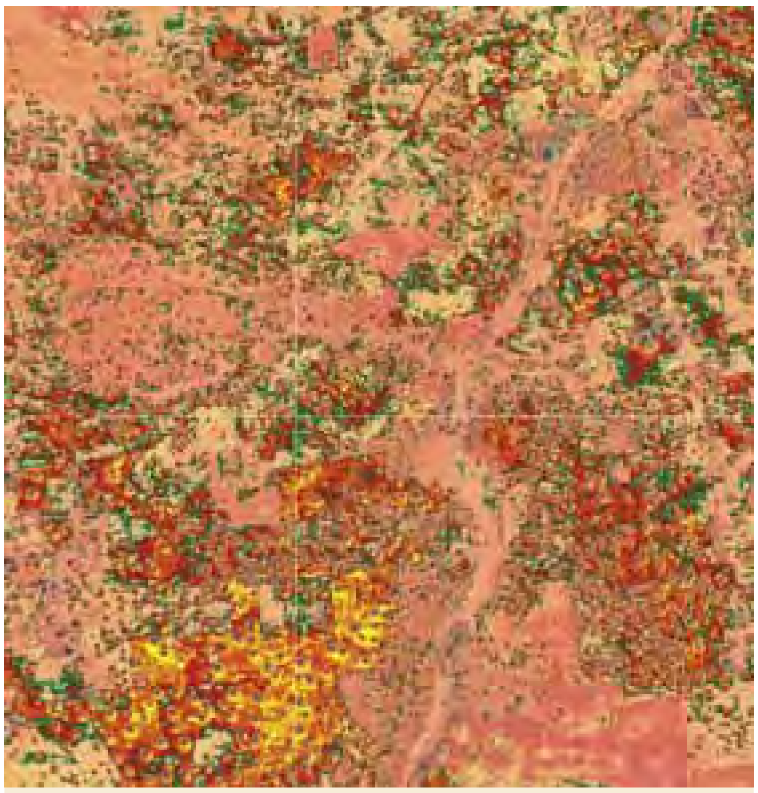
There is generally little systematic information about the state of water, soil and vegetation in the Sahel. This is largely due to a lack of systematic approaches to the measurement and monitoring of changes in for example land cover and use. Yet, such information is necessary to establish appropriate baselines for example for soil and vegetation condition, and to reliably determine the direction and extent of land cover change and processes of land degradation. The same applies to processes of recovery. The Land Degradation Surveillance Framework (LDSF) is the result of several years of active research in various parts of the African continent, and in particular in Western Kenya and Madagascar. This atlas is a product of a UNEP project[1] where the LDSF was applied.

Five "sentinel sites", each 10 by 10 km in size, were established in the Segou Region in Mali, near the villages of Konobougou, Dianvola, Monimpebougou, Zebougou and Sokoura. These sites provide a starting point for reliable change detection and project impact attribution related to afforestation activities in the region, as well as agroforestry interventions and improved soil fertility management in cultivated areas.

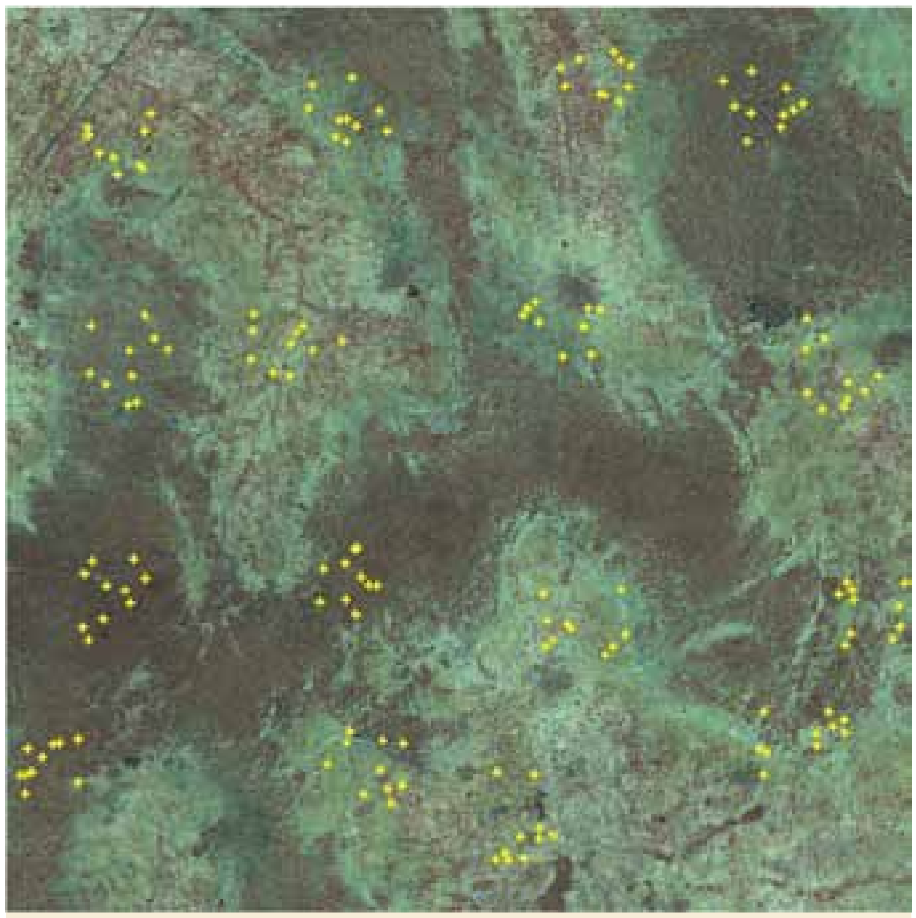
The research was designed to provide baselines that synthesize a quantitative description of the project situation along the ecological and socioeconomic dimensions that are relevant for project implementation. Flexible strategies for selecting priority intervention areas and households at the landscape/population scale are proposed, while also laying the foundation for change detection that considers spatial variability explicitly. We show a selection of results from these sentinel sites, including high resolution assessments of vegetation cover and soil condition. We also demonstrate how the methodology can be applied in the development of regional-level estimates of soil condition constraints and woody vegetation cover densities.

On the next page, an outline of the LDSF is shown, illustrating the main types of information collected as part of the framework. The illustration also shows how the analysis and synthesis of information gathered as part of the LDSF can be used in assessing land degradation risk and targeting interventions. This strongly improves the basis for making land management recommendations. The main image shows a village in Segou region, Mali, with surrounding areas.

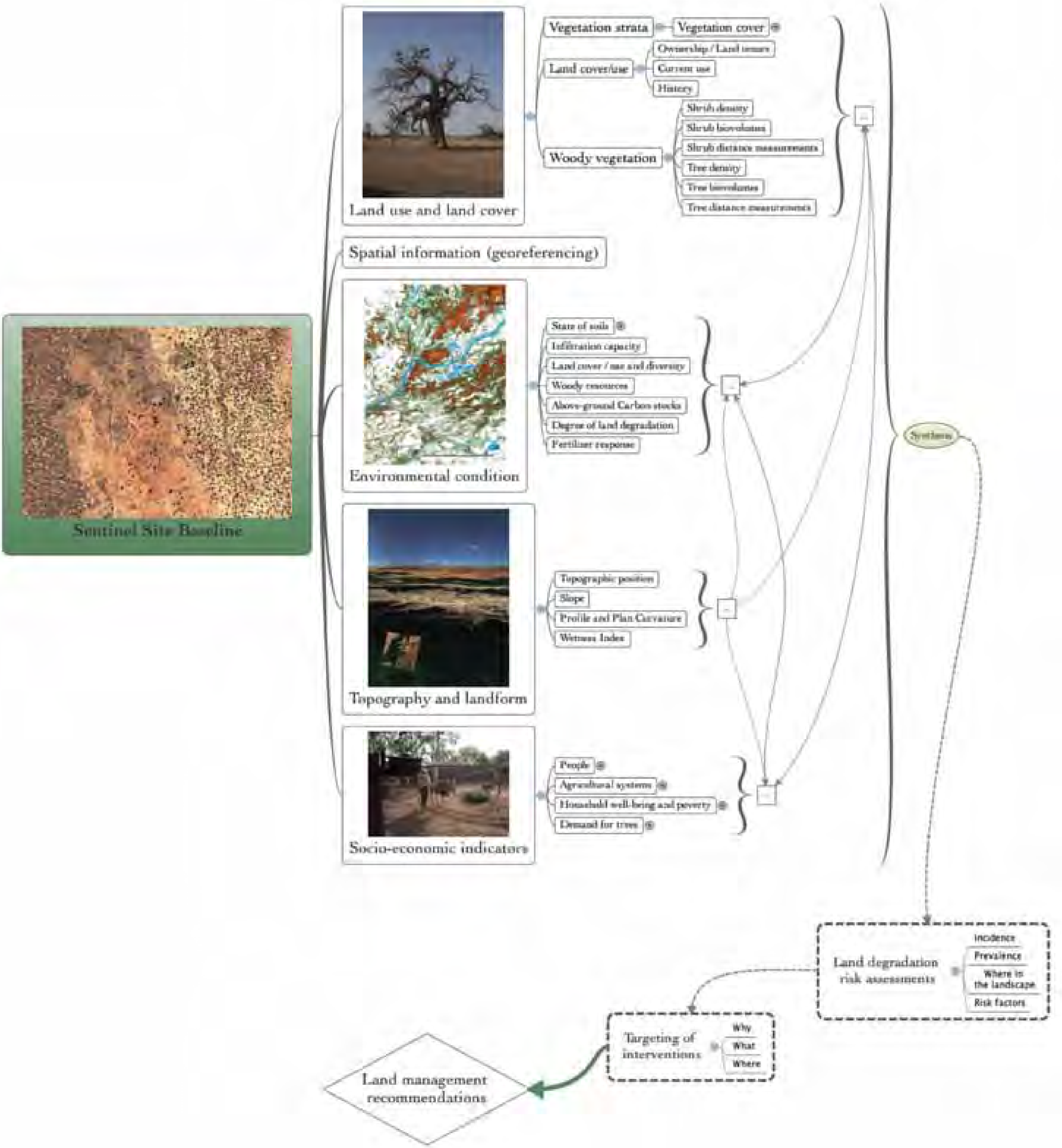
[1] An Ecosystem Approach to Restoring West African Drylands and Improving Rural Livelihoods through Agroforestry-based Land Management Interventions."



Map of soil condition in a section of the Konobougou Sentinel Site, Segou region, Mali. Yellow areas are predicted to have low soil fertility status.



Quickbird false colour composite of the 10 by 10 km site. Yellow points are sampling points.


Sentinel Site Baseline
Land use and land cover
Vegetation strata
Vegetation cover
Land cover/use
Ownership / Land tenure
Current use
History
Woody vegetation
Shrub density
Shrub biovolumes
Shrub distance measurements
Tree density
Tree biovolumes
Tree distance measurements
Spatial information (georeferencing)
Environmental condition
State of soils
Infiltration capacity
Land cover / use and diversity
Woody resources
Above-ground Carbon stocks
Degree of land degradation
Fertilizer response
Topography and landform
Topographic position
Slope
Profile and Plan Curvature
Wetness Index
Socio-economic indicators
People
Agricultural systems
Household well-being and poverty
Demand for trees
Synthesis
Land degradation risk assessments
Incidence
Prevalence
Where in the landscape
Risk factors
Targeting of interventions
Why
What
Where
Land management recommendations

Introduction

The African Sahel, a dryland region in West Africa bounded by the Sahara Desert in the north and the Guinea moist savannah in the south, experienced the most severe droughts in recorded history during the 1970s and 1980s. The droughts had devastating consequences for this ecologically vulnerable region and were major reasons for the establishment of the United Nations Convention to Combat Desertification (UNCCD).

The year to year fluctuations in rainfall are high across the Sahel, leading to large variations in vegetation type, growth and cover between locations and years. Rainfall over the last century has also shown long-term variation. The period 1950–1965 had higher rainfall, followed by drier conditions culminating in the severe droughts mentioned earlier. The droughts led to a widespread decline in vegetation growth and cover, exposing the underlying soil. The negative trend in rainfall was however reversed and rains have since the late 1980s increased, but average rainfall is still below the 1950–1965 level. Vegetation recovery, as recorded by satellite imagery and more recent field studies, has renewed the debate about irreversible land degradation and impacts of land management on the Sahelian ecosystem. One view is that these human impacts, such as overgrazing and conversion of woodland to agriculture, are the main reasons for the observed changes in vegetation cover and increased prevalence of land degradation. These processes tend to expose the soil and weaken the water cycle by reducing moisture supply to the atmosphere. This subsequently leads to land degradation, including erosion and lower water holding capacity, which again reduce the ability of the land to sustain vegetation production. These internal forces are then hypothesized to lead to a new climate-vegetation "equilibrium" with lower rainfall and lower biological productivity.

An alternative view is that global atmospheric circulation and climate changes forced by external variations in ocean surface temperature is the main reason for the changes in vegetation cover. In this "non-equilibrium" hypothesis, humans are seen as victims adapting land management to unpredictable climate variations. There is hence still a debate whether the dryland ecosystems of the Sahel have returned to their pre-drought functionality, or whether irreversible land degradation has trapped these rangeland ecosystems in a less favorable state for food production. What is evident is that a better understanding of the dynamics of the Sahel rangeland and cropland systems is crucial for identifying sustainable policy and management options as the vast majority of people in the Sahel depend on agriculture and livestock production for their livelihoods.

The Sahel

The name 'Sahel' for the region on the southern fringe of the Sahara Desert in West Africa has been used for more than 100 years. The Sahel stretches approximately 5,000 km from the Atlantic Ocean in the west to the Red Sea in the east. There is no exact boundary for the Sahel but it is usually considered as the rainfall transition region bounded by the 100-200 mm per year isohyet (rainfall isoline) in the drier north, to the 600-1,000 mm per year isohyet in the wetter south. The Sahelian rainfall gradient is reflected by a continuum of change in vegetation and ecosystems; the wetter south has denser ground vegetation cover and more trees than the drier north. Species diversity is also larger in the south, with the north being dominated by *Acacia* trees and annual grasses. The central region is characterized by parkland agroecosystems – agricultural fields in which trees are maintained allowing diverse agroecological production. Towards the fringes of the Sahara Desert thorny shrubs interspersed between grasses dominate. The grass- and shrub land gradually grades into the Sahara. The countries of the Sahel today include Senegal, Mauritania, Mali, Burkina Faso, Niger, Nigeria, Chad, Sudan, and Eritrea. The current study focuses on the former five countries occupying the western parts of the Sahel.

Map of Africa highlighting the area covered by the West African Drylands project. The map also shows the long term isohyets for 900, 600, 300 and 100 mm over the Sahel.

Landscapes

The bedrock geology of the Sahel is mainly composed of pre-Cambrian rocks (granites and sandstones) that are deeply weathered. Soils in the south are more heavily leached and poor in nutrients due to higher rainfall. Storms during the dry season bring sand and dust from the Sahara Desert fertilizing not only the Sahel, but large parts of the globe, including the Amazon.

The topography of West Africa is flat, with elevation mostly ranging between 200 and 400 meters above sea level. Isolated plateaus and mountain ranges rise from the flat land, and dominate the landscape in some areas. These heights have different geological and climatic conditions, and are not strictly part of the gradual south to north changes that signify the Sahel in general. The small-scale topography of rolling hills is remnant sand dunes formed during the last ice age (before 12,000 years ago) when the Sahara Desert reached south into what is now the Sahel.

Dry season

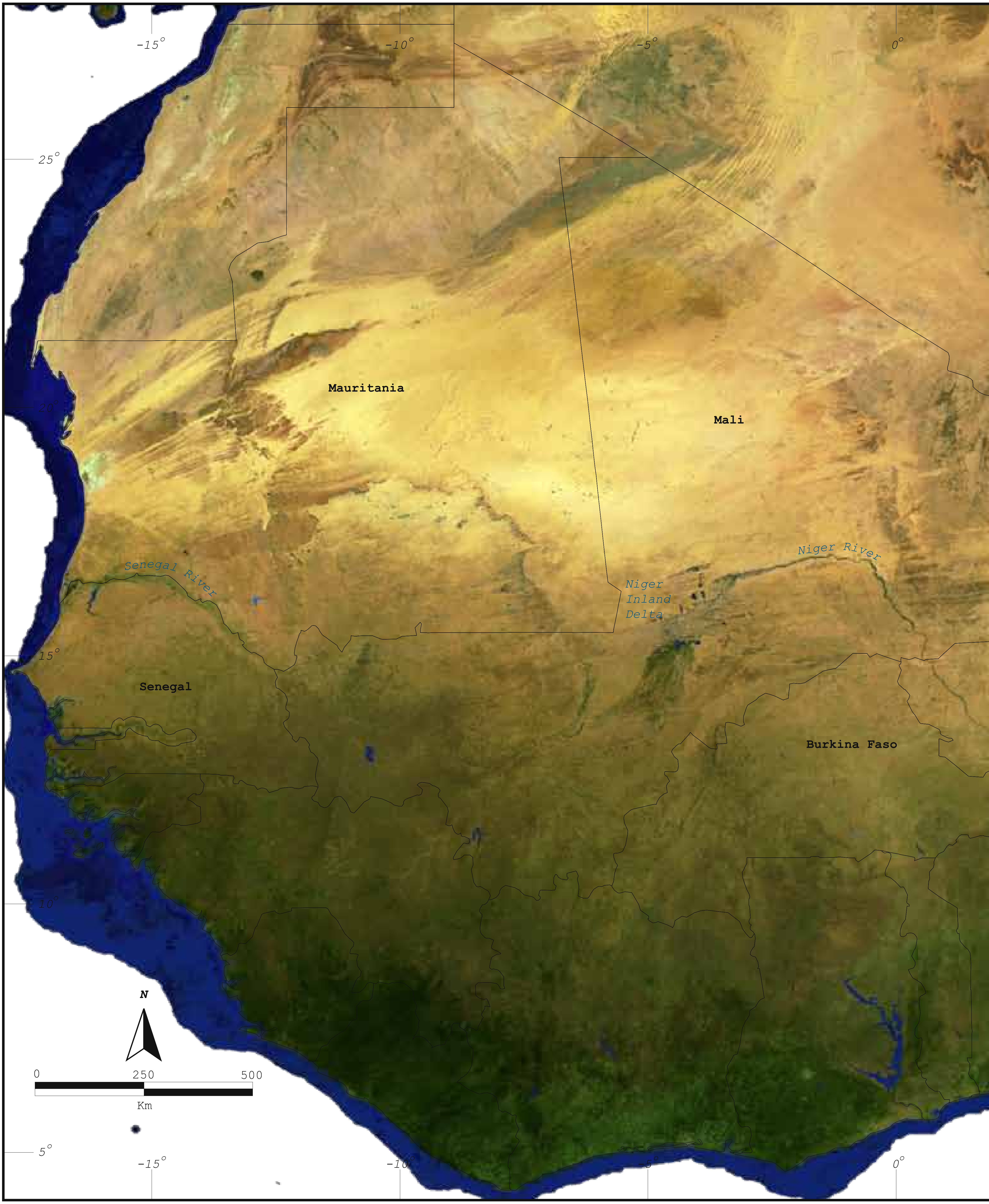
The dry season lasts from October through April. The predominantly annual grasses die and most trees shed their leaves, with the exception for some useful *Acacia* species and *Faidherbia albida* (bottom panel image). This forces herders to migrate south to find grazing for their livestock. The cattle graze freely on communal land, and in many places farmland is also open to grazing during the dry season. To prevent the migrating herds from interfering with crops, farmers plant "live fences" of thorny bushes.

Wet monsoon season

The monsoon season in the Sahel lasts from May to September, with most of the rain falling during August, when the tropical rain belt reaches its northernmost position. The growing season starts immediately after the first rains, and lasts a month or two beyond the rainy season. During the rainy season herders migrate several hundred kilometers to the more fertile grasslands of the north. Over centuries this has altered the species composition of these areas, favouring grasslands with fire tolerant woody species. In the parklands the rains signify the start of the cropping season. In the driest parts (with about 300 mm rainfall per year) Millet (*Pennisetum typhoideum*) is grown (middle panel photo on the left), and then followed by sorghum (*Sorghum bicolor*), ground nuts (*Arachis hypogoea*), cotton (*Gossypium* sp.), cassava (*Manihot esculenta / utilissima*), maize (*Zea mays*) and other more water demanding crops and tubers. Rice (*Oryza* sp.) is grown in irrigated fields adjacent to the rivers or in flood-recession areas.

Soil catena and laterite formation

The heaver rains in the south have leached the nutrients from the soils, and the soils are therefore generally poorer. In hilly terrain, weathering of rocks and soils is accompanied by a downward flow of water which leaches and transports the more easily soluble nutrients from hills to valleys. This process typically creates a sequence of soils from hills to valleys, termed a catena. The hilltops are deprived of nutrients leaving more insoluble iron and aluminum minerals behind, whereas the valleys that receive the nutrients become more fertile. If enough water is evaporated from the hilltops, the iron and aluminum minerals left behind form laterite, a hardened crust that can be several meters thick. If the iron content is high, the encrustacions get the red colour of oxidized iron (“rust”), a common sight in the Sahel. Laterite formation was stronger during the African Humid Period (12,000 to 5,000 years ago), and hence today laterites can be found also in drier areas. Where salts have been washed out from hills to valleys and valleys have high evaporation, salinization occurs.


-15°
-10°
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Mauritania
Mali
Senegal River
Niger River
Niger
Inland
Delta
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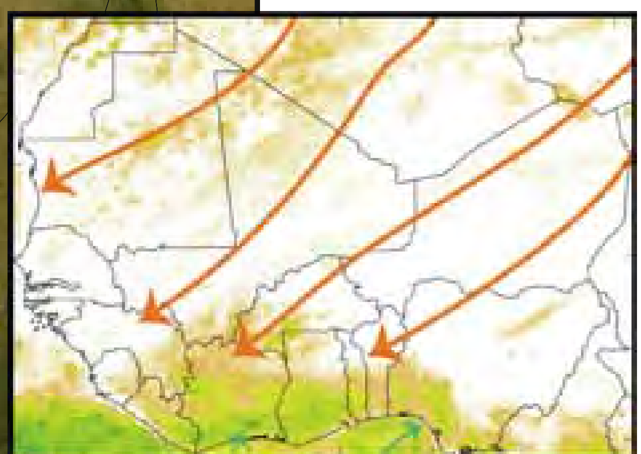
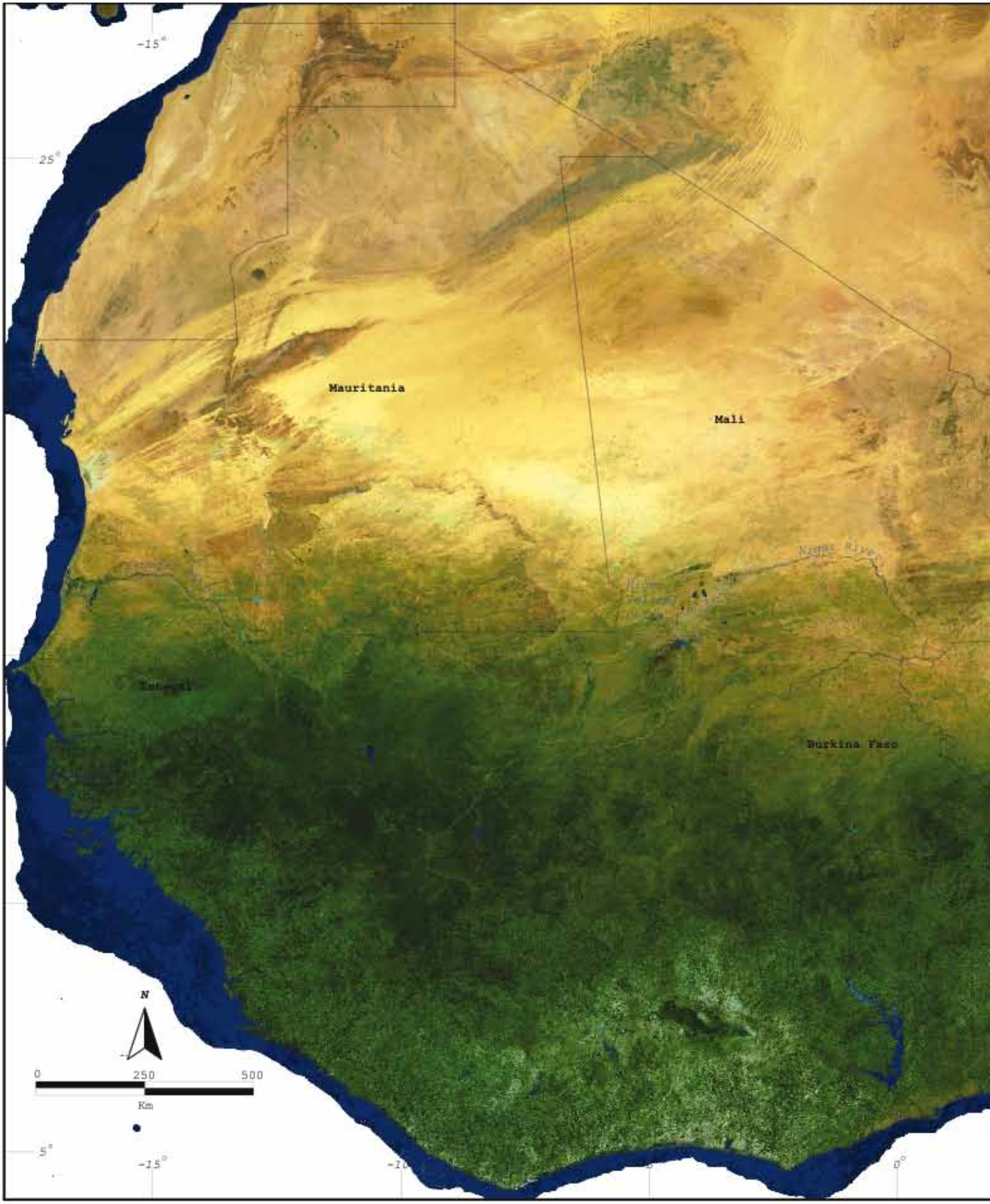
-15°
0°

MODIS (Moderate Resolution Imaging SpectroRadiometer) composite satellite image showing West Africa during the dry season (February 2004). Vegetation growth in the Sahel is sustained in and around the Niger Inland Delta in Mali and Lake Chad in Chad. These two water bodies are the only remaining larger lakes from the African Humid Period. During the ice age (ending 12,000 years ago) the Sahel was much drier and the sand dunes that were then formed can still be seen for example as east-west stripes in the Niger Inland Delta. Today there are no active dunes in the Sahel, but the dry Harmattan trade wind (inset map) still influences the landscape by transporting sand and dust from the Sahara that is then deposited in the Sahel. The general Harmattan wind pattern can be seen as stripes of sand depositions, for example towards the coast in Mauritania. The soils in the south of West Africa are generally poor in nutrients, but the sand and dust brought by the Harmattan winds from the Sahara Desert fertilise both the Sahel and the Guinea coastal rain forest, as well as most other parts of the globe.



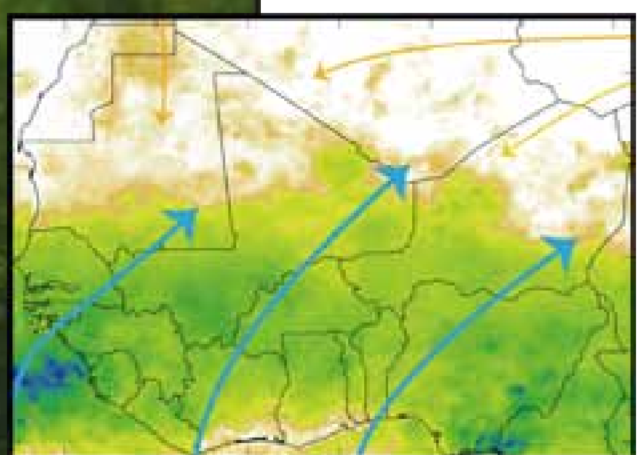
Rainfall over West Africa in February 2004, the arrows indicate the hot and dry Harmattan trade wind dominating the climate of West Africa in the dry season.



-15°
-10°
25°
Mauritania
Mali
Niger River
Burkina Faso
N
0
250
500
Km
5°
-15°
0°

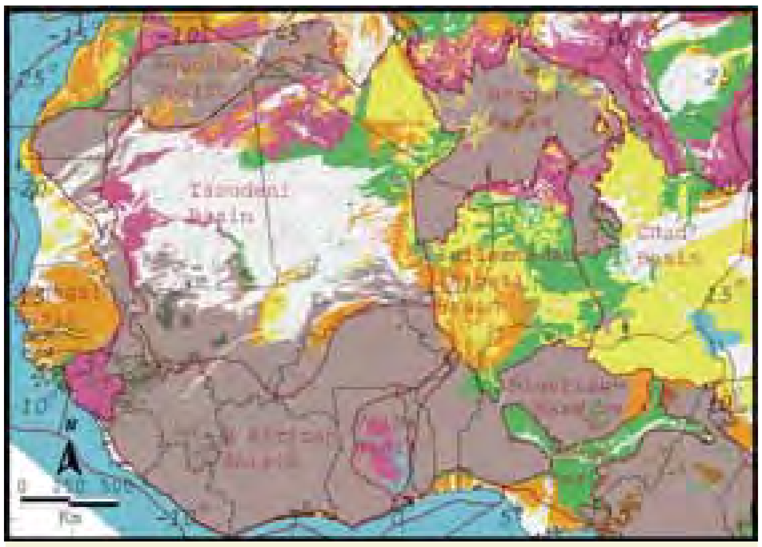
August 2004 MODIS composite satellite image showing West Africa during the wet season. The summer monsoon reaches furthest north in August (inset map), and stays at about 10ºN for about a month. Up to half the annual rain falls during August. The importance of the drainage system for vegetation and agriculture can be seen along the Niger and Senegal rivers, and many minor streams and rivers.

Vegetation growth in the northern parts of the Sahel varies greatly from year to year and decade to decade. The year to year variation is not only dependent on the seasonal rainfall, but also on the previous years rain and grazing pressure. Low rainfall and high grazing pressure prevents the dominantly annual grasses from flourishing and setting seeds, resulting in a diminished seed pool for the following years.



Rainfall over West Africa in August 2004, the blue arrows indicate the wet monsoon bringing rainfall to the Sahel in the wet season.

Geology

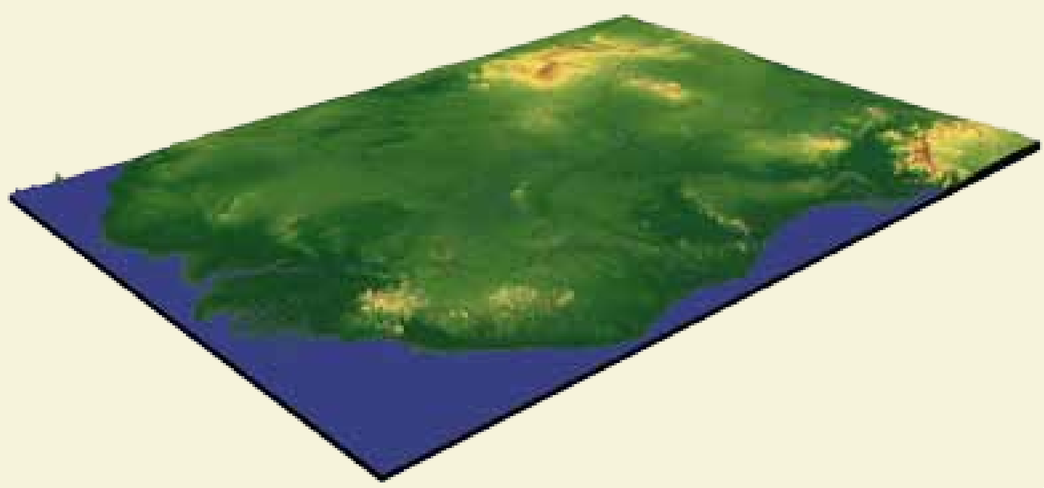


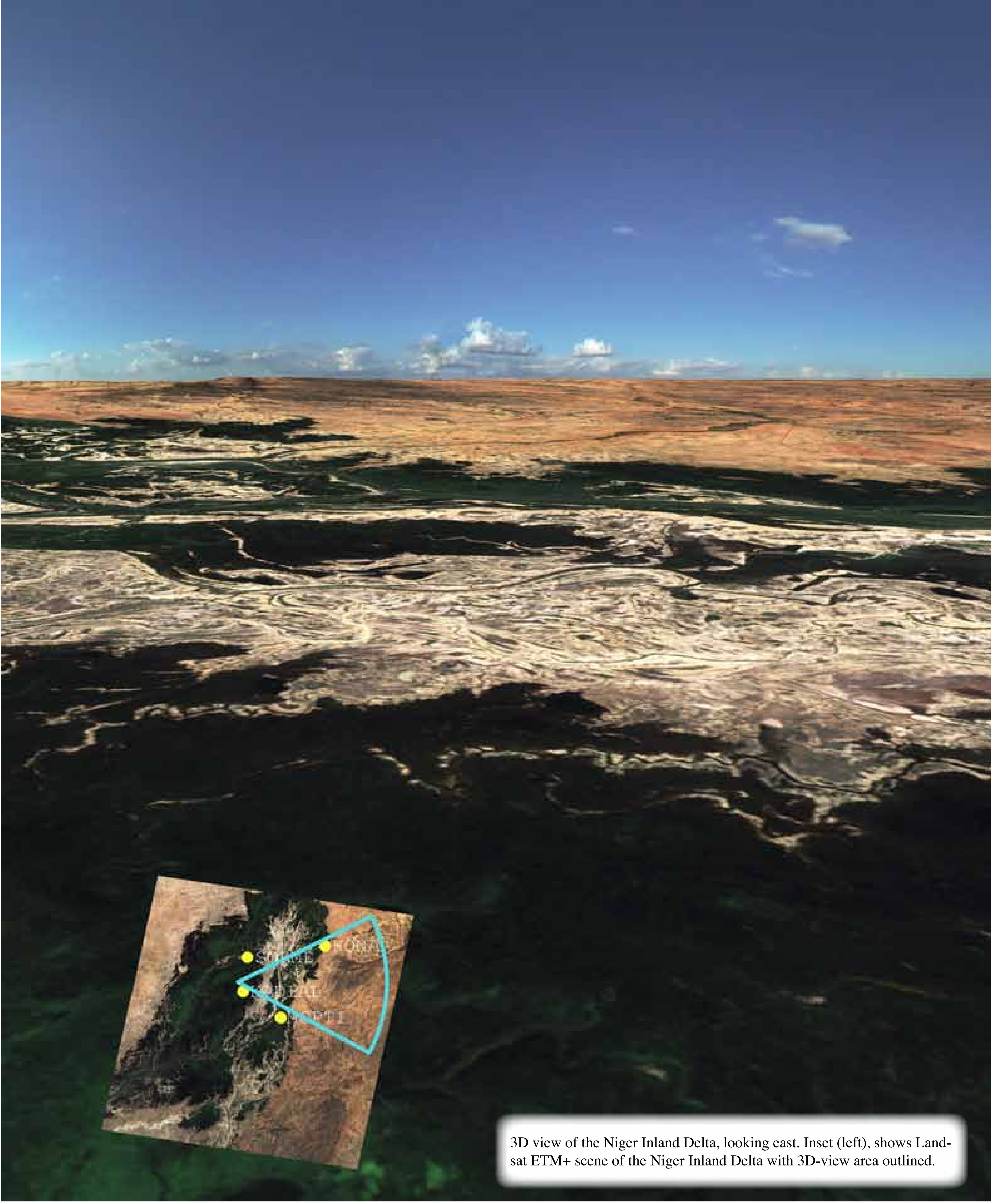
Geological ages and regions in West Africa (Source: USGS)

Geologically, large parts of Africa in general, and West Africa in particular, are very old (Pre-Cambrian). The African Shield (regionally called the West African Shield) underlies the whole of the Sahel. Towards the south the West African shield reaches the surface, whereas further to the north it is covered by younger rocks and sediment. The African Shield formed part of Gondwanaland, the ancient continent that joined Africa with South America, Madagascar, India, Australia and Antarctica about 500 to 200 million years ago. During that period, erosion created extensive plains (peneplains) in West Africa. Many of the highlands are remnants of these plains, including the Jos plateau in Nigeria, the West Cameroon Mountain Range and the Fouta Jallon in Guinea. With the breakup of Gondwanaland large basins formed towards the north and east of West Africa as a result of tectonic movements. The largest basins are the Chad Basin, the Taoudeni Basin, the Iullemmeden (or Niger) Basin and the Senegal (or Senegal – Mauritania) Basin, smaller troughs include the Benue and Volta basins. These basins were subsequently filled with sediments of both marine and terrestrial origin, and the surface rock is hence younger. More recent tilting of West Africa caused a new cycle of erosion, and the present plains in West Africa were formed over the last million years. These plains are separated by distinct scarps or transitions with broken relief. The African shield basement rock is mostly composed of granites, sometimes metamorphosed into gneiss and other rocks of granitic composition, or sediments of pre-cambrian origin formed by erosion of the original basement. The sedimentary rocks of younger age are mostly composed of sand. Paleozoic (Cambrian, Ordovician, Silurian and Devonian) sediments occur in the Volta Basin, and in Burkina Faso and Mali. In northern Burkina Faso the Paleozoic sediments consist of dolomitic limestone of marine origin. Southwestern Niger is largely covered by sandstones of cretaceous age, while the surface of the Senegal Basin largely consists of sandy sediments of Tertiary origin. Quaternary (recent) sediments of sandy composition cover most of the interiors of Mali and Mauritania. Riverine and marine silts and clay fill parts of the Niger and Senegal rivers. The Niger inland delta is an alluvial fan filled with sandy deposits. During Tertiary and Mesozoic times, rocks of volcanic origin (mainly basalt) formed in the Benue trough, and in some other minor outcrops. The sedimentary bedrock is formed of minerals that have undergone at least one erosion cycle, and often more. They are hence depleted of chemical nutrients for plant growth.

Topography

West Africa and the Sahel is a flat region, with elevations usually between 200 and 400 meters above sea level. The Pre-Cambrian surfaces towards the south are generally eroded to very monotonous plains. Elevated plateaus, including the Jos Plateau of Nigeria and the Fouta Jallon (or Djallon) of Guinea, are remnants of Pre-Cambrian peneplains. They are capped by more erosion resistant rocks, either older granites or more recently formed dykes. The Ahaggar (or Hoggar) Mountains were formed as recently as two million years ago. Most of the West African Sahel lies within the Niger and Senegal river basins, which both have a low relief. The Niger River flows north from Fouta Jallon, where rainfall is very high, and then flows in a north-easterly direction on the West African Shield, until it reaches the Paleozoic Niger basin, which is filled with sedimentary rocks, where it makes a large bend south into the Benue Basin. The Niger Inland Delta is an alluvial fan formed by sands carried by the Niger River. Tectonic uplifts during the last several million years were also a prerequisite for its formation. It is confined by scarps and faults linked to other tectonic activities during the Quaternary and late Tertiary periods.

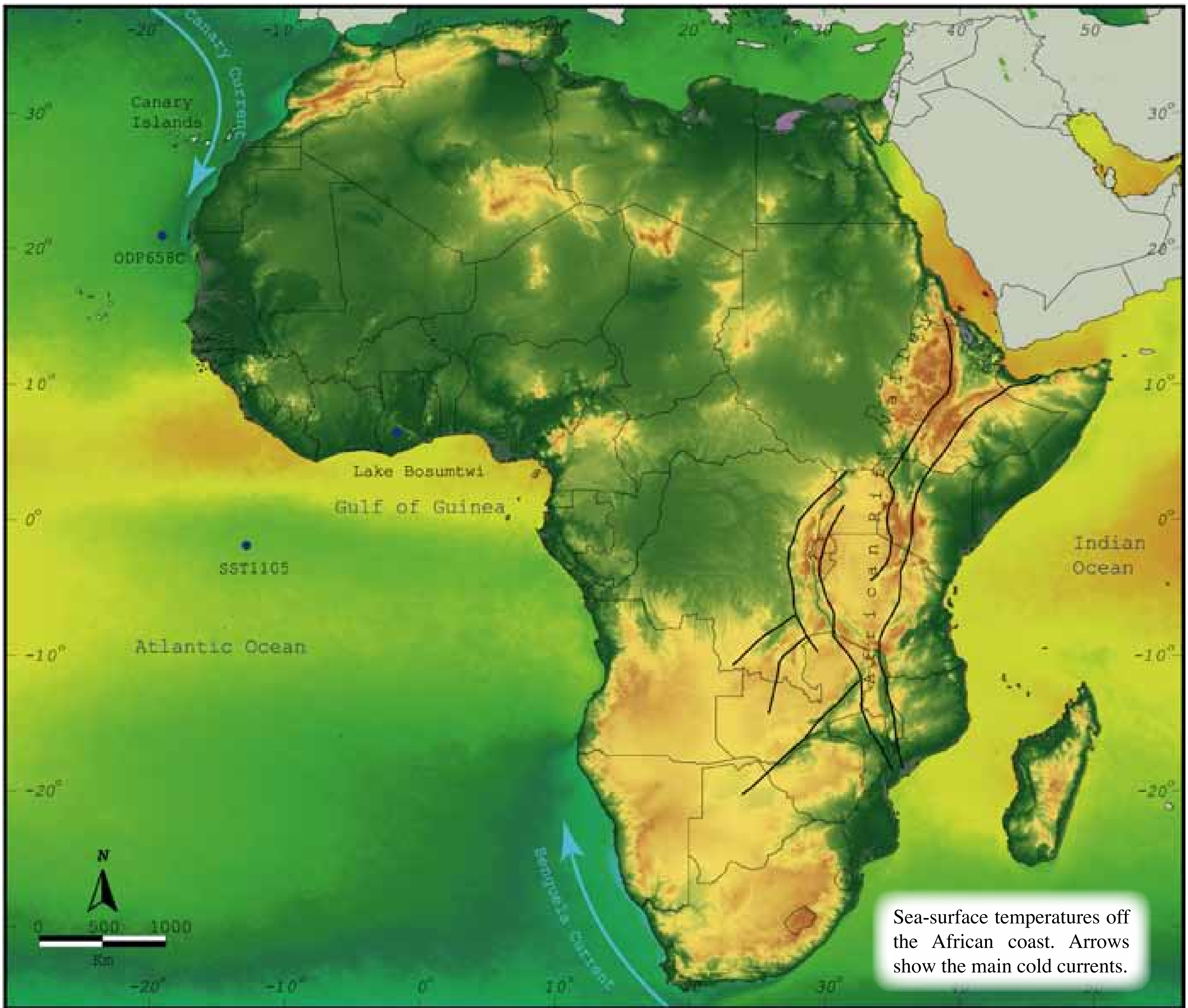




3D view of the Niger Inland Delta, looking east. Inset (left), shows Landsat ETM+ scene of the Niger Inland Delta with 3D-view area outlined.

Climate

Rainfall is the limiting factor for vegetation growth in large parts of the Sahel, although soil nutrients are also often strongly limiting. Hence, climate and rainfall largely determine man's use of Sahelian landscapes. The climate of Africa and the Sahel is constrained by Africa's position across the equator, and the tropical rain belt that forms under the solar equator and follows the annual migration of the sun between the Earth's two hemispheres bringing rainfall to West Africa with the summer monsoon.



Sea-surface temperatures off the African coast. Arrows show the main cold currents.

Africa is the only continent that is divided into approximately equal halves by the equator. Africa is also the highest of the worlds continents, with large parts of southern and eastern Africa having elevations higher than 1,000 meters above sea level. The high elevation of Africa is caused by accumulation of hot magma in the Earth's mantel beneath the continent, which lifts the crust up and also causes the surface to rift, forming the Great African Rift Valley. The main reason for this is probably that Africa is the most stationary of the Earth's continents and heat cannot escape as easily as from other continents. Both the position of Africa on the equator, and its elevated topography lead to a drier climate than elsewhere. Additionally the currents off the African Atlantic coast are cold. In the south the Benguela Current brings cold water to the Atlantic coast of southern Africa, and the West African coast is "licked" by a tongue of cold water from the Canary Island Current. The cold waters limit the amount of clouds formed over the sea, and the elevated land prevents the clouds from blowing in over the continent.

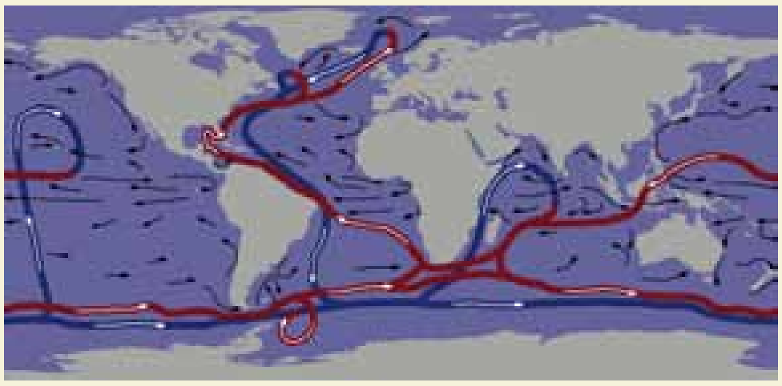
External climate forcing

Rainfall over West Africa is strongly influenced by global atmospheric circulation patterns and annual variations in sea surface temperature (SST). Both the Atlantic and the Indian Ocean are thought to play major roles in controlling the tropical rain belt and the Sahel summer monsoon. In general the tropical rain belt (see next page) will reach further north into the Sahel if the Atlantic Gulf Current transporting warm water northwards in the Atlantic is strong, and when the Indian Ocean cools down. The northward flow in the Atlantic is largely regulated by the Atlantic Ocean overturning driven by surface water sinking in the North Atlantic Ocean around Greenland, a process driven by the northward flowing water becoming heavier as the water cools down and salts are concentrated by evaporation. This process of heavier cold and salt water sinking towards the deep ocean is called thermohaline (meridional) circulation, and is of major importance for the ocean global circulation, sometimes called the conveyor belt. The surface temperature of the Atlantic Ocean along the West Africa coast is however also related to the Canary Current and Atlantic turnover at mid latitudes.

Annual to decadal variations in rainfall over West Africa and the Sahel are related to the surface temperatures in the Indian Ocean, with a warmer ocean depriving the Sahel of rainfall. Over longer time periods, the thermohaline driven circulation of the Atlantic Ocean is thought to be more important, with a stronger northward current in the Atlantic dragging the summer monsoon further north into the Sahel. This is generally accepted as the cause of desert conditions in the Sahel during the last ice age, when the thermohaline driven cycling of the Atlantic Ocean was largely shut off. Reduced thermohaline circulation probably also initiated the drying cycle that led to the droughts in the 1970s and 1980s. The thermohaline overturning of the Atlantic has however continued to decrease also after the rains returned to the Sahel, whereas the transport of Atlantic surface water across 25°N (outside West Africa) has remained nearly constant.

Internal climate feedback

Most of the solar radiation that is received by the Earth is exchanged (or dissipated) at the Soil-Vegetation-Atmosphere interface. Part of the incoming radiation is reflected, dependent on the albedo (brightness) of the surface. Snow has a very high albedo reflecting most of the incoming radiation, and soil usually has a higher albedo than vegetation. A dry surface has a higher albedo than a wet surface.



The global ocean conveyor belt driven by thermohaline circulation. Blue paths represent deep-water currents, red paths represent surface currents of the conveyor belt. Black paths represent other surface currents.

Part of the incoming radiation is absorbed, for instance by vegetation for driving the process of photosynthesis, or directly by the soil or water surface that then warms up. A large fraction of the incoming radiation is used for evaporating water, transferring liquid water at the surface to water vapor in the atmosphere. As evaporation is a highly energy demanding process (boiling water needs large amounts of heat) it keeps the surface cool (hence it is cooler near a water body on a sunny day compared to inland). Vegetation has the ability to transfer water from deep in the soil to the surface. Plants transfer water from the roots to the leaves and then to the atmosphere, which cools the surface and fills the atmosphere with water vapor. Where vegetation is dense it therefore controls surface temperature, and saturates the atmosphere with water. If this process is effective, the lower atmosphere will get saturated with water towards the afternoon when solar radiation decreases and the air temperature sinks. This causes water vapor to condensate into drops and form clouds. If conditions are favorable, afternoon rain will fall after a morning with cloud buildup. In drylands this in an important process for rainfall generation, often in the form of thunderstorms. Vegetation therefore assists in creating a closed vertical loop with evapotranspiration going up and rainfall coming down. If vegetation cover is lost, this closed vertical loop is broken, leading to the land surface heating up. This results in further deterioration of conditions for vegetation growth. This is an important internal climate feedback mechanism thought to have played a role during recent droughts in the Sahel and also in ending the African Humid Period 5,000 years ago.

Climate change and biophysical feedback

The global climate depends on cyclic variations in solar radiation related to the position of the Sun relative to the Earth, and the tilt of the Earth's rotational axis. These variations are reinforced by a sequence of physical and biological responses primarily related to changes in the Earth’s ground cover, atmospheric content of greenhouse gases, and ocean circulation and bioproduction. The major mechanism behind this reinforced change (or positive feedback) is that a general cooling (warming) will lead to growth (decline) of ice sheets reflecting more (less) of the incoming solar radiation, leading to further cooling (warming). In a cooling phase the growing ice sheets will deplete the oceans of water. The sinking water surface will erode accumulated near-shore sediments and thence fertilise the ocean. The nutrients released from the sediments will promote aquatic biological growth that will consume carbon dioxide from the atmosphere – the most important of the greenhouse gases. The oceans will also get cooler and more of the greenhouse gases (notably carbon dioxide and methane) can be dissolved in the colder waters – further depleting the atmosphere of greenhouse gases. The thermohaline circulation is also affected by the global climate and can further reinforce climate changes as deep water formation is a key process for transferring climate gases from the atmosphere to the deep ocean. The loss of greenhouse gases from the atmosphere will lead to further global cooling. A cooler land surface will also lead to more reflection of solar radiation as vegetation cover decreases and is replaced by more reflective soils, and as more dust is produced from the exposed soil.

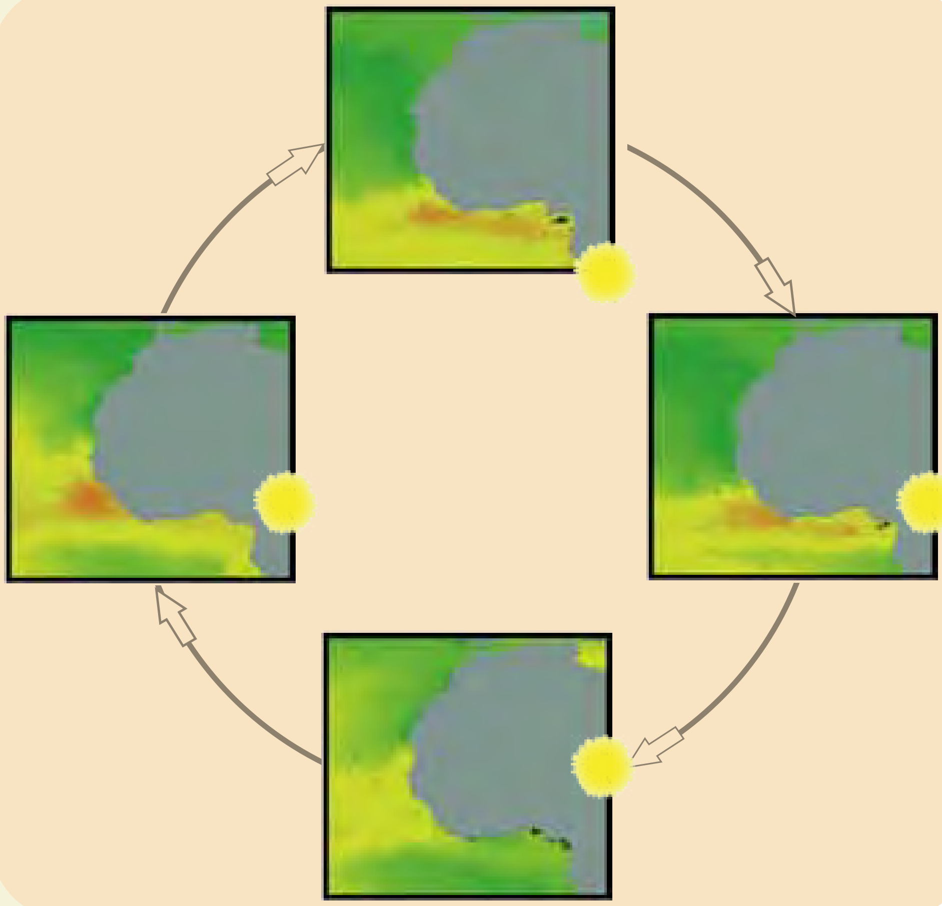
The Inter-Tropical Convergence Zone

The summer monsoon that brings rain to West Africa and the Sahel is caused by a low pressure zone that girdles the Earth and travels under the solar zenith position – the Inter-Tropical Convergence Zone (ITCZ) or tropical rain belt (also known as the Intertropical front, monsoon trough, doldrums or the Equatorial Convergence Zone). The summer monsoon over West Africa consists of two separate monsoons, one weaker monsoon during June that reaches about 5°N and the stronger monsoon in August reaching as far as 10°N, where it normally remains for around a month. The moisture laden monsoon trade winds originate over the Atlantic Ocean where they pick up moisture that is gradually released as rainfall and the winds dry out as they blow in over West Africa. This is the major cause for the strong rainfall gradient of the Sahel. At the position of the rain belt the moist monsoon wind meet the dry Harmattan trade winds originating in the Sahara Desert. The meeting air masses are forced to raise up causing clouds to form and rain to fall. The rising air will then travel away from the rain belt at high altitudes and start sinking towards the surface as very dry and hot air. Once at the surface the air will again blow as trade winds, completing a circle. The cycles of air masses, or Hadley cells, are affected by the Earth's rotation, and hence the trade winds (including the monsoon and the Harmattan) blow in a westerly direction at the equatorial surface, albeit distorted due to local conditions. The sinking dry air of the Hadley cells away from the equator are the causes of the African deserts positioned around the tropics – Sahel at the northern tropic (tropic of Cancer) and Kalahari at the southern tropic (tropic of Capricorn).

For the clouds generated by the winds from the Atlantic to actually produce rainfall, the jet-winds in the higher atmosphere must be strong enough to lift the clouds up. When lifted they lose the ability to hold water and droplets are formed that grow to drops and fall to the ground. The strength of the jet winds over Africa are hence also factors that play a role for the Sahel rainfall. The overall forces that determine rainfall over West Africa and Sahel are however poorly understood, and the monsoon rains cannot be predicted in advance.

Annual sea surface temperature cycle (2004)

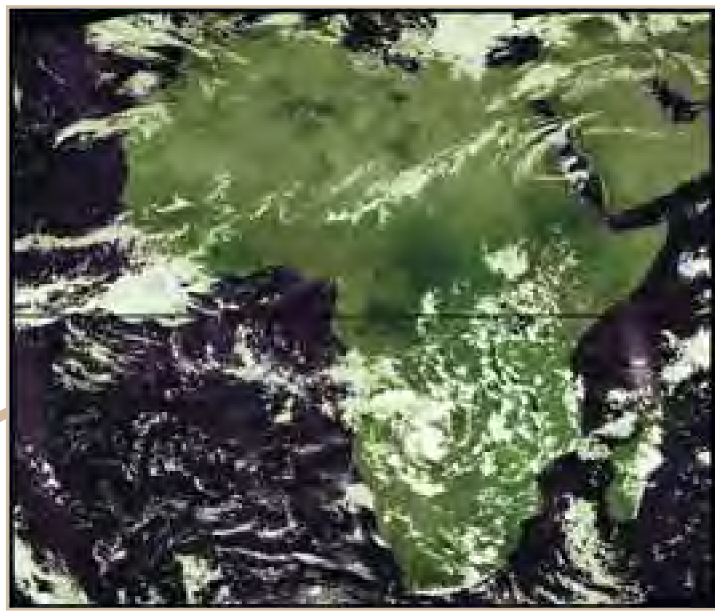
In the southern hemisphere summer (February – top panel) the surface water in the Bay of Guinea is warm, while the Canary Island Current tongue of cold water reaches the West Coast. The cold current water still influences surface water temperature in May (right panel). In August, the surface waters of the Bay of Guinea are colder (bottom panel) and the West Coast waters have warmed up. In November (left panel) the Canary Current again brings cold water to the West Coast. The northward expansion of warm surface water in the northern hemisphere summer is a strong regulator of the rain belt and the monsoon delivering rainfall to the Sahel. The Sahel receives less rainfall due to a reduction in the Atlantic overturning of warm surface water flowing northwards. This phenomenon resulted in expansion of the Sahara Desert during the last ice age across what is today the Sahel. This was probably also a contributing factor for the Sahel droughts during the 1970s and 1980s.



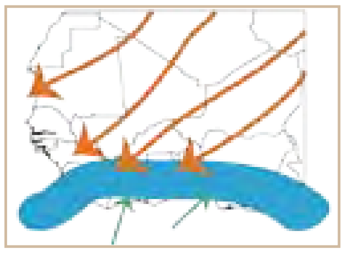
Approximate latitude of the Sun zenith position is indicated on the maps.

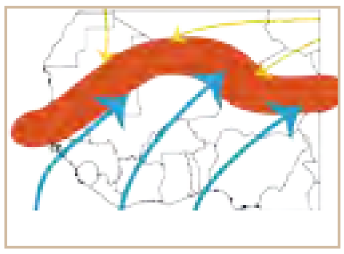
ITCZ annual cycle over West Africa (facing page)

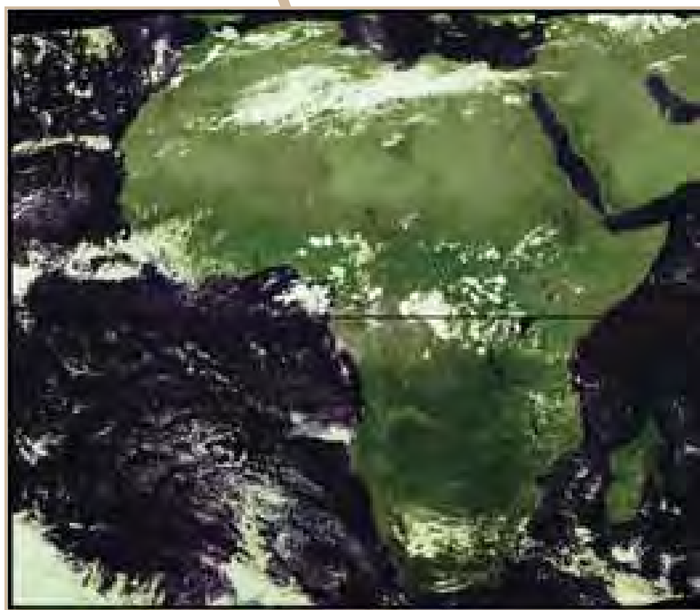
The ITCZ is attracted towards the warmer hemisphere. During the southern hemisphere summer, the ITCZ passes the equator south of West Africa (February – top panel). Over the African continent it reaches as far south as Mozambique and Madagascar, and is usually called the South Indian Convergence Zone. The large land mass of West Africa together with the warm surface waters in the Atlantic Ocean, keeps the ITCZ in a more northerly position over West Africa compared to elsewhere. During the northern hemispheres summer, the ITCZ reaches about 10°N in August (bottom panel) and attracts the rain-bearing monsoon far into the Sahel. Over West Africa the ITCZ passes the region between the equator and 10°N twice every year, in the Boreal spring (May – right panel) when it moves northwards, and in the Boreal autumn (November – left panel) when it migrates south. These regions hence receive two annual rainfall seasons. The coast of the Bay of Guinea receives rainfall almost the whole year, with a short dry season in the Boreal summer.



Satellite image from February 2004 showing the ITCZ situated just north of the equator in West Africa. The ITCZ is more clearly defined over the ocean, and disperses over land. Over the African continent the ITCZ stretches down towards Mozambique and Madagascar. The small maps show the general position of the ITCZ over West Africa during the dry season (top) and the wet monsoon (bottom).







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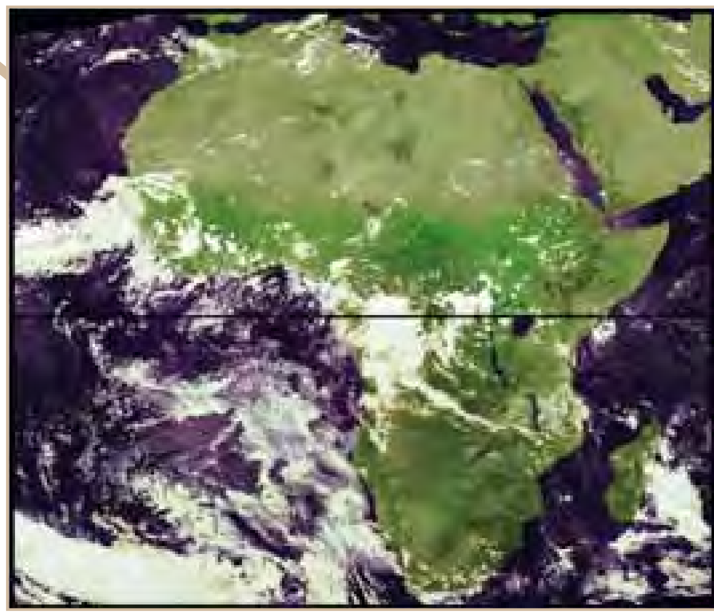
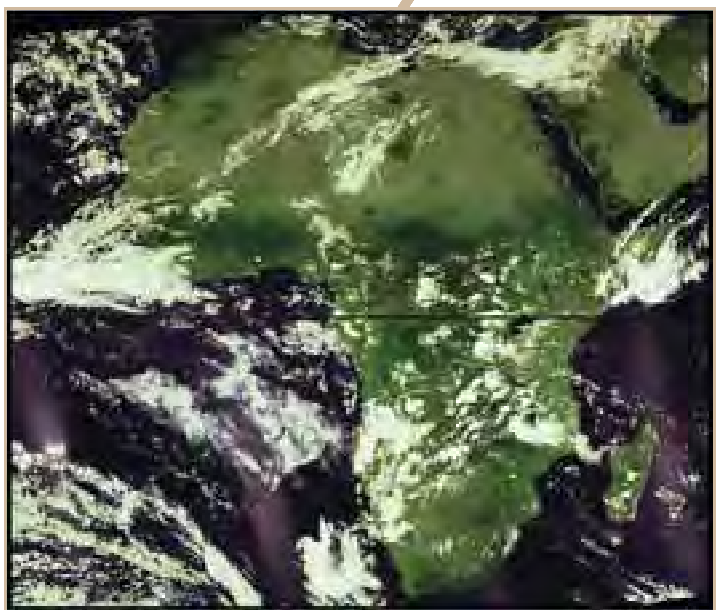


Satellite image from August 2004 showing the ITCZ at its northernmost position about 10°N of the Equator over West Africa. August is the wettest month in the Sahel, with the monsoon delivering almost half of the annual rainfall over the Sahel during this month.



Satellite image from November 2004 showing the ITCZ as it migrates southward with the sun. The monsoonal rains again pour over the Guinea moist savanna, giving the second rainy season. The soil still holds water in the Sahel and vegetation cover is more dense compared to May, even if the ITCZ has approximately the same position. Over continental Africa the ITCZ is again penetrating south of the equator.

The satellite images on this page are composites of Advanced Very High Resolution Radiometer (AVHRR) scenes downloaded from the Comprehensive Large Array-data Stewardship System (CLASS) electronic library operated by the National Oceanic and Atmospheric Administration (NOAA).

Annual climate cycles

The annual cycles of rainfall, temperature and evapotranspiration all follow the annual oscillation of the ITCZ as it moves between the northern and southern hemispheres. Rainfall over the Sahel is highest in the summer, as is temperature and evapotranspiration. The rainy season needs to last two to three months for vegetation to grow, mature and produce seeds, which corresponds to an annual rainfall of approximately 300 mm. As wet soil conditions and a moist atmosphere tend to cool the surface, and lead to higher atmospheric vapor pressure, the temperature cycle is ahead of the rainfall cycle by approximately two months. The actual evapotranspiration cycle lags behind the rainfall cycle, as the latter produces moisture to be evapotranspirated later. Average annual temperature is about 27 to 30°C, varying from between approximately 25°C in December to approximately 32°C in April. Diurnal variations can be as high as 40°C, with temperatures dropping to 0°C at night. Potential evapotranspiration is approximately 1,500 to 2,000 mm per year, with little seasonal variation. Actual evaporation is highly dependent on water holding capacity of soils and surface conditions, and thus also has a marked south to north declining gradient. It is higher during the summer wet season, when the soil is moist and insolation is at its maximum (albeit sunshine hours are fewer due to cloud cover). The annual cycle of relative humidity closely follows the rainfall cycle, ranging from about 30% in the peak dry season to 80% during the summer monsoon.

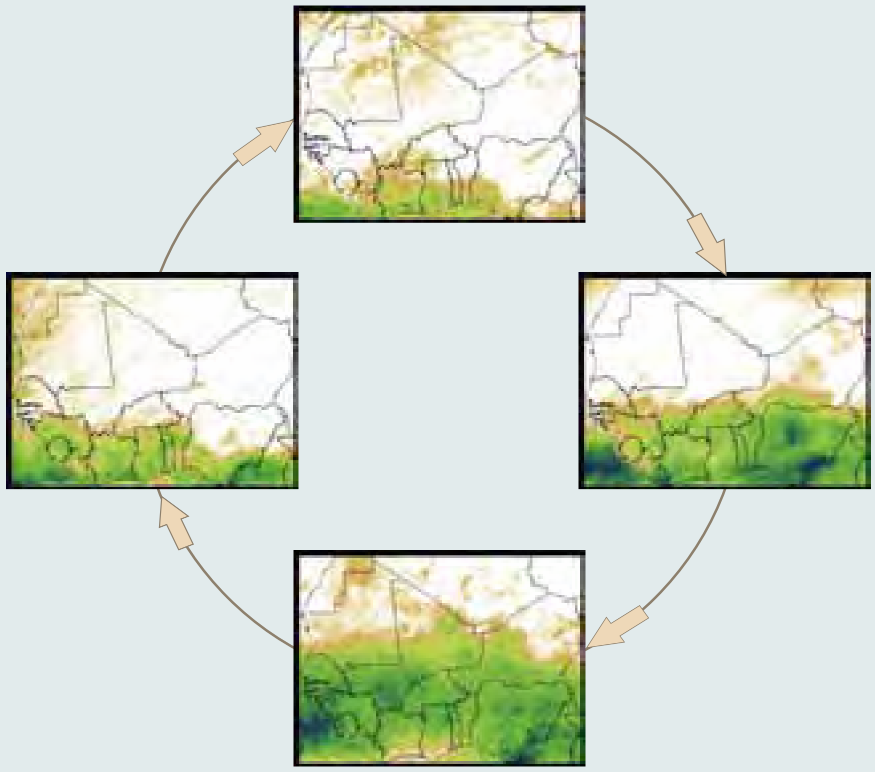
Climate cycles and soil degradation

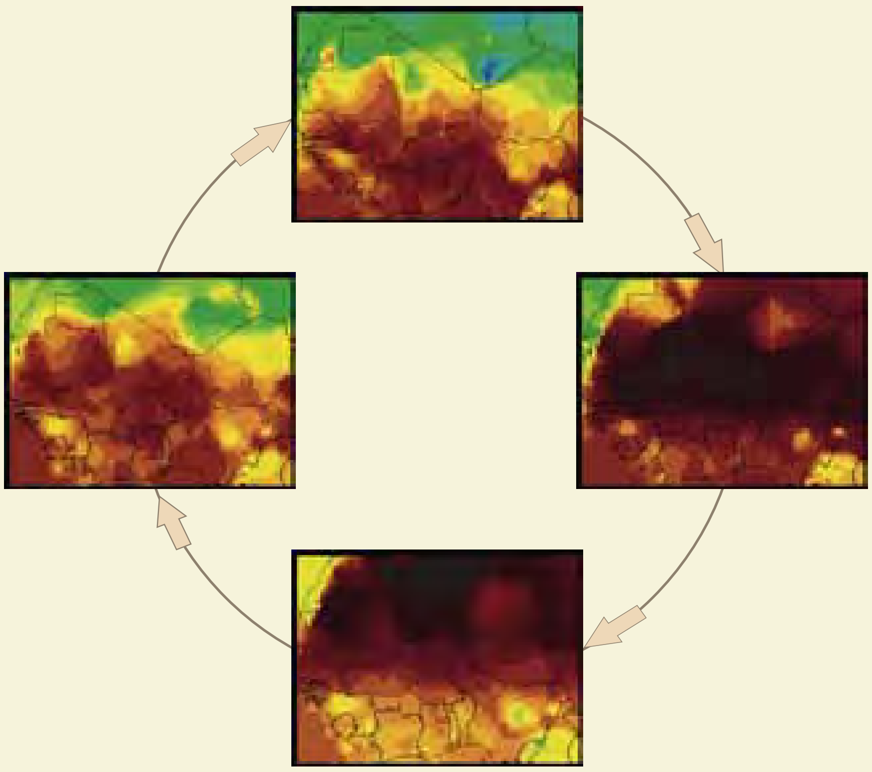
Water available for vegetation growth is determined by both rainfall and evapotranspiration, and by the water holding properties of the soil. In general, clayey soils and soils with higher organic matter content have better water holding capacities compared to sandy soils and soils poor in organic matter. When estimating the water-limited capacity for vegetation growth it is the soil's water content that is of primary interest. This is difficult to measure or estimate, and hence rainfall is commonly used as a substitute for soil water when calculating potential vegetation growth. Degraded soils have typically lost their finer material by either wind or water erosion carrying away finer clay particles.

What is left behind is a skeleton of coarser soil. When tree cover is lost, the protecting canopy disappears and the soils are more exposed to both wind and rainfall. With a loss of tree cover, evapotranspiration also decreases, leading to a larger fraction of the rainfall forming runoff, potentially leading to further erosion. The canopy also dampens diurnal and annual temperature variations, both by shading the soil and by cooling the surface by evapotranspiration during the summer rainy season. Higher ground temperatures and larger diurnal temperature fluctuations following the loss of a protective canopy promotes the breakdown of organic matter, and with less tree cover less new organic matter is produced. Hence loss of tree cover can have devastating effects through subsequent changes in water and temperature cycles, leading to accelerated soil and land degradation.

Annual rainfall cycle

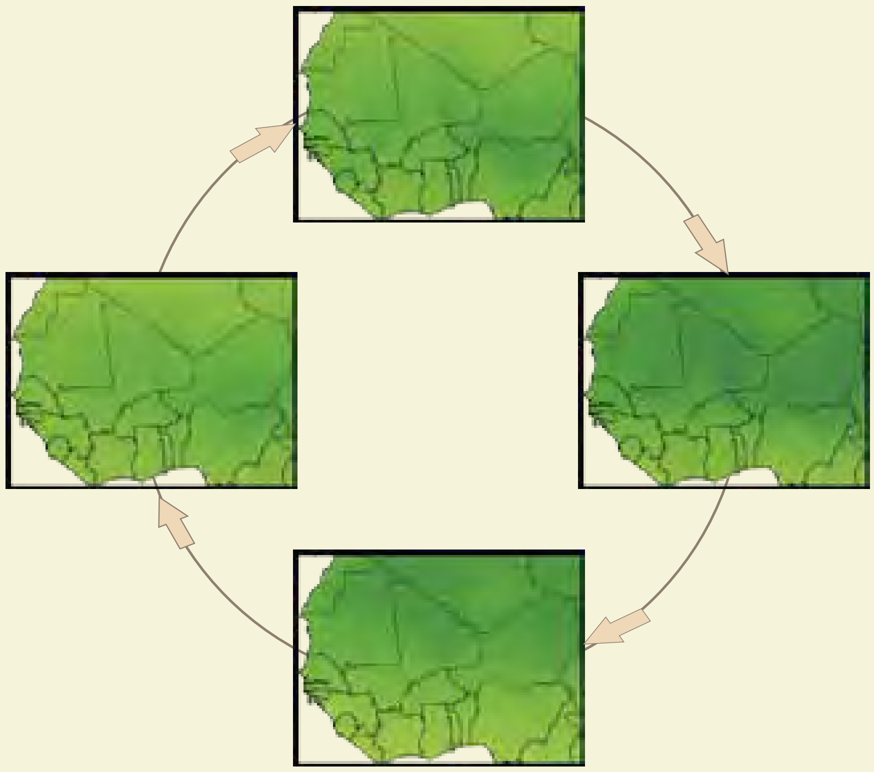
The annual rainfall cycle closely follows the tropical rain belt (ITCZ). During the dry winter, rainfall is very low (February – top panel). The summer monsoon peaks in August (bottom panel). The southern parts of the Sahel and the Guinea moist savannah have two annual rainfall seasons, when the ITCZ migrates northwards in spring (May – right panel) and when it migrates southwards in autumn (November – left panel). The Guinea coastal rain forest receives rainfall almost all year, with a short dry season in the summer. The rainfall gradient in the Sahel is created both by the oscillating position of the ITCZ and the rain-bearing monsoon winds releasing rainfall as they blow northwards from the Atlantic coast towards the ITCZ.





Annual temperature cycle

The annual temperature cycle follows the sun's migration, with adjustment for rainfall that tends to cool the surface as water evaporates. The warmest months are in the early summer before the arrival of the monsoon rains (May – right panel). August (bottom panel) is the hottest month in the northern part of the Sahel, with cooler climates south of the solar zenith where moist soils also reduce temperatures. In November (left panel) the climate in the Sahel is cooler because the wet soils cause the air to cool. In the midst of the dry season (February – top panel) the Harmattan winds blow south from the Sahara Desert and warm the Sahel. Despite the seemingly stable temperatures throughout the year, large diurnal variations occur.

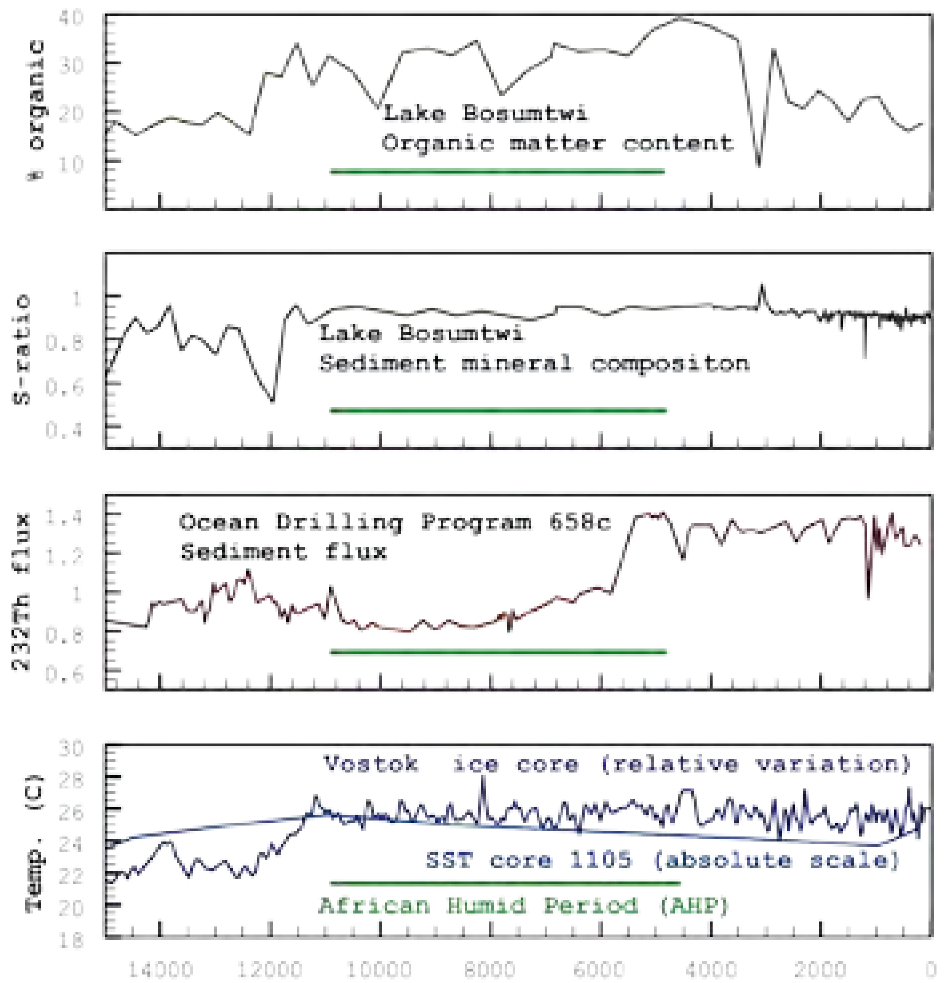


Annual evapotranspiration cycle

Water transfer from the surface to the atmosphere depends on air temperature and water vapor pressure, and water availability at the surface. Potential evapotranspiration is the atmosphere's absorption potential when the ground is saturated, and is mainly dependent on air temperature and vapor pressure. Potential evapotranspiration is high all year in the Sahel. During winter (February – top panel) the desiccating Harmattan makes the atmosphere dry. In the early monsoon season (May – right panel) insolation increases, and the first rains occur. During the monsoon season (August – bottom panel) the solar zenith over the Sahel contributes to a high potential evapotranspiration, but at the same time the monsoon brings in already moist air. After the monsoon, when the air is still moist but before the Harmattan has set in (November – left panel) potential evapotranspiration is slightly lower.

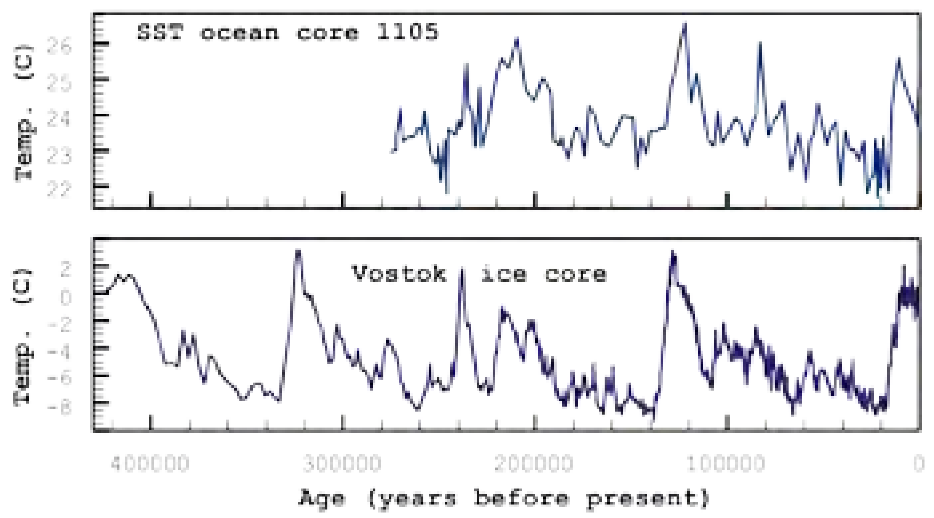
Long term trends in climate

Over tens of thousands of years it is the average temperature of the Earth that regulates ocean temperatures, and hence rainfall over the Sahel. During the latest ice age, which ended about 12,000 years ago, rainfall was much lower over the Sahel, and desert conditions prevailed. During the ice age, sea surface temperatures were lower and the northward flow of warm water in the Atlantic Ocean was periodically strangled. At the end of the ice age, during the period called Younger Dryas, the melting ice created a blanket of fresh water on the surface of the North Atlantic Ocean, prolonging the Sahel dry spell by reducing the northward flow of warm water from the tropical Atlantic Ocean. The ice age was followed by the African Humid Period (AHP), when the Sahel was much greener compared to today. During this period a stronger overturning of the Atlantic Ocean brought warm Atlantic waters further north generating a stronger summer monsoon over West Africa. This green period came to an end about 5,000 years ago. Probably initiated by a reduction in the Atlantic circulation, and then exacerbated by vegetation losses leading to lower evapotranspiration rates and lower soil water holding capacities, further reducing rainfall in the Sahel.



Holocene climate change

Climate variations during the end of the last ice age and the Holocene period (from 12,000 years ago to present). The bottom panel shows the temperature variations as recorded from the Vostok ice core in Antarctica. The two middle panels show export of dust from the Sahara and the Sahel to the Atlantic Ocean, as recorded in a borehole at the Ocean floor (ODP658C), and to Lake Bosumtwi in Ghana. The top panel shows percentage organic matter in the bottom of Lake Bosumtwi with high organic levels indicating more dense vegetation in the area around the lake. As temperatures rose at the end of the ice age, dust export from West Africa decreased and vegetation cover increased. Other studies from bore-holes in the Sahel show that during AHP less drought tolerant trees grew much further north than at present, that water levels in lakes were much higher, and that lakes were less saline than today. Lake Chad and the Niger Inland Delta are the only large remaining water bodies from the AHP. The climate during this period was characterized by a stronger summer monsoon.



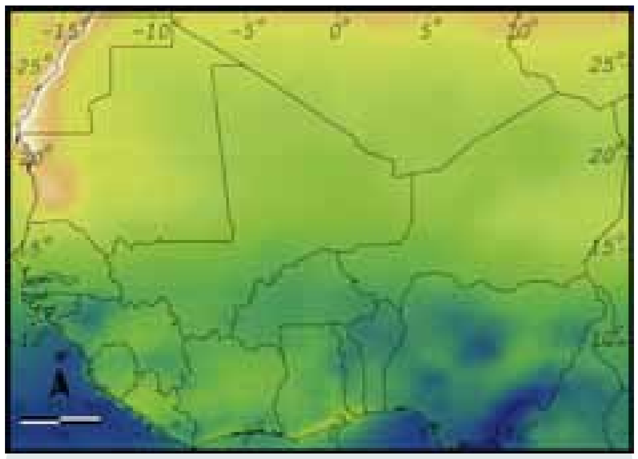
Ice age climate cycles

Temperatures over the last 400,000 years recorded from ice cores in Antarctica (Vostok ice core – bottom graph) and an ocean core (SST1105 – top graph) from the Atlantic Ocean, outside West Africa (see map on page 26). The variations are strikingly similar, indicating that the Atlantic was cooler during the ice ages and that the cooler periods have recurred at regular intervals of approximately 100,000 years. The ultimate cause of these temperature cycles is regular variations in solar radiation received by the Earth as the distance and angle between the Sun and the Earth oscillates (called Milankovich cycles). Apart from being cooler with a weaker northward flow, the Atlantic Ocean was also about 100 m lower than today during the last ice age (water being bound in extended ice sheets). This resulted in less cloud-formation as less water was evaporated from the colder sea surface, and the clouds that actually formed had difficulties reaching inland from the coast. Consequently, rainfall over West Africa was much lower.

West Africa rainfall during Holocene

The amount of sunlight received by the Earth increased after the latest ice age and peaked over West Africa around 7,000 years ago. The map on the right shows estimated rainfall distribution over West Africa during the African Humid Period (AHP), which lasted about 5,000 years and ended around 5,000 years ago.

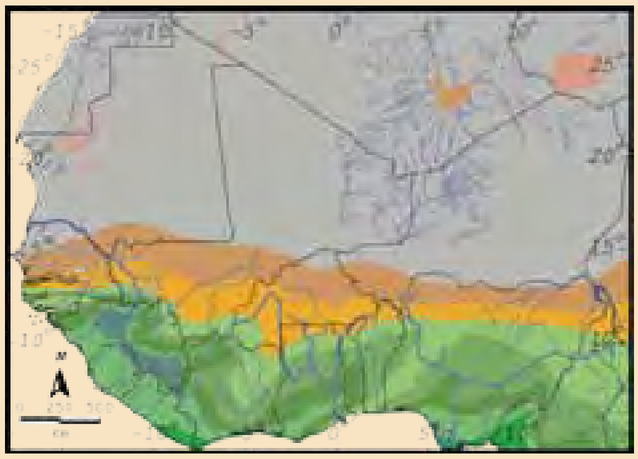
As is evident from the map on the right, higher rainfall extended further north (into what is today the Sahara Desert) than at present (map on page 34).



Map showing rainfall over West Africa during the African Humid Period.

Vegetation in West Africa during the last glacial maximum (22,000 to 13,000 years ago)

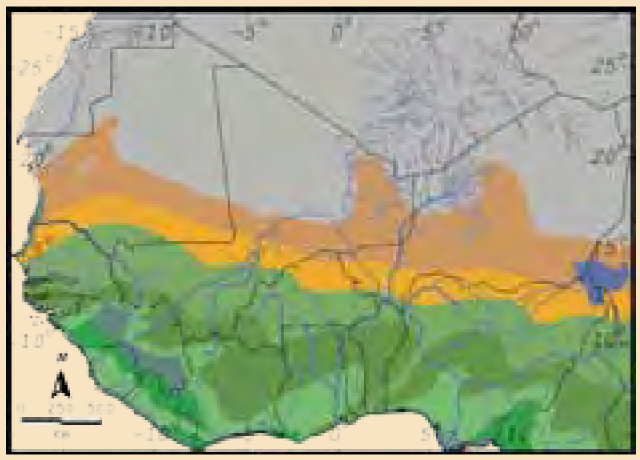
During the latest glacial maximum the Sahara Desert extended several hundred kilometers further south than at present. Sand dunes extended far into present-day Sahel and lakes dried out. Pollen found in old lake cores indicate both a drier and a cooler climate over West Africa. The vegetation belts of grasslands (brown), savannahs (orange) and woodlands (shades of light green) were compressed, and the tropical rain forest (dark green) was restricted to a few patches along the Bay of Guinea coast.
The map on the right shows vegetation conditions 18,000 years ago (data from Dieter Anhuf).



Vegetation in West Africa 10,000 years ago

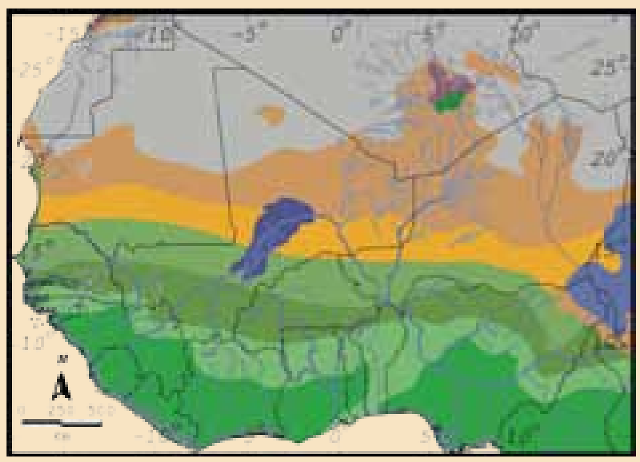
When the last glacial period came to a rapid end, it was followed by a cooler period (Younger Dryas), discussed earlier. After Younger Dryas, rapid warming allowed the woodlands and savannahs to expand northwards, and the tropical rain-forest colonized larger patches along the coast of Bay of Guinea. Conditions were similar to at present, and the vegetation 10,000 years also represents potential vegetation cover (without human interference) of West Africa today.

On the right we have compiled a map showing vegetation conditions 10,000 years ago (data from Dieter Anhuf).



Vegetation in West Africa during the AHP (6,000 years ago)

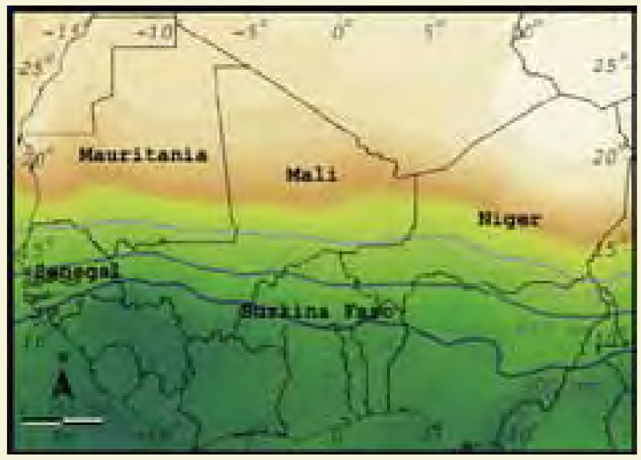
During the African Humid Period, the more northerly position of the summer monsoon allowed the woodlands and savannah vegetation belts to migrate into what is now the Sahara Desert, and the lakes and wetlands also expanded. The river networks grew larger, connecting ancient dry riverbeds (wadis) to actively flowing rivers. The evergreen forests expanded further inland from the coastline of the Bay of Guinea.



Map showing vegetation conditions 6,000 years ago (data from Dieter Anhuf)

Climate during the last century – rains and droughts

The last century has seen extended periods of both high and low rainfall over the Sahel. Rainfall increased quite strongly in early 20th century, followed by a wet period in the 1920s and 1930s. The 1950s and early 1960s had very high rainfall, followed by a striking decline in the 1970s and 1980s of about 40%. Such declines in rainfall have not been observed elsewhere on Earth during the last century. The Sahel experienced droughts also in earlier centuries, with recordings for the coastal region from the 1640s, 1660s–1670s, 1710s, 1750s, 1770s–1780s. Famines also raged in the coastal regions during the first half of the 19th century. Closer scrutiny of rainfall records in the Sahel, and elsewhere in Africa, reveal (quasi) cycles of 80 years. Whether this cycle is linked to variations in sea surface temperature or ocean circulation patterns is not understood. Recent droughts were most likely initiated by lower rates of overturning circulation in the Atlantic Ocean. The slowdown of the Atlantic thermohaline circulation has, however, continued after the rains have recovered, while the currents in the mid-latitude Atlantic Ocean (at latitudes outside West Africa) have remained relatively constant. On this shorter time scale it is more probable that sea surface temperatures in the Indian Ocean have the major influence on rainfall in the Sahel.

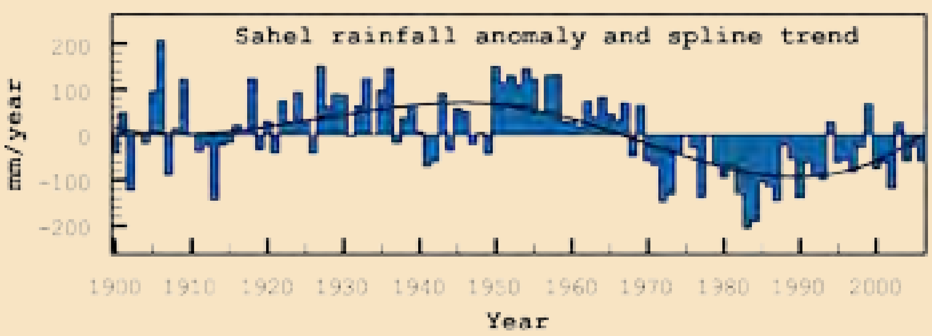


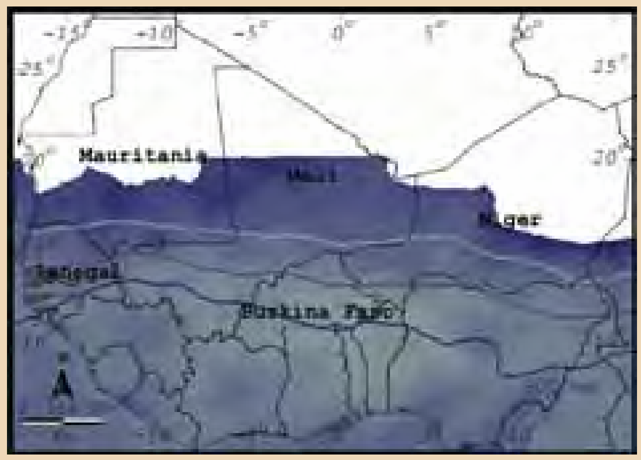
Average rainfall 1930 to 2006

This map was created from a combination of historical rainfall records between 1930 and 1995 (approximately 1000 rainfall records), and satellite-based rainfall estimates from 1996 to 2006. The isohyets (line showing equal rainfall levels) for 300, 600 and 900 mm annual rainfall 1930–2006 are also shown.

Variations in rainfall over the Sahel from 1900 to 2006.

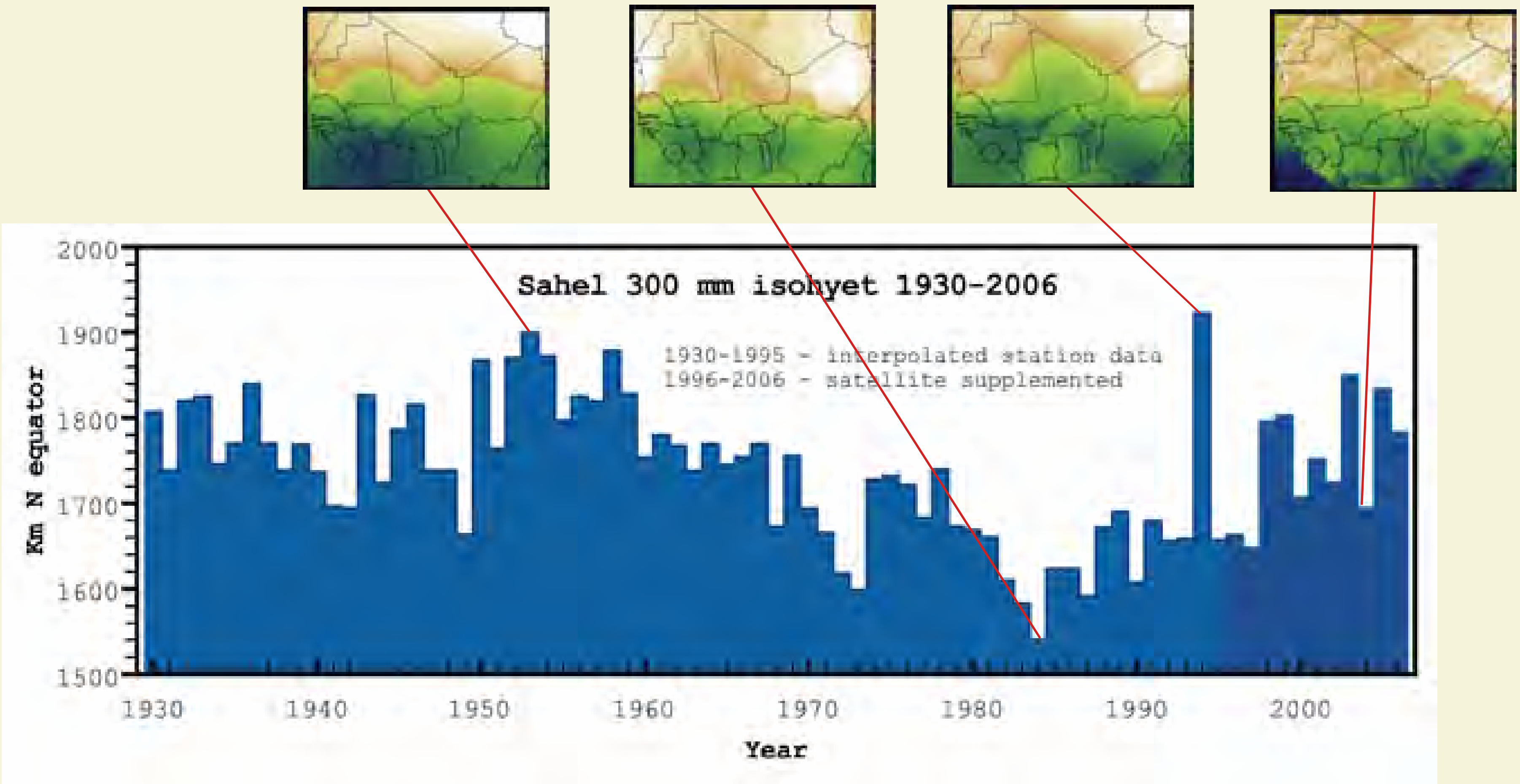
The rainfall data over the last century show a quasi 80-year cycle of high and low rainfall periods (line in graph below). This quasi 80-year cycle is well known from many hydrological time-series in Africa. If the cycle continues into the future, the rainfall increase over the Sahel over the last two decades will continue for approximately another two decades before the next drying cycle begins.





Rainfall variation 1930–2006

Coefficient of Variation (standard deviation divided by average) for rainfall over the Sahel for the period 1930 to 2006 (77 years) is higher towards the drier north (map limited to 100 mm isohyet). Large variations are a problem for farmers and pastoralists, especially as no forecasts can be made about monsoon rains.

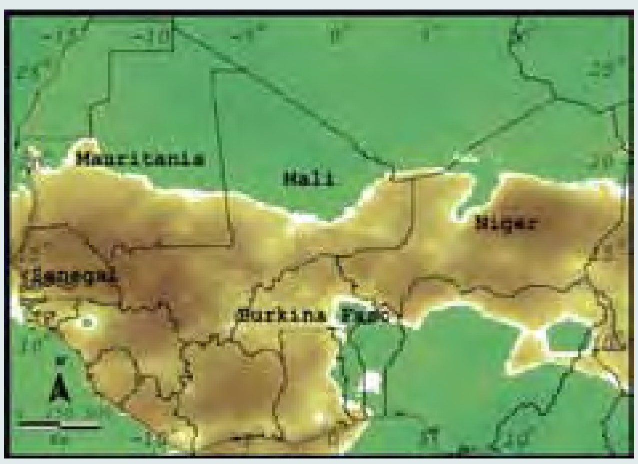


Rainfall latitude shifts 1930 to 2006

The 300 mm isohyet is an indicator of how far north into the Sahel it is possible to grow pearl millet (*Pennisetum glaucum*), which is well adapted to areas characterized by drought, low soil fertility status and high temperatures. The 300 mm isohyet is not an absolute ecological boundary, but a threshold below which growing crops becomes difficult. The above figure shows the north-south (latitude) variation in the position of the 300 mm isohyet in the Sahel between 1930 and 2006. The variation in the position follows the overall variation in rainfall (previous page). During the period with high rainfall in the 1950s and early 1960s, the 300 mm isohyet traveled far north in the Sahel, reaching furthest north in 1953 (map top left). The rains started to decline in the 1960s and droughts hit the Sahel in the early 1970s and 1980s. 1984 is the driest year on record during this period, with the 300 mm isohyet migrating almost 400 km south as compared to 1953. After these droughts, rainfall increased strongly and in 1994 the isohyet again reached the 1953 position, albeit mostly restricted to Mali, and partly caused by early (so called "mango") rains. In recent years the overall variation has been lower, but with considerable variations in the onset of the monsoon rains (not shown). The map on the top right shows rainfall in 2004, which is a "normal" year.

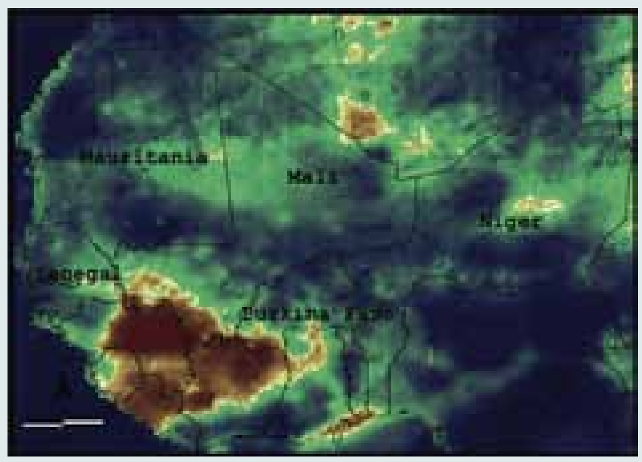
Change in rainfall 1930–2006

Over the period 1930 to 2006, there has been a decline (brown to red colour) in rainfall over the Sahel, and large parts of the coastal regions of West Africa. Despite the recovery in rainfall since the droughts, rains over the Sahel have not yet reached the levels of the 1950s.



Change in rainfall 1982–2006

Rainfall has increased (green to blue colour) strongly, almost doubled in Burkina Faso, southern Mali and western Niger since the droughts in the 1980s.



What are the causes of climate shifts in the Sahel?

There are two main hypotheses for the causes of climate variations and droughts in the Sahel. The older "internal" or "equilibrium" hypothesis points at internal changes in vegetation and land cover as the regulator of climate. Initially this hypothesis focused on changes in the reflection of incoming solar radiation from bare soil compared to vegetation. Overgrazing and conversion of woodland to agriculture increase surface reflection (albedo), and decrease moisture supply to the atmosphere. Later research has shown that it is vegetation and the capacity of the soil to keep water in a closed cycle that is important, not the albedo as such. Dense vegetation cover promotes soils with more water holding capacity and closes the water cycle by transpiring water and thus causing a faster water vapor saturation of the atmosphere, which leads to morning cloud formation and afternoon rainfall, the typical daily rainfall pattern for many drylands. The capacity to close the water cycle is lost when vegetation cover decreases and the soil is degraded. This leads to less rainfall and less favorable conditions for vegetation. The reduction in rainfall is further reinforced by increased dust generation from bare soil compared to vegetated surfaces. Atmospheric dust shades the sun and cools the Earth surface, causing clouds to be composed of smaller water drops which fail to reach the surface. The Sahara Desert is the largest source of dust on Earth, and dust generation from the Sahel increases when vegetation cover decreases.

The second "external" or "non-equilibrium" hypothesis was developed later based on a better understanding of global atmospheric circulation, global wind patterns are largely determined by latitudinal high and low pressure zones that form as a result of the sun's radiation and the heat this produces on the ground. The tropical rain belt follows the annual oscillation of the solar zenith position between the hemispheres. The ITCZ low pressure zone attracts trade winds from both north and south and if these winds are generated over the oceans the moisture laden air rises at the ITCZ and rainfall is generated. The strength and position of the ITCZ is hence crucial for rainfall around the equator and in the tropics in general. Distribution of land masses on Earth and ocean surface temperatures are the major regulators of the ITCZ. The dryness of the Sahara Desert is related to the ITCZ position at the northern tropic (tropic of Cancer). Additionally, the fact that West Africa is such a large landmass, and that the ocean surface temperature is low in the Atlantic Ocean off the West African coast, contributes to the dryness of the interior of West Africa. South of West Africa the Atlantic Ocean surface temperature is warm, allowing moist trade winds (monsoons) to deliver rainfall to the coastal strip most of the year. Between the Guinea coastal rain forests and the Sahara Desert a steep gradient in rainfall develops – the Sahel. Rainfall in the Sahel is hence sensitive to small variations in sea surface temperatures, both in the Atlantic and the Indian oceans. This second hypothesis on rainfall variation in the Sahel attributes changes in rainfall to external variations in sea surface temperatures and subsequent changes in the ITCZ and the strength of the summer monsoon.

In the older, internal "equilibrium", hypothesis humans are regarded as the cause of rainfall decline during drought, through land degradation caused by for example overgrazing. In the second, external "non-equilibrium" hypothesis humans are regarded as "victims" of climate variations forced by natural and unpredictable changes in sea surface temperatures.

Future climate

Many efforts have been made at understanding and predicting rainfall and climate variations in West Africa and the Sahel. Models (mathematical calculations) developed for predicting future climate in the Sahel focus mostly on ocean circulation, and seldom consider local dust conditions. The climate models hence give contradicting and unreliable results. Models taking into account global climate change resulting from fossil fuel burning and land conversion in the Sahel predict both a drier and a wetter climate for the Sahel, depending on which model is used. The contradicting results are a problem, and their causes are not fully understood.

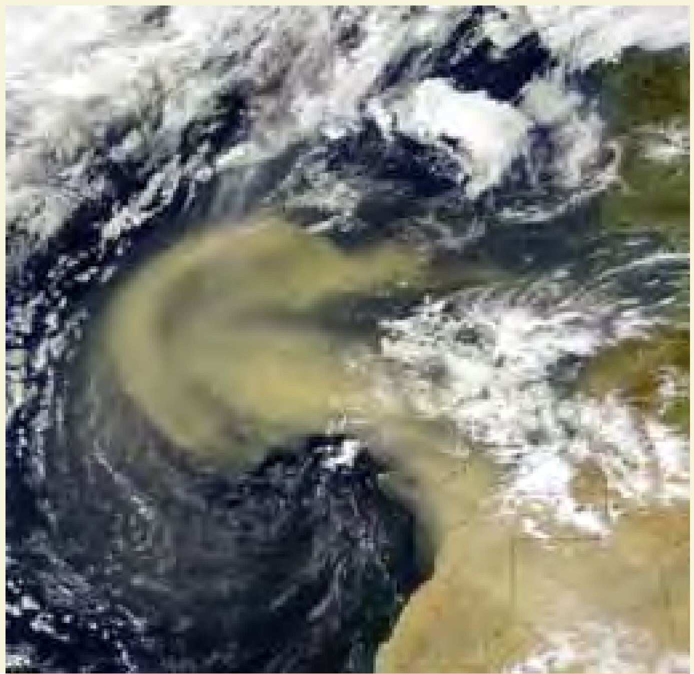
The extended (multi-decadal) periods with high and low rainfall indicate that the Sahel climate system oscillates between different climatic and ecological states. Shifts between high and low rainfall levels are probably caused by changes in sea surface temperatures. These shifts are then reinforced by different vegetation regimes that assist in keeping the climate and ecosystems of the Sahel in meta-stable states.

Many hydrological records in Africa show a quasi 80-year cycle, oscillating between extended periods of high and low rainfall and river flow. This 80 year cycle is also present in the Sahel rainfall data (see our earlier discussion). If this cycle continues, the next decades will see higher rainfall in the Sahel, followed by another drought period. Larger scale changes in global climate can potentially strongly perturb the Sahel rainfall cycle, sparking catastrophic shifts in ecosystem functions. For instance through changes in the overturning of the Atlantic Ocean, which is thought to continue to decrease as a consequence of global warming.

Despite the fact that the future livelihoods of a growing population are highly dependent on climate trends in the Sahel, it is currently not possible to predict how climate will develop. Whether we see a continuation of the 20th century drying trend, or a continuation of the strong wetting trend since the droughts, will greatly affect Sahelian ecosystems, the economy, and the livelihood options for people living in this region.

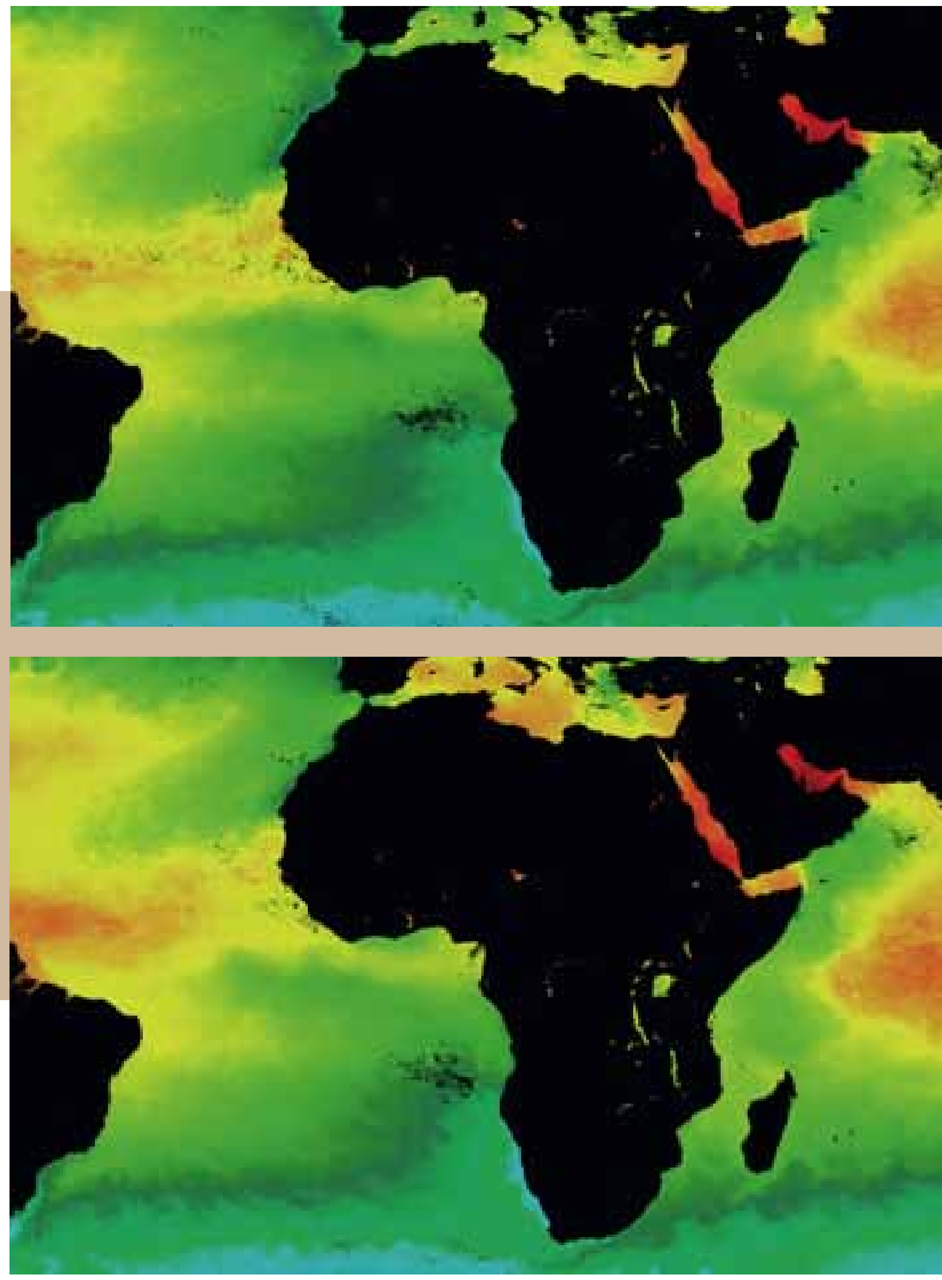
Atmospheric dust

Dust from the Sahara is one of the factors contributing to the regulation of both global climate variations and regional climate over West Africa. The Sahara Desert exports between one third and half of total global atmospheric dust transport. The dust particles reflect incoming solar radiation and cool the Earth during daytime. The dust also helps form small water droplets, so clouds form faster, further increasing reflection of solar radiation from the clouds, and the dust acts as a blanket keeping the surface warm during nights. Increased dust production in the 1970s and 1980s, as a consequence of the reduction in vegetation and more exposed soils, probably worsened the droughts by decreasing rainfall. On the other hand, dust export from the Sahel is important for fertilizing not only the Sahel with minerals and nutrients, but also the Atlantic ocean as well as other land masses around the globe, including the Amazon rainforest.



This map shows a huge dust storm over West Africa on the 26th of August 2000, caused by strong Harmattan winds bringing a large dust plume off the coast and out into the Atlantic Ocean. Satellite Image Courtesy of NASA/GeoEye.

Global atmospheric dust distribution, 25th to 29th of August 2000. Dust concentration is highest just off the coast of West Africa, enlarged in the image above right. This image is a composite of TOMS (Total Ozone Mapping Spectrometer) satellite data.



Sea surface temperatures in August 2002 and August 2003.

The latest generation of Global Circulation Models (GCMs) point at sea surface temperatures in the Atlantic and Indian Oceans as the major external forcing factors controlling annual to decadal variations in Sahel rainfall. The year-to-year variations in temperatures of the Indian Ocean seem to have a short term (annual to decadal) influence on rainfall, whereas the strength of the northward warm water current in the Atlantic exerts a larger control over longer time periods, including ice-age variations. The most notable change between 2002 (dry year in the Sahel – top map) and 2003 (wet year in the Sahel – bottom map) is the warmer waters off the coast of West Africa in 2003.

Vegetation

Vegetation in the Sahel is a reflection of the steep south to north rainfall gradient discussed in the previous sections. In general, climatic factors such as rainfall and relative humidity determine vegetation growth and composition. However, local factors like soil and water are important, especially near climatic margins and where lateritic crusts, saline or water-logged soils occur.

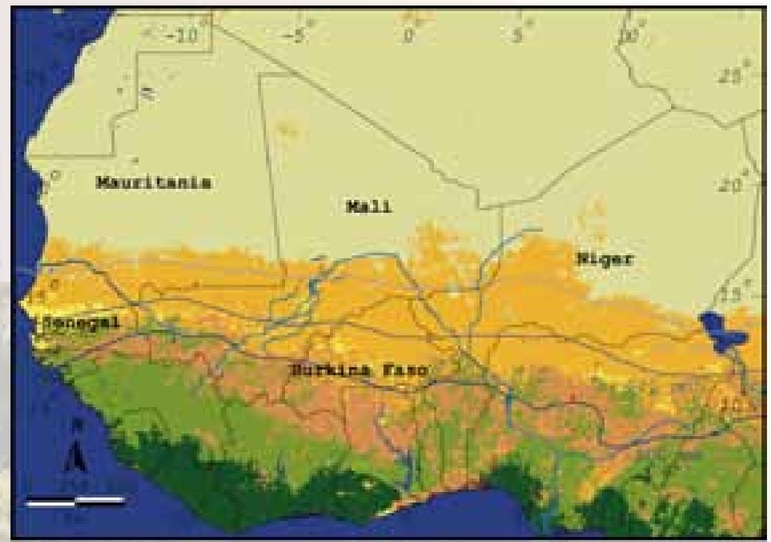
River corridors and seasonal rivers (wadis or dallols) in the drier north support richer vegetation communities, often naturally dominated by trees that can be readily detected using satellite imagery. Vegetation cover in general, and tree densities in particular, increase towards the south. In the drier north where rainfall is lower than 200 to 300 mm per year, vegetation cover is less than 50% and dominated by tussocky grasses (orange in map on the right). These regions have few trees, usually species of Acacia along wadis. Soils are sandy and prone to wind erosion, but with more clayey soils in wadis.

As rainfall increases beyond 300 to 400 mm the diversity and density of trees increase. The central parts of the Sahel, which has between 400 and 600 mm annual rainfall, has an open savannah landscape (brown in map). The plains are dominated by sandy soils, interrupted by lateritic hills with high iron content, and valleys with more clayey soils. Natural tree cover on sandy soil is around 10%, increasing to over 50% in valleys. Lateritic hills and rock outcrops are dominated by bush or shrubs, with the climber *Combretum micranthum* being most common. Open savannahs have been under agriculture for centuries, but people have traditionally preserved valuable tree species. This conversion of savannah to farmland with selective preservation has created the parkland ecosystem typical of the central Sahel. Further south where annual rainfall is between 600 and 1,000 mm per year, open savannah gradually changes into woodland savannah dominated by deciduous trees (light green in map). Tree clearing and frequent burning has reduced tree cover in this region, largely converting it into grasslands and parkland agriculture.

This atlas is not an authority on vegetation zonation in the Sahel, but contains a general description of vegetation zones and agricultural activities in the different zones as a basis for interpreting vegetation changes and land degradation. Detailed zonations usually include the following classes from north to south;

- Sahelo-Saharan zone
- Sahel zone
- Sahelo-Sudanian zone
- Sahel woodland (or Sudanian) zone
- Guinea Moist Savannh (or Doka) zone.

A more general classification is into Sahelian (open) and Sudanian (woodland) savannah. These zones are described in more detail on the facing page.



Agriculture in the Sahel

In the south, agriculture is more diversified with both cash crops (wheat, sugar, peanuts, cotton and cowpeas) and subsistence crops (sorghum, manioc, maize). Further north, in the central parklands region, trees are harvested for a variety of products, and the main cash crop is cotton. Subsistence crops include millet, sorghum, and to some extent maize. Field sizes are often small and crop management is adapted to utilize microscale variations in topography. Farmers in parklands generally also keep livestock, but are not nomadic. They adopt a transhumance lifestyle where they move with the animals following seasonal cycles if necessary. Favoured crops and livestock species vary between the cultural groups of the Sahel, with for example the Touareg favouring camels, while the Fulani favour cattle.

Where rainfall is above 300 mm per year, dryland agriculture (millet, sorghum) is common, but with highly variable crop yields. Crop failure also increases risk of wind erosion as the soil is laid bare after clearing of the natural vegetation. The Sahel is a high–risk environment for agricultural production and farmers traditionally planted a range of subsistence crops to secure a minimum harvest in dry years. At the onset of the rains, pastoralists migrate northwards with their cattle, then return to the south in November or December. Large herds are favoured both for cultural reasons, and as security for drier years. Population growth and changing political environments now limit the extents of these traditional migration patterns.

Vegetation history and human impacts

Over the last 5,000 years, humans have been a major agent in changing the vegetation of the Sahel. During prehistoric times, livestock and slash and burn activities for creating temporary fields were probably the main factors leading to changes in vegetation cover. The records of Hanno the Navigator lend support to bush burning 2,500 year ago, and other records support accentuated bush burning in the then woodland dominated empires along the Niger River during medieval times. The human impact has resulted in expansion of grasslands, caused both by tree clearing and extensive grazing and burning of shrub lands and woodlands. In areas with very high grazing pressure the grasslands are replaced by less palatable grasses and shrub lands.

West Africa was the first part of Africa to be opened up for trade with the outside world. Coastal rainforests were cleared to give way to agroforestry cultivation of oil palm (*Elaeis guineensis*), cocoa (*Theobroma cacao*), coffee (*Coffea* spp.), bananas (*Musa* spp.) and rubber (*Hevea brasiliensis*). The woodlands to the north were cut for timber, and converted to agriculture. In some regions (mainly in Senegal) ground nuts became the dominating crop, and still is today. The tree species cut for timber included mahogany (*Khaya ivorensis* and *K. anthotheca*), Sapele (*Entandrophragma cylindricum*), Guarea (*Guarea cedrata*), Makoré (*Mimusops heckelii*), African Walnut (*Lovoa trichiloides*) and Dahoma or Ekhimi (*Piptadeniastrum africanum*). Tree-clearing today is mostly done to create more arable land, and for production of fuel wood and charcoal. Pressure is particularly high in savannah woodlands and moist savannah woodlands as population densities are high in these regions.

During the droughts in the 1970s and 1980s, trees succumbed under the climate pressure, and were also cut for economic reasons. With the recovery of the rains trees were again planted, especially in regions with the strongest recovery (e.g. Burkina Faso). But overall the last century has seen a strong decline in woodlands in preference for grasslands and farmlands. The large clearings of forests and woodlands in the Guinea coastal rain forest and moist savannah may also have contributed to a drying of the summer monsoon that brings rainfall to the Sahel.

Sahel savannah

Where rainfall is less than 500 mm per year and the growing season shorter than four months, the drier savannah or Sahel savannah dominates. This zone includes southern Mauritania and northern Senegal, Mali north of the Niger River and northern Niger. This heavily grazed region is dominated by thorny *Acacia*. The small tree *A. seyal* dominates valleys with finer soils. The taller *A. radiana* is common on sandy soils. *A. senegal*, *A. laeta* and *A. ehrenbergiana* grow on fixed dunes. Along streams and rivers *A. nilotica* and *A. sieberiana* are found in profusion. Shrubs in this region are also thorny, and can form a steppe landscape. Common shrubs include *Commiphora africana*, desert date (*Balanites aegyptiaca*) and balsam spurge (*Euphorbia balsamifera*). Grasses are tussocky and heavy grazing keeps the grasslands short. Fires are less severe than further south.

Sudan savannah

The central region of the Sahel, with rainfall roughly between 500 and 1,000 mm per year hosts the typical savannah landscape or Sudan savannah. The dry season typically lasts seven months. Species composition varies in this region, with species from the drier north and wetter south interwoven dependent on both edaphic conditions and man's use of the landscape. Common tree species throughout most of the Sudan savannah include the dum (or doum) palm *(Hyphaene thebaica*), desert date (*Balanites aegyptia*) and baobab (*Adansonia digitata*). However, the most common tree species are various species of *Acacia*.

Savannah woodland expansion

The southern fringes of the Sahel, with rainfall above 1,000 mm per year and a dry season of approximately six months, is dominated by moist savannah woodlands. The savannah then gradually changes into a lowland rainforest towards the wetter south. The margin between the savannah woodland and the rainforest is today dominated by fire tolerant species, including red oak/ironwood (*Lophira lanceolata*), idi (*Terminalia schimperiana*: synonym: *glaucescens*), digbe (fr) (*Hymenocardia acida*), meru-oak (*Vitex doniana*), tallow tree (*Detarium microcarpum*) and *Afzelia africana*. These trees have invaded the transition region as a result of cutting of the original forest, and frequent fires and high grazing pressure. The frequent fires cause the trees to be twisted and gnarled, and also prevent the rainforest from regaining foothold. In areas with less fires, common species include Isoberlina species (*Isoberlina* spp.), red cedar (*Uapaca togoensis*: synomym *U. somon*) and *Monotes kerstingii*. Most of Burkina Faso, and the southern parts of Mali and Niger lay within the savannah woodland region.

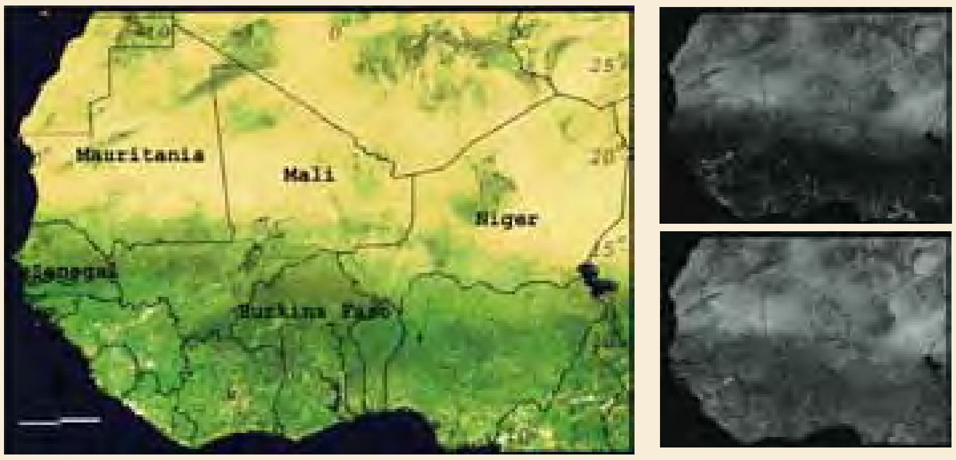
Satellite mapping of vegetation

The growing archives of satellite images have become major sources for mapping and exploring regional and global vegetation changes. The most consistent long-term time series of vegetation data obtained from satellites is from the series of AVHRR (Advanced Very High Resolution Radiometer) sensors operated by National Oceanic Atmospheric Administration (NOAA) of the United States of America (USA). AVHRR measures radiation at 1.1 km resolution (nadir) in five wavelengths; red, near infrared (NIR), and three thermal wavelengths. Vegetation absorbs the visible light, but reflects infrared, and vegetation mapping is done by comparing the relative reflection in the red versus the NIR wavelengths.

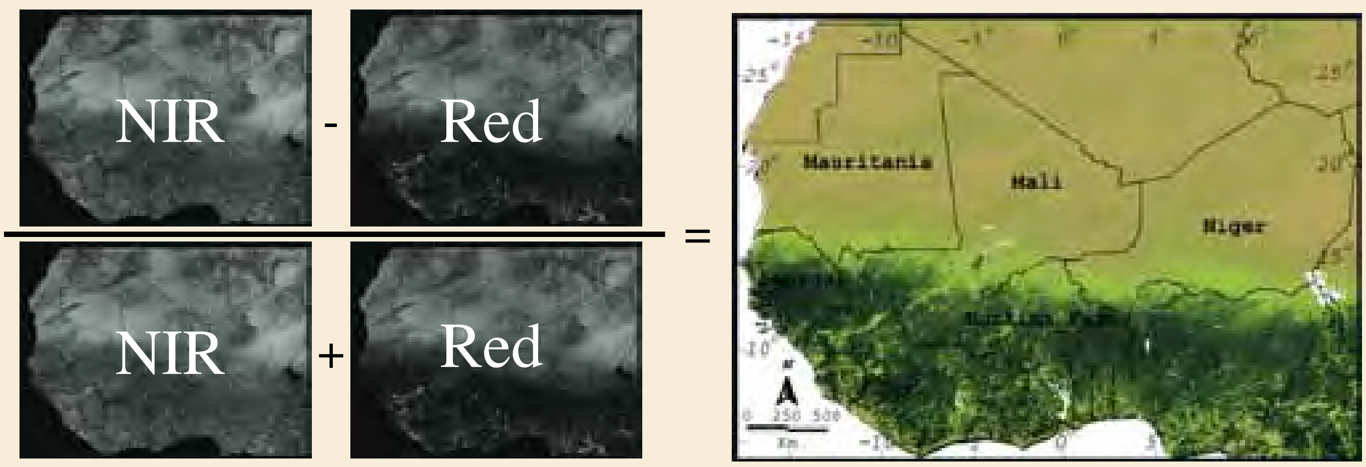
The AVHRR sensor has been in operation since 1978, with historical images of global vegetation at eight km resolution available from 1981. The AVHRR sensor was not designed for vegetation mapping, but is still a very useful instrument for estimating vegetation density, photosynthesis and vegetation production. The data used in this study come from six generations of AVHRR sensors (NOAA 7, -9, -11, -14, -16 and -17). The data has been calibrated between the sensors and corrected for variations in solar radiation and atmospheric disturbances. The more recent MODIS (Moderate Resolution SpectroRadiometer) sensor, onboard the satellites TERRA and AQUA, is a much more accurate sensor with automatic calibration, and gives vegetation data at 250 m resolution.

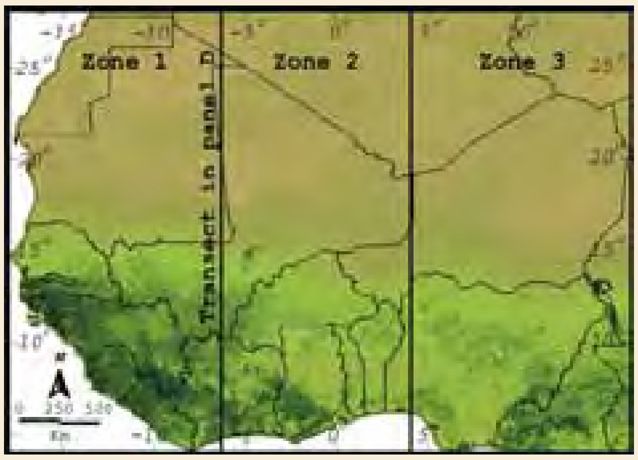
Vegetation Indices

Vegetation mapping from satellite images is possible because vegetation only uses light of certain wavelengths for photosynthesis. The visible wavelengths ("colours" seen by the human eye) are utilised for photosynthesis, but infrared light, which has longer wavelengths than visible light, cannot be used for photosynthesis (nor seen by the human eye). Hence vegetation absorbs most of the visible light (less of the green though, so we see vegetation as green), but reflects infrared wavelengths. Vegetation cover and density can hence be mapped by comparing the reflected amounts of visible and infrared light. Both visible and infrared wavelengths as recorded by a satellite sensor are affected by particles and dust in the atmosphere, and of course the day of the year and time of the day the image is acquired. The effects of such disturbances are however rather similar in the visible and infrared wavelengths, and the most common method for estimating vegetation cover from satellite data is to use a normalized index that compares relative differences in visible and infrared light. The most commonly used vegetation index (VI) is the Normalized Difference Vegetation Index (NDVI). For the MODIS sensor and other more advanced sensors purpose- built for vegetation mapping, more advanced vegetation indices exist. These indices are based on the same basic principles of differences in reflections in the visible and infrared wavelengths, but with adjustment factors for disturbances originating from both atmospheric and ground (soil and water) conditions.



AVHRR full resolution (1.1 km at nadir) composite scene. The large colour composite is created by blending the red visible band (small top image) and the near infrared (NIR) band (small bottom image), adding cloud and water information from thermal bands (not shown). The reflection (brightness) from the red wavelength (top) is lower over vegetated areas compared to the reflection from the NIR wavelength (bottom). The relative difference in reflectance in red and NIR is the basis for estimating ground vegetation from satellite data such as for example NDVI (below).





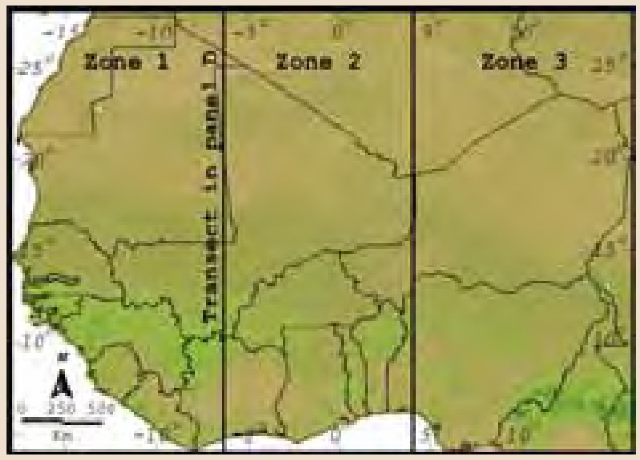
Cloud problems

Clouds are a problem when mapping vegetation cover from satellite data. This is usually solved by combining several images to find cloud free scenes for all areas of the ground. The AVHRR sensor records a complete image of the Earth every day. From this data the vegetation indices are composited by extracting the maximum vegetation value (i.e. cloud free image) in each pixel (location) over periods of 10 consecutive days. If cloud problems still exist, statistical methods are used to estimate the vegetation under the clouds using images from adjacent dates.

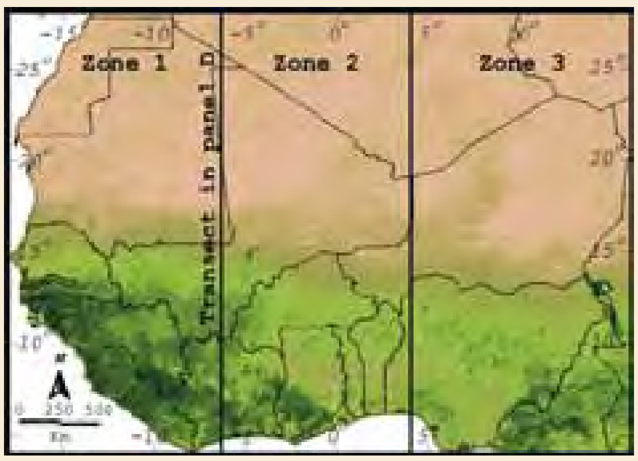
This image is a Maximum Value Composition.

Soil influence on NDVI

As the AVHRR sensor was not designed for vegetation mapping, it has some shortcomings. Soils influence NDVI as calculated from AVHRR data, resulting in estimates of vegetation cover that are too high when the underlying soil is not fully covered by leaves. In the Sahel, with bare soils exposed for large parts of the year and also only partly covered during the growing season, the soil signal presents a problem. We handled this problem by finding NDVI values of bare soils and then adjusting all the NDVI values accordingly. The values for bare soils were found by looking at the images from the droughts in the early 1980s, and assigning the lowest NDVI as the underlying soil influence.



The image shows minimum NDVI for the drought years 1982 to 1984.



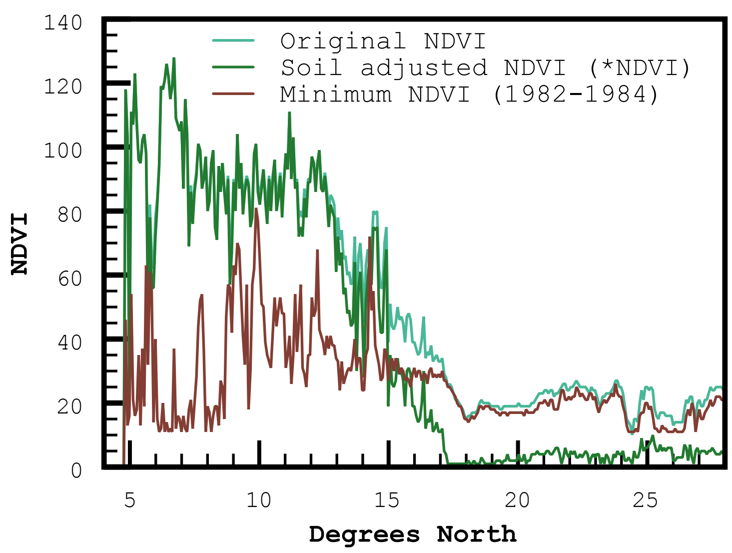
Soil adjustment

We applied soil adjustment to all NDVI images with vegetation cover less than 100%, where the underlying soil can be suspected to influence the NDVI value. The lower the vegetation cover, the stronger the adjustment, on a scale ranging from 0% to 100% vegetation cover.

The image on the left shows a soil adjusted version of the NDVI image in the top panel (note the difference in the Sahara Desert, which has overestimated NDVI in the top image).

Original versus soil adjusted NDVI

The transects on the right show original and soil adjusted NDVI, and minimum NDVI for the drought years, respectively. As vegetation cover is 100% in the Guinea coastal rain forest and the moist savannah, no soil adjustment is made is these regions. The largest soil adjustment is for the Sahara Desert, which is shown as partly vegetated in the original NDVI image.

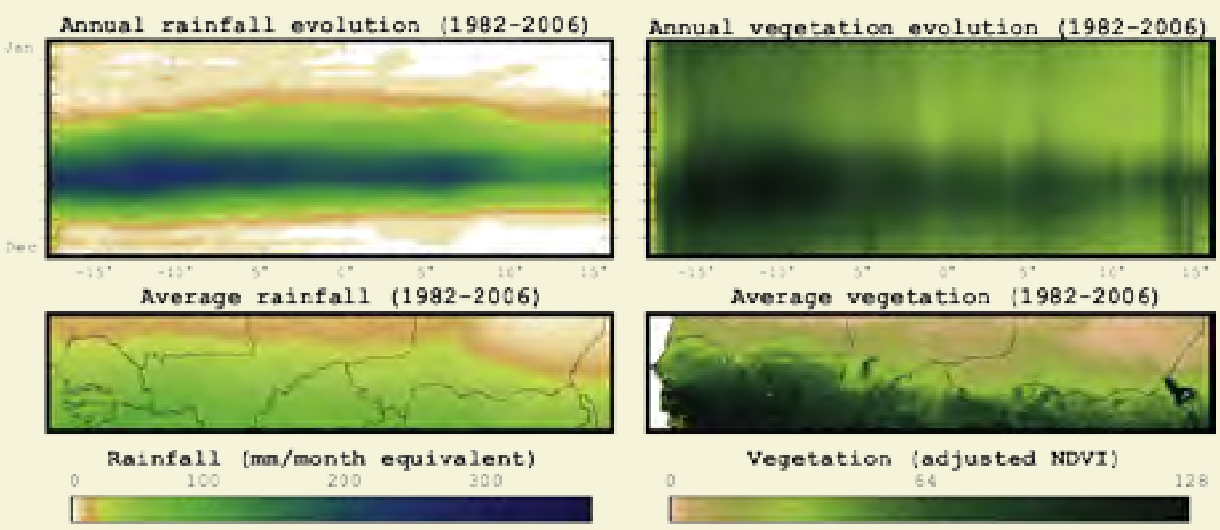


Annual vegetation growth

Annual vegetation production mapped from time series of AVHRR satellite images shows a strong south to north declining trend in the Sahel. The trend closely corresponds to the steep rainfall transition from high rainfall in the south to low rainfall in the north. By and large, vegetation growth in the Sahel is limited by water availability. The annual vegetation growing cycle closely follows the seasonal rainfall patterns shown earlier. During the dry winter season, there is hardly any rain, and vegetation in the Sahel is dormant. Vegetation growth starts immediately with the arrival of the monsoon rains in early summer. The peak growing season in the Sahel is around August, when the summer monsoon reaches as far as 10ºN. The growing season in the northern parts of the Sahel lasts for around three months, with areas towards the southern fringes having two annual rainfall seasons, and hence two growing seasons. Vegetation growth lags one to two months behind rainfall, and is sustained longer around ephemeral streams and larger rivers that have water flow the whole year.

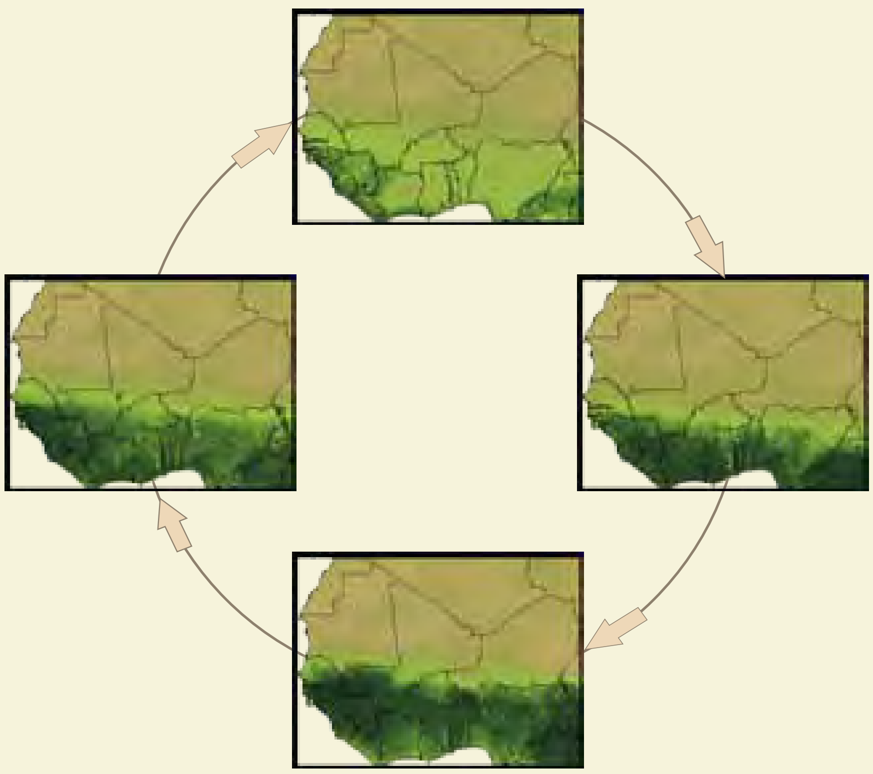
Annual rainfall and vegetation cycles

The top left panel below shows average annual rainfall evolution (January to December) for the period 1982 to 2006, averaged over the central Sahel region (11 to 19ºN). Most of the precipitation in the area occurs in the summer monsoon period. Average rainfall is shown in the mid-left panel. The top right panel shows the annual vegetation cycle. There is a clear lag in vegetation response to rainfall of one to two months, with extended vegetation growth into the dry season, notably around the major lakes and rivers (Niger Inland Delta, Lake Chad, and the Niger and Senegal rivers).



Vegetation cycle 2004

The top panel shows the satellite mapped vegetation (soil adjusted NDVI) for February, in the middle of the dry season; the right panel shows vegetation cover in May, at the onset of the summer monsoon; the bottom panel shows vegetation cover in August, the most rainy month in the Sahel; the left panel shows satellite mapped vegetation for November, after the monsoon season. Due to lag in vegetation response to rainfall, vegetation cover in November is higher than in May, despite similar climatic conditions.

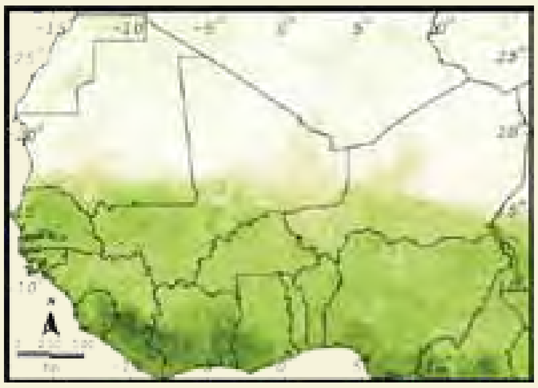


Vegetation variations

Vegetation growth in the Sahel is almost directly (linearly) related to rainfall up to about 800 mm annual rainfall. Variation in annual vegetation production has, however, been high over the period 1982 to 2006, driven by a climatic transition from dry to wet conditions. During the droughts, reductions in livestock numbers and migration from drought stricken regions led to changes in the vegetation communities of these areas. Grazing pressure after the return of higher rainfall was lower than previous to the droughts and the production of seed pools less affected by grazing. Years with both plentiful rains and a good seed pool tend to produce good grazing and hence attract large herds of cattle. This can cause the seed pool in the following year(s) to diminish, causing a lagged fluctuation pattern in vegetation growth compared to the rainfall pattern.

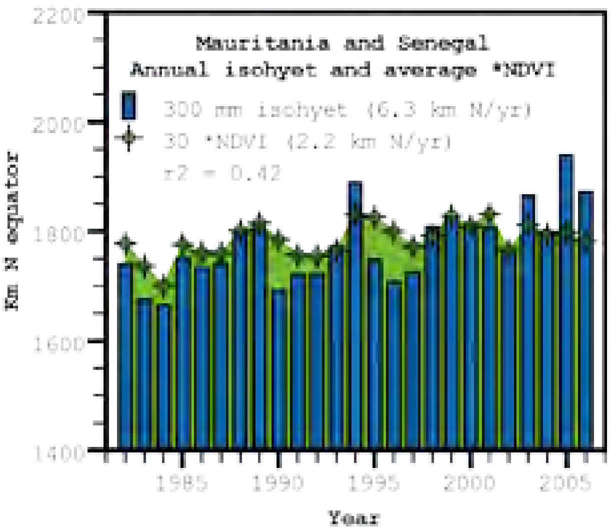
Vegetation variation 1982–2006

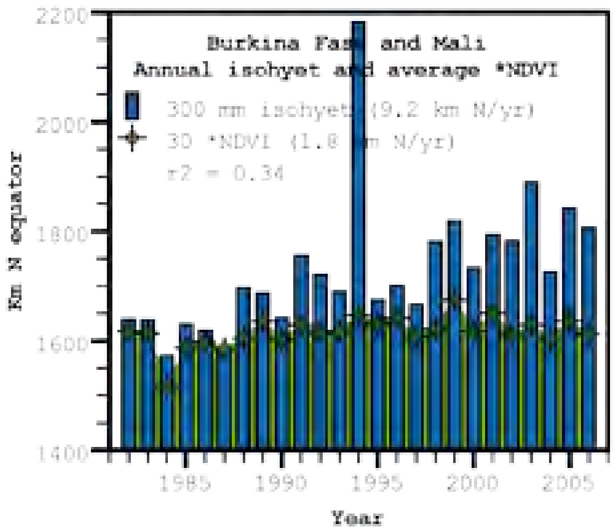
Coefficient of Variation for annual vegetation growth between 1982 and 2006. The variation in annual vegetation growth is largest in the Guinea rain forest, which is largely due to artifacts in the data caused by cluod contamination, and throughout most of the Sahel transitional ecological region.

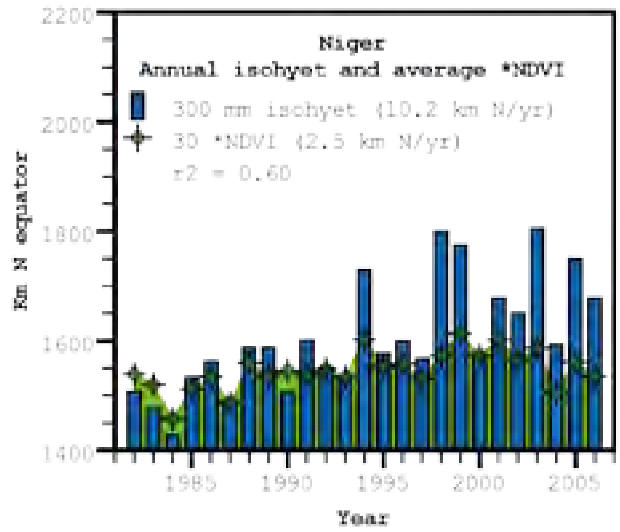


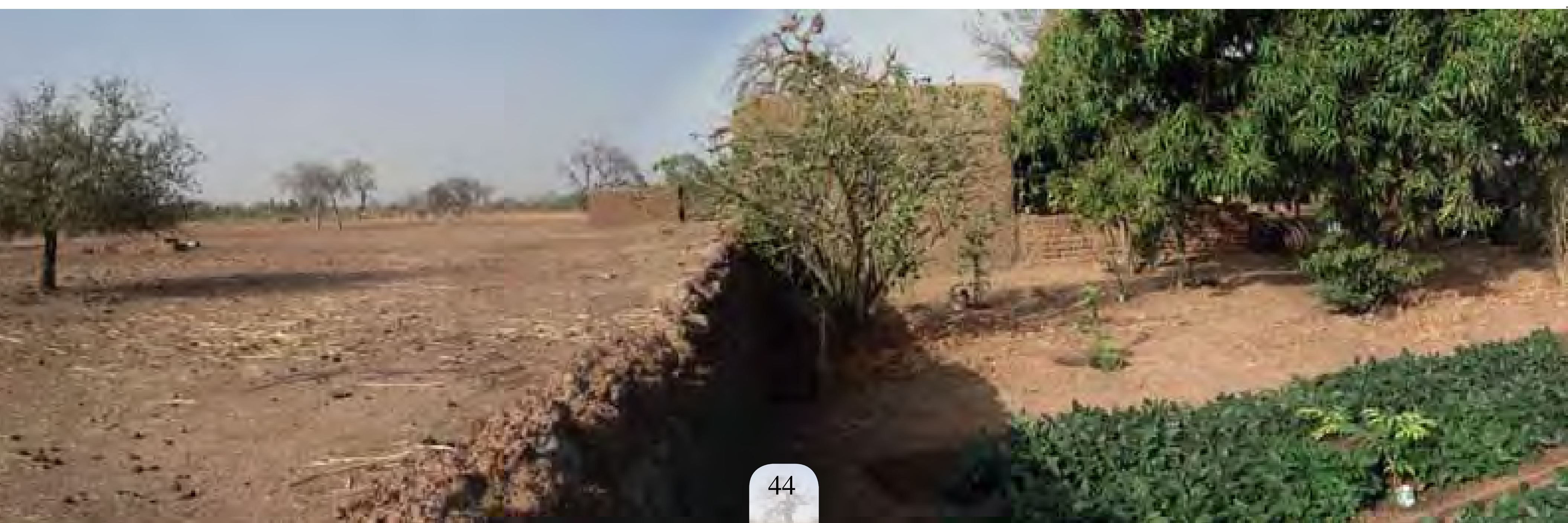
Average vegetation production 1982–2006 The close relation between vegetation growth and rainfall in the Sahel transition zone is indicated by the positions of the isohyets for 300, 600 and 900 mm. The points (dots) on the map show the locations for the rainfall and vegetation distribution graphs on the opposite page.

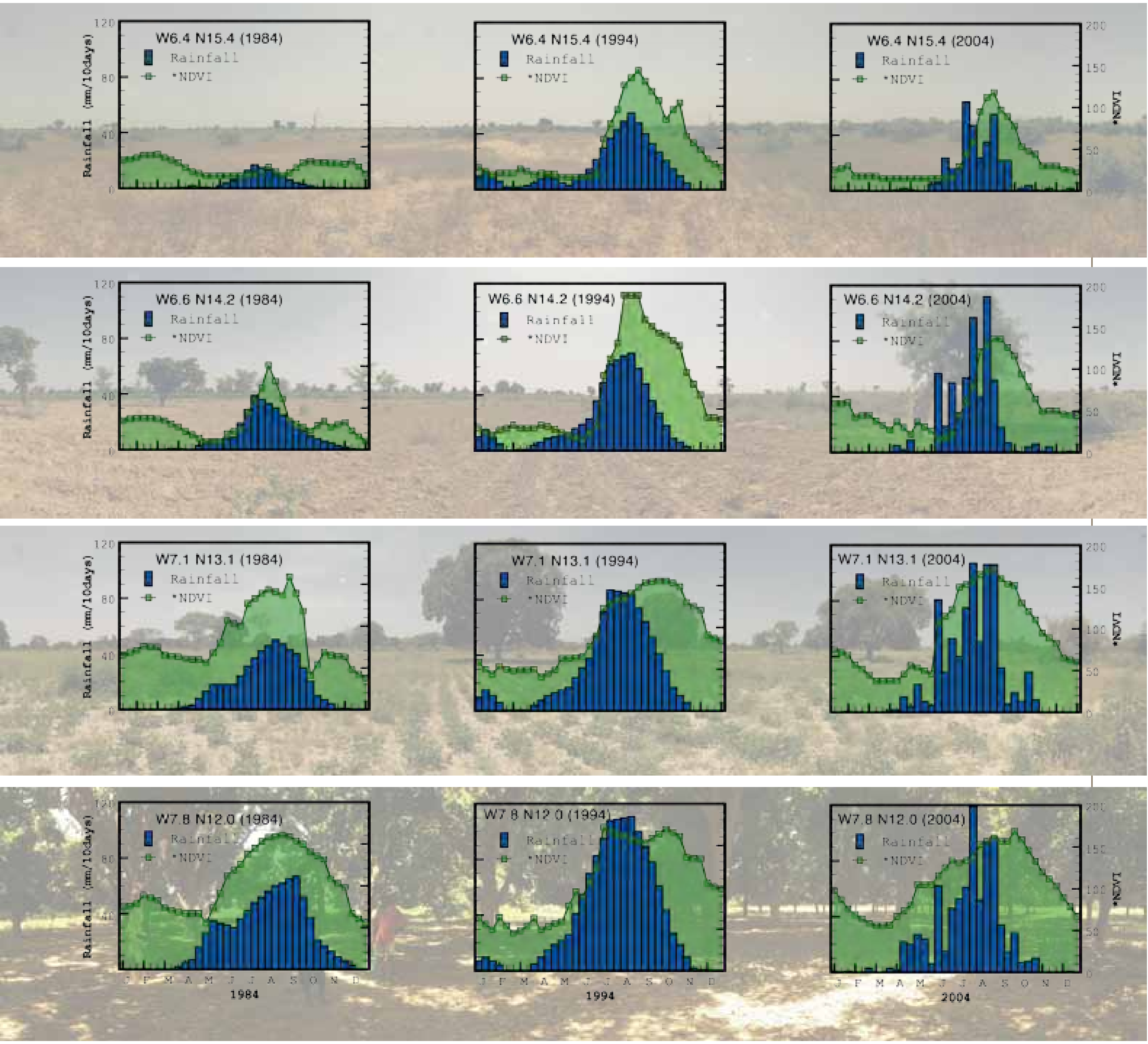
Shifts (km north of the equator) in annual isohyets and average NDVI by year for countries in the Sahel (zones 1 to 3 in maps on page 41)











The above graphs illustrate the large variations in rainfall and vegetation growth in the West African Sahel. The transect is from Mali (see map on the facing page). Even if the distance on the ground is reltatively short, changes in rainfall and vegetation growth are dramatic from north to south (rows above).

The columns show 1984 (very dry year), 1994 (very wet year) and 2004 ("normal year"). Changes in rainfall and vegetation growth are perhaps most dramatic between years. 1984 is the driest year of the last century and the worst recorded drought in recent history. After the droughts in the 1970s and the 1980s, rainfall has recovered and rainfall in 1994 (mid column) reached as far north as the high rains in the 1950s and early 1960s. The early rains seen in the graphs from 1994 are locally known as "mango rains". They cause premature vegetation growth, and annual grasses to succumb during the drier period before the main rains. Rainfall records from 1984 and 1994 were taken from monthly rainfall station data that were recalculated to 10 day periods, and rainfall for 2004 is derived from a combination of station data and satellite data for every 10th day. The smoothness in the 1984 and 1994 rainfall records is therefore to some extent artificial.

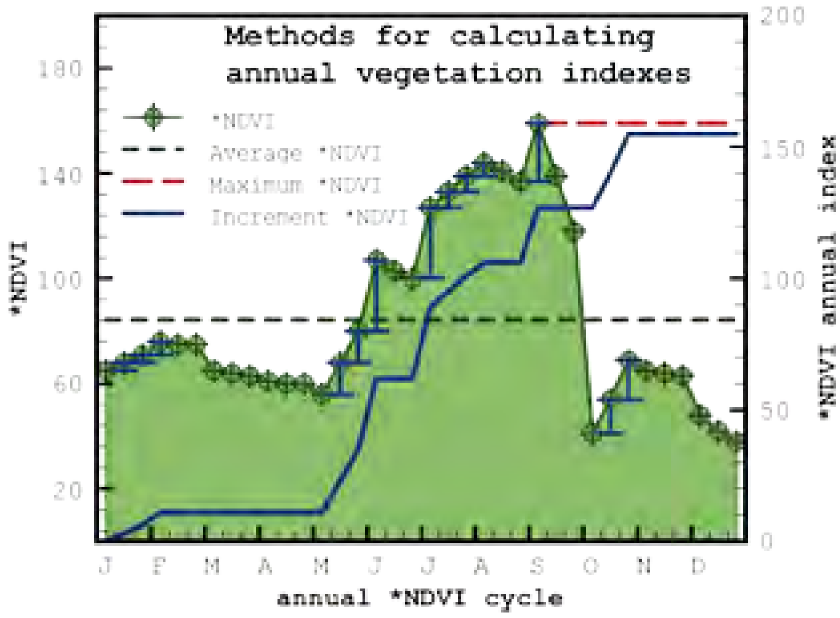
Calculating annual vegetation production

For AVHRR, an annual cycle is composed of 36 images, each covering a 10 day period. The annual average NDVI is often used as a proxy for annual vegetation production. As the growing season in the Sahel starts around April and lasts until around November, we calculate annual vegetation production using the calender year from January to December.

In farmlands, where crops can be assumed to grow from seed to plant and then be harvested, it is better to use annual maximum NDVI, assuming that this is vegetation cover before harvest. Either of these methods work well in landscapes with stable vegetation cover types and land use. In the Sahel, however, large changes in rainfall have driven changes in vegetation types and land use. Grazing areas and fallows have been converted to farmland, and trees have been planted. These changes in vegetation cover and land use alter average and maximum NDVI values, even where there has been no change in vegetation production. In general, woodlands will have higher NDVI.

Vegetation production in rangelands (grazing land) may be as high as in fallows or farmlands, but vegetation cover rarely reaches its potential due to intermittent grazing. This effect is probably affecting most of the Sahel where free-grazing on communal lands is widely practiced.

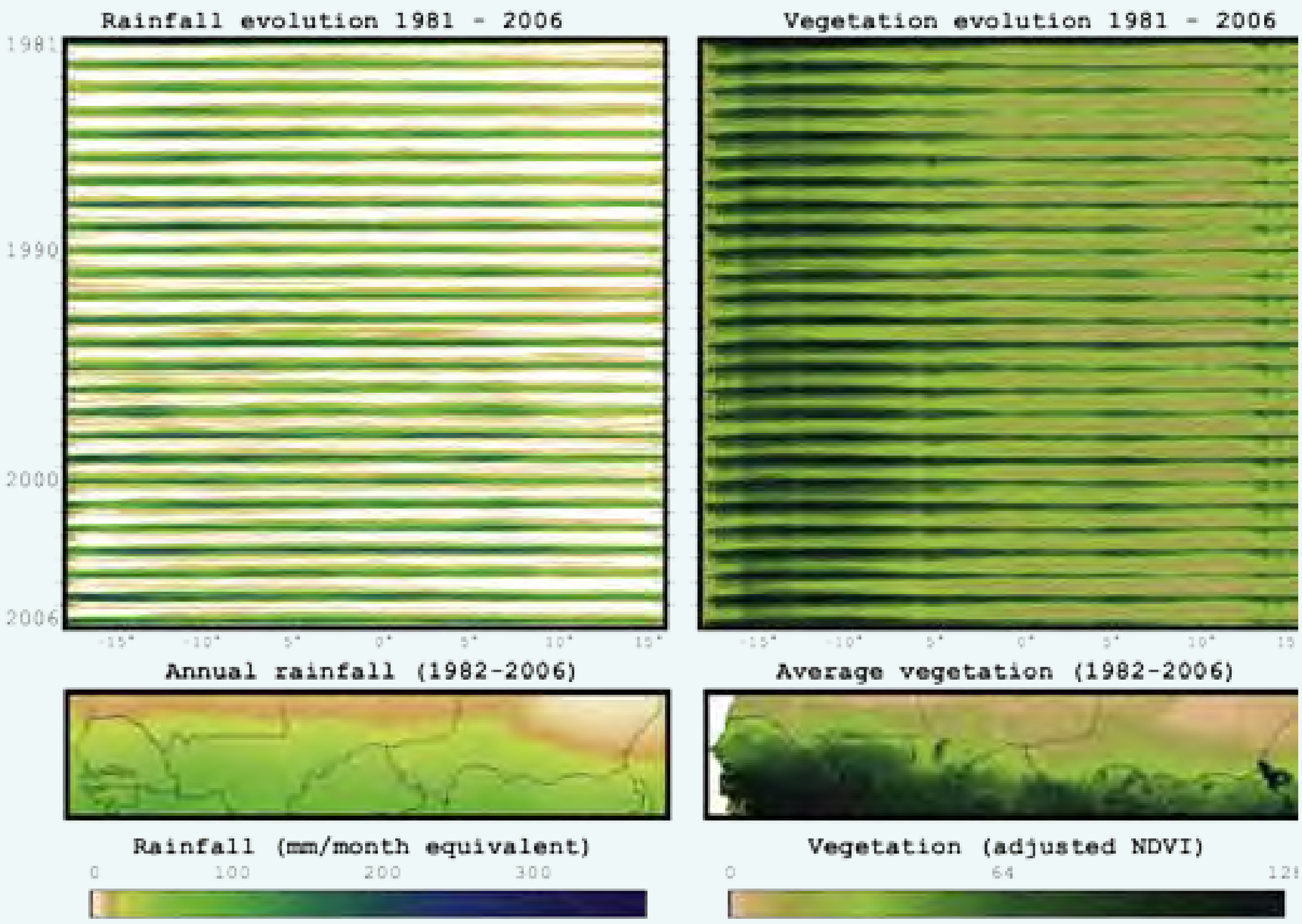
To overcome the problems of using average or maximum NDVI to estimate annual vegetation production in the changing environments of the Sahel, an alternative annual production index was developed in this study. The alternative index calculates the annual increment in vegetation growth, if NDVI is higher in one period compared to the previous it is added to the annual index, if it is lower it is not considered. In an ideal situation with a crop starting from seed, reaching maximum growth just before harvest, the increment index will have exactly the same value as maximum NDVI. On grazing land, the index captures vegetation growth after each intermittent grazing period. The increment index also has the advantage of adjusting for initial conditions on the ground at the start of the growing season.



Vegetation evolution 1981 to 2006

In the graphs below, the top diagrams show the evolution of rainfall (left) and vegetation (right) for each 10-day period from July 1981 to December 2006 across the parklands of the Sahel, between 11 and 18°N (mid-panels).

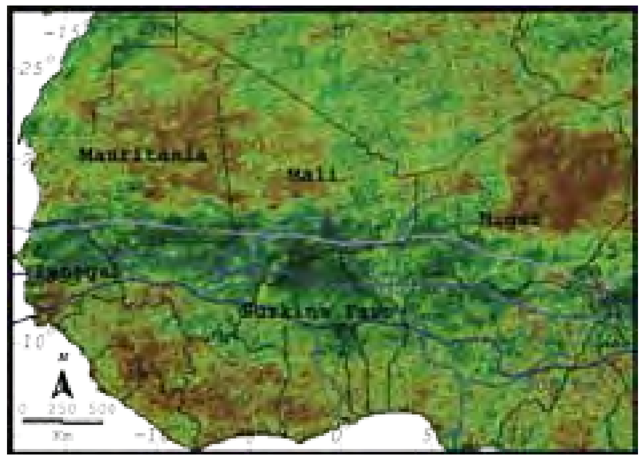
The low rainfall (droughts) in the early 1980s (especially 1984) is evident, as is the higher rainfall in for example 1994 and 1998. The "mango rains" of 1994 are also visible in the graph, but are more or less restricted to Mali. The evolution of vegetation over this 25 year period closely follows the rainfall pattern, with the lowest vegetation in 1984 and the highest in 1994. Note that the vegetation is differently scaled in this figure compared to the maps.



Annual maximum vegetation production 1982 to 2006

Annual maximum NDVI is less affected by clouds compared to average annual NDVI, and is frequently used as a measurement of primary production in farmlands, under the assumption that the maximum value represents standing crop biomass before annual harvest. The maximum NDVI index shows a surprisingly abrupt transition from areas with high growth to areas with virtually no growth in the northern fringe of the Sahel. This might be correct as the soils in the northern part are more fertile than the soils in the southern parts. On the other hand, grazing pressure during the growing season is highest towards the north.

The trend image to the right shows the normalized vegetation production trend using annual maximum NDVI from 1982 to 2006.

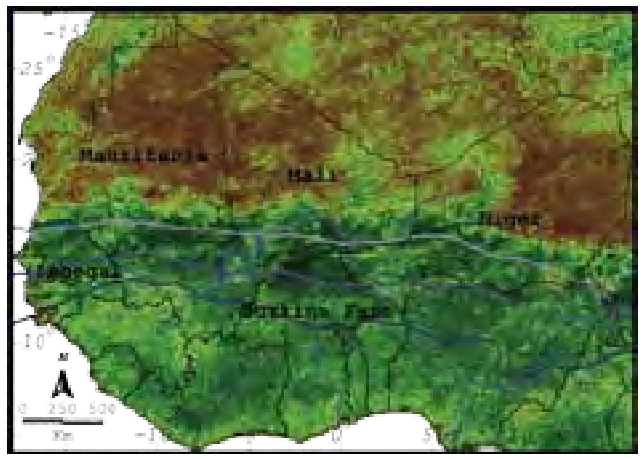


NDVI increment vegetation production 1982–2006

The increment index is calculated as the accumulated positive difference in soil adjusted NDVI between the present and previous NDVI recording over an annual cycle. This index is sensitive to cloud problems, but has the ability to capture changes in grazing land.

The increment index shows a more gradual pattern at the transition between the Sahel and the Sahara Desert than the other indices (average and maximum).

The trend image on the right shows the normalized trend in vegetation production using annual increment NDVI from 1982 to 2006.



NDVI vegetation trends

Trends in annual vegetation growth between 1982 and 2006 show increasing vegetation growth in the central Sahel region (area south of 18° N). Mauritania and Niger have seen slightly negative vegetation growth development north of 18° N. In Mali, vegetation increase has been strong in the central Sahel region, however, about half the country has experienced increases and the other half decreases in vegetation growth over the 25 year period studied here. The strongest greening trends found in the data occur in Senegal and Burkina Faso. For the central Sahel region (area south of 18° N, and with mean annual rainfall below 900 mm per year), the area greening-up in the five countries is approximately 1.6 million km^2 (75% of the area).

Spatial vegetation changes as recorded from soil adjusted NOAA-AVHRR NDVI data in the central Sahel region (11°N to 18°N with average rainfall below 900 mm per year) for five Sahelian countries 1982–2006. Figures in parentheses are significant values ($p < 0.05$) calculated by comparing the actual trend with 999 random trends.

Country	Central Sahel Area km²	Average *NDVI Increase	Average *NDVI Decrease	Maximum *NDVI Increase	Maximum *NDVI Decrease	Increment *NDVI Increase	Increment *NDVI Decrease
		%					
Mali	601.344	89 (55)	11 (1)	82 (40)	19 (3)	83 (52)	17 (5)
Mauritania	290.944	85 (46)	15 (2)	74 (39)	25 7)	72 (43)	28 (9)
Niger	688.768	66 (29)	34 (12)	58 (21)	42 (20)	61 (37)	39 (28)
Senegal	176.064	93 (62)	7 (1)	78 (40)	22 (7)	89 (44)	11 (1)
Burkina Faso	205.504	98 (78)	2 (0)	92 (55)	8 (1)	98 (68)	2 (0)

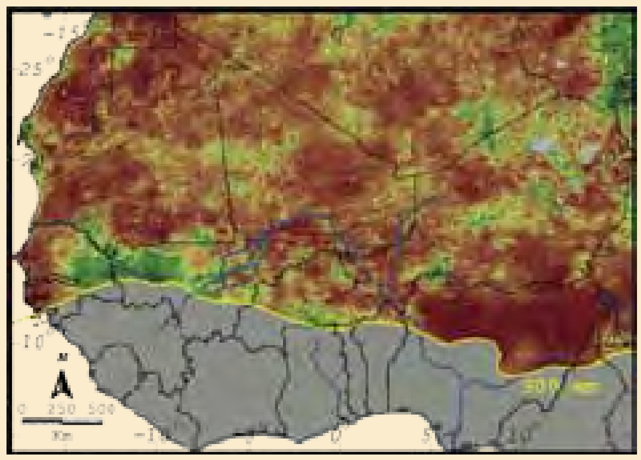
Rainfall Normalized NDVI (rNDVI)

As rainfall in many drylands in general, and particularly in the Sahel, is characterized by large annual and decadal variations, vegetation growth or changes in vegetation growth alone cannot be used as an indicator for land degradation. A simple way of adjusting annual variations in vegetation growth for variations in rainfall, is to calculate the ratio between vegetation production and rainfall (total vegetation growth divided by total rainfall). The result is a rain adjusted vegetation index, which is an indicator for how efficiently the vegetation is able to convert available rainfall into biomass. The trend in rainfall normalized vegetation growth can then be used to map vegetation growth performance over time.

Vegetation communities in the Sahel are composed of plants adapted to conditions in dry areas, both in terms of soil and drainage conditions, and average rainfall of their habitats. The efficiency by which they convert rainfall to biomass is hence highest when rainfall is at or near the longer term rainfall average, at which the vegetation community developed. This is also due to physical factors and vegetation response to rainfall is likely to be asymptotic, converging at the average rainfall level. As rainfall steadily increases, vegetation composition will change and the peak response will also change.

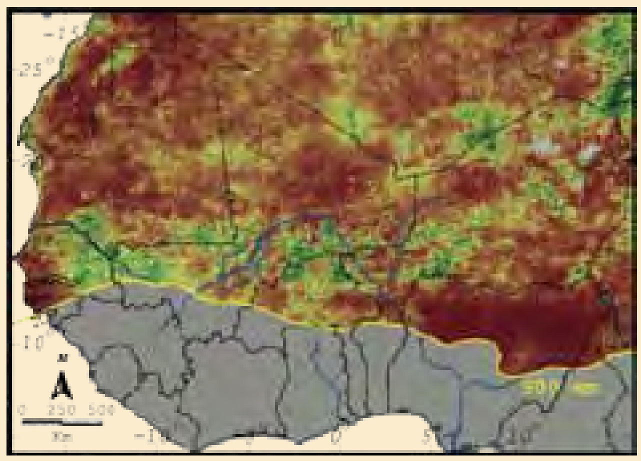
Average rNDVI

The left map shows average rNDVI for the period 1982 to 2006, while the right map shows the trend in average rNDVI for the same period. The left graph on the facing page shows changes in average rNDVI at specific isohyets (top map on facing page). The right graph shows vegetation response to rainfall in the previous year at different rainfall levels.



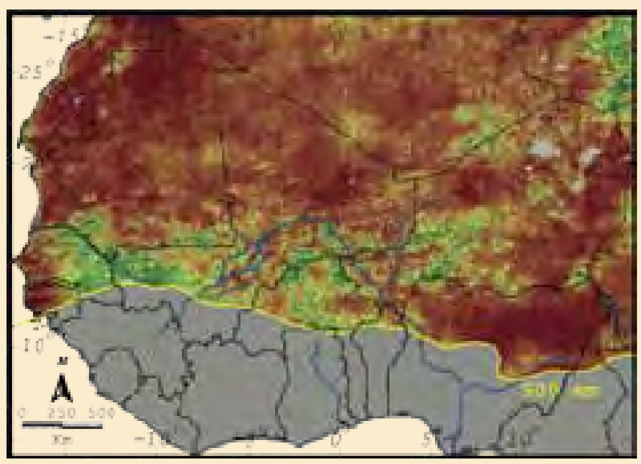
Maximum rNDVI

The left map shows maximum rNDVI for the period 1982 to 2006, and the right map shows the trend in maximum rNDVI for the same period. The left graph on the facing page shows changes in maximum rNDVI at specific isohyets. The right graph shows response in maximum vegetation cover to rainfall in the previous year at different rainfall levels.

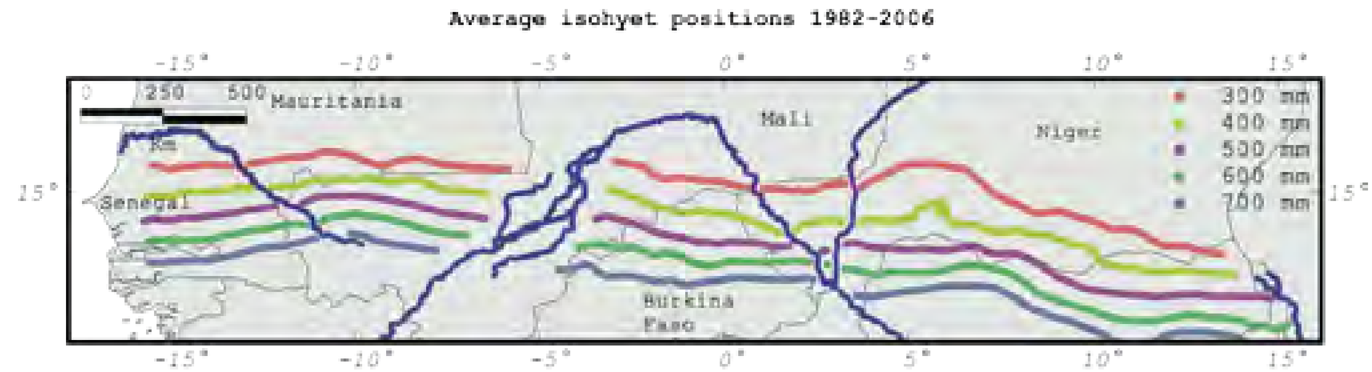


Increment rNDVI

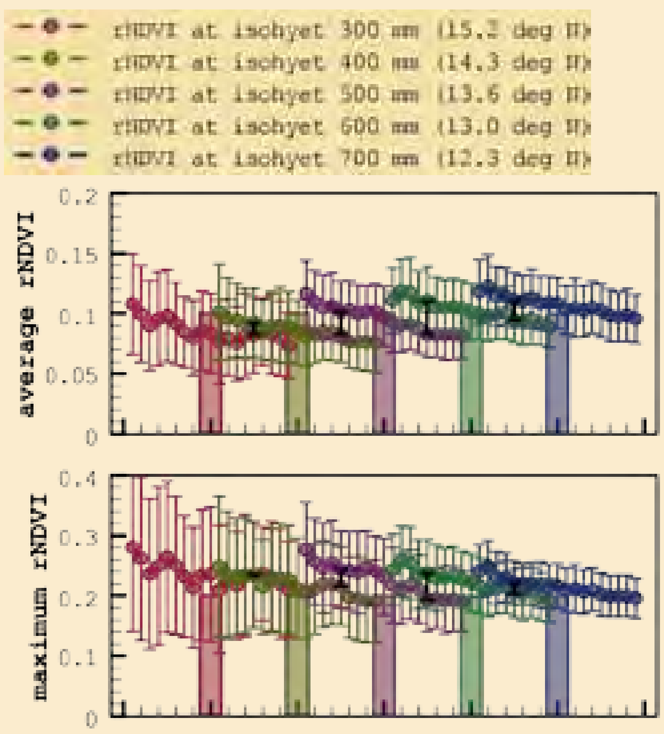
The left map shows the increment rNDVI for the period 1982 to 2006, and the right map shows the trend in increment rNDVI for the same period. The left graph on the facing page shows changes in increment rNDVI at specific isohyets. The right graph shows increment rNDVI response to rainfall in the previous year at different rainfall levels.

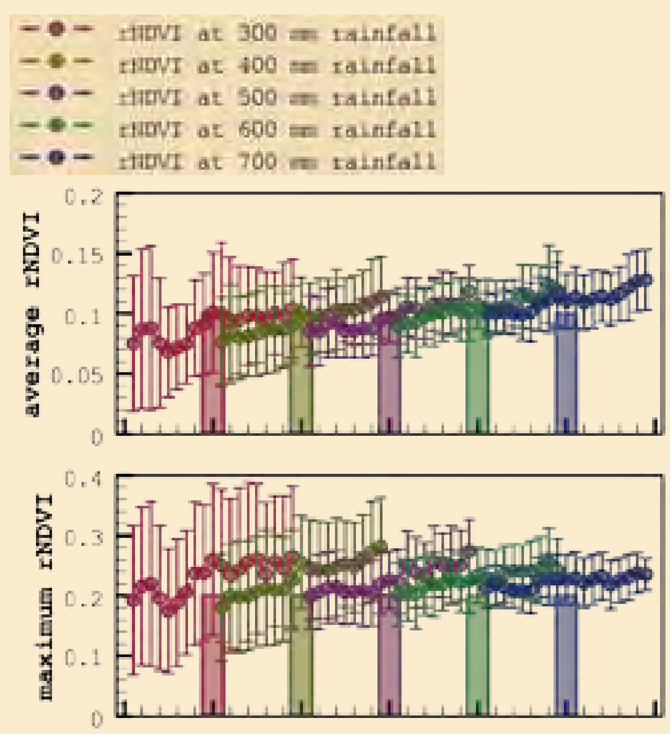


The trends in rainfall normalized vegetation growth show that vegetation has not recovered to its full potential during the period studied here. One reason for this could be that a change in vegetation composition towards more drought resistant species has taken place. These species may not be able to fully utilise the increased rainfall. Another possible explanation is land degradation, which leads to soils having lower water-holding capacities due to lower organic carbon contents, physical degradation and poorer soil fertility. In some cases, farmers may also have adapted their crops and management strategies to lower rainfall.

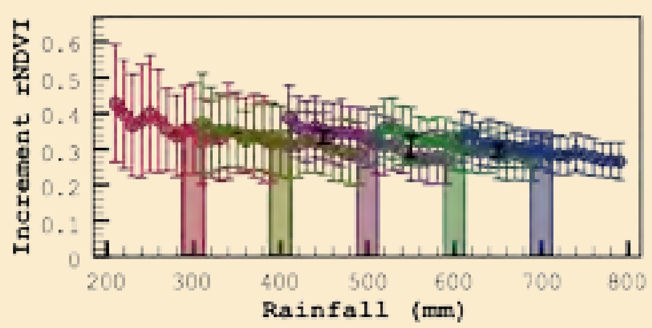


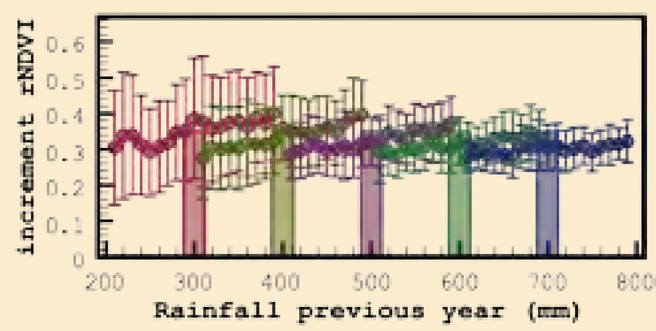
Average isohyets for 300, 400, 500, 600 and 700 mm rainfall for the period 1982 to 2006. The left column below shows NDVI extracted from these isohyets, where vertical bars indicate average rainfall, or isohyet position. The dots and error bars show how rainfall variation influences rNDVI.





Theoretically, the highest rNDVI should occur at the long- term average rainfall (vertical bars).





rNDVI change at specific isohyets

Vegetation rain use efficiency is higher at lower rainfall. The higher efficiency at lower rainfall can also be due to lower grazing pressure since pastoralists migrate over large areas and/or animal die-back allowing vegetation to recover, or it may be a result of more fertile soils towards the north.

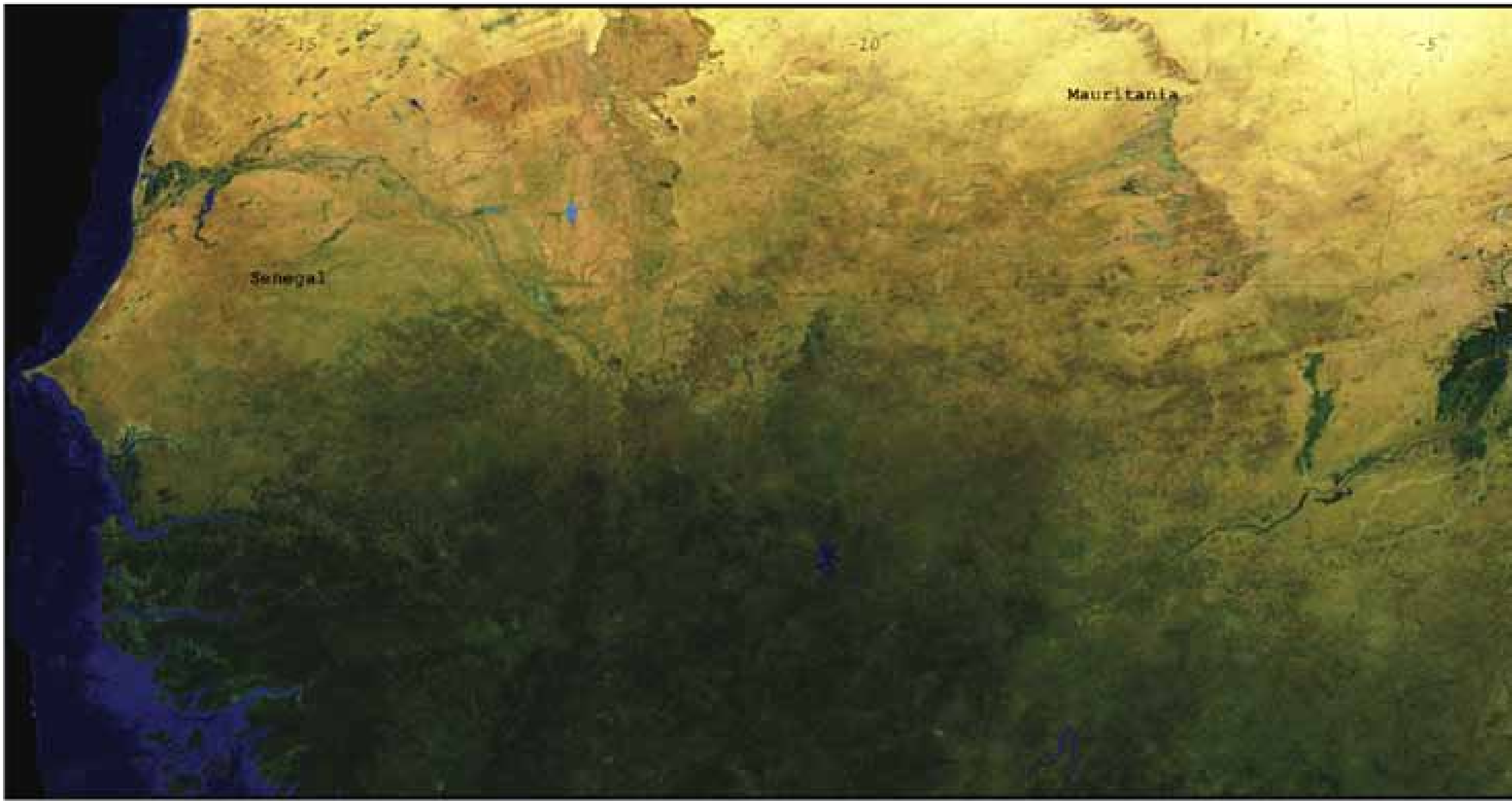
The upward shift in vegetation efficiency with higher rainfall shown for average rNDVI in both top graphs, contradicts the result that vegetation efficiency increases as rainfall decreases. This error is a result of shortcomings in the underlying satellite data for estimating vegetation growth, and the use of the annual average NDVI for calculating vegetation production. Average NDVI is more sensitive to site-specific soil condition and vegetation types. Also, maximum rNDVI shows the same (erroneous) tendency, albeit less strongly. The increment rNDVI gives the most consistent results, largely in agreement with detailed field studies.

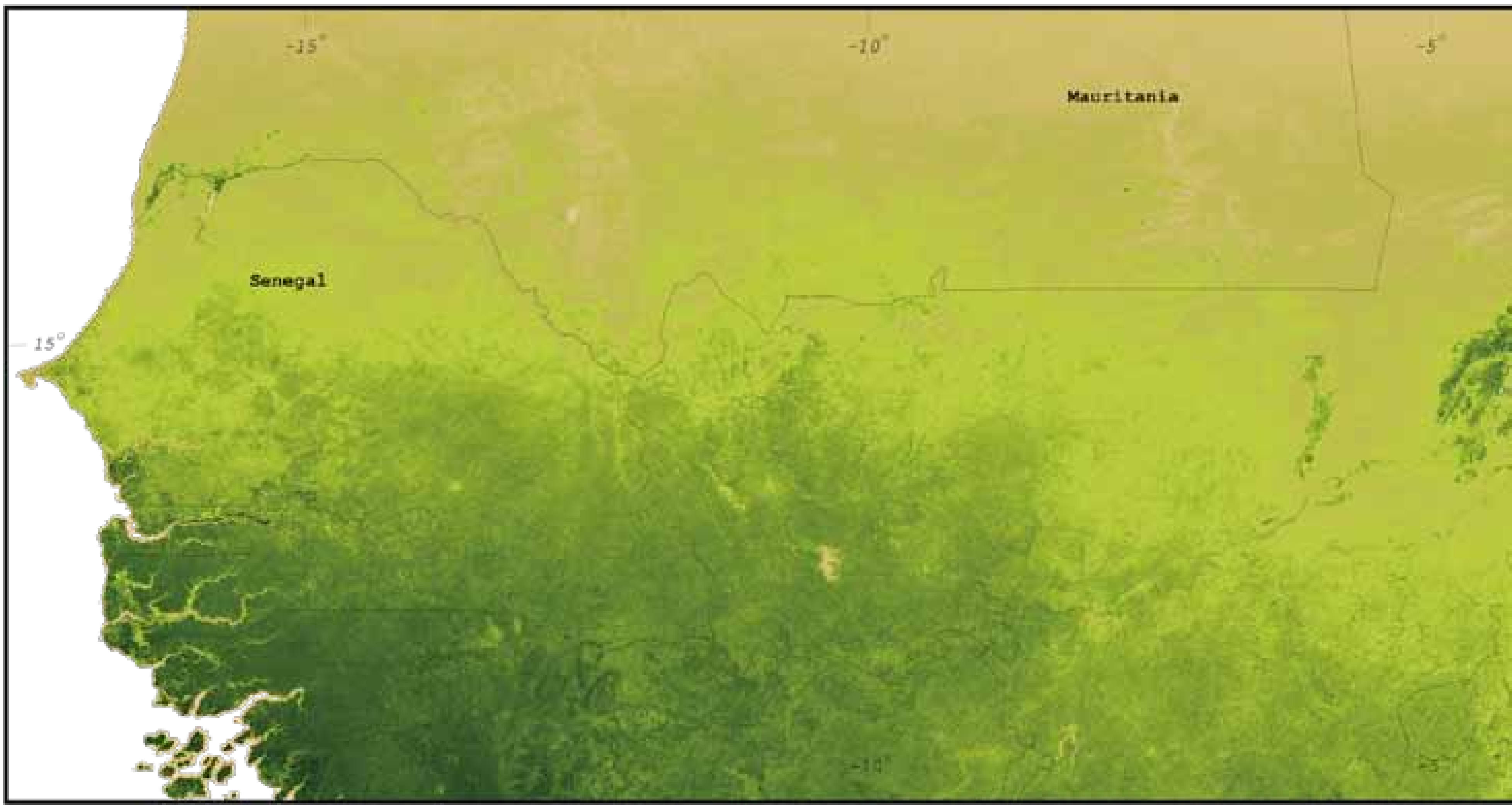
rNDVI response to rainfall

Vegetation responds strongly to rainfall in the previous year. The erratic response at lower rainfall levels can be due to grazing pressure the previous year, as over-grazing might lead to diminished seed pools of annual grasses.

The MODIS Enhanced Vegetation Index (EVI)

The Moderate Resoultion Image SpectroRadiometer (MODIS) acquires daily global images at 250 to 1000 m resolution. Vegetation cover is mapped using 8 or 16 consecutive days of images at 250 m resolution from cloud free scene compositions.

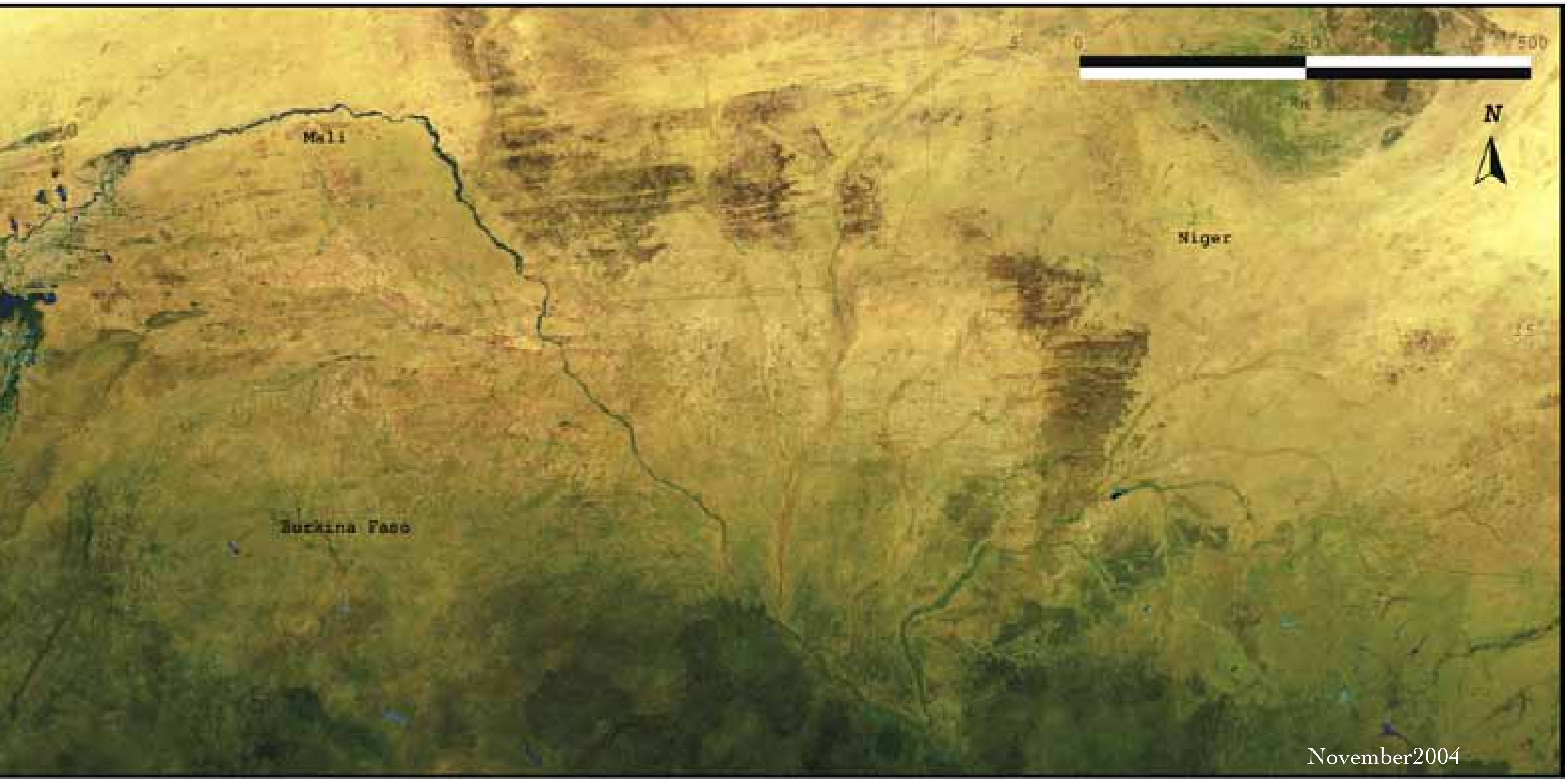




MODIS average EVI annual increment index 2000–2006

The MODIS derived EVI has a much higher spatial resolution than the AVHRR derived NDVI. Details related to drainage patterns and small scale topography are visible. Vegetation growth is stronger near streams and rivers, and the same is generally true in valley bottoms.

The MODIS sensor is superior to the AVHRR sensor and the data collected by MODIS can be used to calculate a better vegetation index – the Enhanced Vegetation Index (EVI). In this study, the 16 day EVI composite index was used for estimating vegetation cover and changes for the period 2000 to 2006.



MODIS EVI calculations

The MODIS EVI satellite derived vegetation data cover the period 2001 to 2006, which is rather short for studying vegetation changes. However, spatial patterns are much more resolved and the influence of drainage and topography can be studied. The MODIS EVI data used in this study was not adjusted for soil disturbances. Rainfall normalized EVI (rEVI) was calculated from the same rainfall dataset used to calculate rNDVI, which was originally at eight km resolution, but resampled to 250 m resolution to fit the EVI. This introduces some uncertainty in the rEVI data and consequent analysis.

Variations in EVI 2001–2006

Coefficient of Variation (CV) in increment EVI for the per period 2001 to 2006 (six years). The drier areas of the Sahel have a larger relative variation in vegetation growth compared to further south.

Average increment EVI for the period 2001 to 2006

Trend patterns for rEVI during the period 2001 to 2006 are similar to those observed earlier for rNDVI. The EVI timeseries is rather short for a trend analysis, and rainfall trends in the period 2001 to 2006 are not very strong.

An increase in the efficiency of vegetation in utilizing available rainfall would normally be expected during stable rainfall periods, as this gives the vegetation time to adapt to edaphic conditions. The largely decreasing trends in vegetation efficiency observed in many parts of the Sahel indicate incipient land degradation.

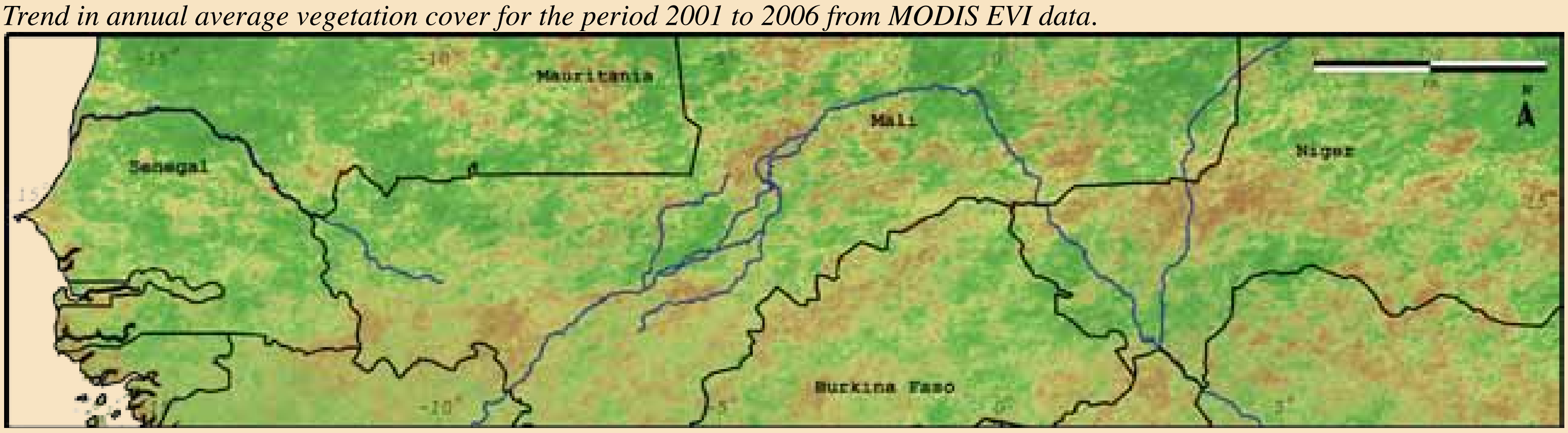
Trends in increment rEVI for the period 2001 to 2006.

Annual vegetation production from EVI data was calculated using the same three methods as for NDVI presented earlier. The analysis of the performance of these indices clearly indicates that the increment index is superior to the more commonly used average- and maximum indices.

Average vegetation cover (MODIS EVI) 2001 to 2006

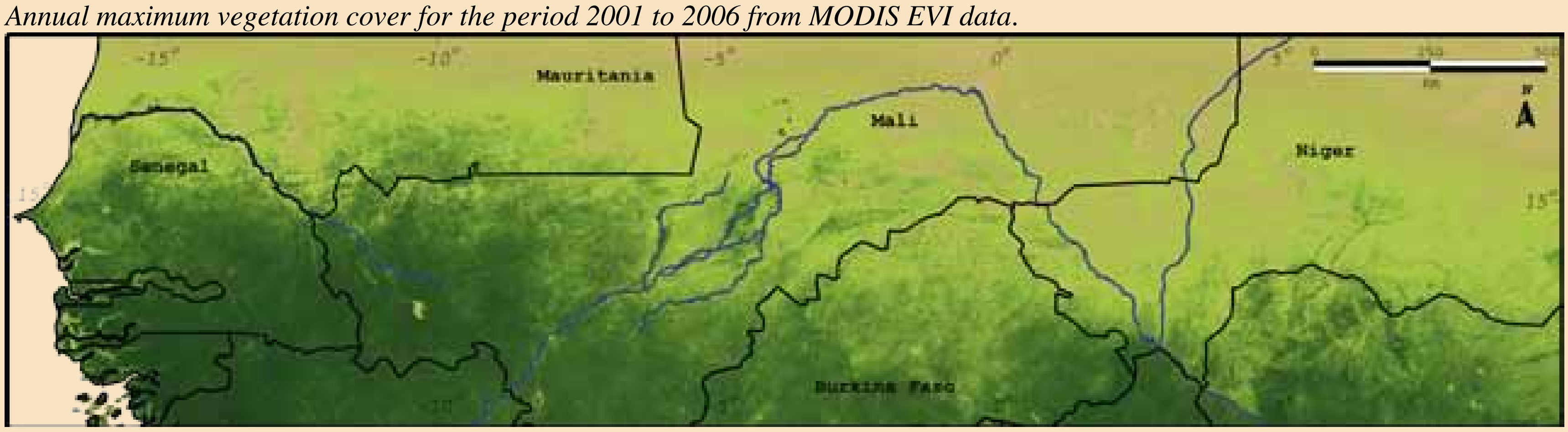
Annual average vegetation cover for the period 2001 to 2006 from MODIS EVI data.

Trend in annual average vegetation cover for the period 2001 to 2006 from MODIS EVI data.



Maximum vegetation cover (MODIS EVI) 2001 to 2006

Annual maximum vegetation cover for the period 2001 to 2006 from MODIS EVI data.



Trend in annual maximum vegetation cover for the period 2001 to 2006 from MODIS EVI data.

Land degradation hotspots

Land degradation is one of the most important environmental concerns facing humanity. It threatens habitats, economies and societies the world over.

In sub-Saharan Africa (SSA), land degradation is a direct threat to food security and livelihoods. Although the processes leading to land degradation are generally considered slow, recent (post 1950s) near exponential population growth coupled with inappropriate environmental and agricultural management practices and abject poverty, have lead to rapid soil and land degradation in many areas. Despite the importance of, and increasing prevalence and incidence of, land degradation in SSA, current measurement and information systems in developing countries are grossly inadequate for the task of planning and evaluating land health and land management policies and practices.

In particular, there is a lack of systematic data on land health risks to enable efficient targeting of land management or to answer questions such as;

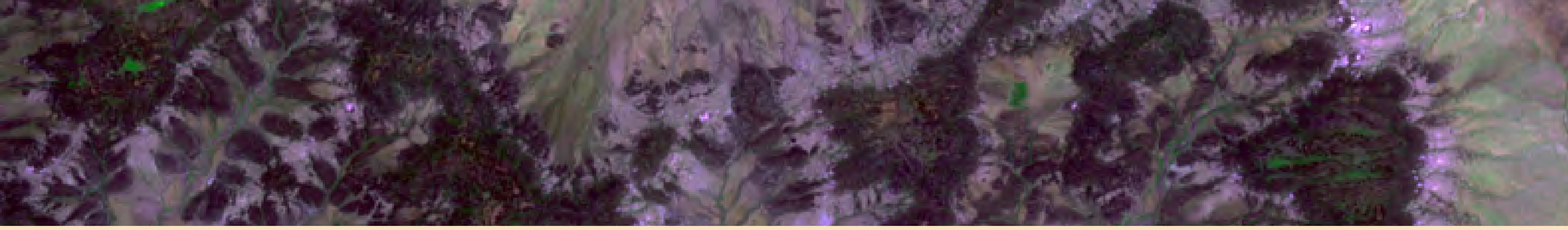
- What are the socioeconomic and biophysical determinants of land degradation and how are they geographically distributed?
- How much land degradation can be avoided or reversed?
- How cost efficient are preventative and rehabilitation interventions under different conditions?

To be able to address the above questions, rigorous measurement and monitoring systems need to be developed that allow assessment at multiple spatio-temporal scales.

In the current section, we analyse data from multiple remote sensing platforms along with climate data to map and identify potential land degradation hotspots in the Sahel.

For the broader patterns of land cover change we use the NOAA-AVHRR NDVI and MODIS EVI time-series presented earlier, while potential hotspots in more detail using Landsat Multispectral Scanner (MSS), Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) imagery, coupled with Advanced

Soil erosion by wind and water, soil physical degradation (for example crust development) and salinisation are important processes of soil degradation in the Sahel, impoverishing soils and decreasing food production. During the droughts in the 1970s and 1980s, exposed soils were vulnerable to wind erosion, and large areas lost their top soils. Winds transported the eroded soils (dust) and deposited them elsewhere forming new layers of topsoil up to a decimeter thick. Water erosion occurs when surface runoff is high, and is often observed in areas with compacted soils having low water infiltration capacity.



Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery in some areas. The examples presented here illustrate effective approaches to isolating areas that may be degraded, while also demonstrating the highly complex nature of land degradation in the Sahel.

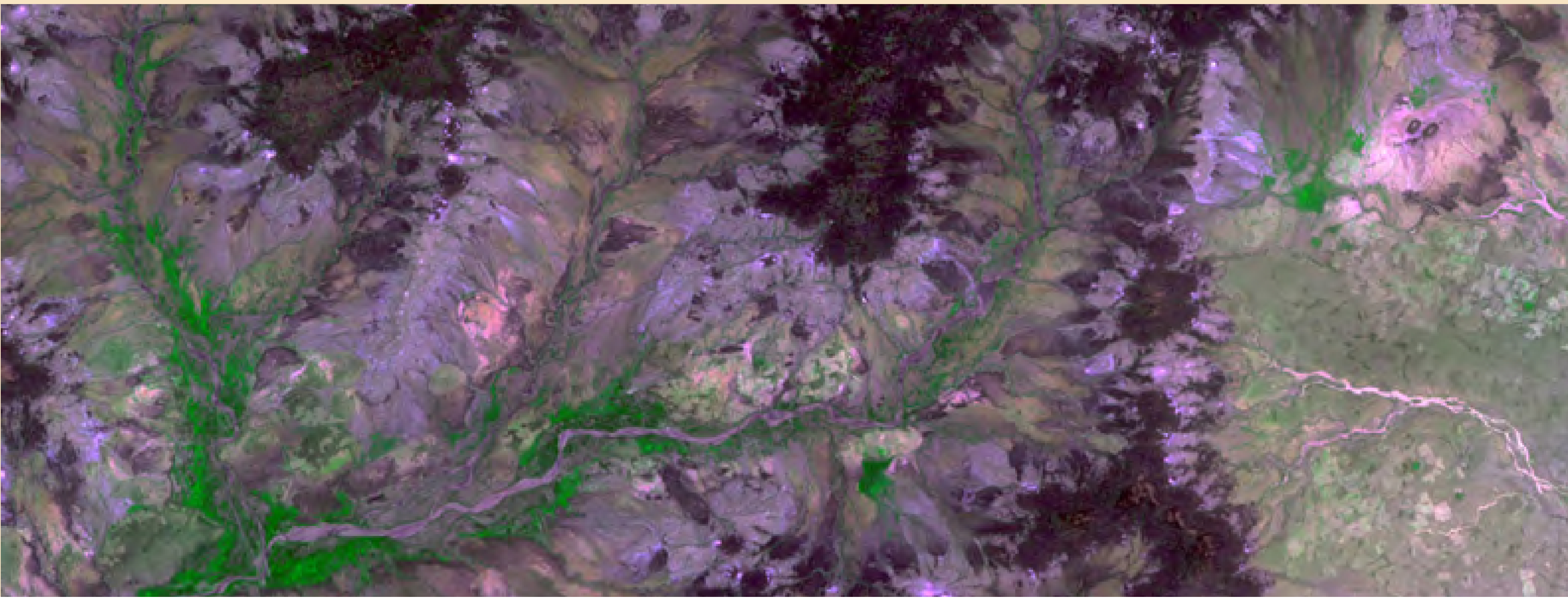
In summary, our analysis shows that vegetation recovery has not been as strong as the increases in rainfall after the droughts of the 1980s. This is indicated both by the rainfall front having moved approximately twice as far north as the vegetation front and that vegetation seems less efficient in converting each drop of rainfall into biomass. In other words, vegetation is not responding fully to increases in rainfall.

The normalization of vegetation growth to rainfall and calculation of trends in vegetation efficiency as annual average, annual maximum and annual increment indices gives estimates of vegetation response to available rainfall on an annual basis.

Each AVHRR sensor passes the Sahel at a different time of day, with different amounts of solar insolation and a slight degradation of the sensor over time. Atmospheric dust content is also known to have varied between 1982 and 2006, mainly due to large volcanic eruptions, but also due to local conditions in the Sahel. A combination of these artifacts can cause artificial trends in the AVHRR vegetation data.

As discussed earlier, the MODIS sensor has a much higher spatial resolution and provides for the calculation of a vegetation index (EVI) superior to the NOAA-AVHRR NDVI. The length of the time-series from MODIS is, however, much shorter than AVHRRNDVI. Processing of MODIS EVI data is also more computationally expensive. We use 16-day composites (which generally yields two scenes per month) to calculate maximum monthly EVI and scale the EVI images to between zero and one. Unlike NOAA-AVHRR NDVI data, the spatial resolution of the MODIS EVI allows us to assess changes in vegetation cover at spatial scales relevant to local changes in management.

The extent and degree of human-induced land degradation in the Sahel is still widely debated. The results from the regional screening studies presented here, using archives of satellite imagery and historical rainfall, indicate incipient land degradation in many parts of the Sahel. The large increases in rainfall over the last two decades, however, mask some of these degradation processes and remotely sensed data seem insufficient to quantify the prevalence and incidence of land degradation in the region. In the current section we use a combination of low- and moderate resolution satellite imagery to investigate some of the areas identified as potential land degradation hotspots in the previous section of the atlas.

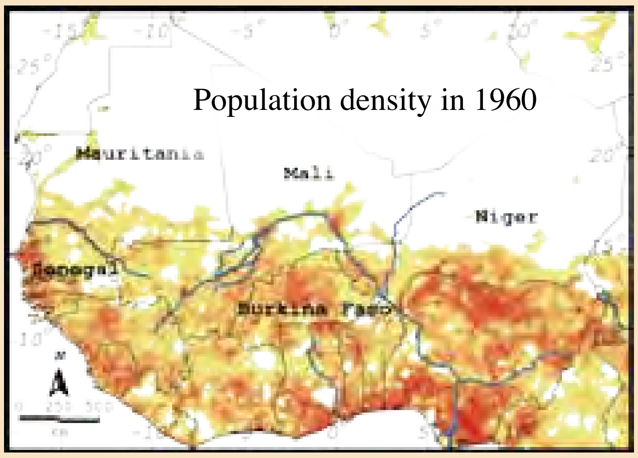


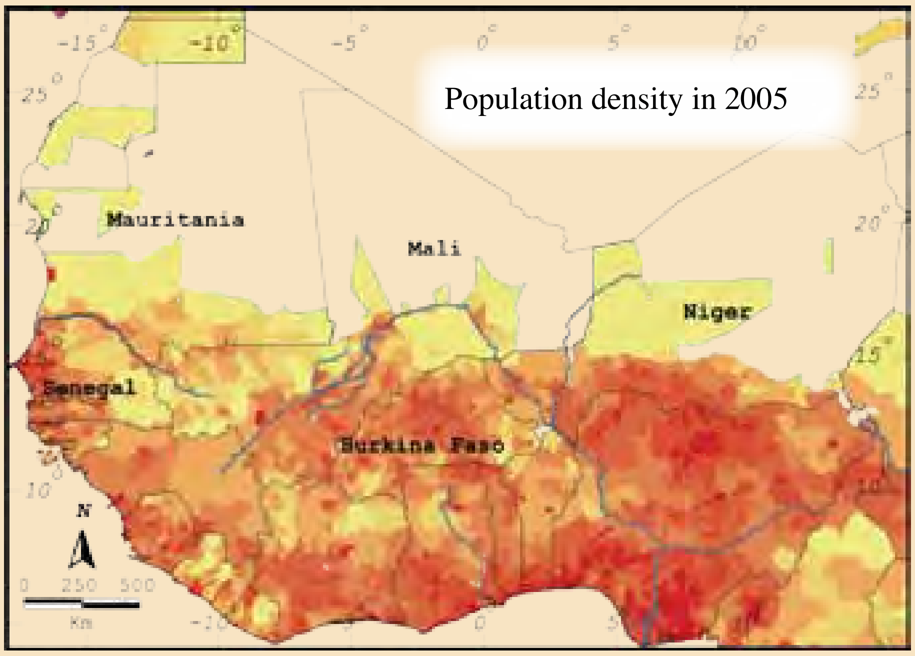
Agriculture in the Sahel

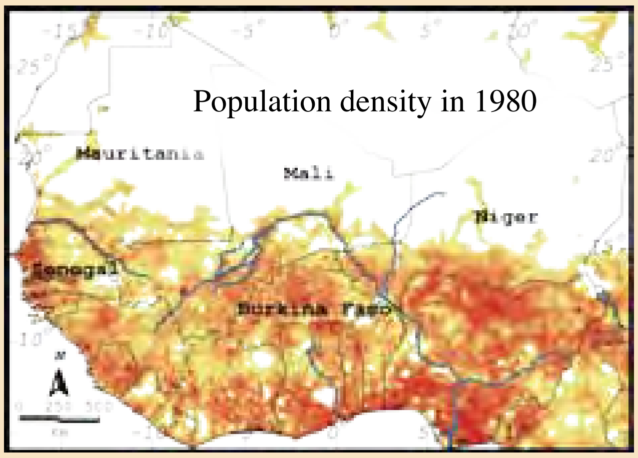
The economy of Sahelian countries is largely based on agriculture, with between 80 and 90% of the workforce active in the agricultural sector. Rainfed agriculture is dominated by cereals such as millet (*Pennisetum glaucum* L.) and sorghum (*Sorghum bicolor*). Rice cultivation is important along major rivers and wet depressions (fadama), and in large scale irrigation projects along the Niger (Office du Niger).

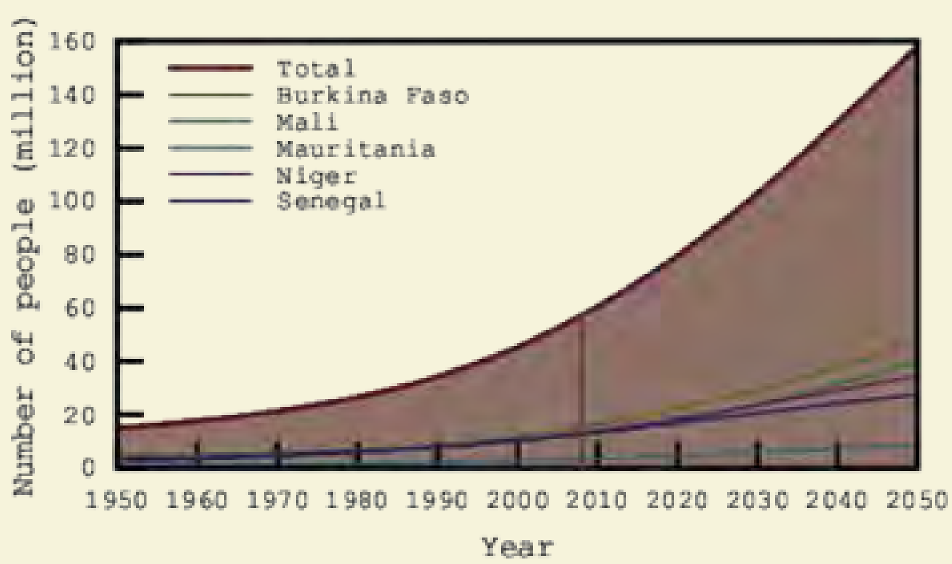
The most important export crops are groundnut and cotton, which account for about 50% of export earnings in the region, except for Mauritania. Traditional methods for improving production and preventing soil degradation include pit planting with organic amendments, contoured stone lines, and damming of gullies. Irrigation and application of chemical fertilizers are mainly restricted to maize and rice cultivation.

About a quarter of the population is fully dependent on animal husbandry. The importance of livestock progressively increases towards the north where pastoralism predominates. Stocking densities are high in many areas and overgrazing common, leading to erratic plant growth patterns, de-linked from seasonal rainfall. Fire is a key component of traditional rangeland management systems, promoting growth of palatable grasses. However, in areas with heavy overgrazing, palatable grasses give way to bush encroachment and less palatable grasses. In many parts of the Sahelian drylands, population growth during the last five decades in particular, combined with policies promoting a more sedentary lifestyle, have resulted in many of the ancient response mechanisms to climate variability breaking down. This potentially also increases vulnerability to drought and future climate change. Our analysis indicates that in regions where a combination of traditional cultivation methods and fertilizer use occur, such as in southern Mali, Tahoua and Maradi regions of Niger and northern Burkina Faso, vegetation response to increases in rainfall have been strongest. We examine some of these areas in more detail in this section.

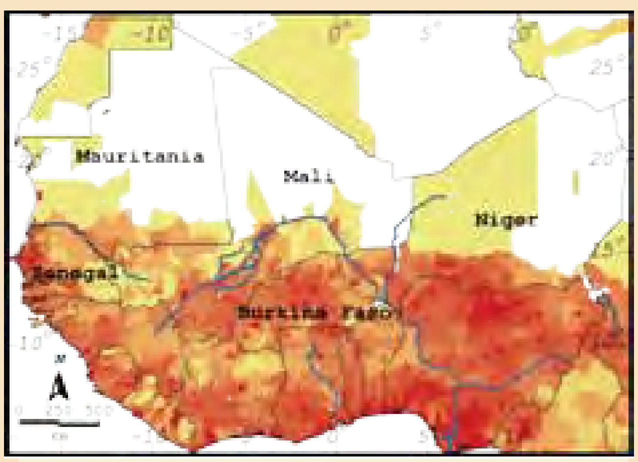








Population estimates for the West African Sahel 1950 to present, and projected population 2008 to 2050.



Projected population density in 2015.

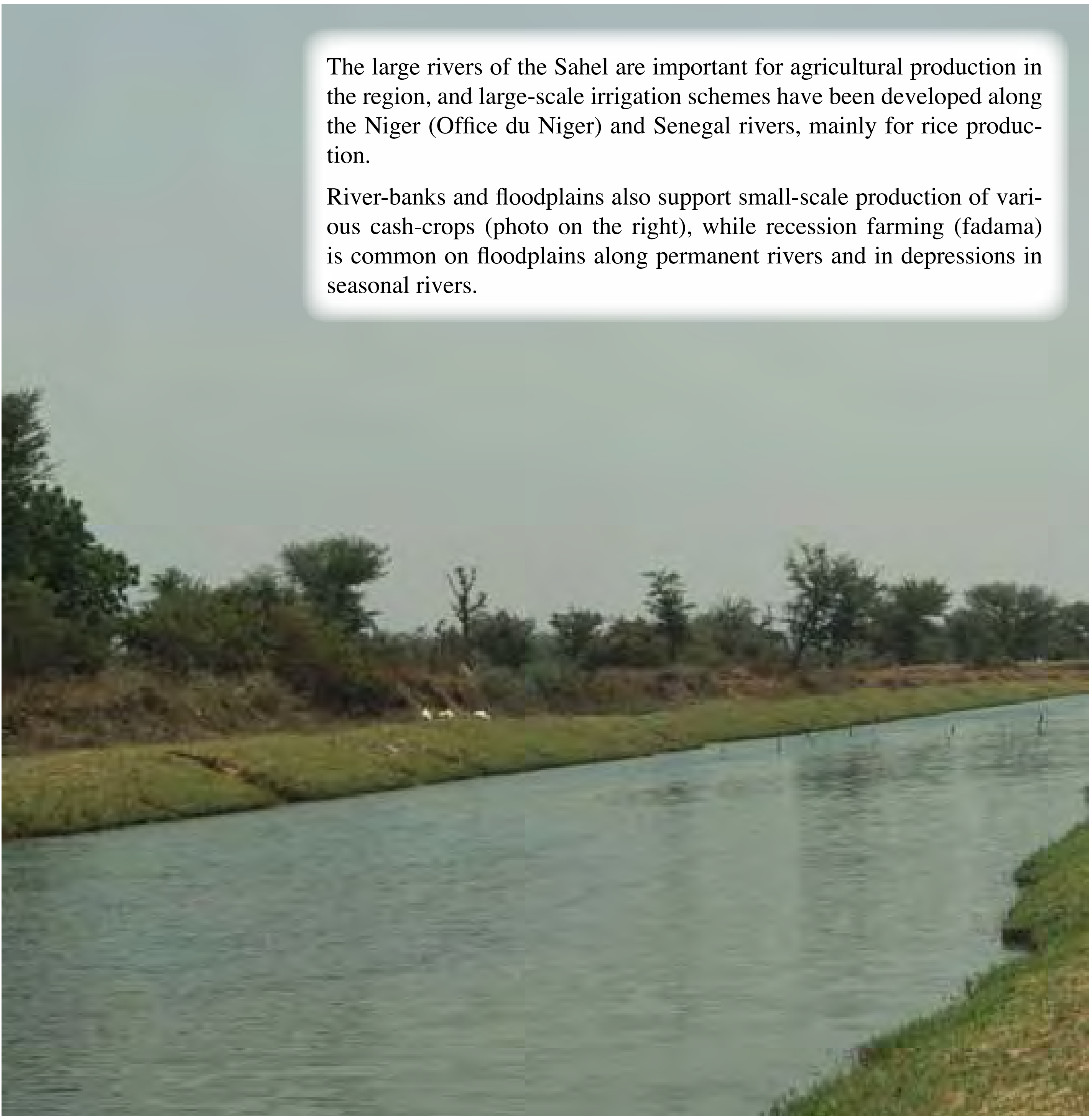
High rates of evaporation can cause surface crust development and formation of laterites.

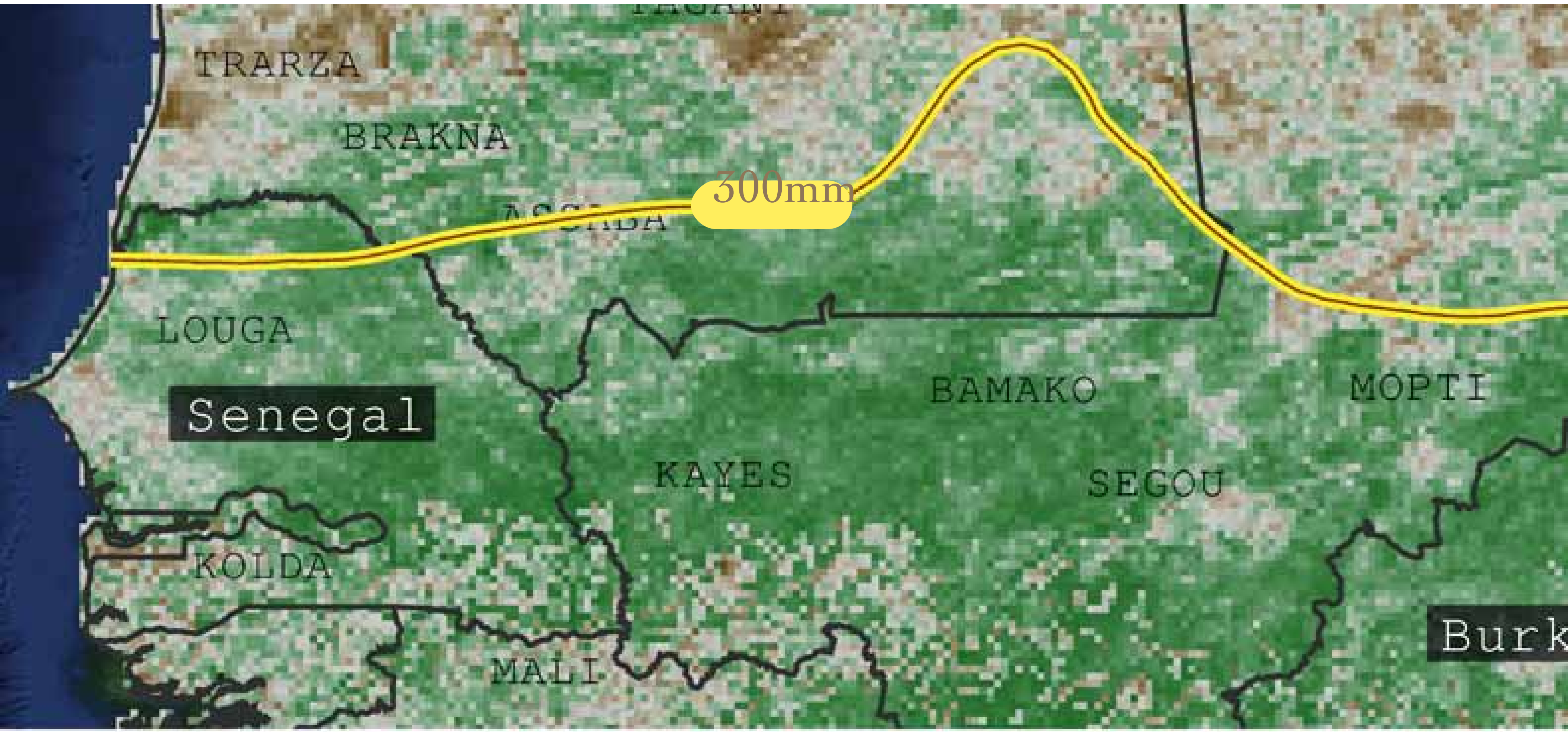
Laterites can become several metres thick, or form small nodules, resembling rocks rather than soils. Water generally infiltrates poorly, resulting in large amounts of runoff during rainfall events.

In soils with higher clay content, termites can also create crusts in the form of termite mounds. Termite activity results in localized increases in infiltration rates and soil nutrient content, which leads to the formation of fine–scale vegetation mosaics where more water–demanding plants grow.

The large rivers of the Sahel are important for agricultural production in the region, and large-scale irrigation schemes have been developed along the Niger (Office du Niger) and Senegal rivers, mainly for rice production.

River-banks and floodplains also support small-scale production of various cash-crops (photo on the right), while recession farming (fadama) is common on floodplains along permanent rivers and in depressions in seasonal rivers.

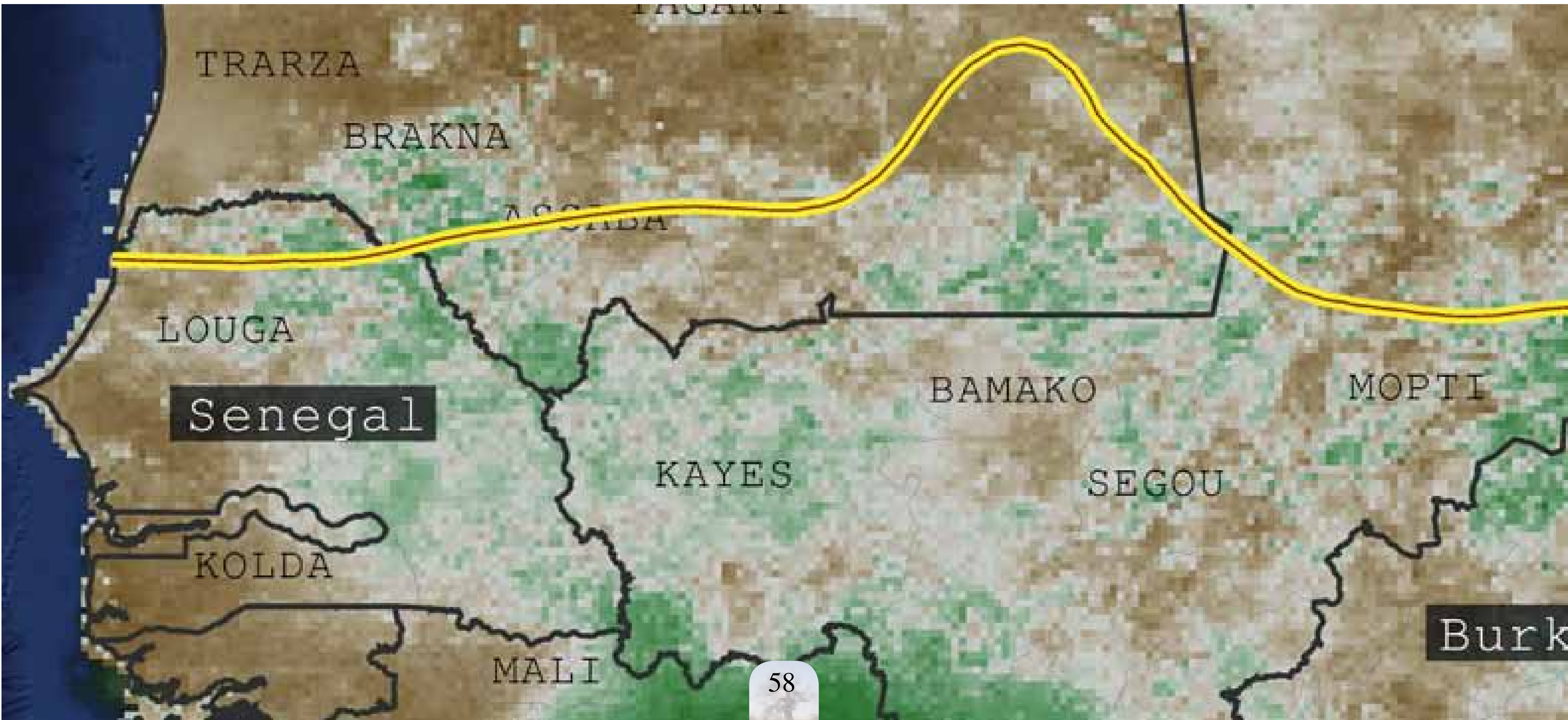


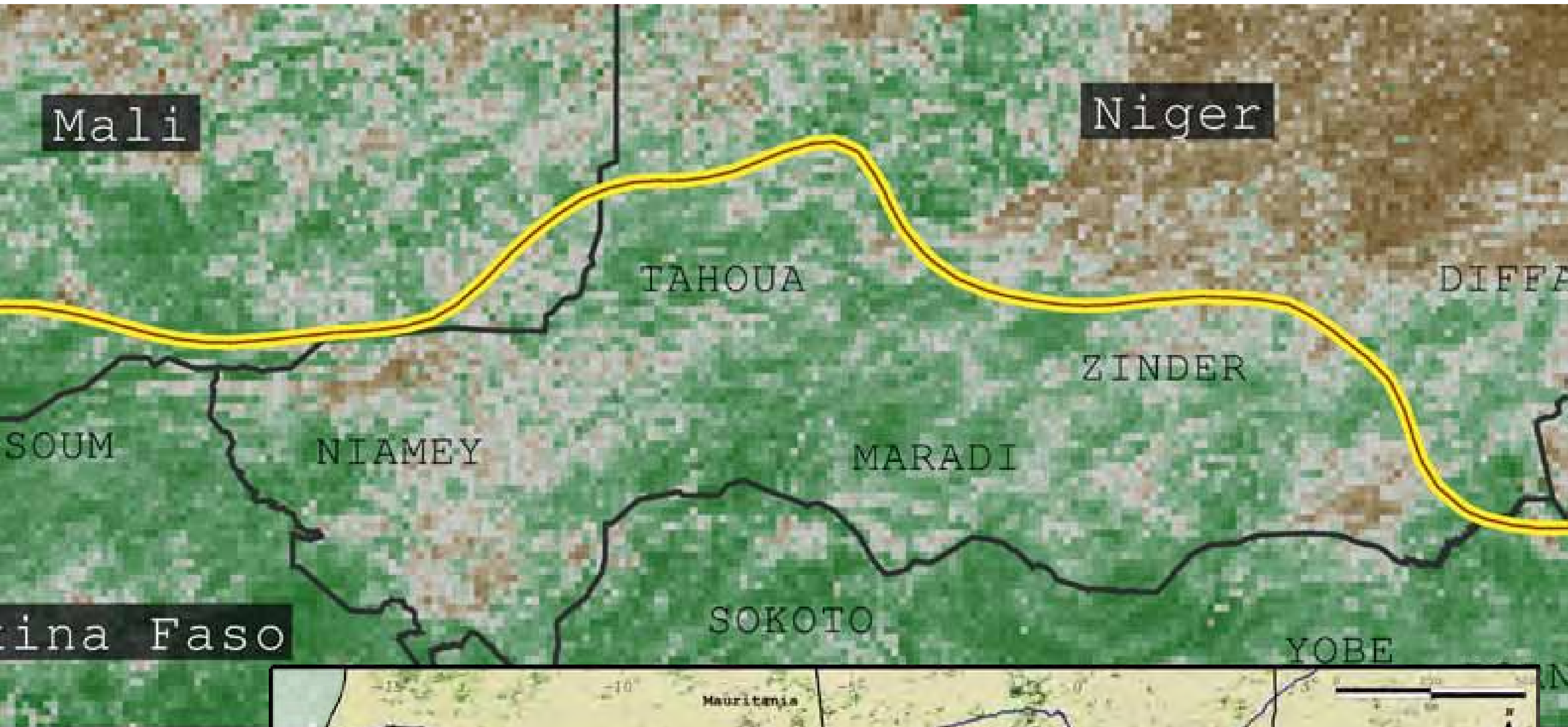


Mapping land degradation hotspots in the Sahel

The map above shows linear trends in annual integral NDVI for the Sahel after adjusting NDVI in each pixel to z-scores (a statistical method to reduce the influence of extreme values in the data), but without adjusting for rainfall. From these trend estimates, large parts of the Sahel seem to be greening up, with only smaller patches browning down.

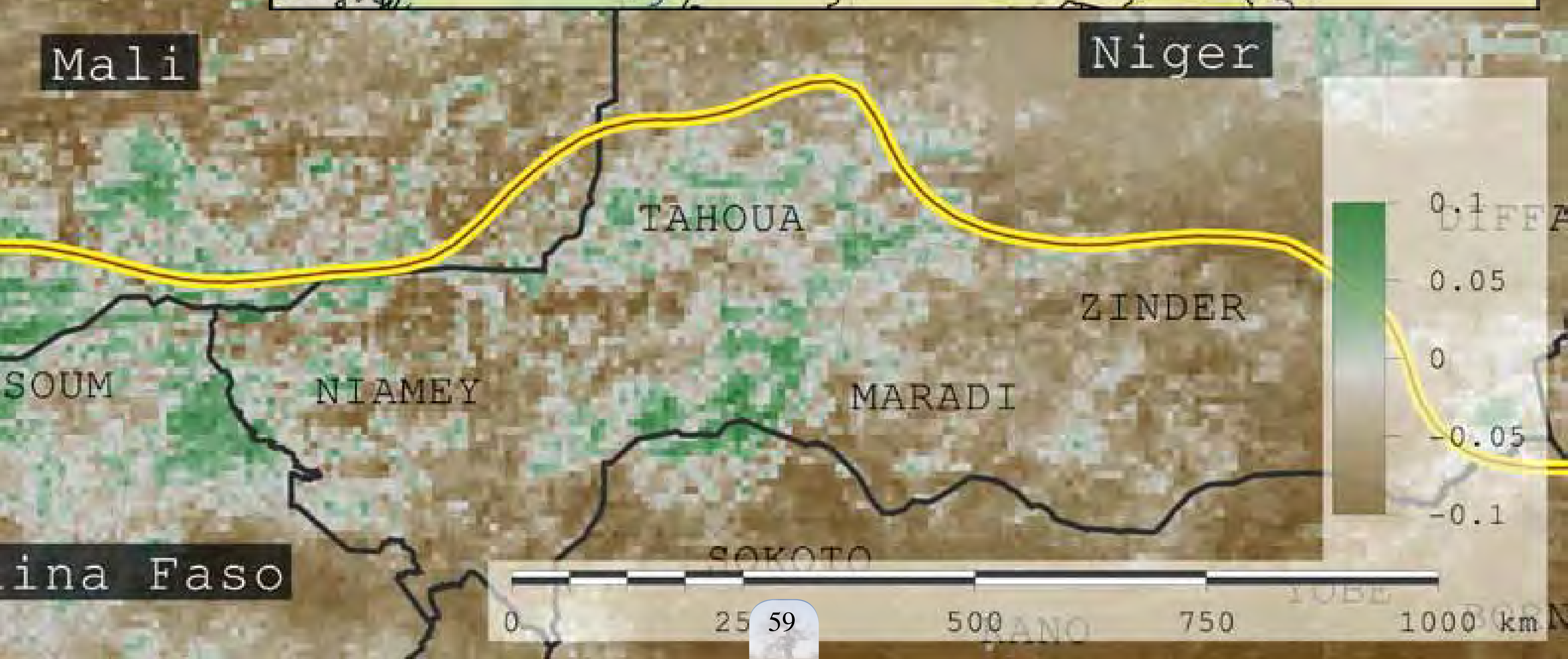
If, however, we look at linear trends in rainfall normalized NDVI (rNDVI – bottom map), the picture changes dramatically and many of the areas that are seemingly greening in the top map are in fact browning. In other words vegetation recovery does not directly follow increases in rainfall over large parts of the region. Most of the areas browning down in the upper map are also browning down in the bottom map, while several of the areas that seem to be greening up in the upper map show opposite trends in the lower map. This is the case in, for instance, western Senegal, parts of Mali, central and eastern Burkina Faso, and northern Nigeria. The smaller map (below) shows areas with strong browning-down trends ($p < 0.05$), while more recent (higher resolution) trends based on EVI and rEVI are shown on the facing page.



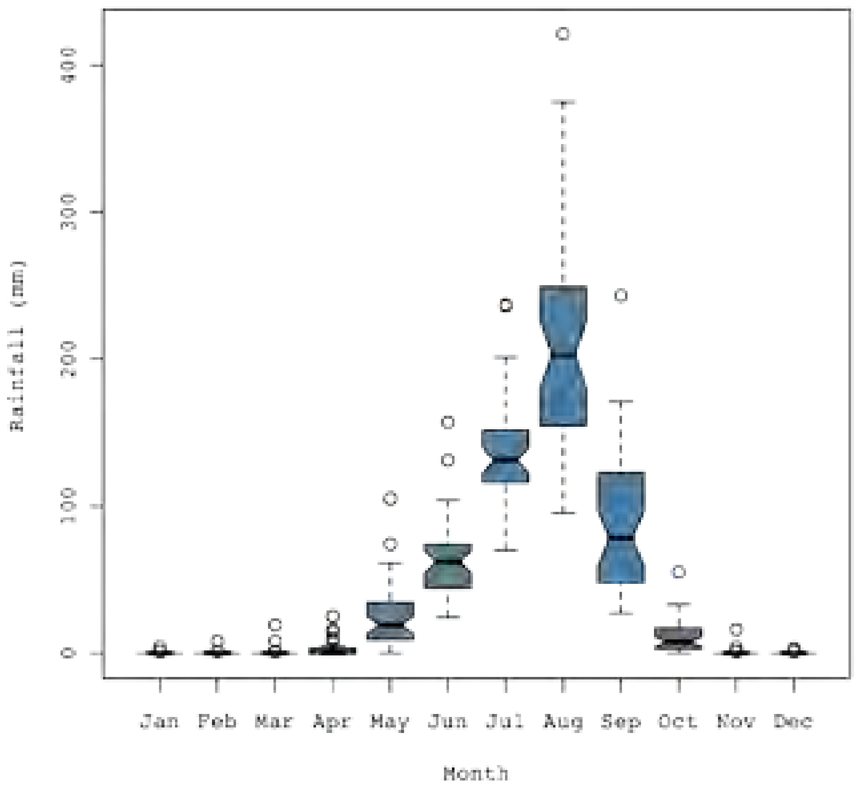


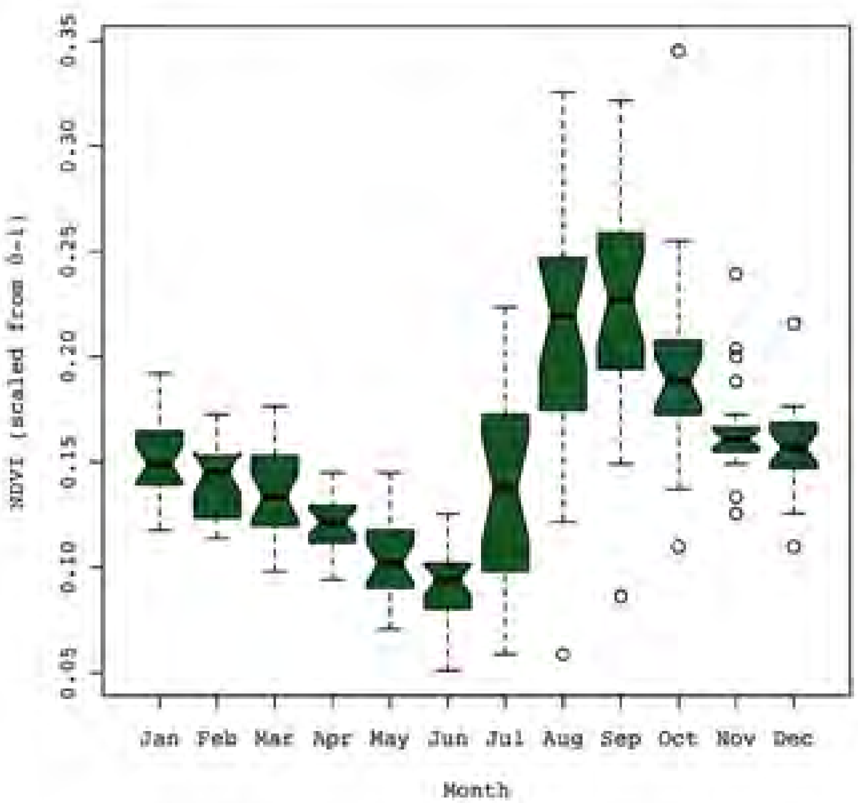
Areas with significant ($p < 0.05$) negative (brown) and positive (green) trends in vegetation production (EVI) over the period 2001 to 2006.

Areas with significant ($p < 0.05$) negative (brown) and positive (green) trends in rainfall normalized vegetation production (rEVI) over the period 2001 to 2006.



Tahoua, Niger





Tahoua in southern Niger, is an important trading town located between the cultivated zone in the south and the drier pastoral zone in the north. The population in Tahoua was estimated at about 73,000 in 2001.

Rainfall in the area (based on data from 1925 to 2000) is highest in August (graph on left), with a mean annual sum of approximately 328 mm. Vegetation growth largely peaks in August or September and is at its lowest in June. As shown in the lower boxplot on the left, there is large inter annual variation in vegetation growth performance for the different months, with virtually no growth in August or September in very dry years (circles in box plot).

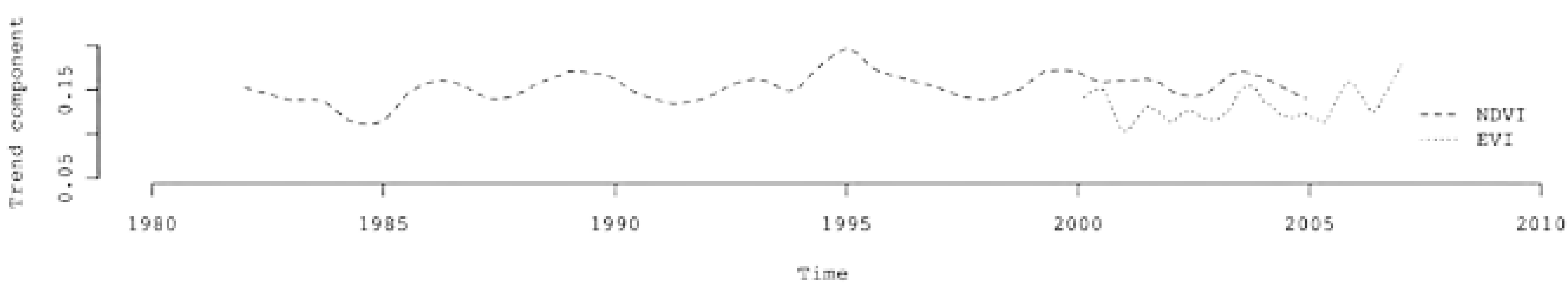
Several studies have reported relatively strong greening trends in this area, some suggesting a 100% increase in vegetation cover in the period 1982 to 1999[1]. Our own analysis of rainfall normalized NDVI time-series shows similar, although more conservative, greening trends in this area (map on top of this page (red cross is Tahoua)).

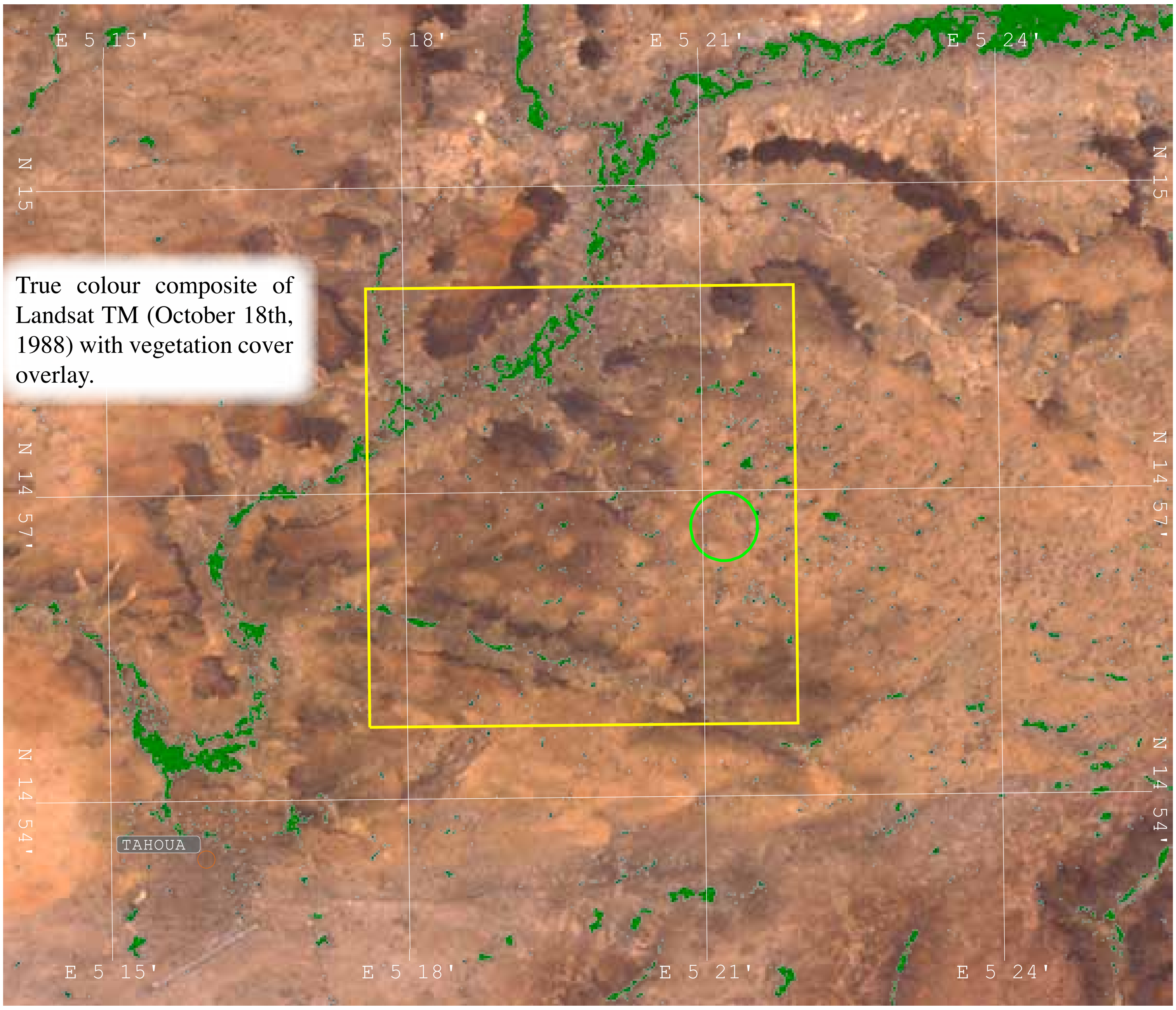
An analysis of these trends for a NOAA-AVHRR NDVI image pixel north-east of Tahoua (yellow box on facing page) shows a decline in the early 1980s, culminating in 1984 (trend plot at foot of this page) and followed by a relatively rapid recovery in the second half of the 1980s, with a peak in vegetation production for the area in 1994 (very wet year).

Overall the trend for the last two decades is not particularly strong. The same is the case for the period from 2000 to 2006, as shown in the MODIS 250 m EVI trend-line below (green circle in map and red dashed line in bottom graph). A closer examination of vegetation cover in the area using Landsat TM (October, 1988) and ETM+ imagery (October, 2000) suggests marginal vegetation increases in valley bottoms and decreases higher in the landscape (facing page).

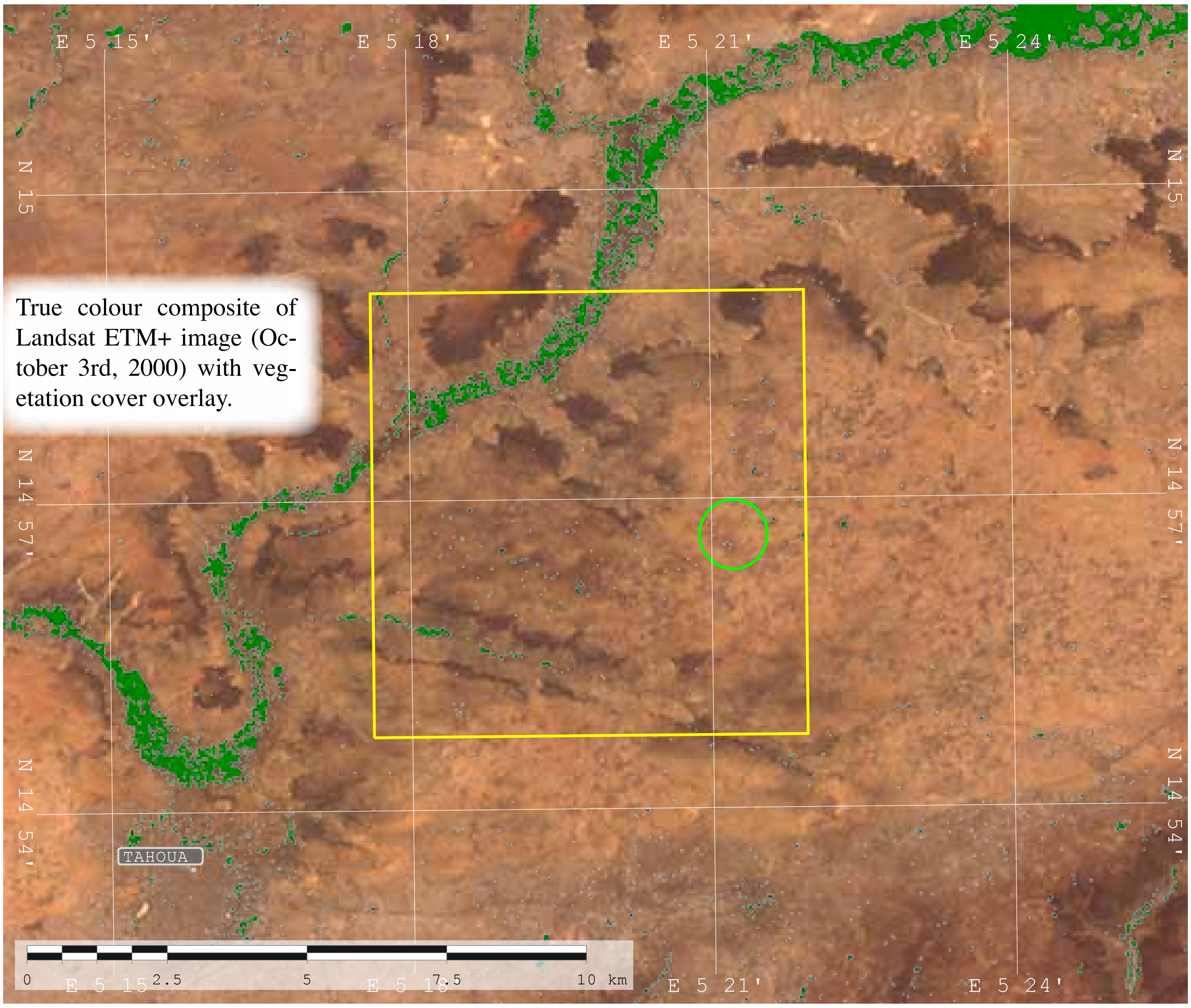
Vegetation cover in the image pair on the facing pages was analysed using spectral mixture analysis techniques.

[1] L. Olsson, L. Eklundh, and J.Ardö. A recent greening of the Sahel – trends, patterns and potential causes. Journal of Arid Environments, 63:556-566, 2005.

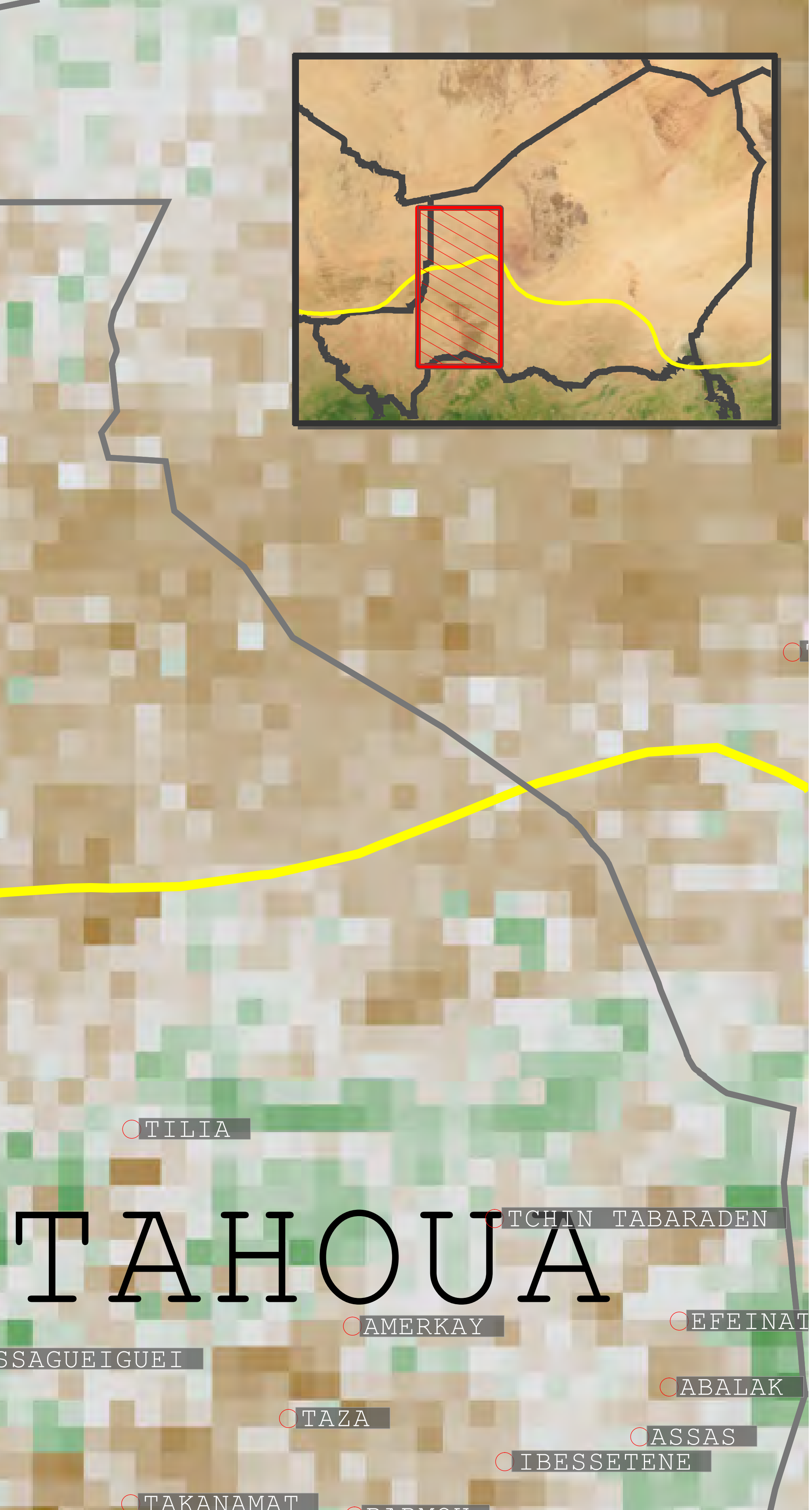




True colour composite of Landsat TM (October 18th, 1988) with vegetation cover overlay.



True colour composite of Landsat ETM+ image (October 3rd, 2000) with vegetation cover overlay.



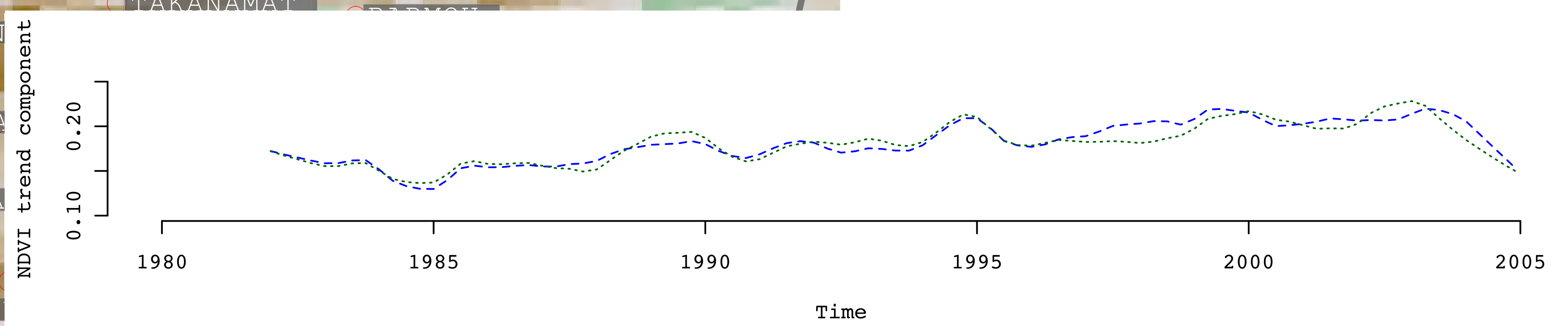
Dabnou - Tahoua region, Niger

In large parts of southern Tahoua, there are areas that show increases in vegetation cover after normalizing by rainfall (map on the left). Here, we focus on an area with relatively strong greening trends east of the town of Dabnou (yellow box on map below trend plot below).

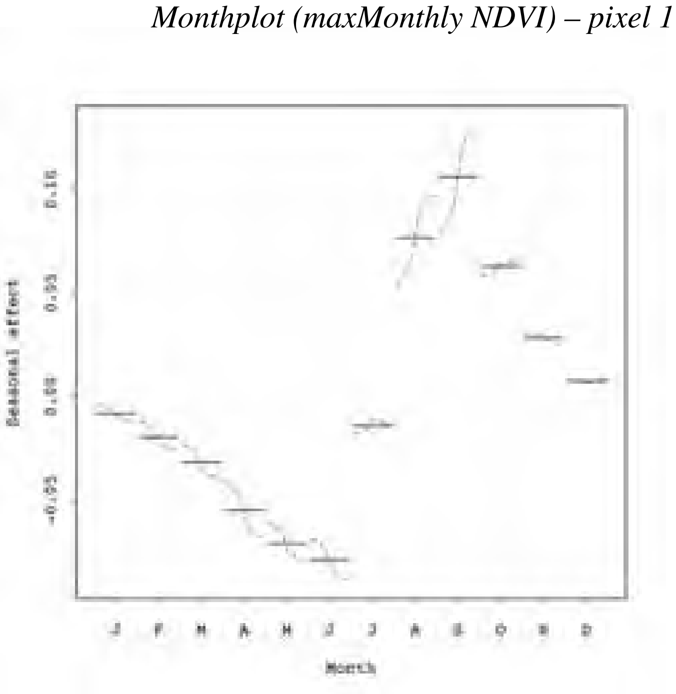
According to some reports, farmers in this region have intensified their agricultural production systems during the last two decades as a response to increasing population pressure, which might account for some of the increases in vegetation cover observed. In some areas, greening does not necessarily mean more trees in the landscape, but is rather a consequence (albeit temporary) of agricultural intensification. In other areas farmers have planted and/or protected and managed trees to increase woody cover as a response to the droughts of the 1970s and 1980s.

In the example shown here, we have relatively strong greening trends in both NDVI and rNDVI. The NOAA-AVHRR image pixel boundaries are superimposed on the Landsat scenes on the opposite page (in yellow – 1 and 2). From our analysis of the Landsat images from 1988 and 2000, most of the increases in greening seem to be occuring on lateritic soils (dark red/brown in the images), suggesting that it is mainly a result of increases in woody cover (as these areas are generally not arable due to shallow soils and hard-setting).

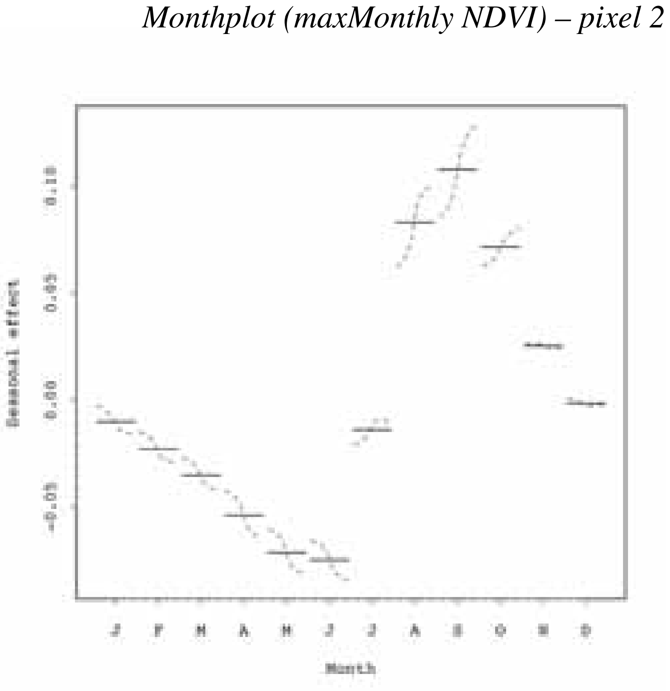
In the graphs on the opposite page, monthplots are shown for the two NDVI image pixels, after seasonal adjustment of the time-series. The trend components for the two NDVI image pixels are similar (bottom plot), with a strong recovery, particularly between the 1984 drought and 1994, and a drop in vegetation cover towards the end of the time-series. It is, however, difficult to verify these trends in the Landsat and MODIS EVI satellite imagery due to the patchy nature of changes in these landscapes. MODIS EVI trend components are shown for two EVI pixels (points A and B on maps).

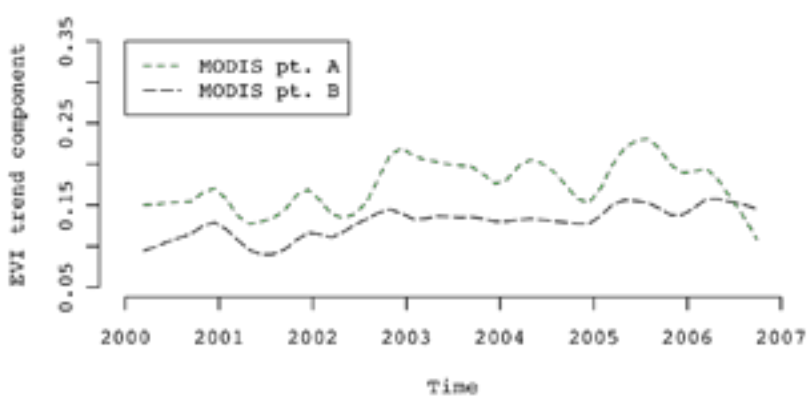


Monthplot (maxMonthly NDVI) – pixel 1

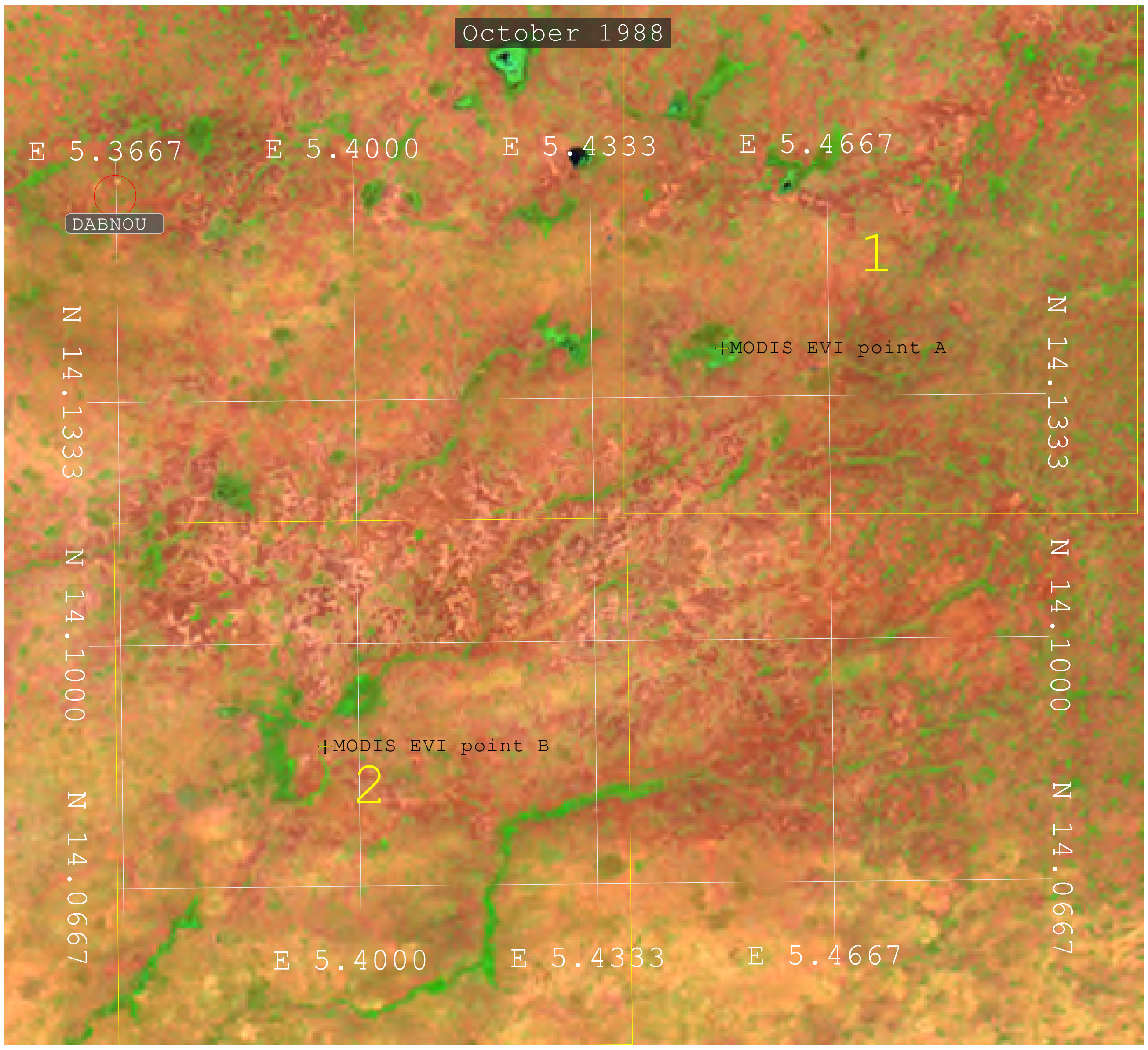


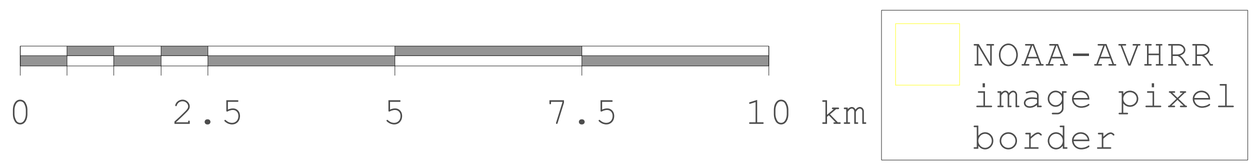
Monthplot (maxMonthly NDVI) – pixel 2

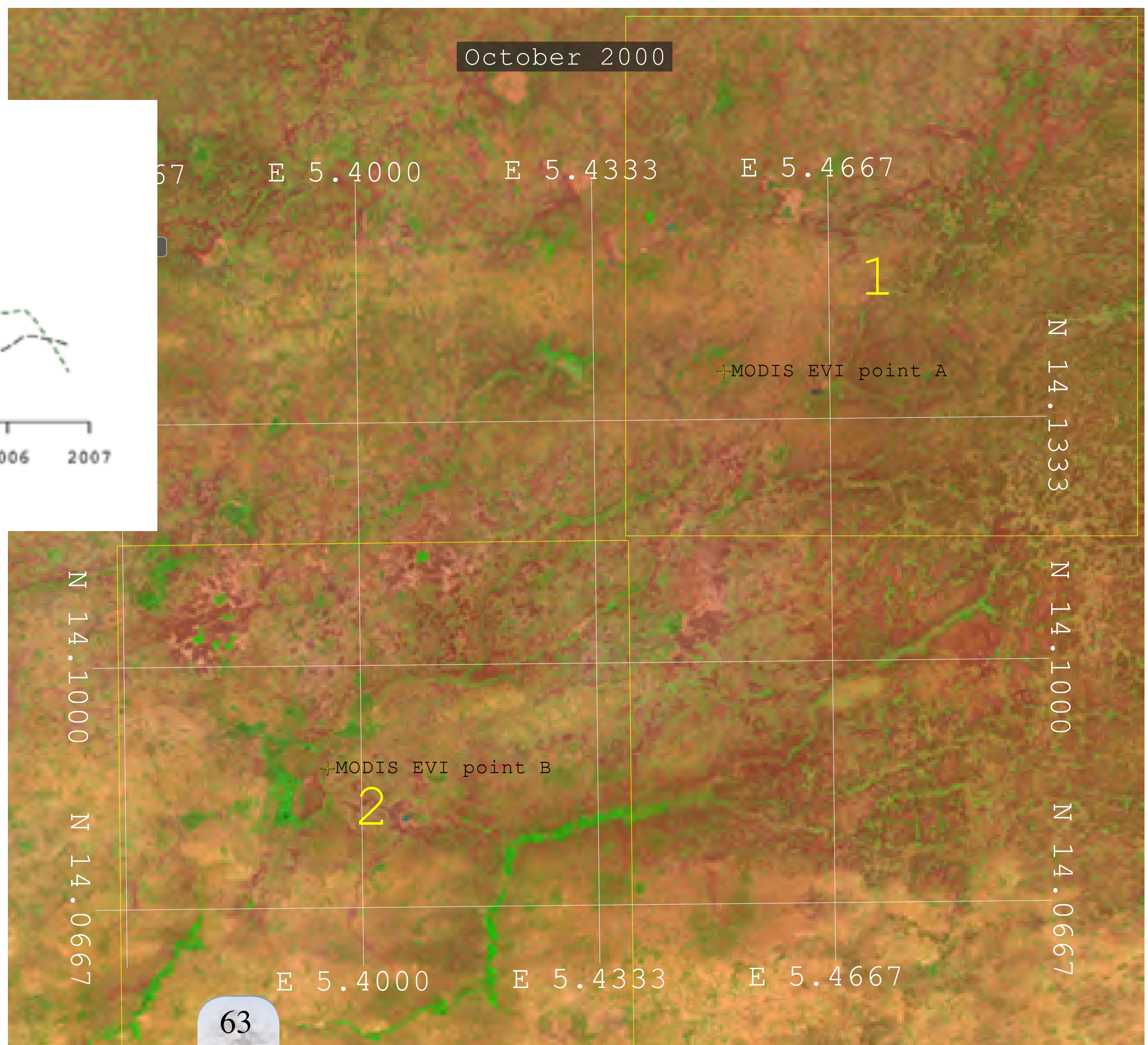


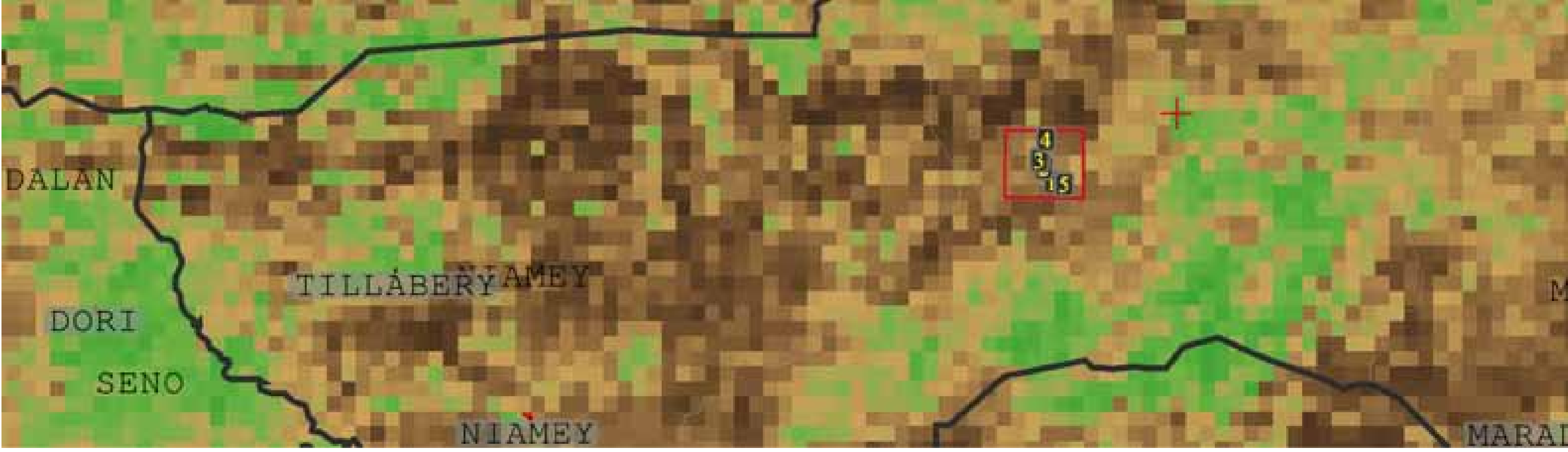


Horizontal bars in monthplots are averages, while dashed lines are monthy trends.



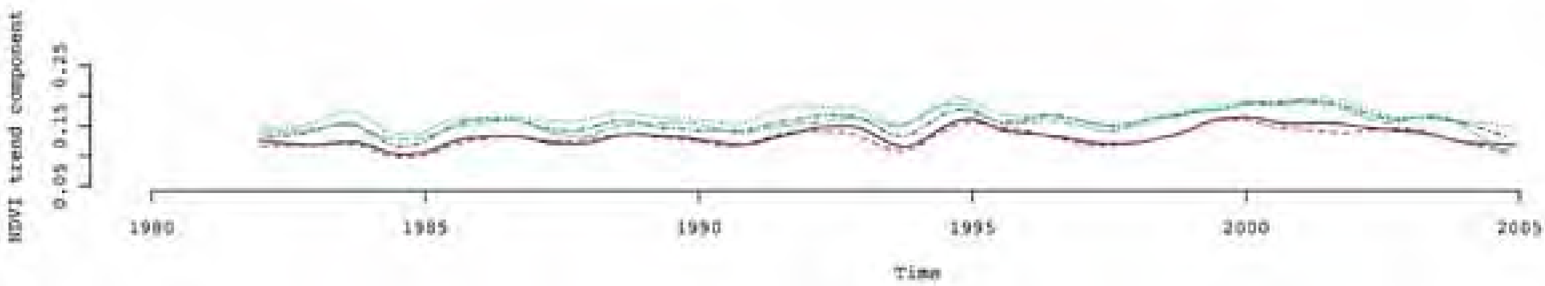




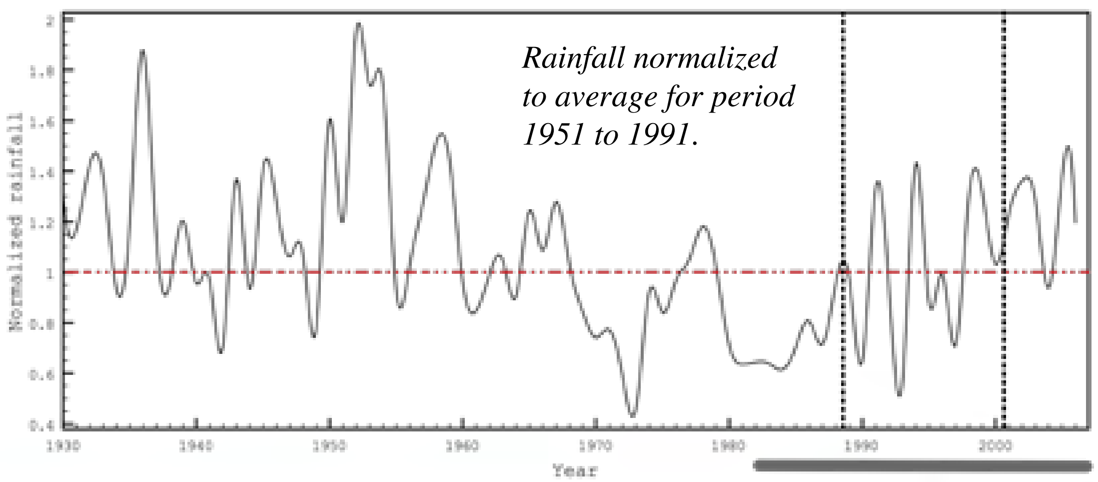


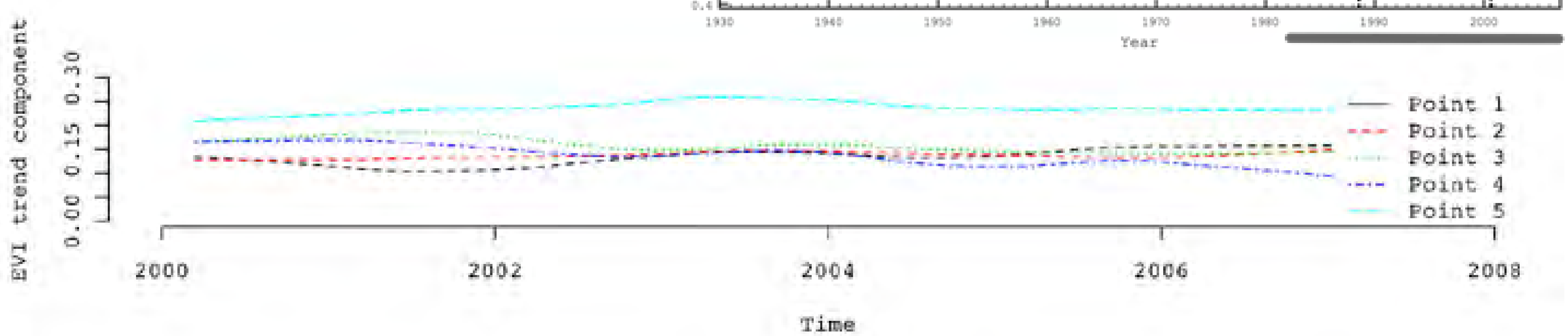
NDVI dynamics

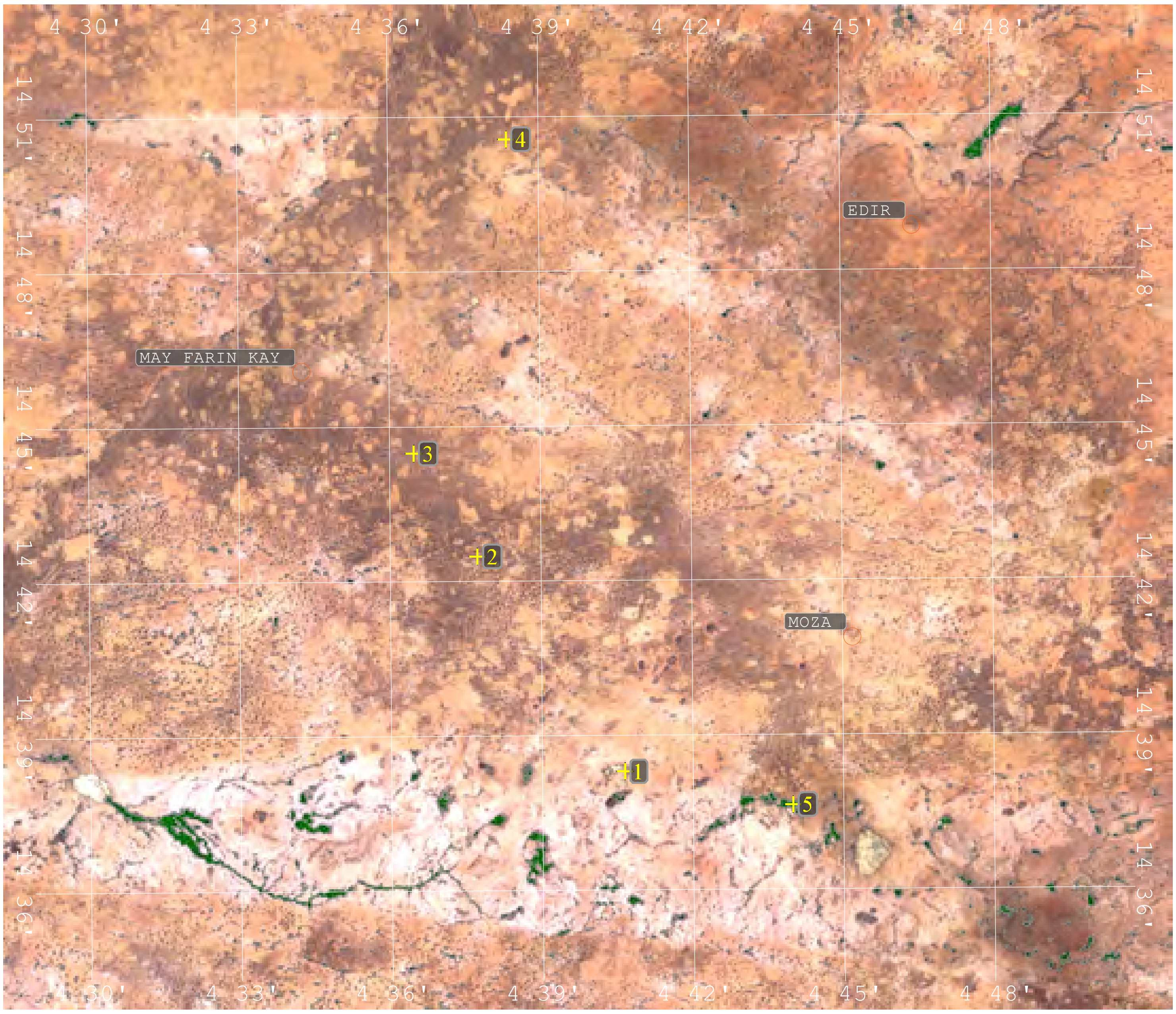
Trends in NOAA-AVHRR NDVI during the last two and a half decades show decreases (brown) in the area near Moza, Edir and May Farin Kay in Niger. Overview map at top of page shows extent of the area analysed in more detail here and on the opposite page. In the graph below we have randomly selected five locations (8 x 8 km pixels) in this area of interest, and extracted a time-series of NDVI for each of these locations. The graph shows trends after removing the seasonal components from the time-series and applying a two-year smoothing window on the trends. As expected, the lowest recorded vegetation production was in 1984 in most of the locations, with positive trends culminating in the wet year of 1994. The net trend between 1988 and 2000 seems to be an increase in vegetation cover, as is also evident from the Landsat TM and ETM+ image pairs. There is, however, a relatively strong negative trend after about 2002. We examine this further below, using MODIS EVI imagery for the period 2000 to 2006.

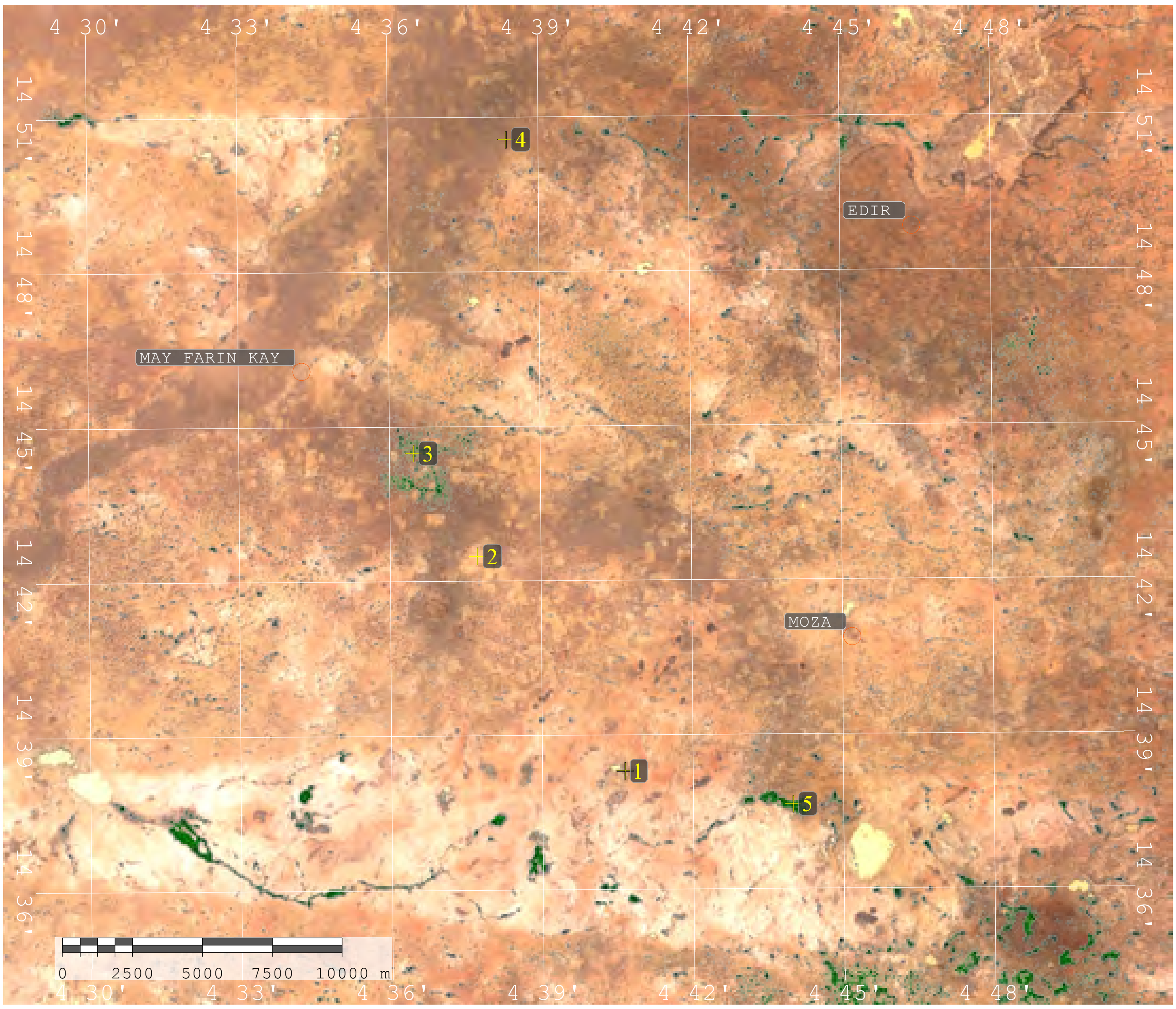


Trend analysis of vegetation cover as assessed using MODIS EVI from February 2000 to December 2006 indicates a reduction in vegetation cover (brown in left image) for most of the area, although parts of the southern section show increases in EVI (for example points 1 and 5). Vegetation dynamics in the area are therefore fairly complex and variable, as illustrated for a selection of points (1–5 on map and graphs at foot of page and on facing page). All in all, trends in vegetation cover in the area are marginal for the period from 1982 through 2006, with major inter-annual variations, largely determined by rainfall (graph below).



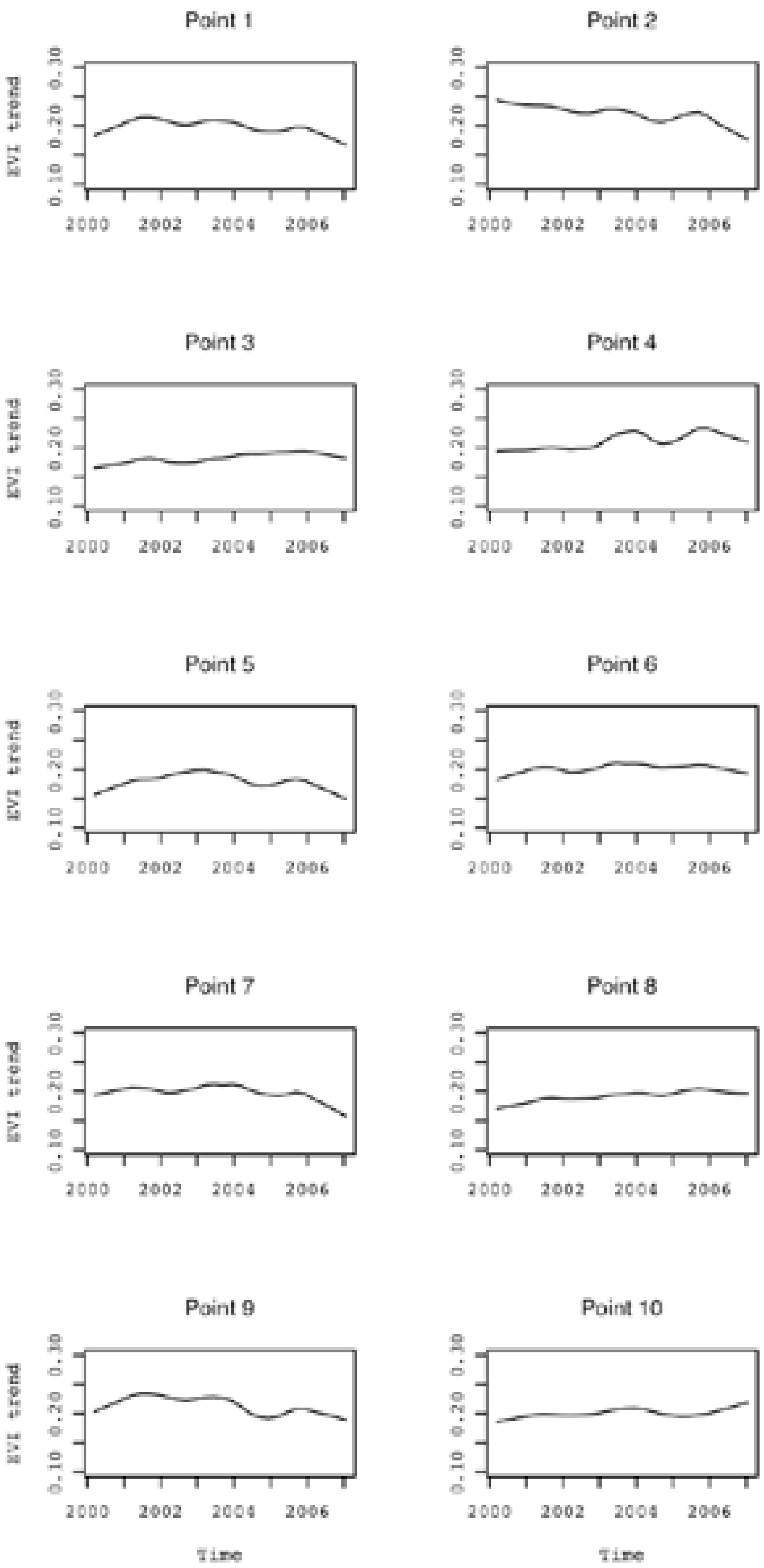






The Landsat TM and ETM+ image pair shown on the right are true-colour composites produced after correcting the images for atmospheric disturbances. The green areas overlain are areas having dense (mainly woody) vegetation cover. The area has very low vegetation cover densities. Cultivated fields (light brown to beige in image) can be clearly seen, and are more widespread in the early (1988 – top) image than in the lower image, which was acquired in 2000.

The Landsat scenes clearly illustrate the patchy nature of vegetaton in drylands, with changes occuring on a very local scale. Annual rainfall was lower in 1988 than in 2000, which may account for some of the apparent increases in vegetation cover in 2000. Some areas, however, clearly have more woody cover (point 3). The same area (point 3) shows a decline in MODIS recorded vegetation cover between October 2001 and October 2006, as shown in the bottom graph on the facing page.



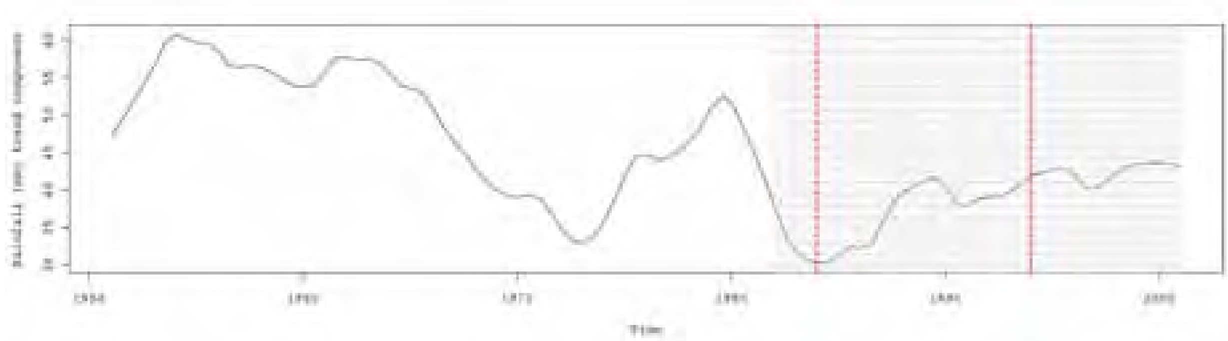
Zinder region, Niger

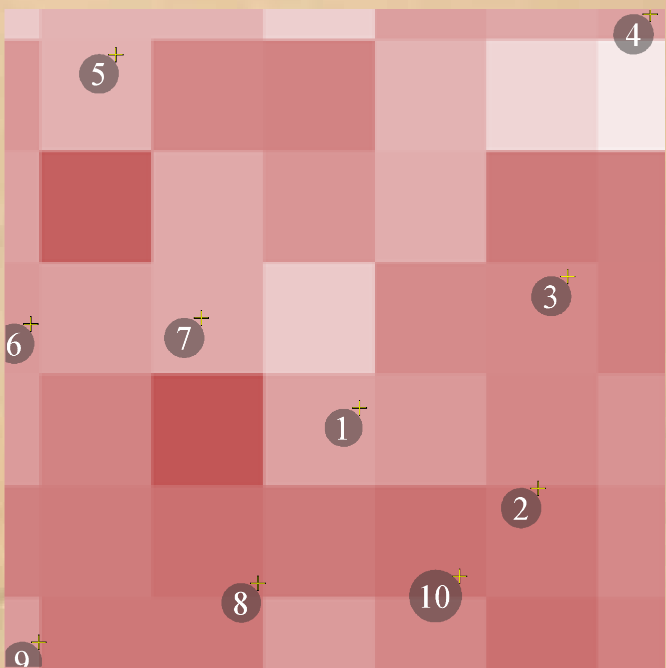
On this and the facing page, we examine NDVI and EVI dynamics and trends in the Zinder region in Niger (red box in map at top of page). This area is part of the more densely populated regions of Niger, which have been reported to have experienced large-scale re-greening beginning in the mid-1980s. As for most of the Sahel, rainfall has been increasing in this area after the mid 1980s (below), although it is still significantly lower than during the wetter periods in the mid-1940s, 1950s and early 1960s.

Trends in NDVI range from neutral (~0) to weakly positive (~0.08), which translates into an average increase in NDVI of upto 8% for the area. On average (graph at top of page), there is a recovery in vegetation cover after the drought culminating in 1984 and 1985, until 1994-95, after which there is no trend in our data until about 2003, when the trend has been towards lower vegetation cover.

Trend estimates for the area based on rNDVI, on the other hand, indicate a relatively strong browning, which is consistent across the area shown here (map inset on facing page). This shows a lack of vegetation response to increased rainfall in the area, probably due to land degradation.

Randomly selecting 10 points, we examine MODIS EVI trends for this area. As is evident from the plots on the right, trends are highly variable, with points 1, 2, 5, 7 and 9 in the maps on the opposite page showing reductions in vegetation cover after 2000, while points 3, 4, 6, 8 and 10 show increases in EVI. Point 2 shows a strong (consistent) negative trend.

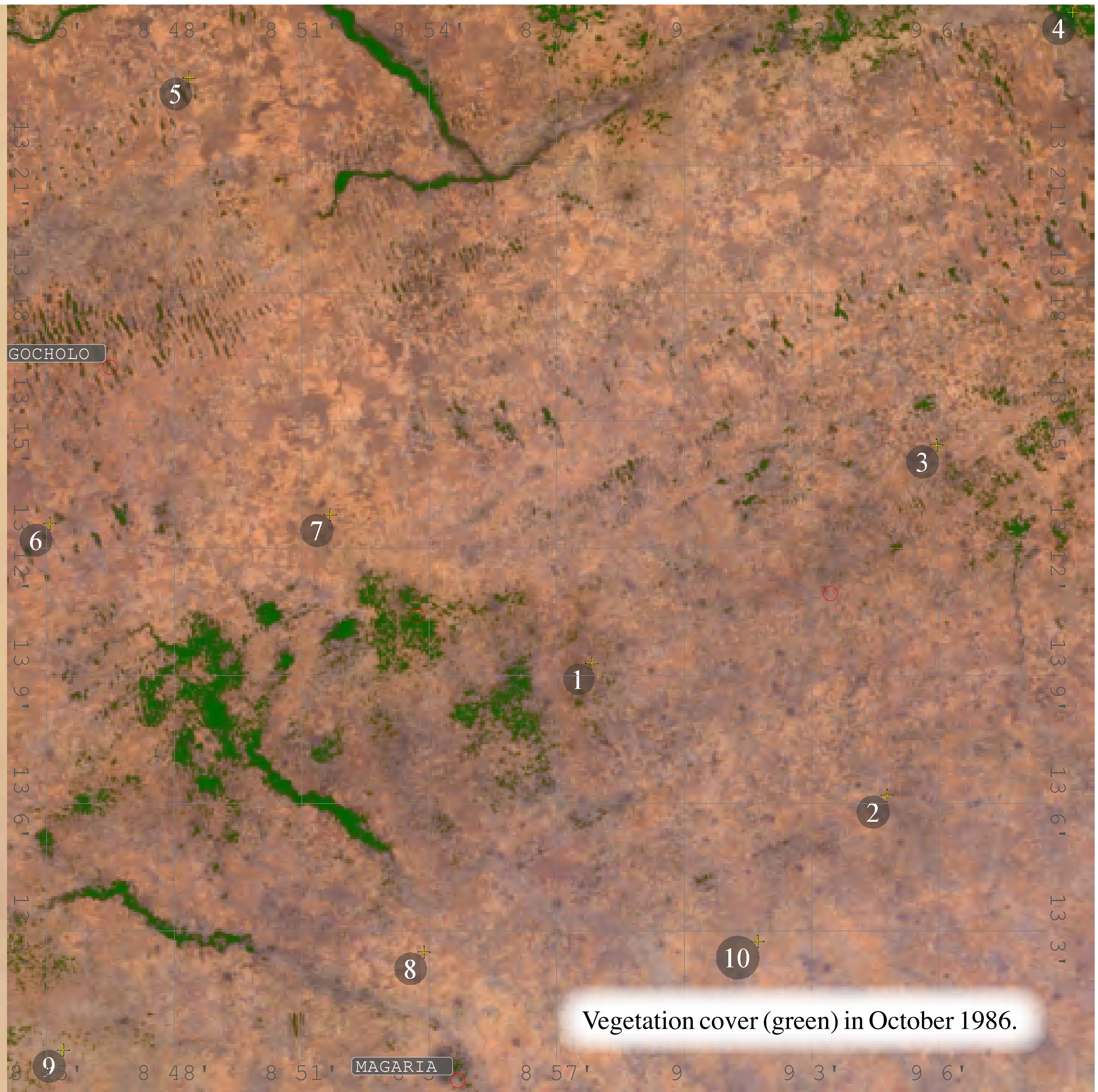




Maps inset above;

Top; Trends in rNDVI (red indicates decreases in vegetation cover relative to rainfall).

Bottom; Trends in MODIS EVI (2000 to 2006). Each AVHRR pixel corresponds to about 1,000 MODIS pixels.



Vegetation cover (green) in October 1986.

Vegetation cover (green) in October 2000

Vegetation dynamics in Gao district, Mali

In our analysis of vegetation trends based on rNDVI between 1982 and 2006, significant areas along the Mali/Burkina Faso border show increasing vegetation cover (map below). One such area is in Gao district, Mali. The Landsat images (facing page) selected for this analysis are both from the dry season in the region and date from January 1987 and November 1999, respectively. We calculated a soil (background) adjusted vegetation index based on reflectance calibrated imagery. The vegetation index is given by;

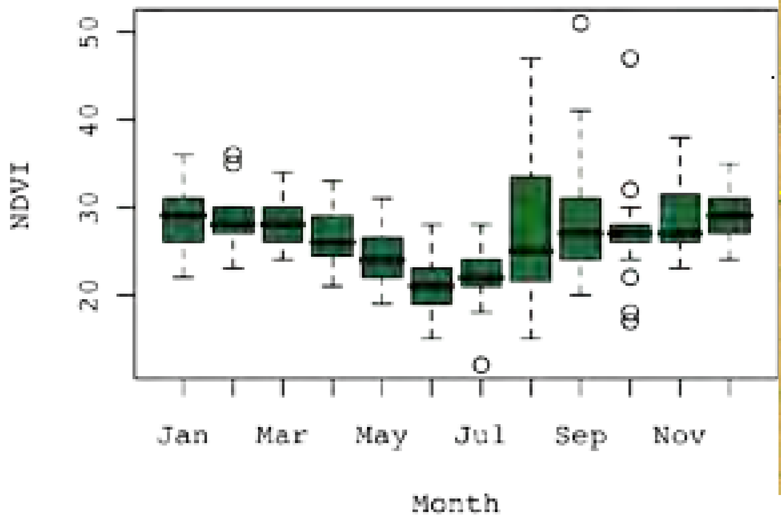
$$SAVI = (NIR-R)(1+L) / (NIR+R+L)$$

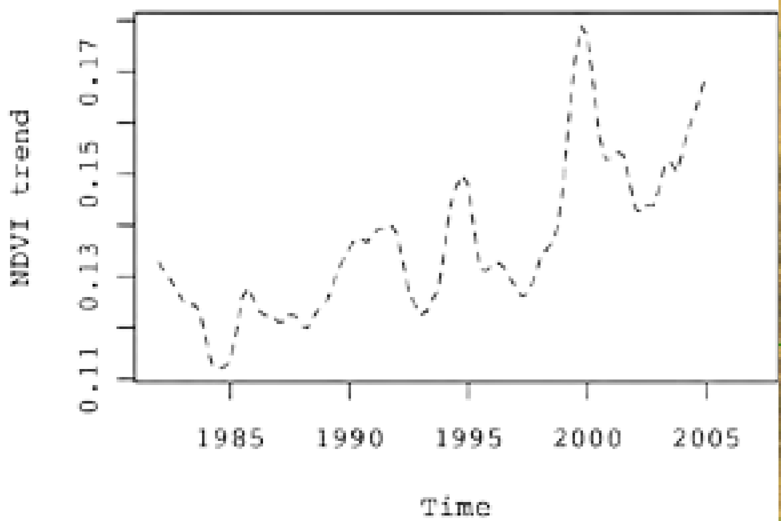
where L is a soil brightness correction factor, while NIR and R represent reflectance from the near-infrared and red bands.

Since the Landsat scenes represent discrete "snapshots" of vegetation cover, they should be interpreted with care. This is particularly the case when changes are subtle and not the result of major land cover/use conversions, as seasonal- and inter-annual variability in vegetation cover may be large.

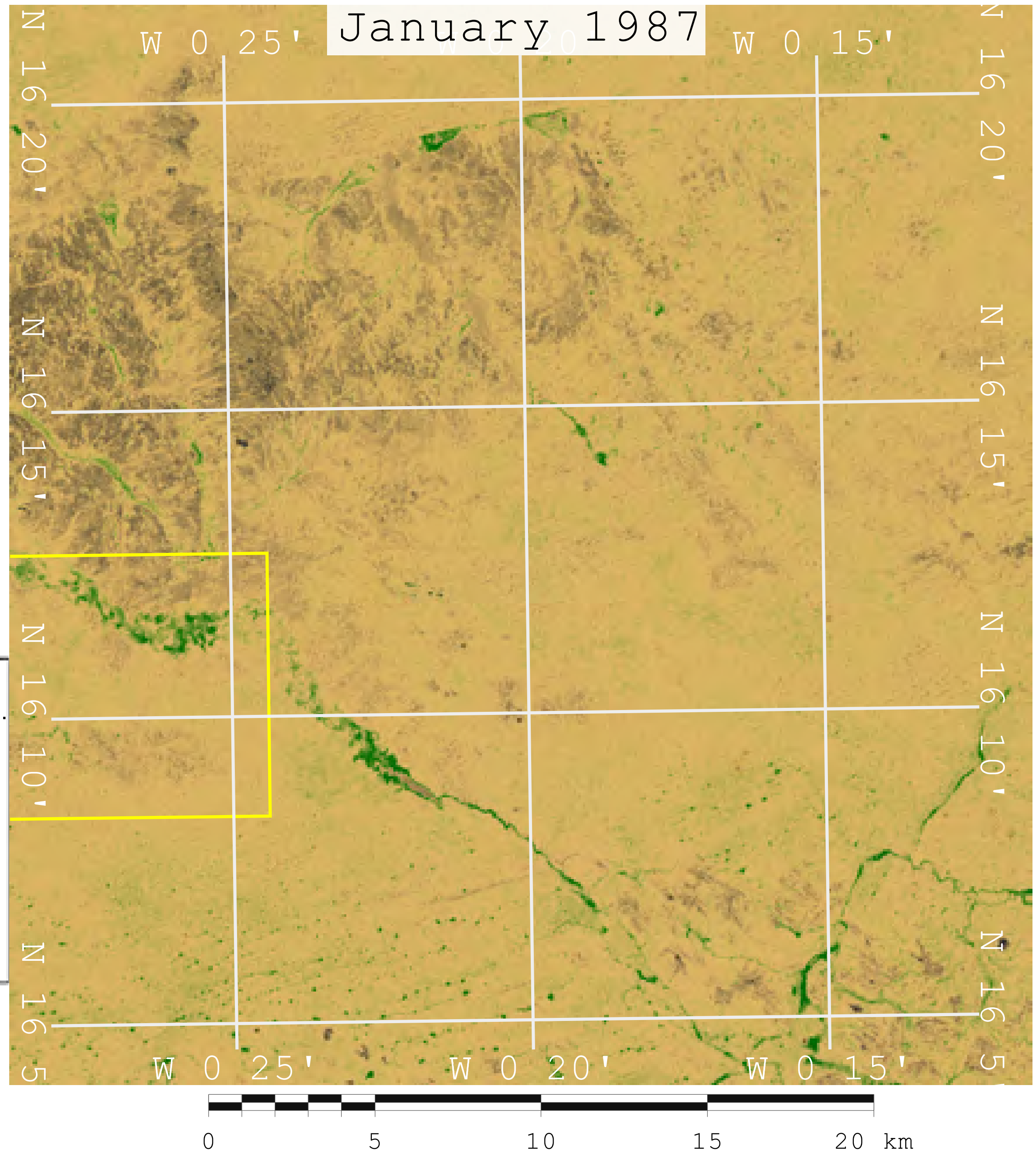
As we have seen in earlier examples, we combine information from low- and moderate resolution satellite imagery in identifying potential land degradation hotspots. In order to understand the dynamics of ecosystem changes on the ground, more detailed assessments must be made. The next section of this atlas shows examples of such detailed assessments for the Segou region in Mali.

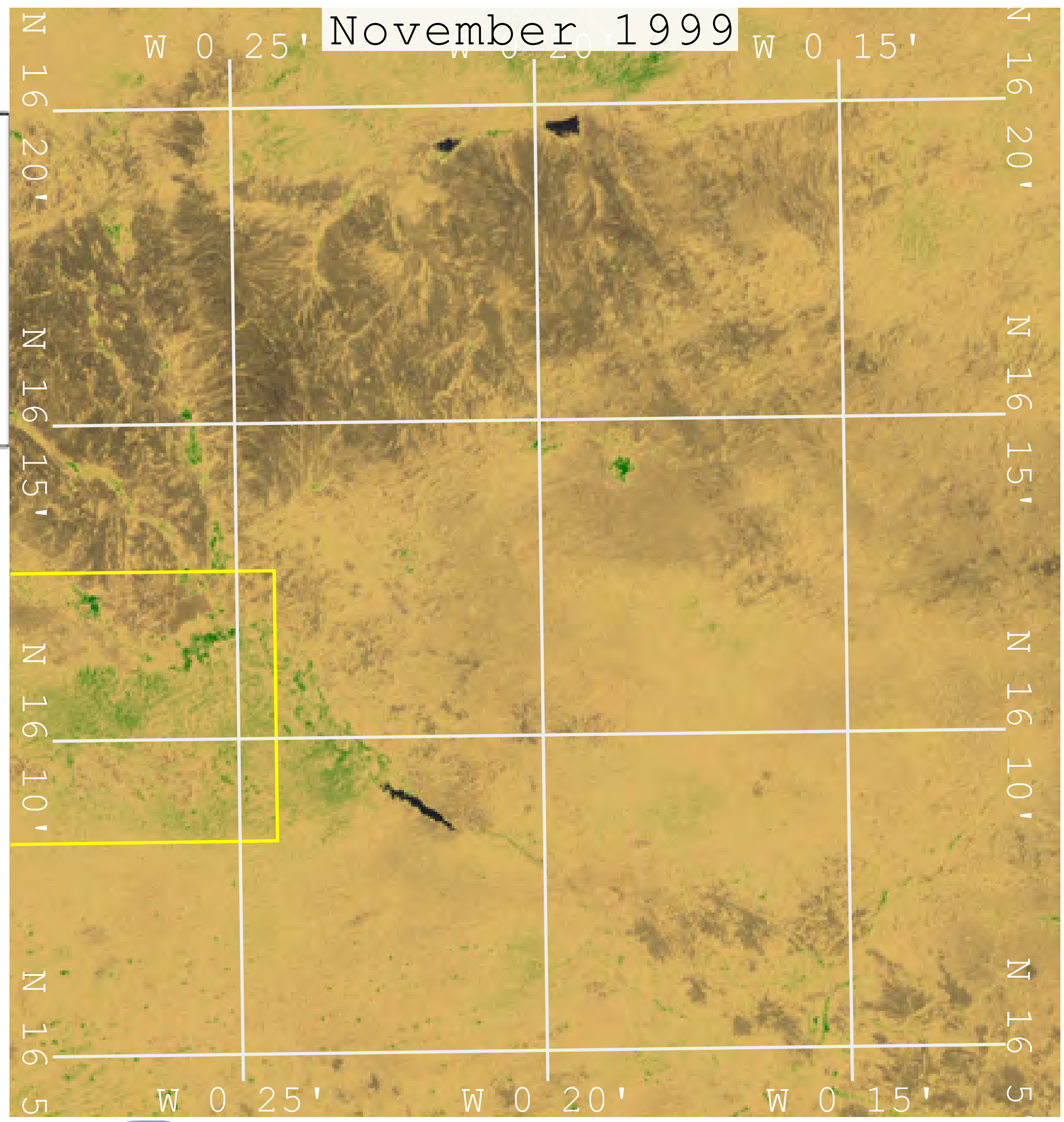
The Gao region (yellow box in map on the right) is very dry with mean annual precipitation below 300 mm. This can be clearly seen from the seasonal dynamics in vegetation cover (NDVI) as shown in the boxplot below. The vegetation signal is on average relatively "flat" across the year, with a peak in September and with extreme variability in the rainy season (August and September) due to high levels of variability in rainfall.





The NDVI trend in the yellow box on the right shows a strong overall increase in vegetation cover after 1984 (trend plot above), peaking in 1999. This increase is also evident in the Landsat soil background adjusted vegetation indices (SAVI) on this page, and is most probably due to increases in woody cover.



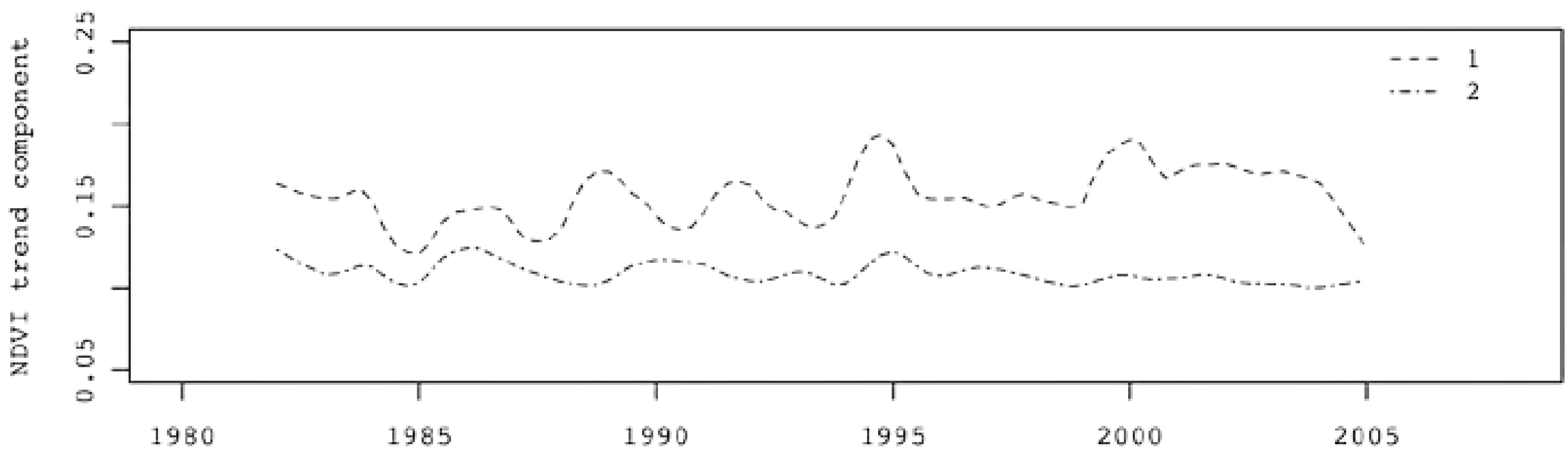


Further south-west in Gao district, near Lake Gossi, and the towns of Gossi and Borenta, rNDVI trends range from neutral to negative between 1982 and 2006. A closer examination for two areas in this region (black and red boxes in map on facing page) shows how vegetation dynamics may vary significantly over relatively small areas.

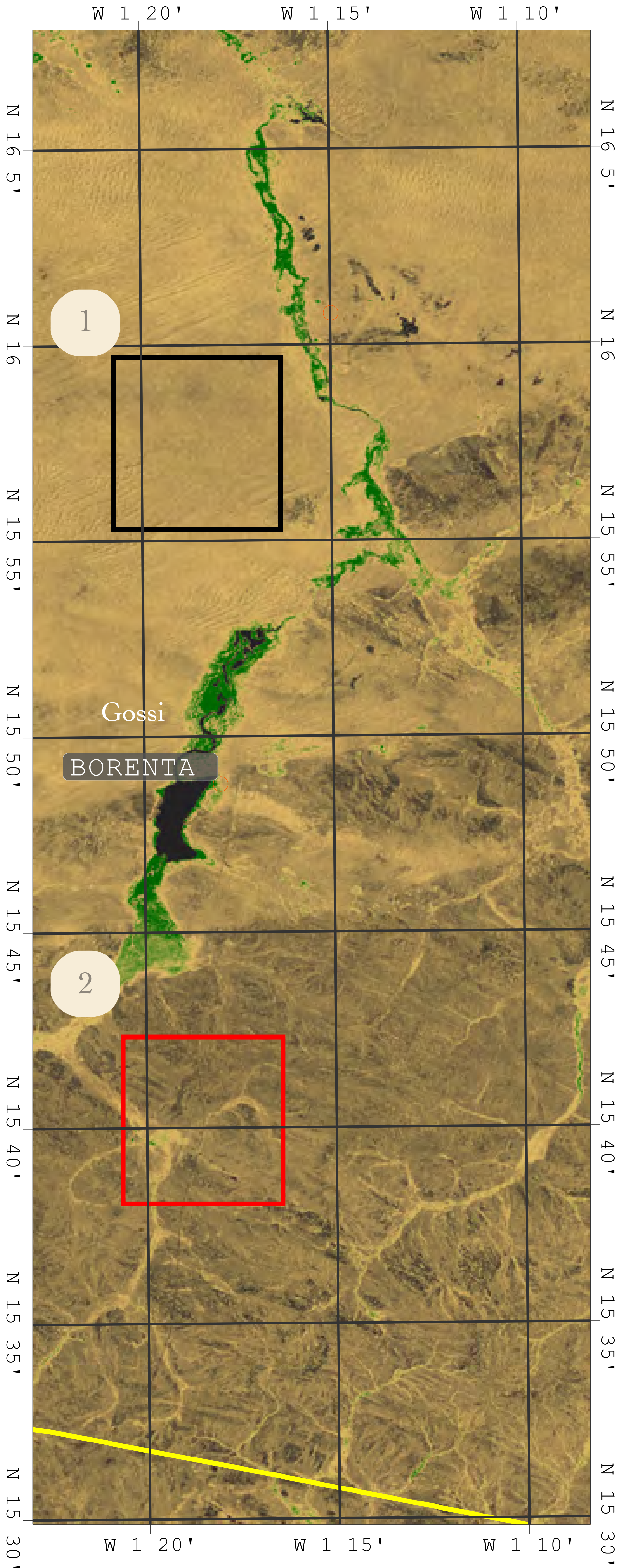
In area 1 (black box), the linear trend in rNDVI is negligible due to a sharp decrease after 1999. Between 1984 and 1999, however, (Landsat image pair) there was an increase in vegetation cover, as shown in the plot at the foot of this page. The vegetation in this area has a banded pattern (tiger bush), and it appears, from the Landsat SAVI images shown on the facing page, as if vegetation cover increases in these bands (arcs) account for the positive trend observed between 1984 and 1999.

In area 2 (red box), the trend is towards decreasing vegetation cover (on average), with lower inter-annual variations in vegetation cover after 1999 than in previous years. This area is virtually bare, as seen from the trend component in the below graph (2), and overall the trend is therefore negligible.

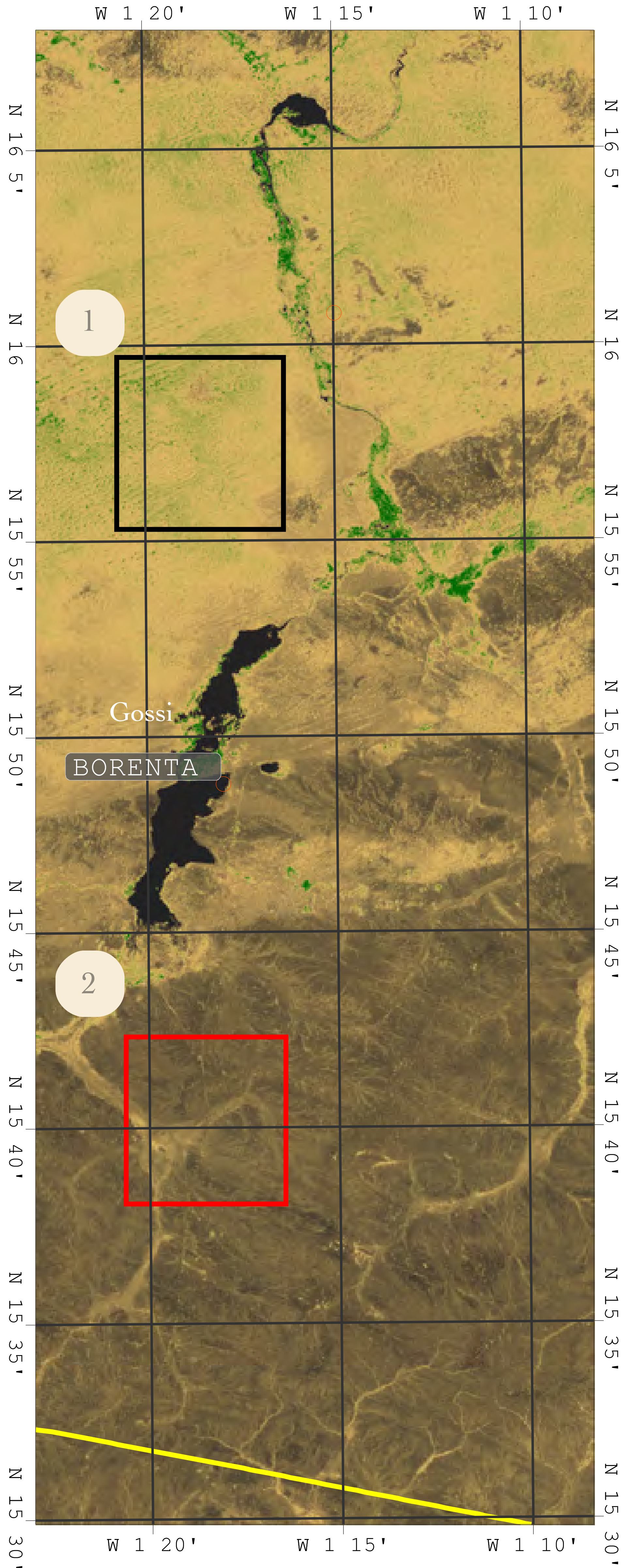
There is little evidence of agriculture in the Landsat scenes for this area. Water surfaces appear as dark. As can be seen from the Landsat image pair, Lake Gossi had a greater extent in 1999 than in 1987.

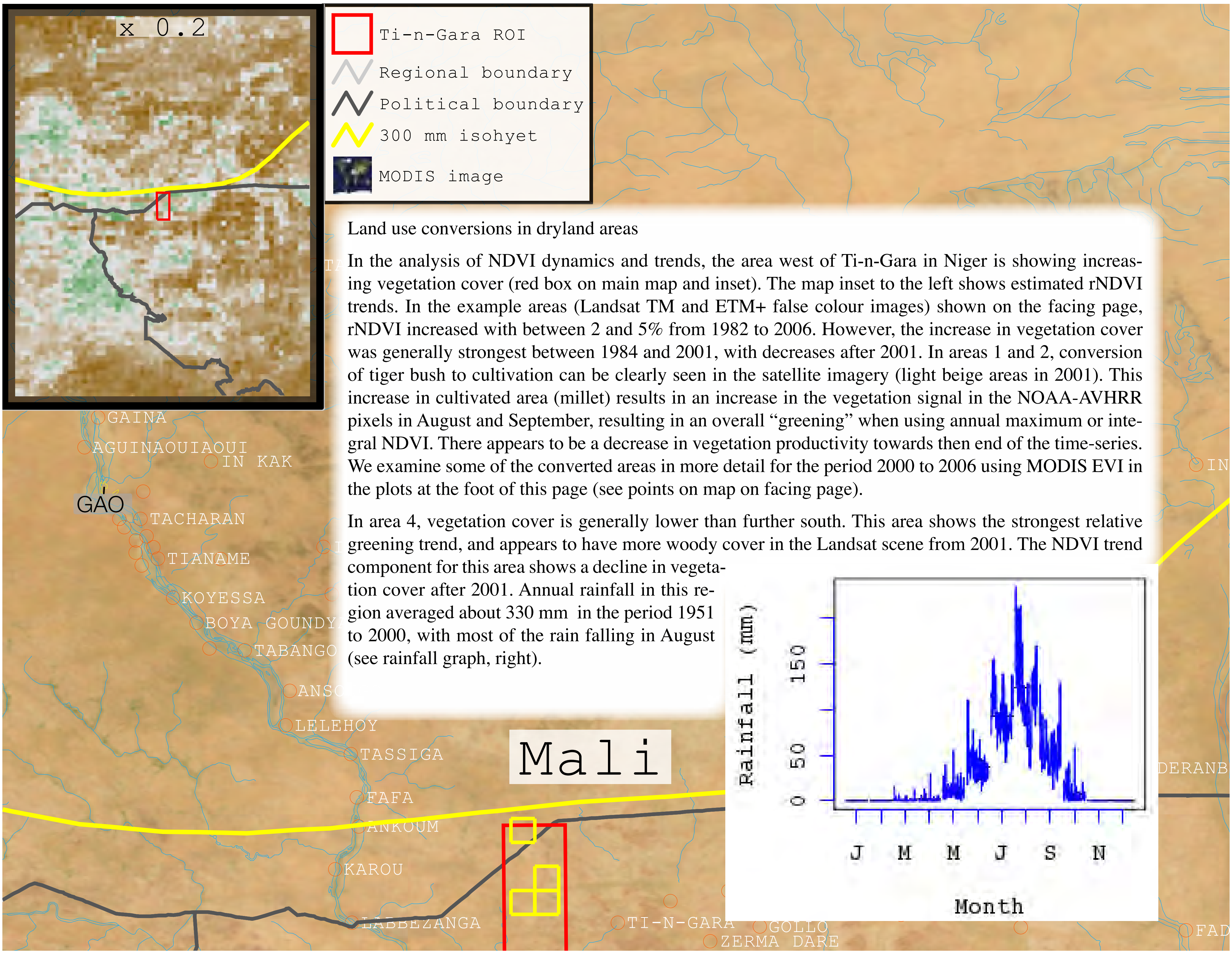


January 1987



November 1999

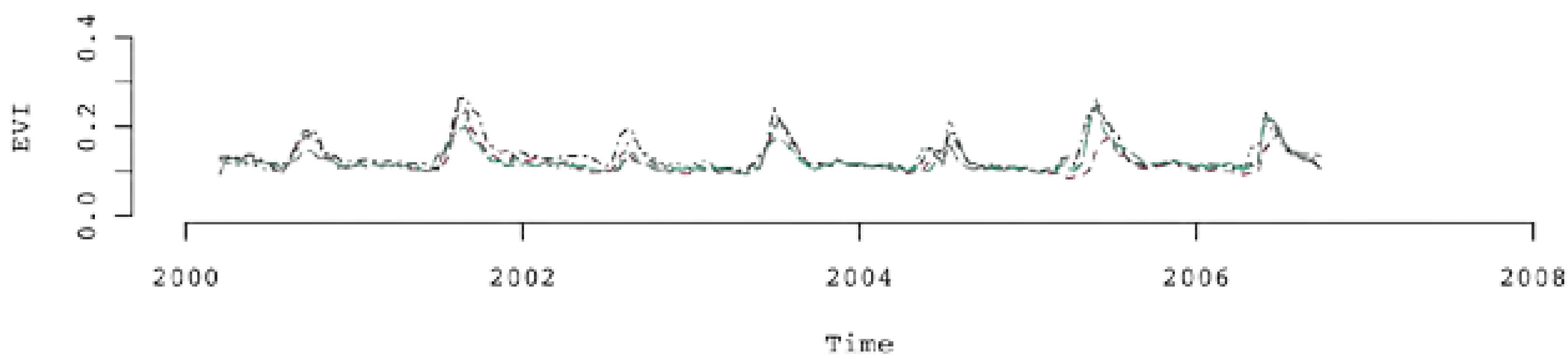


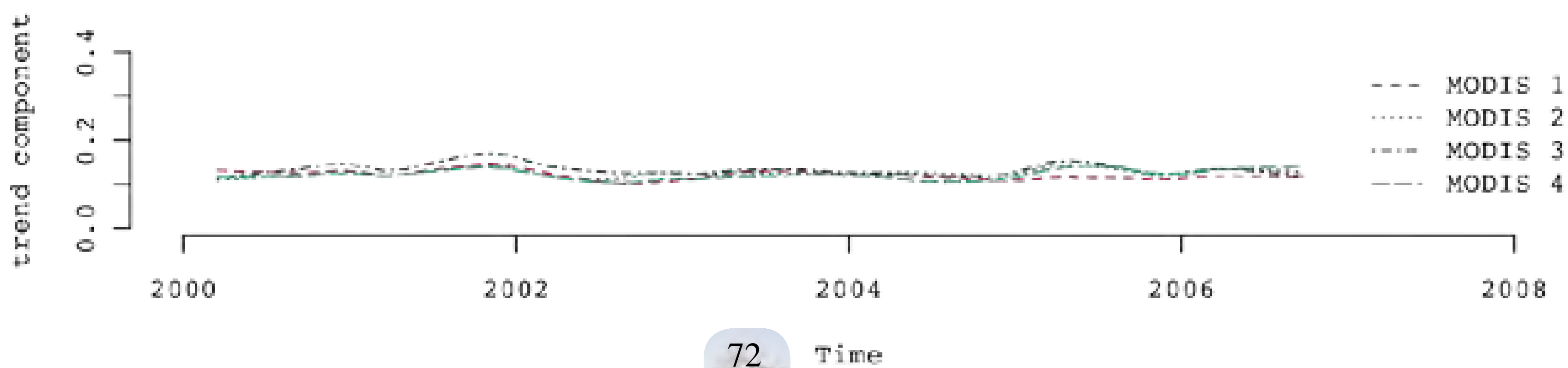


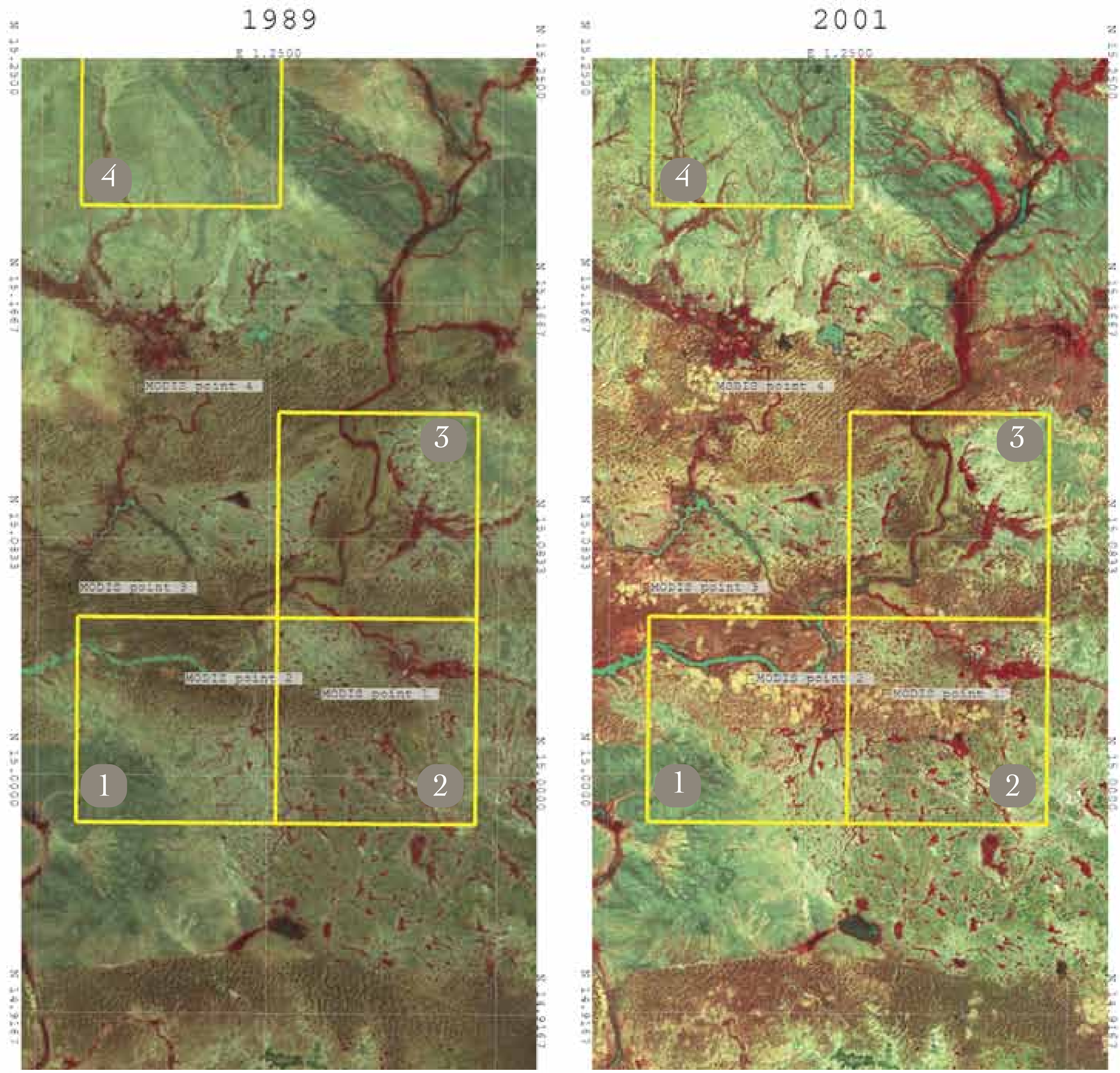
Land use conversions in dryland areas

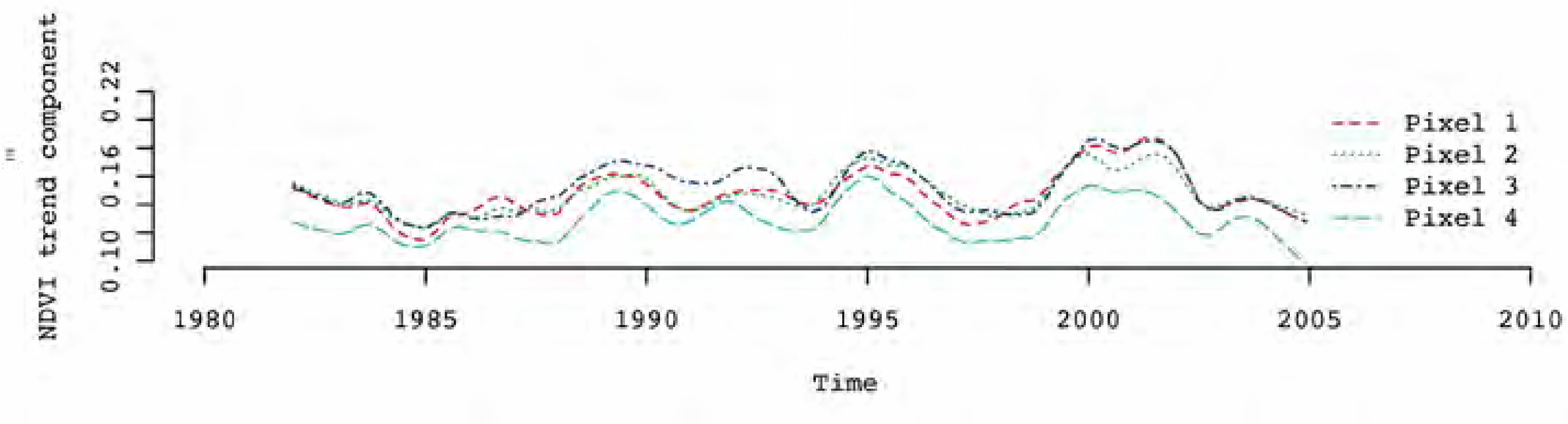
In the analysis of NDVI dynamics and trends, the area west of Ti-n-Gara in Niger is showing increasing vegetation cover (red box on main map and inset). The map inset to the left shows estimated rNDVI trends. In the example areas (Landsat TM and ETM+ false colour images) shown on the facing page, rNDVI increased with between 2 and 5% from 1982 to 2006. However, the increase in vegetation cover was generally strongest between 1984 and 2001, with decreases after 2001. In areas 1 and 2, conversion of tiger bush to cultivation can be clearly seen in the satellite imagery (light beige areas in 2001). This increase in cultivated area (millet) results in an increase in the vegetation signal in the NOAA-AVHRR pixels in August and September, resulting in an overall "greening" when using annual maximum or integral NDVI. There appears to be a decrease in vegetation productivity towards then end of the time-series. We examine some of the converted areas in more detail for the period 2000 to 2006 using MODIS EVI in the plots at the foot of this page (see points on map on facing page).

In area 4, vegetation cover is generally lower than further south. This area shows the strongest relative greening trend, and appears to have more woody cover in the Landsat scene from 2001. The NDVI trend component for this area shows a decline in vegetation cover after 2001. Annual rainfall in this region averaged about 330 mm in the period 1951 to 2000, with most of the rain falling in August (see rainfall graph, right).





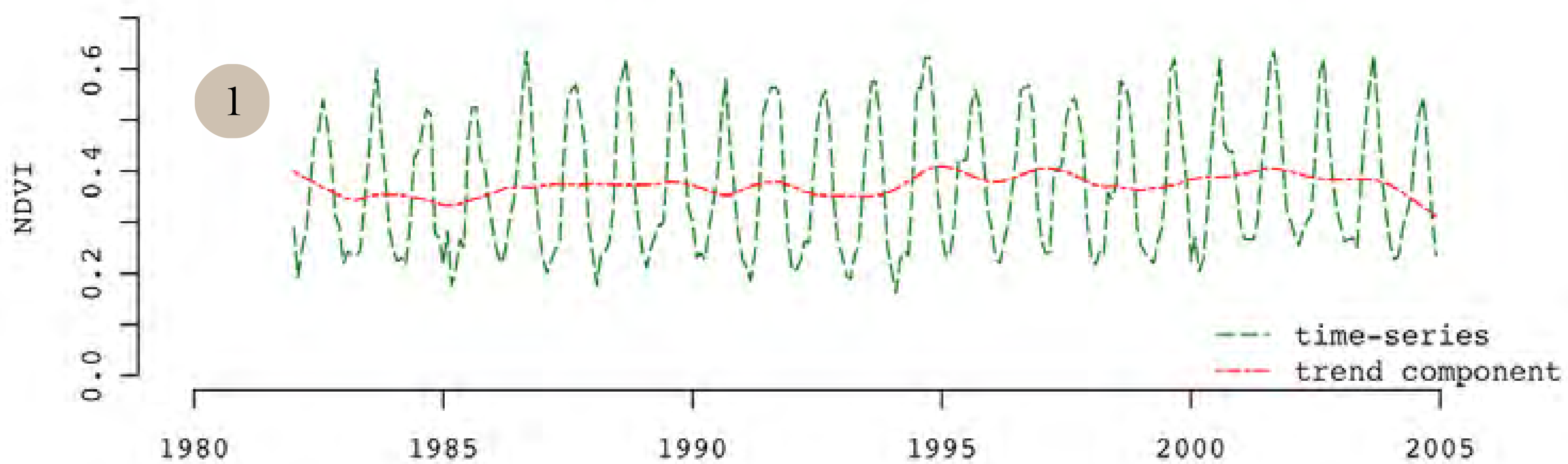

1989
2001
4
3
2
1
MODIS point 4
MODIS point 3
MODIS point 2
MODIS point 1


NDVI trend component
0.10 0.16 0.22
1980
1985
1990
1995
2000
2005
2010
Time
Pixel 1
Pixel 2
Pixel 3
Pixel 4


1986
KALANBOULI
BOROMO
FARA
TONE
1
W 3 5'
W 3
W 2 55'
W 2 50'
W 2 45'
N 11 40'
N 11 30'
N 11 25'
Burkina Faso
900 mm
0
5
10
15
20 km

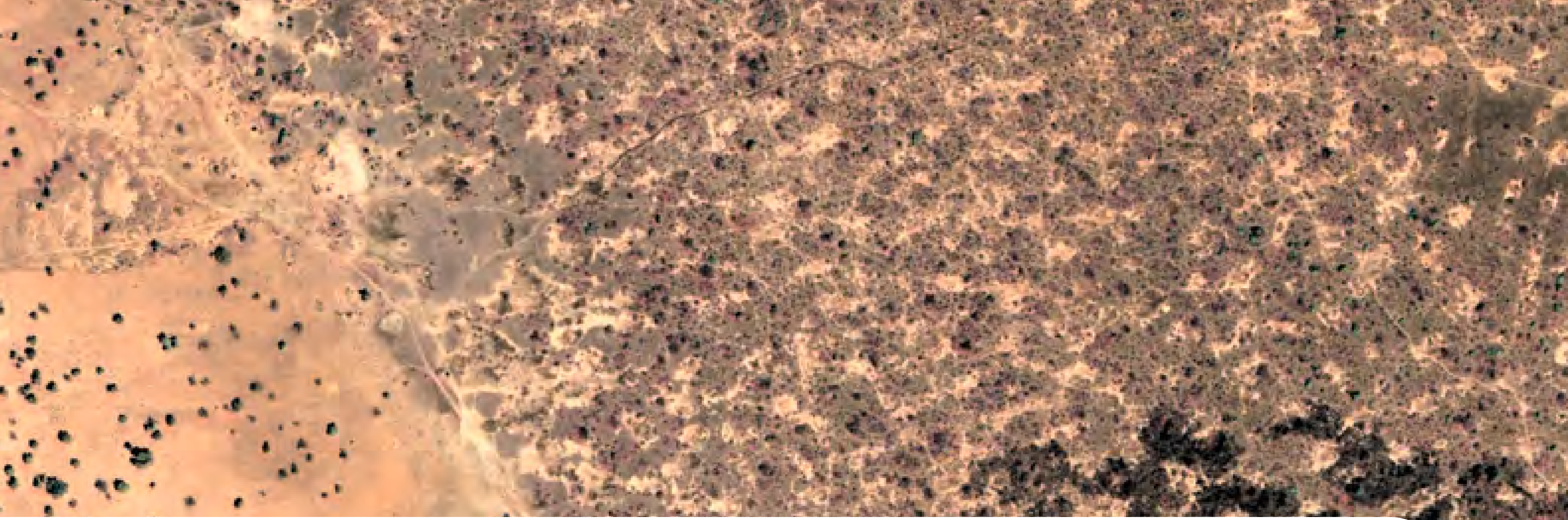
Land cover change – Boromo, Burkina Faso

The area presented on this and the facing page has an annual precipitation of about 900 mm (see map inset on facing page). The images shown here are soil background calibrated vegetation indices based on Landsat TM and ETM+ images from October 1986 and October 1999, respectively. As we see from the Landsat image pair, we have quite significant decreases in vegetation cover (conversions) between 1986 and 1999 (arrows on maps). The trends in rNDVI are negative, but negligible, and do not pick up the changes in vegetation cover observed in the Landsat imagery (see graph below for area at arrow 1).



Land degradation surveillance

Quickbird image from Segou region, Mali. The image was taken in February 2006.



As we have seen in several of our previous examples of potential land degradation hotspots, reliably determining the direction and extent of land cover change is often difficult due to the complexity of the processes involved.

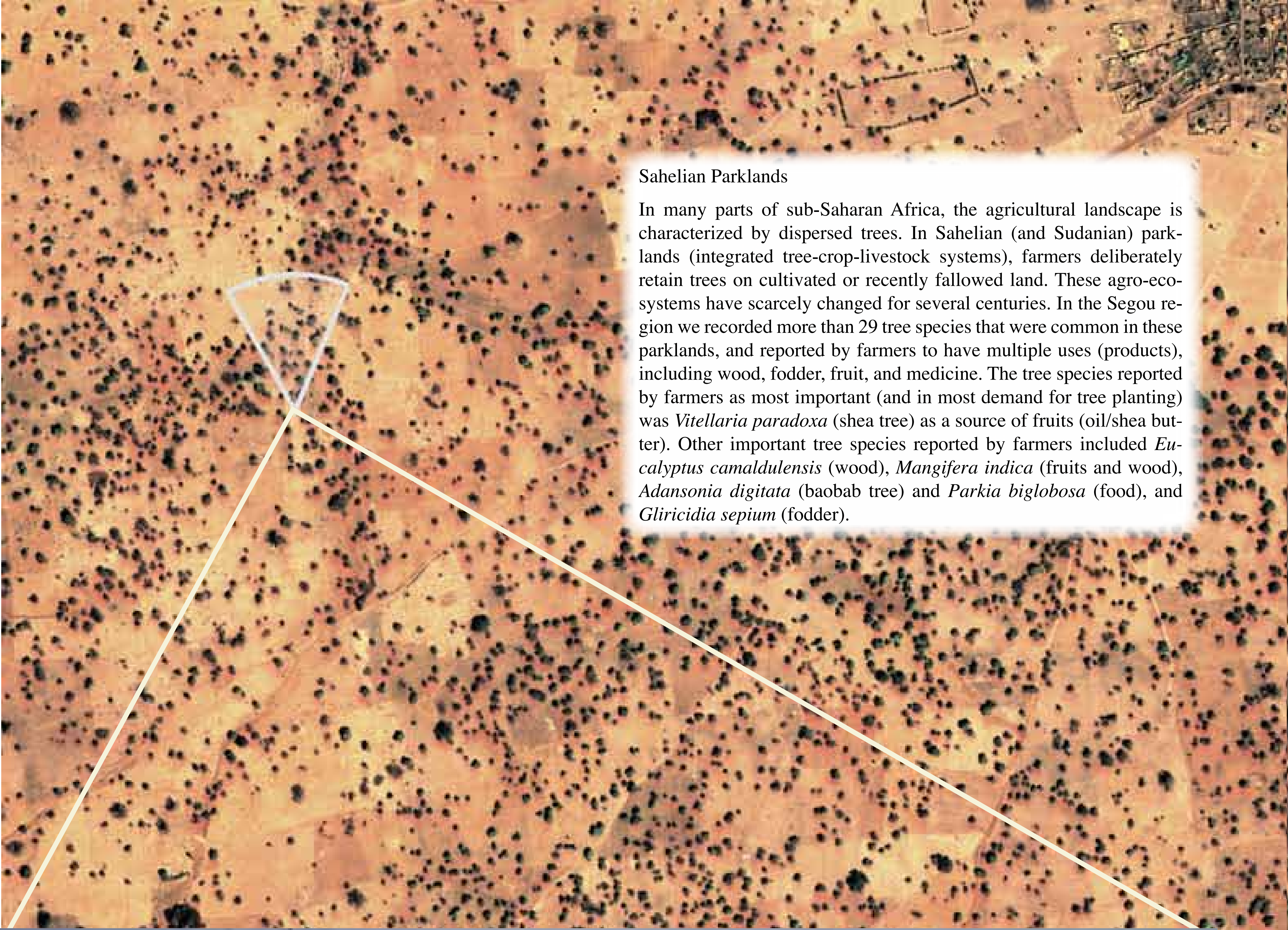
Also, reliable information about the state of soils, vegetation and other local conditions are often lacking, making impact attribution and monitoring of progress difficult. In the current section we focus in much more detail on one part of the Sahel, the Segou region in Mali, where our study focused on the degradation (and restoration) of West African Parklands.

This study was conducted using a framework for land degradation surveillance developed by a team of scientists from the World Agroforestry Centre. The project[1] was a joint effort between UNEP and the World Agroforestry Centre, where five "sentinel sites" were established in the Segou region. Baselines were established in Konobougou, Dianvola, Monimpebougou, Zebougou and Sokoura (see map below) to provide a starting point for reliable change detection and project impact attribution related to afforestation activities, agroforestry interventions in cultivated areas and/or improved soil fertility management.

The baselines should synthesize a quantitative description of the project situation along the ecological and socioeconomic dimensions that are relevant for project implementation. In this context, flexible strategies for selecting priority intervention areas and households at the landscape/population scale are proposed.

Another aim is to lay a foundation for change detection that considers spatial variability explicitly. In the current section we show a selection of results from these sentinel sites, including high resolution assessments of vegetation cover and soil condition.

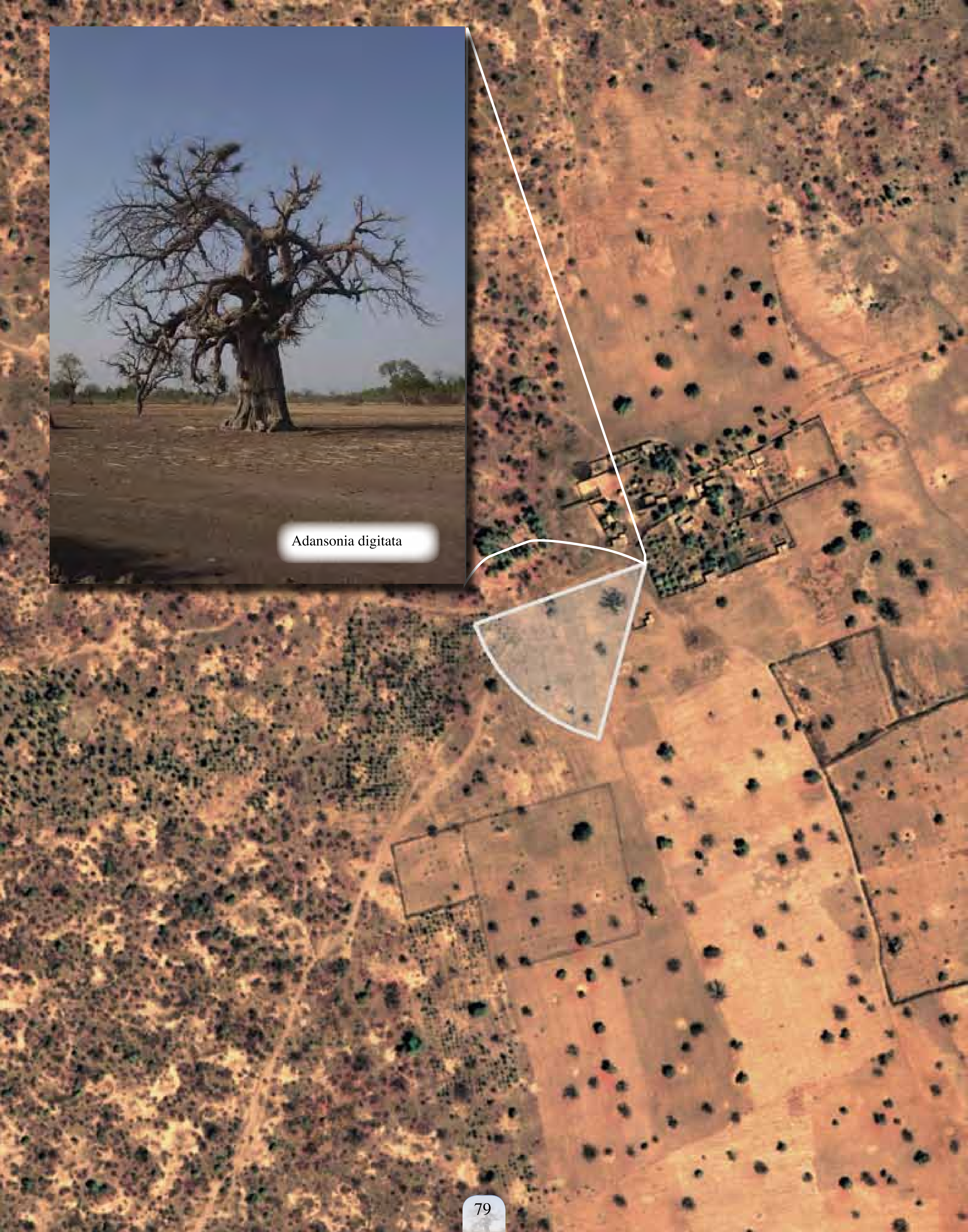
[1] An Ecosystem Approach to Restoring West African Drylands and Improving Rural Livelihoods through Agroforestry-based Land Management Interventions."



Sahelian Parklands

In many parts of sub-Saharan Africa, the agricultural landscape is characterized by dispersed trees. In Sahelian (and Sudanian) parklands (integrated tree-crop-livestock systems), farmers deliberately retain trees on cultivated or recently fallowed land. These agro-ecosystems have scarcely changed for several centuries. In the Segou region we recorded more than 29 tree species that were common in these parklands, and reported by farmers to have multiple uses (products), including wood, fodder, fruit, and medicine. The tree species reported by farmers as most important (and in most demand for tree planting) was *Vitellaria paradoxa* (shea tree) as a source of fruits (oil/shea butter). Other important tree species reported by farmers included *Eucalyptus camaldulensis* (wood), *Mangifera indica* (fruits and wood), *Adansonia digitata* (baobab tree) and *Parkia biglobosa* (food), and *Gliricidia sepium* (fodder).

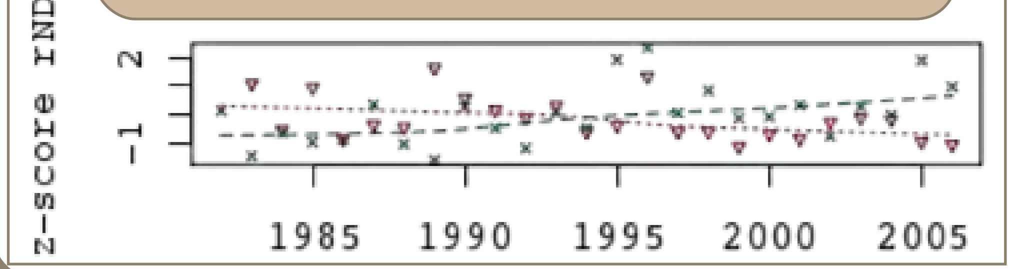
Parkland in Zebougou.

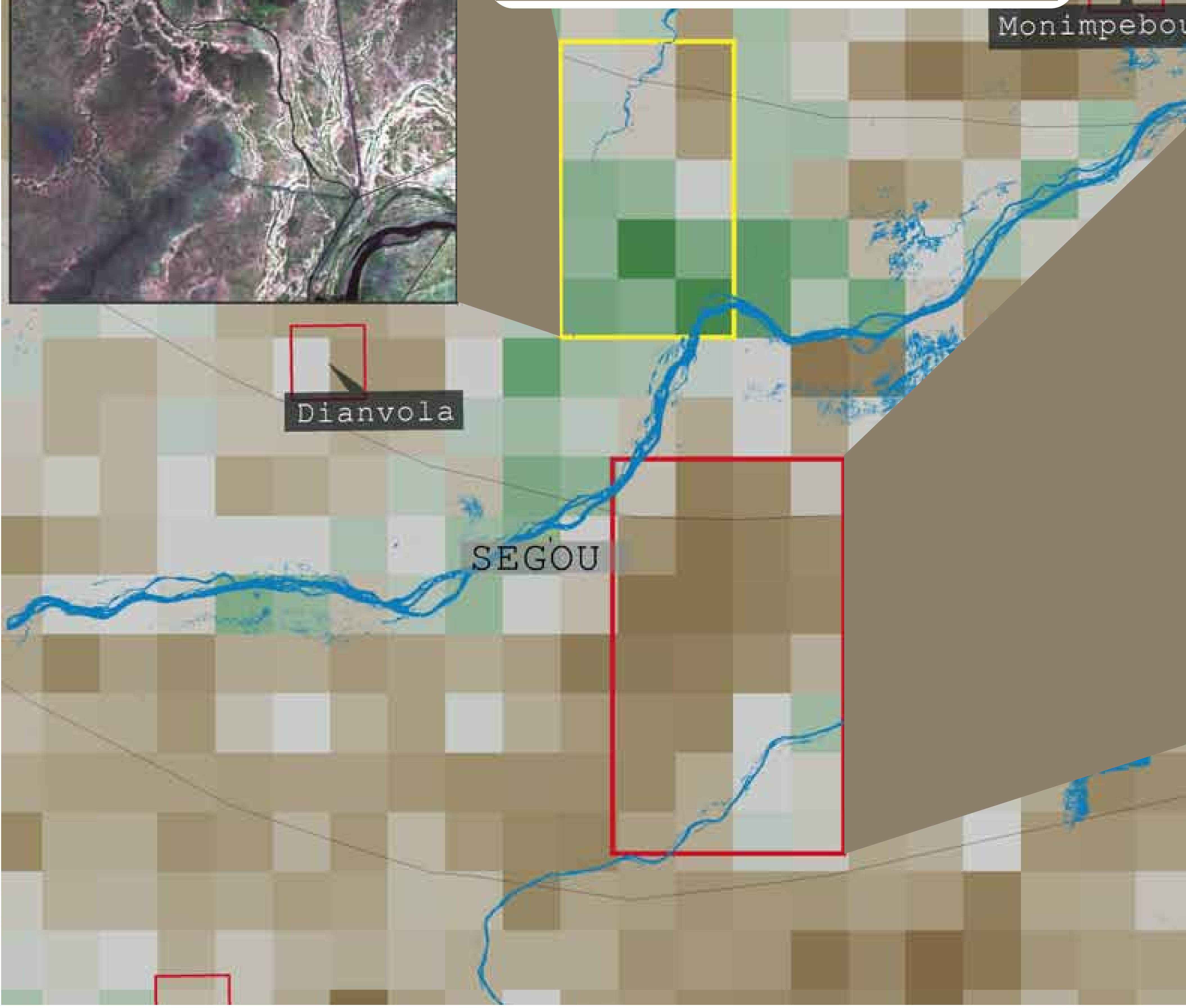

Adansonia digitata

Vegetation cover trends in Segou region

Most of the Segou region displays negative trends in rNDVI between 1982 and 2006, although some areas are greening up in the same period. In some of the areas showing a green-up, this appears mainly along irrigation canals (below and left). Several of the irrigated areas display negative trends in vegetation cover, but this is largely due to image artifacts caused by water in flooded areas. The ASTER satellite image (January 2003) on the left shows an area in Segou displaying both these trend scenarios (yellow box on trend map).

rNDVI trends in area greening below (green, lower part of yellow box below) and in area browning-down, east of Segou town (red dots, large area outlined in red below).

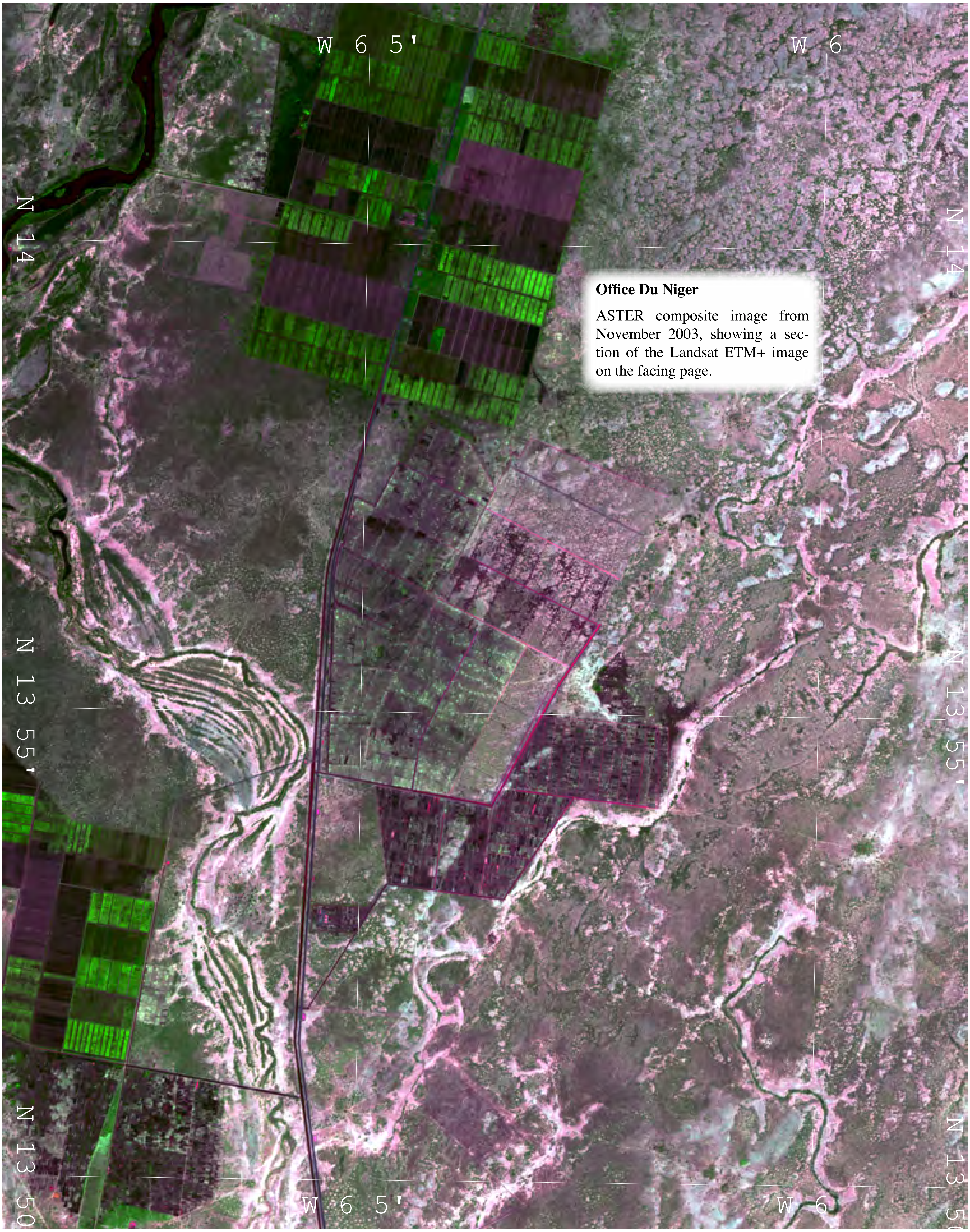




The area east of Segou town generally shows a browning-down trend. Significant parts of this area consist of laterite plateaus, which appear as red to purple in the ASTER colour composite on the right. These trends seem to be mainly the result of a lack of response in woody vegetation cover to increasing rainfall in the region as the trends in NDVI are mostly neutral.

Office Du Niger

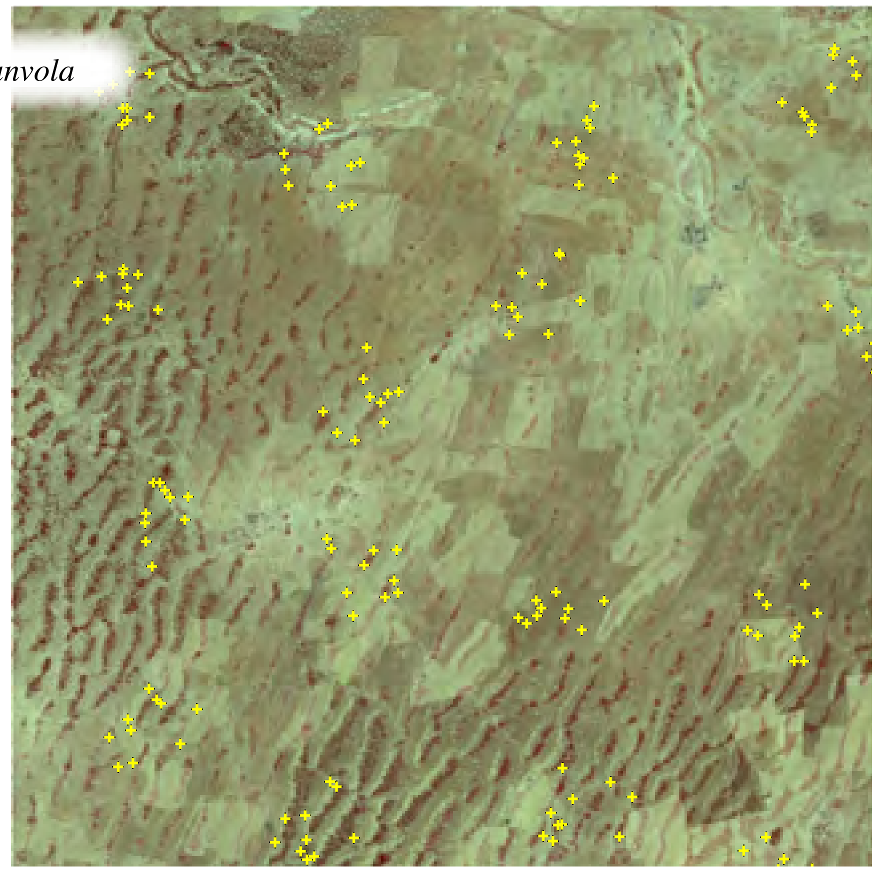
Large–scale irrigation schemes along one of River Niger's tributaries in Segou region, Mali. Background image is Landsat ETM+ true-colour composite from October 2001.



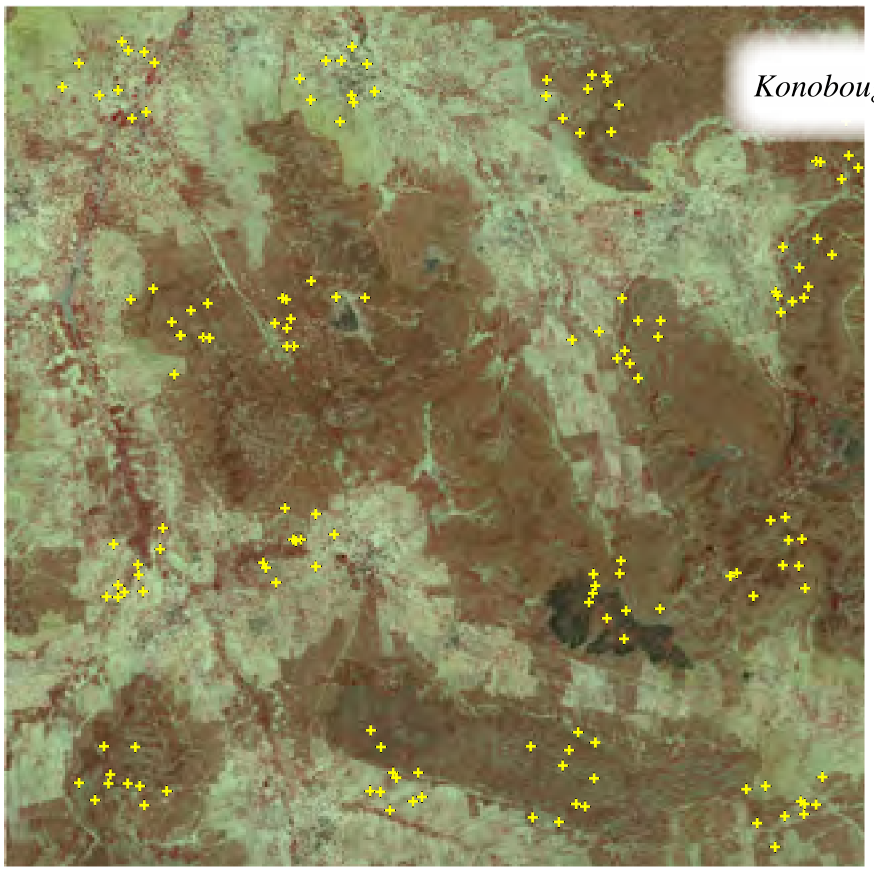
Office Du Niger

ASTER composite image from November 2003, showing a section of the Landsat ETM+ image on the facing page.

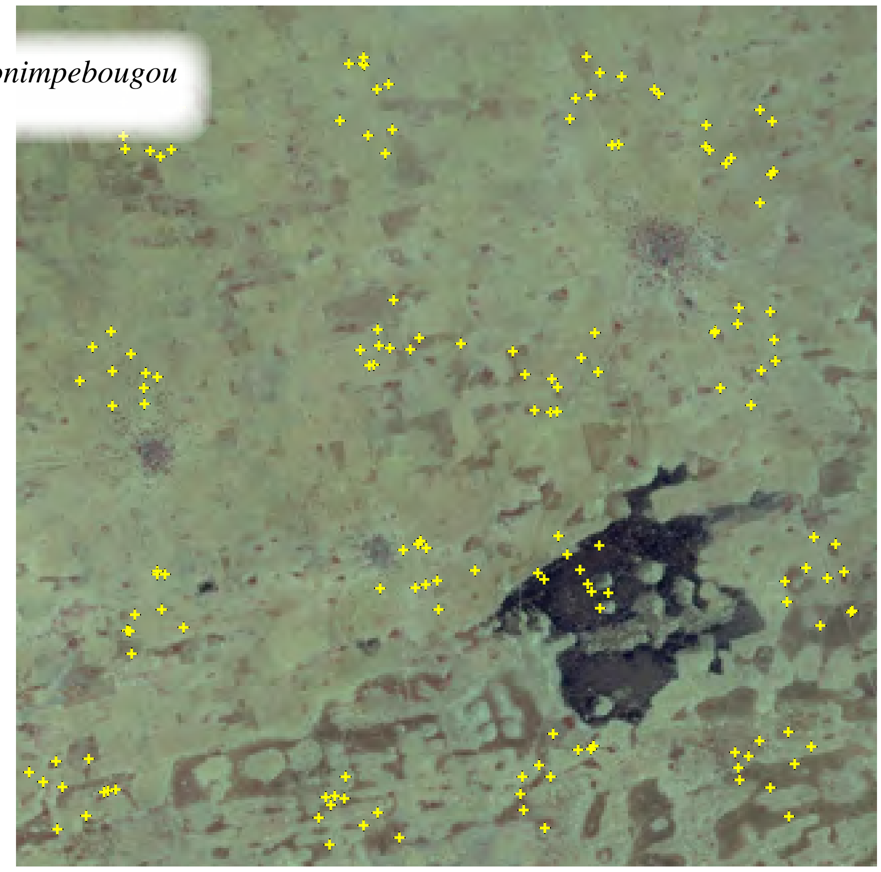
Village on the River Niger.
(Segou region, Mali)



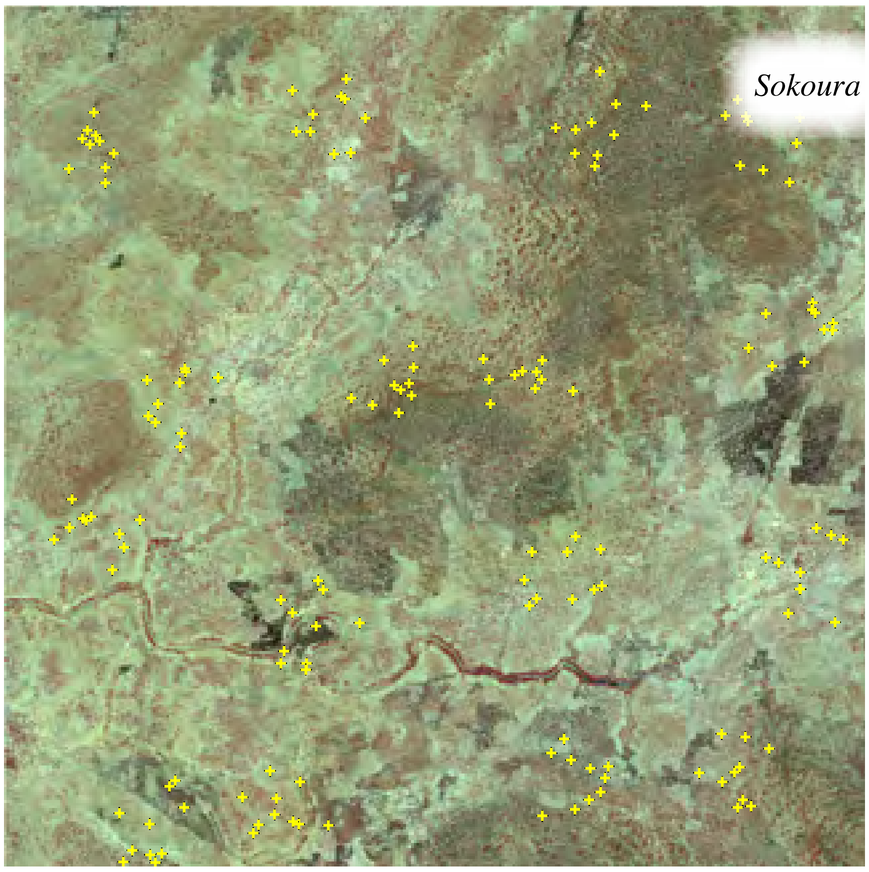
Dianvola



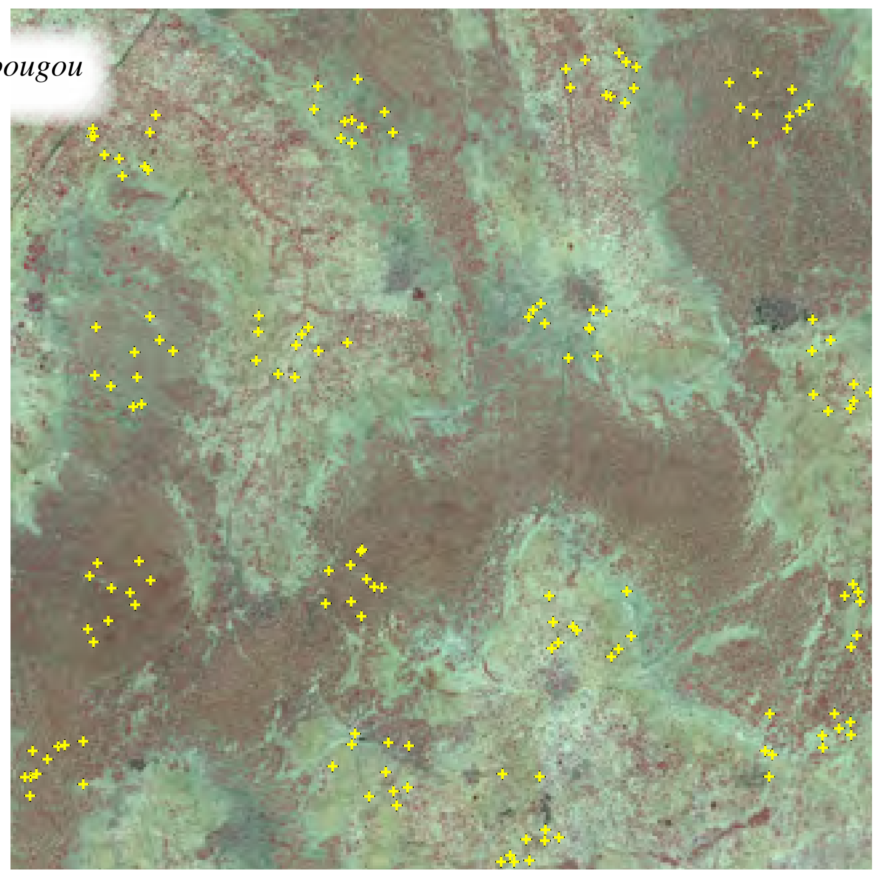
Konobougou



Monimpebougou



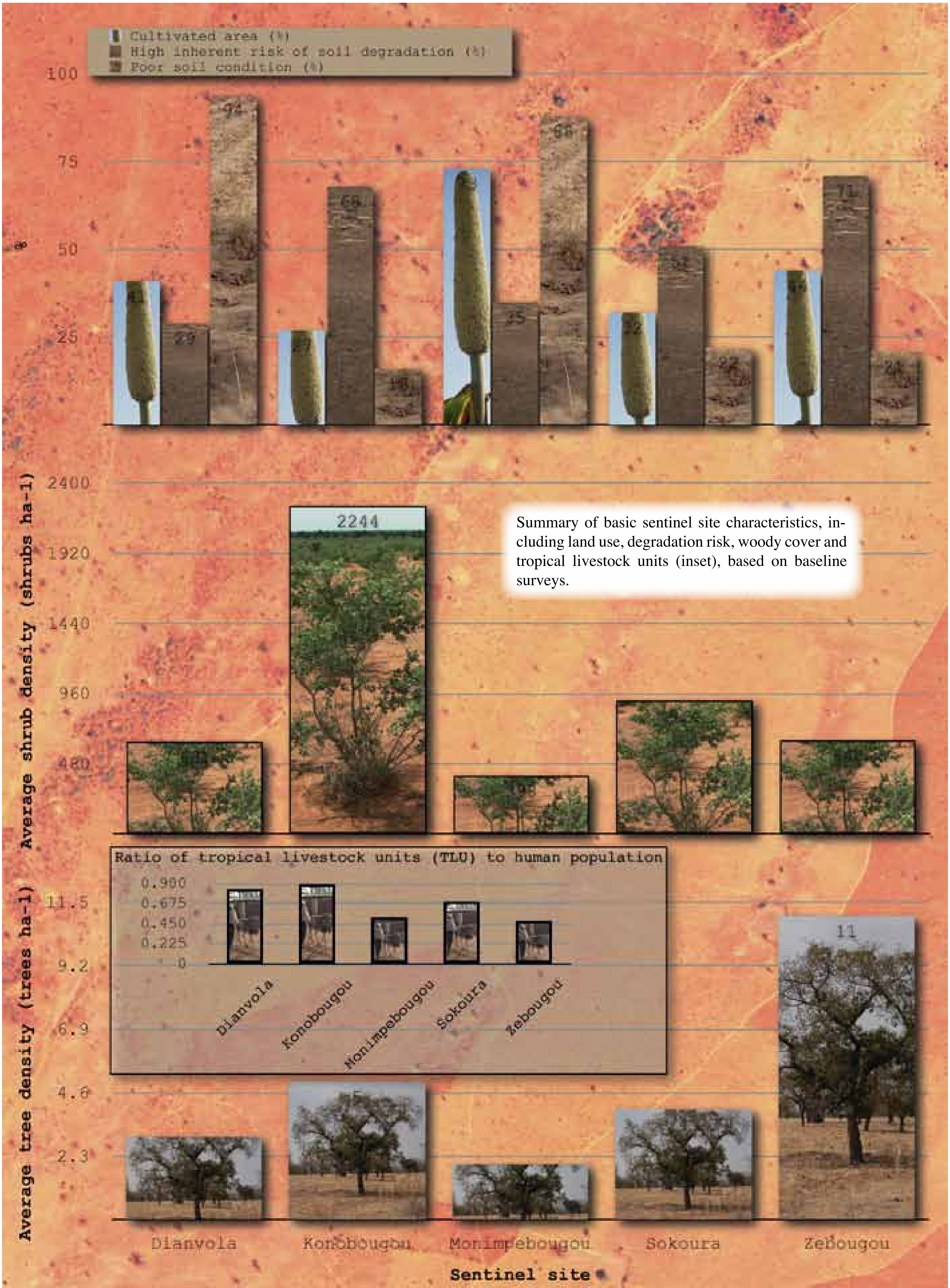
Sokoura



Zebougou

The approach to land degradation surveillance presented here is based on a spatially stratified, randomized sampling design. Sampling is conducted within sentinel sites, which are 10 by 10 km in size and consist of 16 sampling clusters. A cluster consists of 10 plots (yellow crosses on maps). One important rationale behind this approach is to avoid biases that may arise from convenience sampling (for example close to roads). Cluster and plot locations are always randomly selected, and in most cases, the locations of sentinel sites are also randomized.

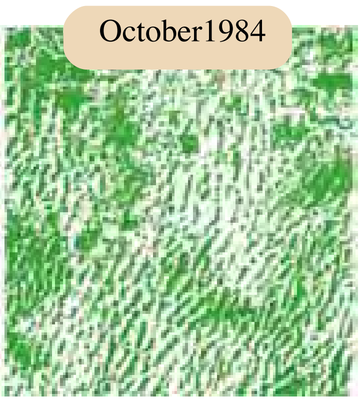
The randomized points are loaded into GPS-units and field teams navigate to the respective plots and conduct the sampling and characterization work. Georeferenced data on topography and landforms, land cover, land use history, main vegetation types, woody and herbaceous cover densities and distributions, visible signs of soil erosion and other degradation processes are entered into the baseline database. Soil samples are also collected and characterized in the laboratory using infrared spectroscopy. A smaller subset of samples is analysed using conventional chemical and physical analytical techniques.

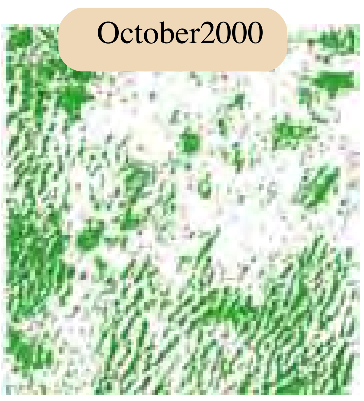


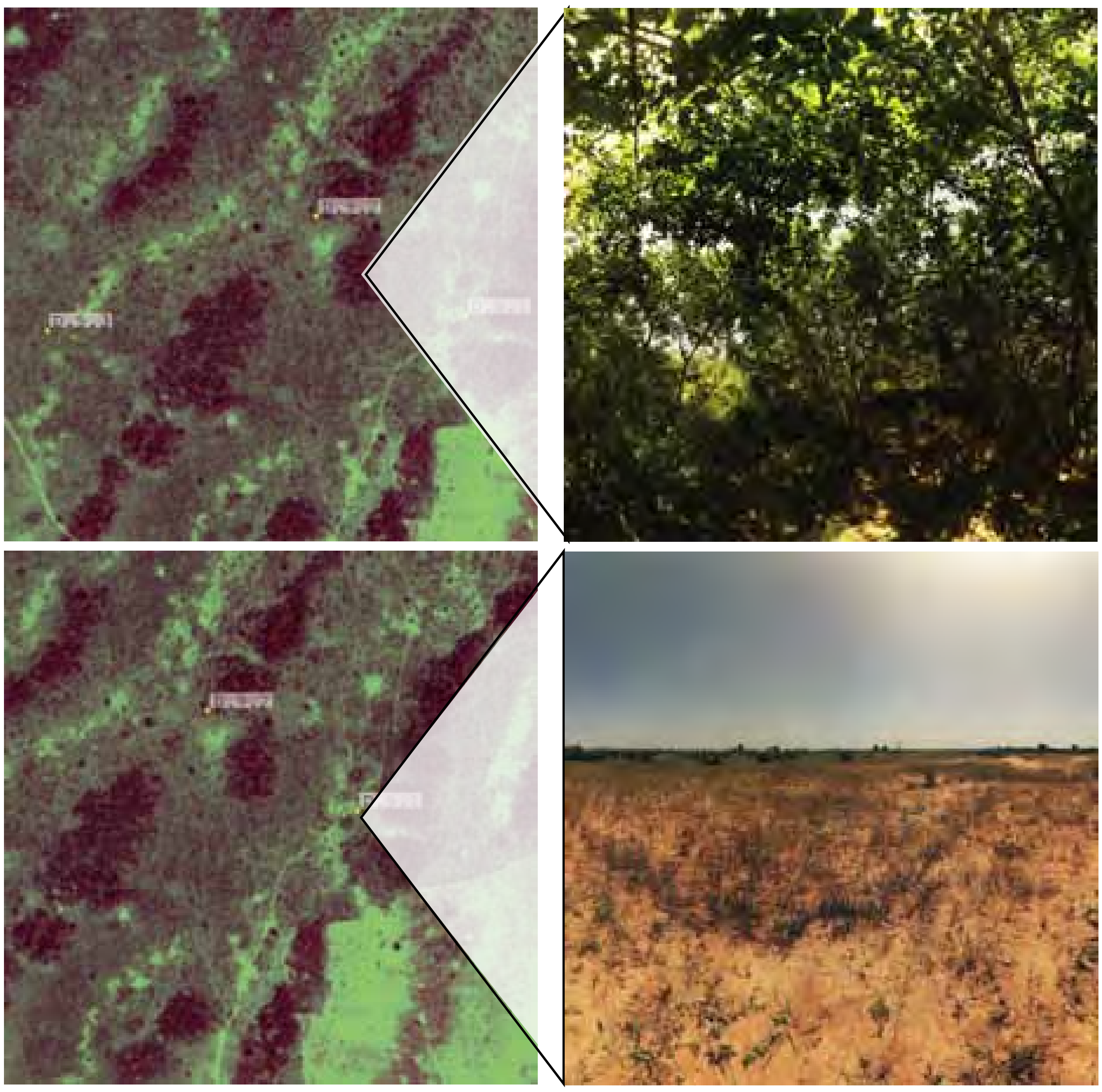
Summary of basic sentinel site characteristics, including land use, degradation risk, woody cover and tropical livestock units (inset), based on baseline surveys.

Banded vegetation patterns ("tiger bush")

In Dianvola we have strips of shrubs and trees (mainly Sclerocaria birea and Guiera senegalensis thickets, but also including *Adansonia digitata*, *Balenites aegyptica*, *Combretum micranthum* and *Piliostigma reticulatum*) alternating with open areas with bare soil, grasses or herbs and small shrubs. The latter is generally three to ten times the width of the woody vegetation bands. Below, false colour composite Quickbird satellite images (February 2006) and geo-referenced photographs from Dianvola (October 2007) illustrate a tiger bush vegetation strip where vegetation densities may be very high and an open area with herbs and grasses with significant patches of bare soil. The photographs are 360 degree panoramas. Hard-setting and crust formation is often observed in the open areas and in former tiger bush areas following cultivation. As shown in the Landsat TM and ETM+ derived woody vegetation maps below from October 1984 and 2000, significant areas of tiger bush in Dianvola were converted to agriculture (millet and sorghum production) in this period. This is a response to increasing population pressure in the area, as well as increasing demand for fire-wood in Segou town.

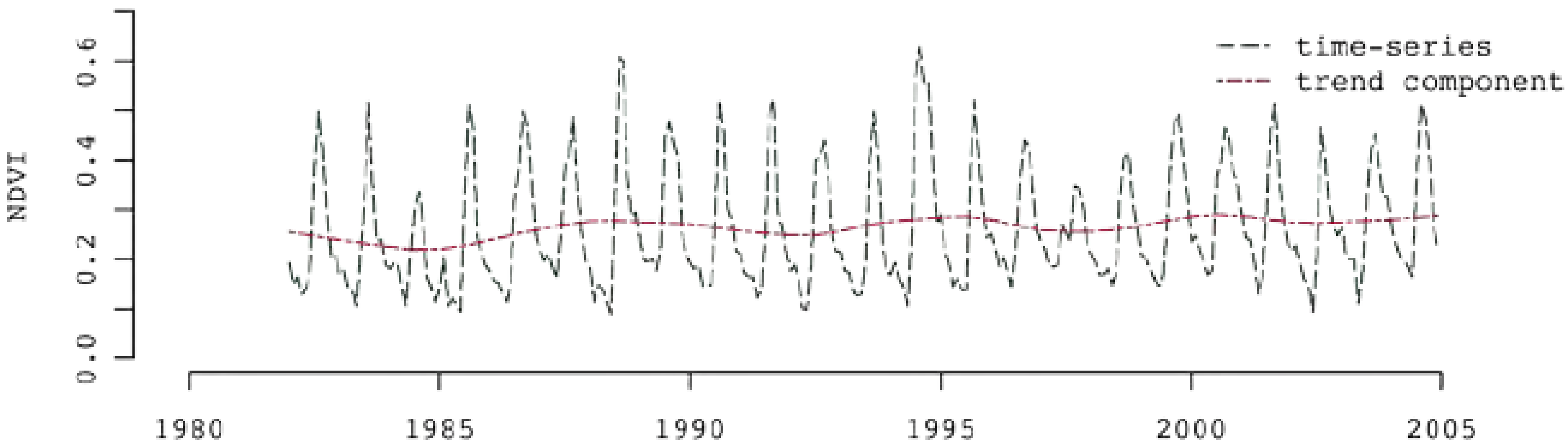






Trends in vegetation cover

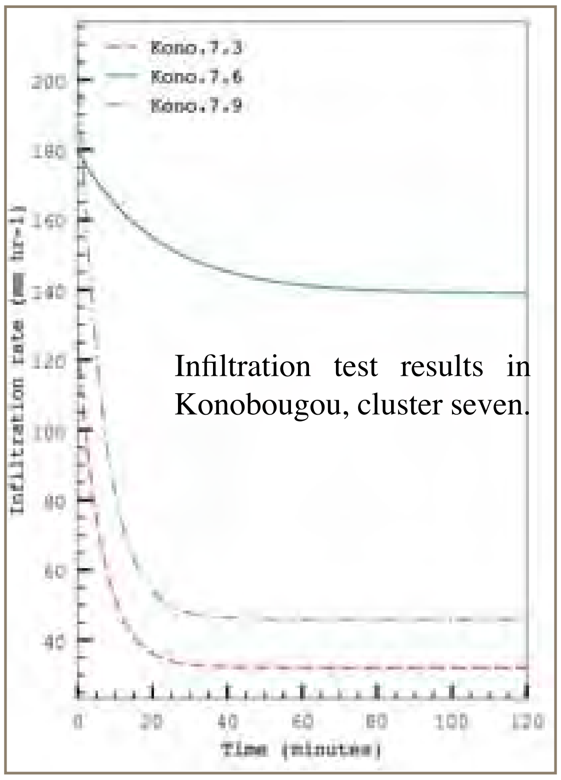
Our analysis of trends in vegetation cover for Dianvola using rNDVI shows a decrease in the eastern part of the sentinel site, indicating increased land degradation. Simply taking linear trends on NDVI shows a greening-up in the same area, but is misleading as the virtual collapse in vegetation cover in 1984/85 has excessive influence on the linear trend. The trend plot below shows the lack of any trend in vegetation cover after 1987/88.



Vegetation patterns on laterite plateaus

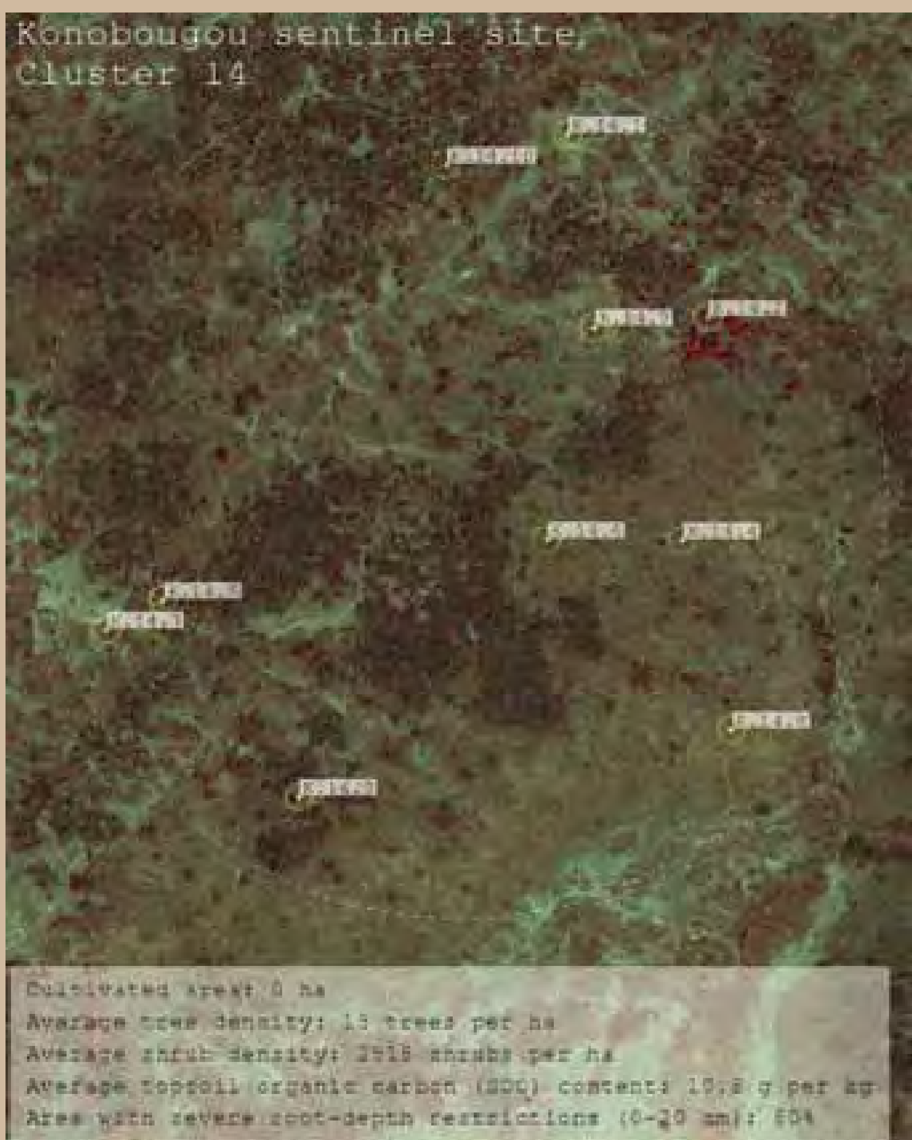
Laterite plateau near the village of Zanabougou, north of Segou town.

Laterite areas occur mainly as plateaus in the Segou region. In our sentinel sites, laterite plateaus occur in Konobougou, Sokoura and Zebougou. These areas have a high prevalence of soil physical constraints, including severe rootdepth restrictions. Infiltration capacity is generally very low, but varies depending mainly on woody cover densities on these soils (see infiltration curves below), leading to rapid runoff during intense rainfall. Soil erosion is therefore often observed at the lower parts of the plateaus in the transition to the flatter cultivated areas. Laterite plateaus are therefore not cultivated, but used for grazing/browsing and as sources of firewood. Vegetation on the laterite plateaus is predominantly shrubby, with the highest densities occurring in Konobougou, where we have about 5000 shrubs ha^{-1} on average in cluster seven (map below). Soil water infiltration capacity reflects these differences in shrub density between plots in cluster seven (graph on the left). Vegetation is mainly distributed as dense shrub thickets (clumps) of *Combretum* sp., *Piliostigma reticulatum*, *Acacia* sp. and *Pterocarpus lucens*.



Infiltration test results in Konobougou, cluster seven.

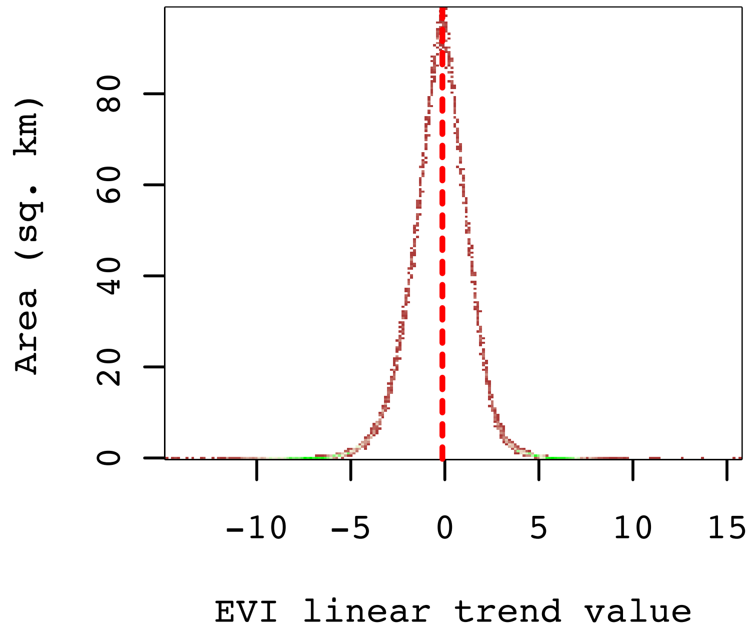
False colour composite Quickbird satellite images. Bright red areas are large trees, while shrubs have a dark red colour. Bare, lateritic soils are beige to dark gray in colour. Sampling plots (0.1 ha) are included for reference, with plot boundaries to scale in yellow.

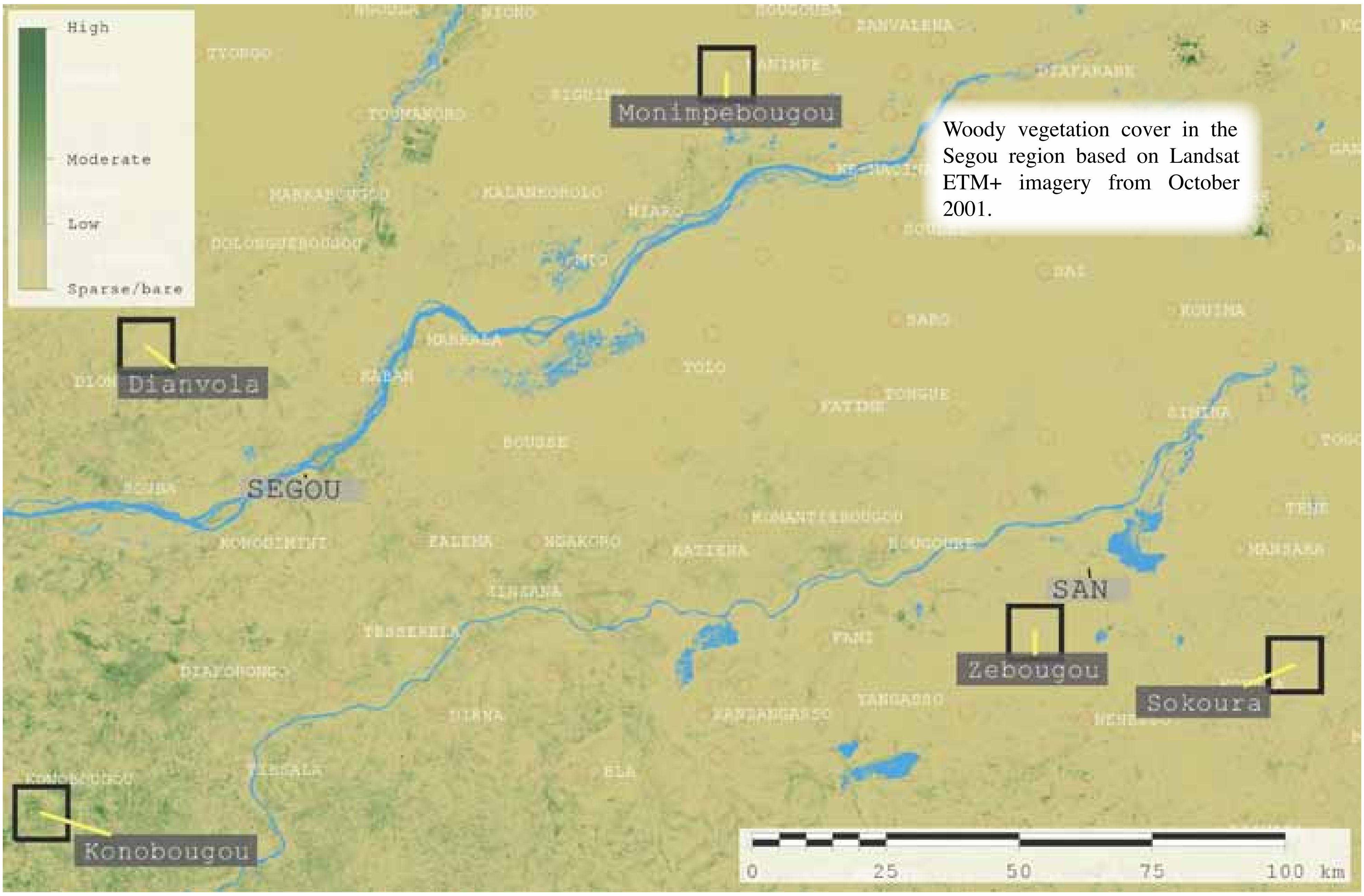


Laterite plateau in Segou region, Mali

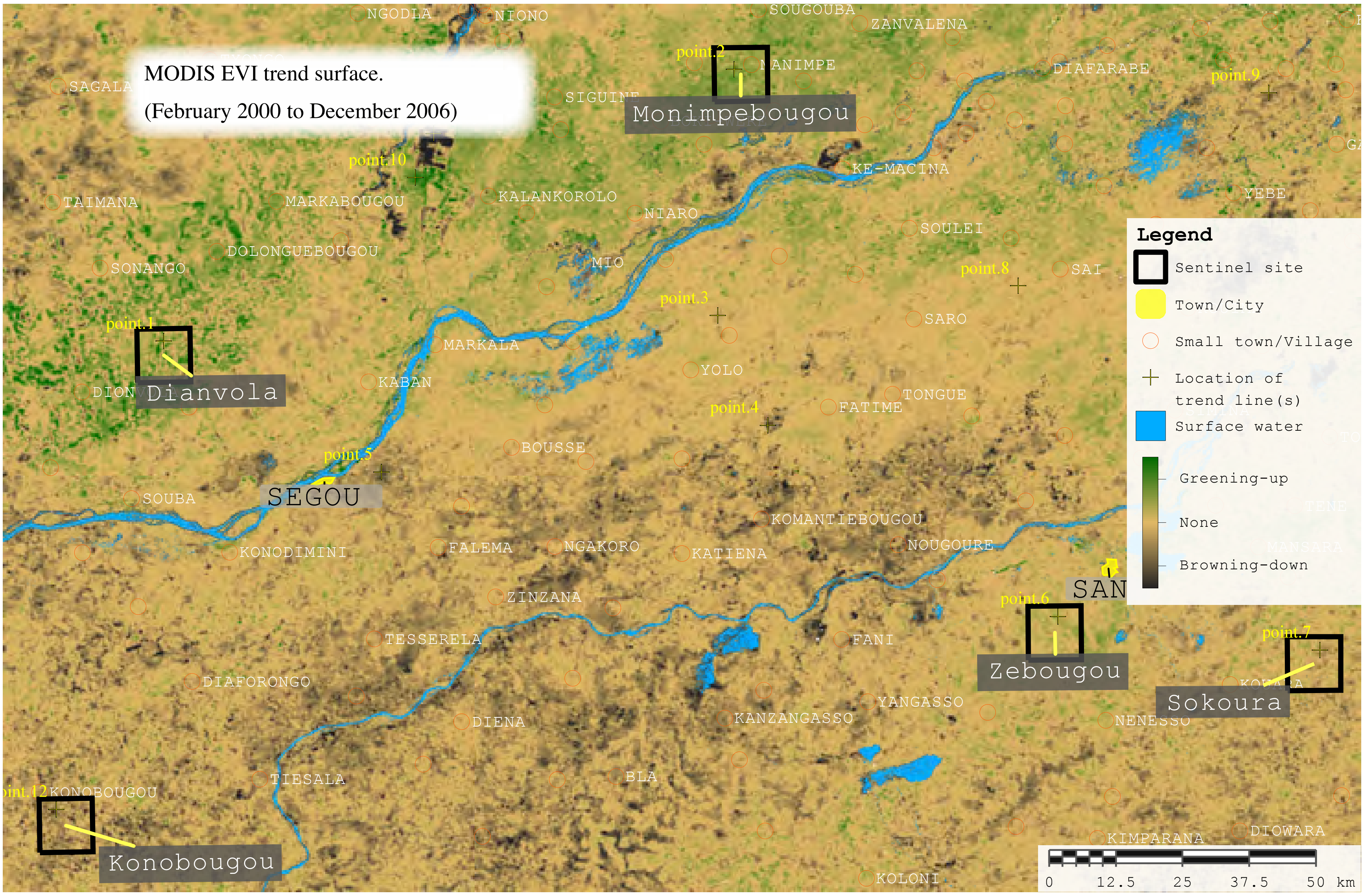
Regional mapping of woody cover

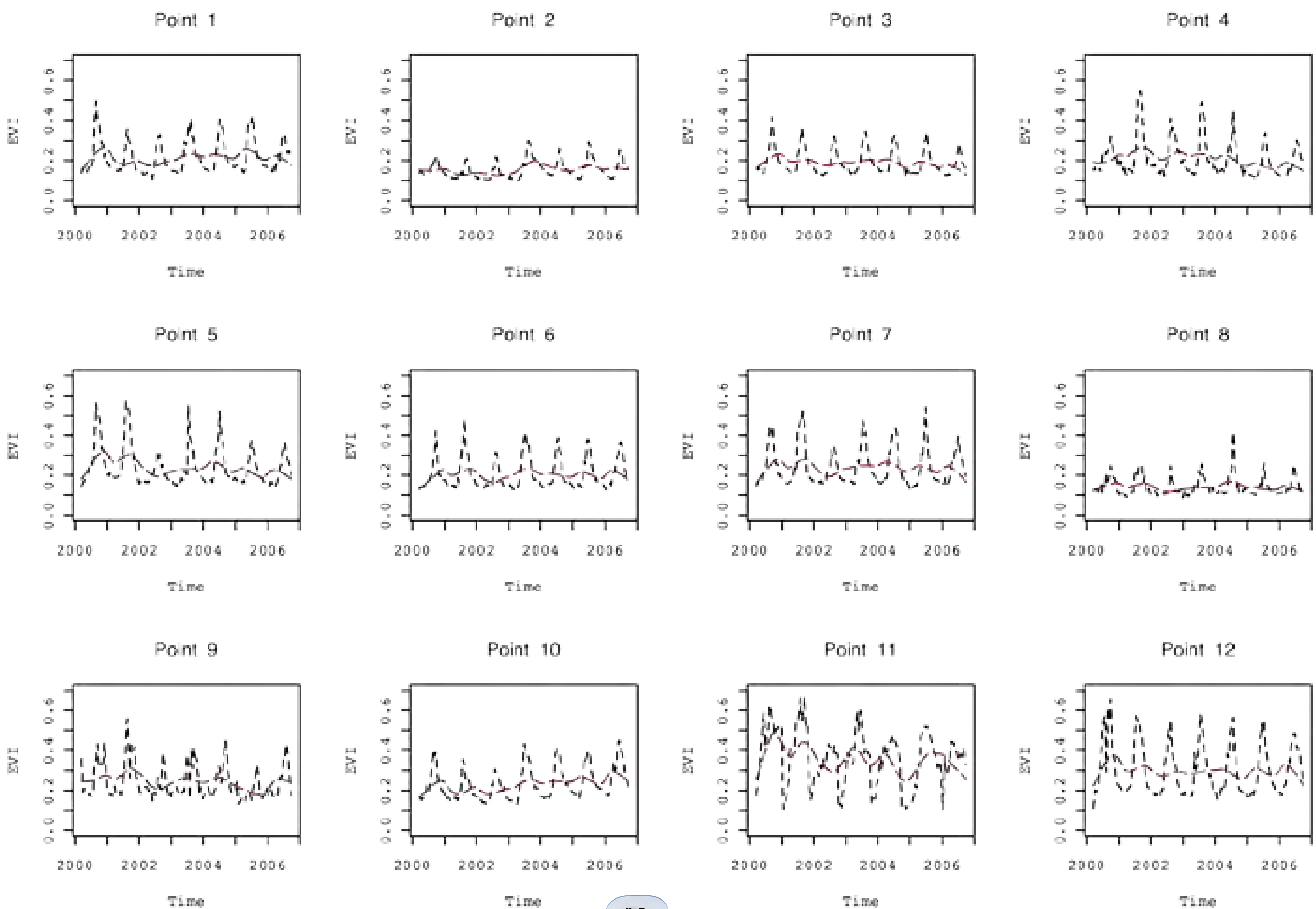
Using data on woody cover collected during baseline surveys in conjunction with satellite imagery, we can estimate woody cover densities in the Segou region using, for example, Landsat and ASTER imagery. In the results shown here we have estimated woody cover densities from Landsat reflectance using woody cover ratings from our sentinel site baseline surveys. As is evident, there is a relatively strong increase in woody cover going from north to south, mainly due to the strong rainfall gradient. North of the 500 mm isohyet, dense woody vegetation cover is mainly associated with flood-plains around the Niger and its tributaries and in irrigated areas. At this spatial resolution (~ 30 m), maps of woody cover provide relatively accurate baselines for estimating future changes (i.e. greening-up or browning-down trends) associated with woody vegetation cover. On the facing page, MODIS EVI trends are shown for the same region presented on this page, showing large areas that are browning-down in the southern section of the study area. Just east of Segou town (point 5 on map and in chart at bottom of facing page), we see a relatively strong negative trend in vegetation cover. The EVI trends are positive over large areas north of the Niger, although these trends are moderate for the most part (points 1 and 2 in map on facing page), with the exception of parts of the Office du Niger (point 10). Trends in irrigated areas (Office du Niger) are generally not very reliable due to regular flooding, as is also the case along to the Niger. At the bottom of the facing page, MODIS EVI time-series (black) are shown for a random selection of points in the region (top map on facing page). The time-series trend components are also included as red lines in the same graph. These graphics also illustrate the high level of complexity and patchiness in vegetation change in the Segou region, largely confirming our earlier observations for other parts of the Sahel.





Woody vegetation cover in the Segou region based on Landsat ETM+ imagery from October 2001.


MODIS EVI trend surface.
(February 2000 to December 2006)
Legend
Sentinel site
Town/City
Small town/Village
Location of trend line(s)
Surface water
Greening-up
None
Browning-down
Monimpebougou
Dianvola
SEGOU
SAN
Zebougou
Sokoura
Konobougou
point.1
point.2
point.3
point.4
point.5
point.6
point.7
point.8
point.9
point.10
NGODLA
NIONO
SOUGOUBA
ZANVALENA
DIAFARABE
SAGALA
SIGUINE
TAIMANA
MARKABOUGOU
KALANKOROLO
NIARO
KE-MACINA
SOULEI
YEBE
SONANGO
DOLONGUEBOUGOU
MIO
SAI
SARO
MARKALA
YOLO
KABAN
TONGUE
FATIME
BOUSSE
SOUBA
KOMANTIEBOUGOU
KONODIMINI
FALEMA
NGAKORO
KATIENA
NOUGOURE
ZINZANA
TESSERELA
FANI
DIAFORONGO
YANGASSO
KANZANGASSO
DIENA
NENESSO
TIESALA
BLA
KONOBOUGOU
KIMPARANA
DIOWARA
KOLONI
0 12.5 25 37.5 50 km


Point 1
Point 2
Point 3
Point 4
Point 5
Point 6
Point 7
Point 8
Point 9
Point 10
Point 11
Point 12
EVI
0.0 0.2 0.4 0.6
2000 2002 2004 2006
Time

Photographs showing a selection of soil samples prior to IR scanning.

Rapid assessment of soil health

Understanding the relationships between changes in vegetation cover discussed earlier and soil health is important for proper assessments of historical and current trends, present use, as well as future management of Sahelian Parklands. Developing the empirical basis for such assessments is, however, a challenge due to the size of the area involved, which makes costs prohibitive, at least when using conventional methods. In the Segou region, novel approaches developed at the World Agroforestry Centre, together with other partner institutions, were applied for rapid and less costly analysis of soil health in these landscapes, also including estimates of soil organic carbon, a soil condition index and other soil physical and chemical properties.

The keystone in the framework used to make such assessments possible is the statistical sampling framework based on randomized sampling applied in our sentinel sites in Segou region. Another linchpin in the land degradation surveillance framework (LDSF) is the use of infrared (IR) spectroscopy, which when combined with field baseline data on soils and vegetation, field infiltration tests and remote sensing data at various scales provides a powerful tool for assessing soil condition over large areas. In the current section, we present IR spectroscopy in more detail using results of our studies in the Segou region to illustrate some of the potential uses of these techniques.

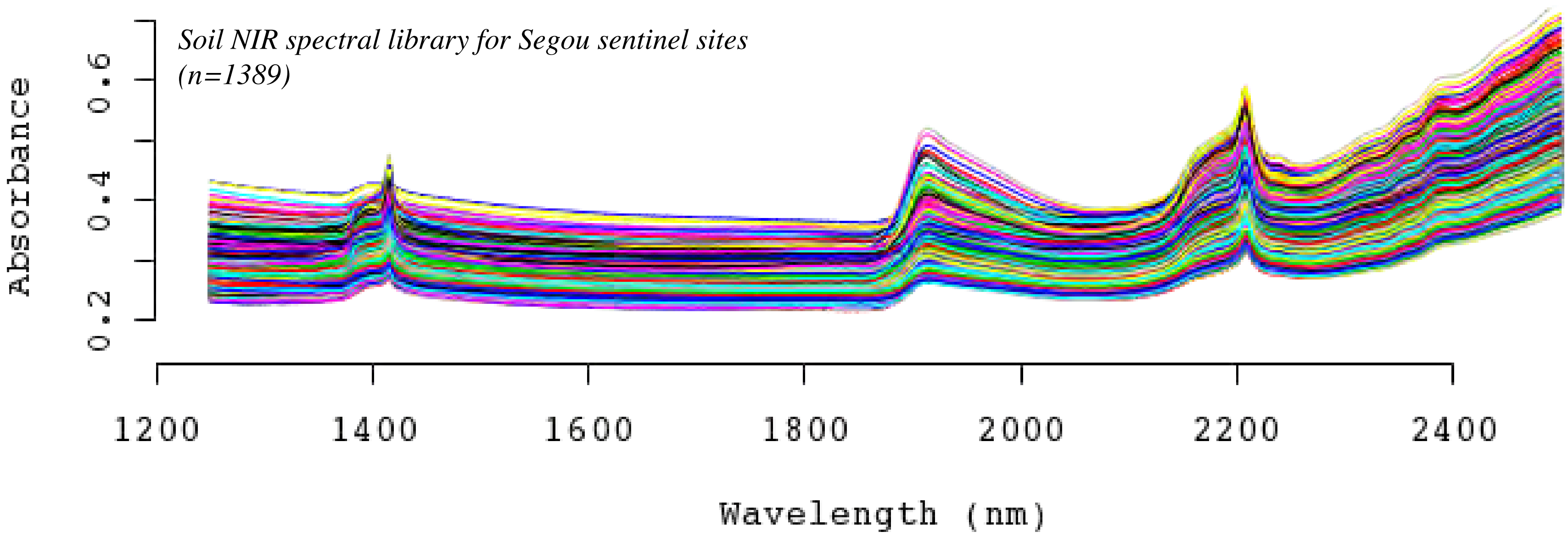
In infrared spectroscopy, we shine light on a soil sample and record how much of this light is absorbed at different wavelengths. This can be compared to taking a photograph, but using light that the human eye cannot detect. This analytical method is cheap and rapid, and can also be used directly in the field using handheld devices.

Infrared (IR) spectroscopy

The use of IR spectroscopy is an approach where the vibration of specific sets of chemical bonds is correlated to the absorption of electromagnetic radiation at specific frequencies and forms the IR spectrum, as is given as the sum of the contributing energy terms;

$$E_{total} = E_{electronic} + E_{vibrational} + E_{rotational} + E_{translational}$$

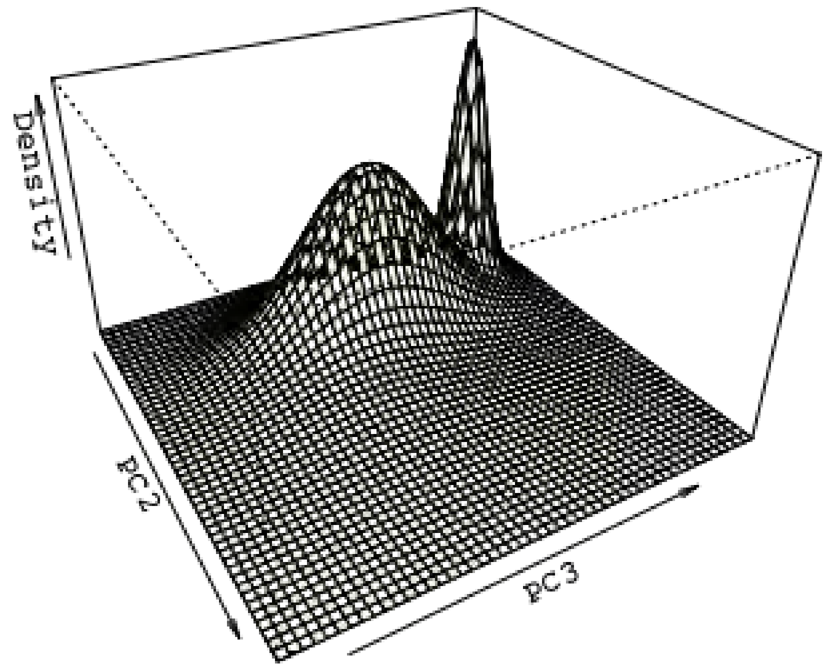
The most important part of the spectrum for our purposes is the 690 to 3,000 nm region (near-infrared (NIR)), where the harmonic vibrations of the CH stretch fundamental and their corresponding combination bands occur. The molecule's vibrational properties is considered to be a unique physical property of that molecule, and the IR spectrum can therefore be used as a fingerprint which allows us to compare “unknown” spectra to previously recorded reference spectra. Quantitative NIR methods typically require the application of multivariate calibration algorithms and statistical methods to model the NIR response to chemical or physical properties of the previously recorded sample. These methods are possible where changes in the response of the NIR are proportional to changes in the concentration of chemical components, or in the physical characteristics (scattering/absorptive properties), of samples being analysed.

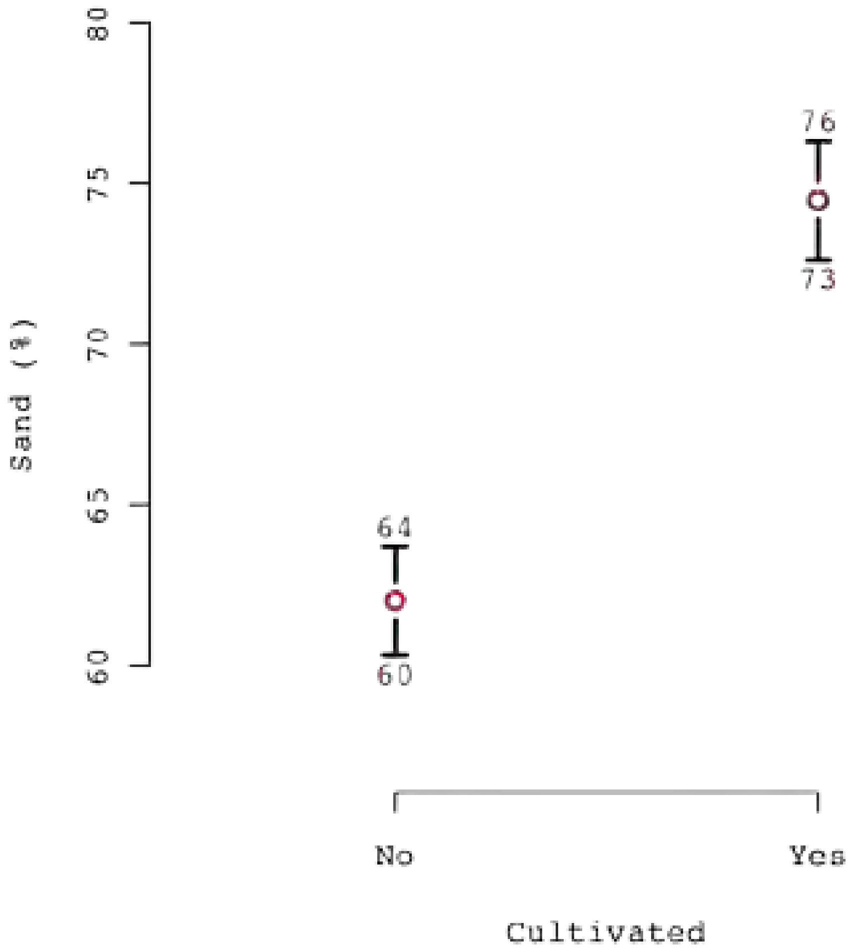


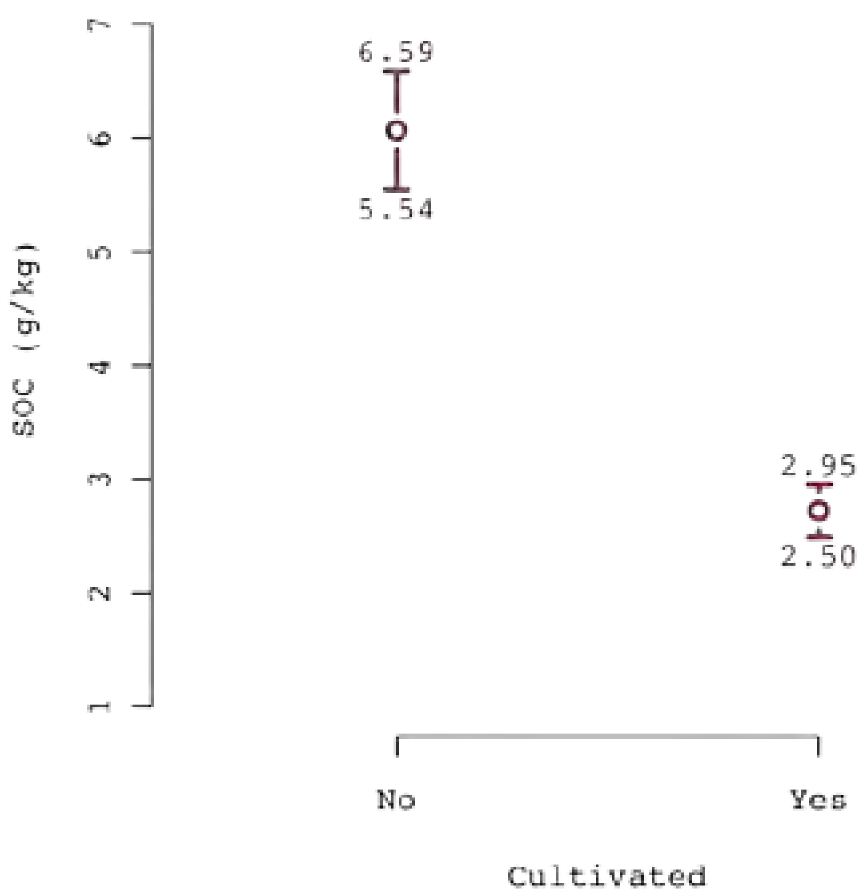
Soil organic carbon and soil condition

Soil organic carbon (SOC) is a key indicator of soil condition (or quality) in terms of nutrient status and availability (soil fertility), soil physical properties, and water holding capacity, and can be predicted from IR spectroscopy. In our sentinel sites in Segou region, SOC contents are generally low, with a median content of 3.12 g kg^{-1} in topsoils (0-20 cm) for all sites. Cultivated areas have significantly lower topsoil SOC contents than semi-natural sites (areas that are not cutlivated or managed, plot bottom right), which is mainly a factor of the higher sand content in these areas (lower plot on the left), as well as an effect of cultivation. Management of soil organic matter is therefore of critical importance in this region, and in the Sahel in general. We use NIR soil spectral signatures to predict the likelihood of having poor soil condition in our sentinel sites using model-based clustering techniques. The surface plot on the right shows the presence of two distinct clusters after principal components (PC) decomposition of the NIR spectra. In this particular example, components two and three are displayed. The presence of such clusters in the data allows us to model the probability of the various samples in our data set belonging to a particular class or group (i.e. "poor" or "good" soil condition).

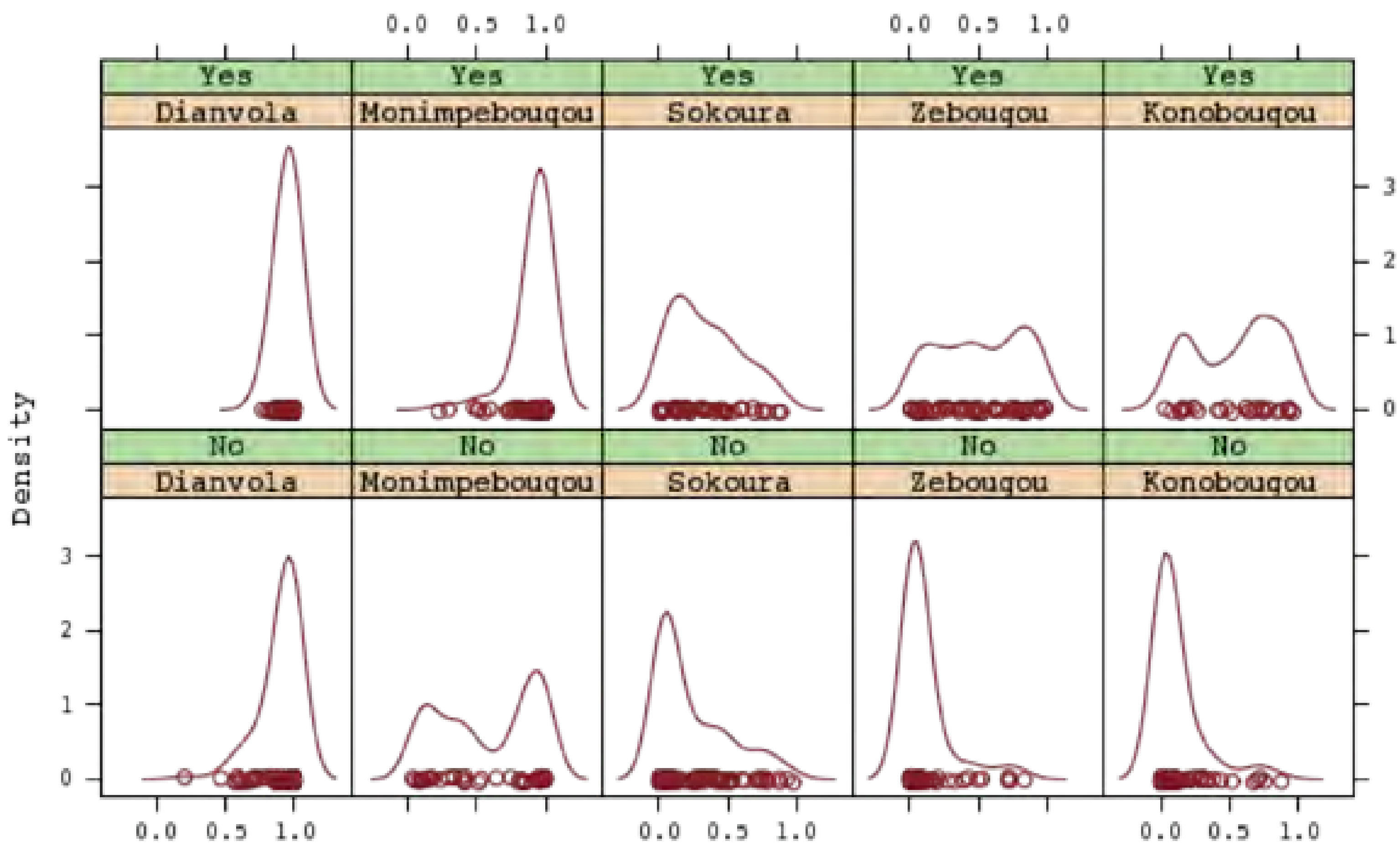
As is evident from the plots at the top of the facing page, soil condition varies significantly between sentinel sites, with Dianvola and Monimpebougou having the highest probabilities of poor soil condition overall. As expected, soil condition is poorest in cultivated areas. Soil physical degradation is more prevalent in semi-natural areas (due to their location on laterite plateaus), also resulting in lower infiltration capacity and higher runoff, as shown earlier.







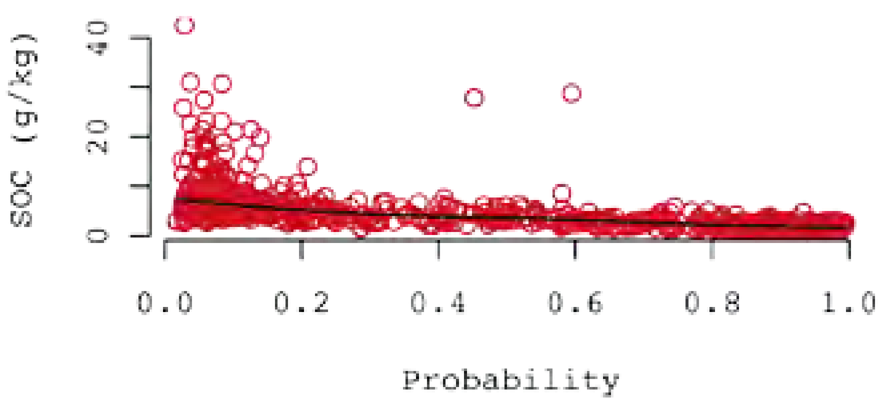
Predicted likelihood of poor soil condition in cultivated or managed ("Yes")and semi-natural ("No") areas of the five sentinel sites. Plots that have poor soil condition (i.e. low SOC and high sand content) show likelihoods closer to one.



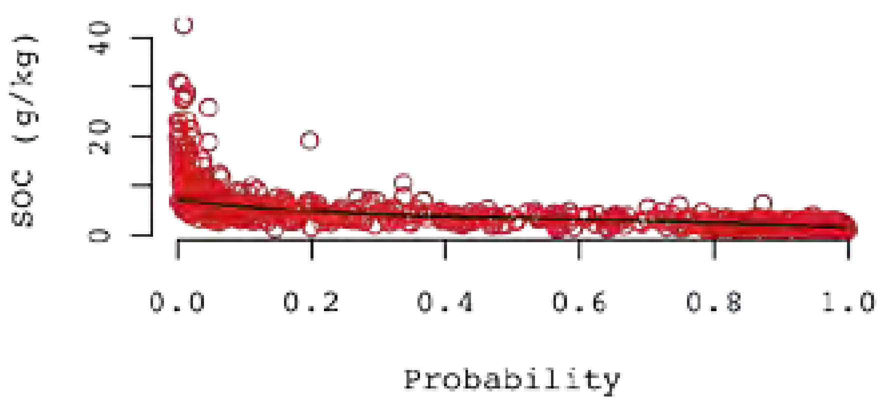
Mapping soil condition

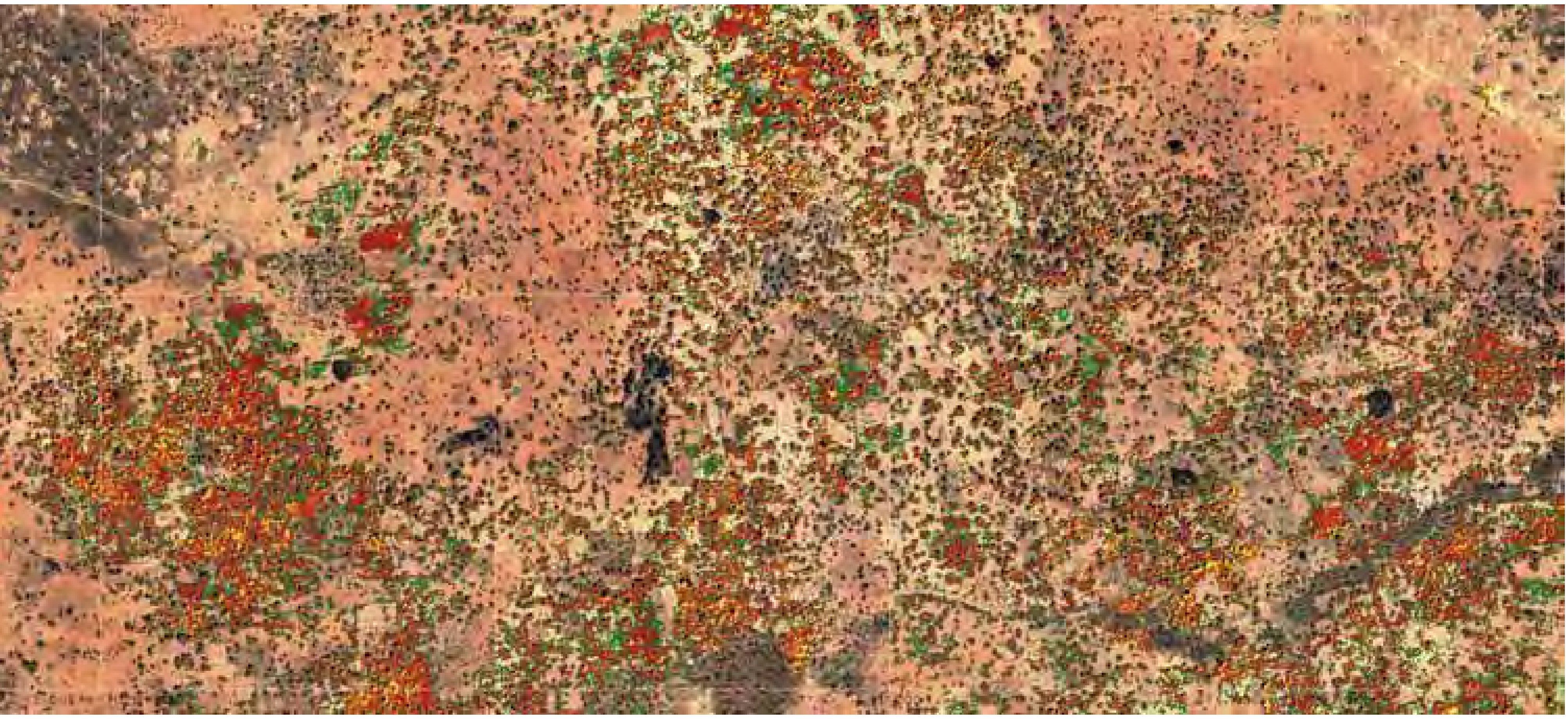
In order to be able to successfully map soil degradation risk in our study area, we must be able to relate our predictions of poor soil condition from NIR spectral data to remotely sensed spectral signatures. Maps of areas predicted to have poor soil condition are shown on the following pages. In our case, we looked at potential models for predicting soil degradation risk maps from Quickbird (pixel size ~ 2.4 m) and Landsat imagery (pixel size ~ 28.5 m), respectively. This approach has its limitations, particularly in densely vegetated areas, but our results so far show great promise in terms of identifying hotspots in the Sahel having high likelihoods of poor soil condition and low SOC concentrations.

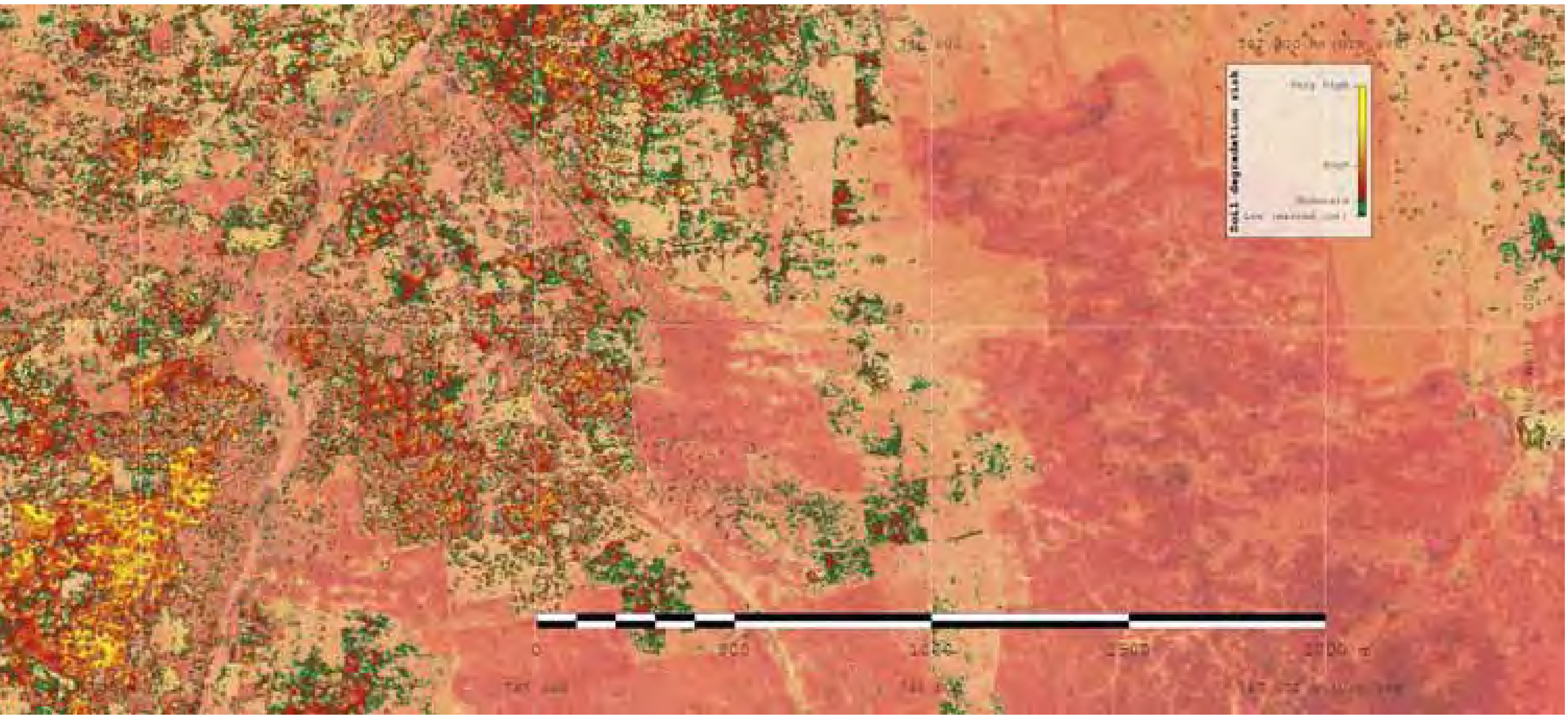
Relationship between soil degradation risk predicted from Quickbird reflectance and SOC content.



Relationship between soil degradation risk predicted from Landsat ETM+ reflectance and SOC content.



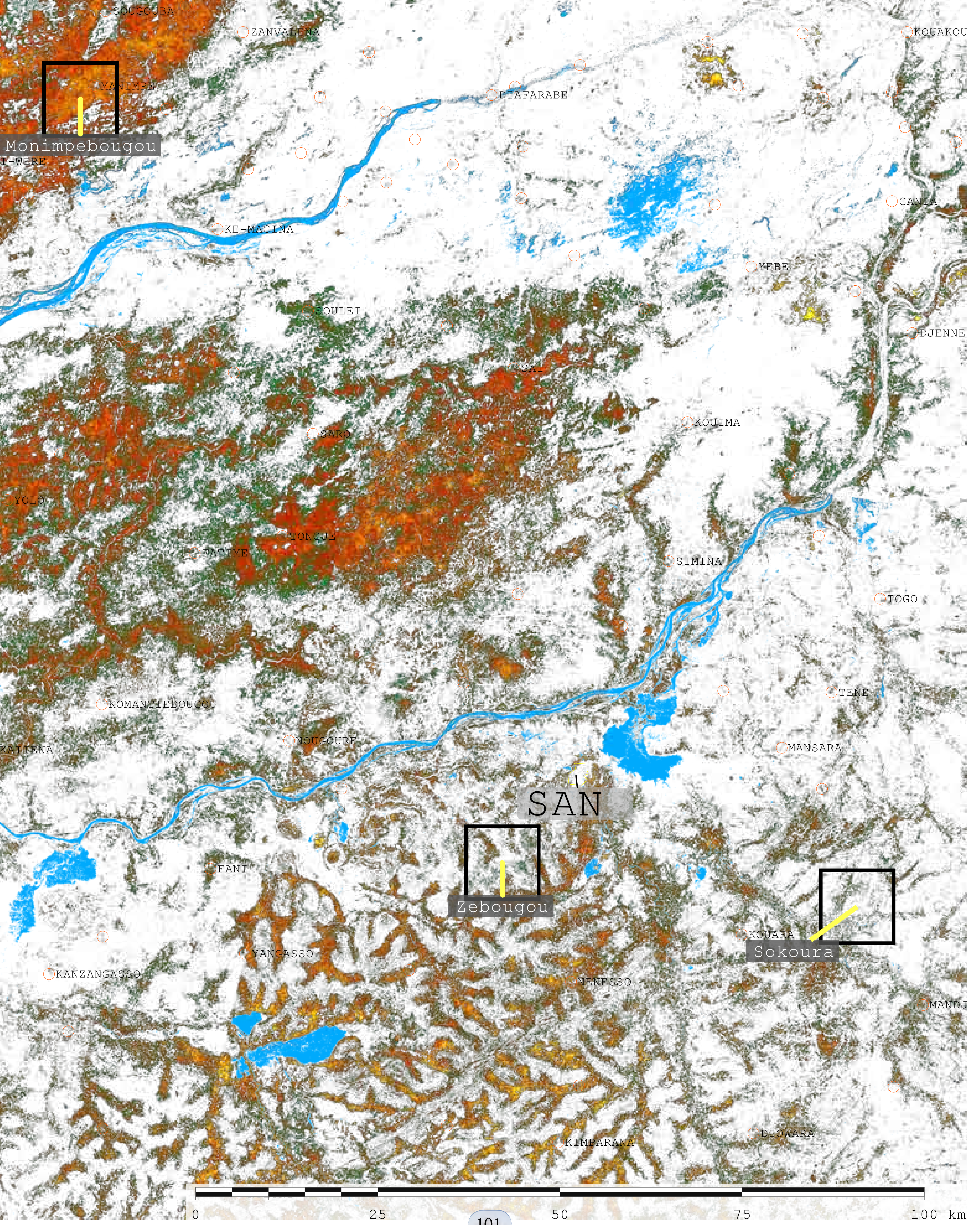




Above we show two examples of high resolution soil degradation risk maps based on Quickbird imagery from Zebougou and Konobougou, respectively. Yellow areas are soils with high risk of soil organic matter depletion and low soil fertility status. At this spatial scale (resolution ~ 2.4 m), farmers and advisory services can identify risk areas with a relatively high level of precision on the ground.

By predicting soil degradation risk using Landsat ETM+ reflectance we can develop maps of soil degradation hot-spot areas at the regional scale. This allows policy makers and land managers to target interventions.

This Map of poor soil condition (i.e. low SOC, high sand content) hotspots in the Segou region. The map covers an area of approximately 45,200 km^2.


SOUGOUBA
ZANVALENA
KOUAKOU
MANIMPE
DIAFARABE
Monimpebougou
I-WERE
GANIA
KE-MACINA
YEBE
SOULEI
DJENNE
SAI
KOUIMA
SARO
YOLO
TONGUE
FATIME
SIMINA
TOGO
KOMANTIEBOUGOU
TENE
KATIENA
NOUGOURE
MANSARA
SAN
FANI
Zebougou
KOUARA
Sokoura
YANGASSO
KANZANGASSO
NENESSO
MANDJ
DIOWARA
KIMPARANA
0
25
50
75
100 km

Epilogue

Using a combination of historical records, ground data and satellite imagery at various scales, this atlas has traced trends and variations in climate and vegetation, relating these to soil condition and processes of land degradation in the Sahel. People in the Sahel have learnt to adapt their livelihood strategies to the extreme variations in climate and prevalent droughts in the region. However, there has been an unprecedented increase in population density as well as demographic changes over the last half century that make it more difficult for people to adapt to changes in climate. A pertinent question is – how can livelihoods be sustained during the next drought cycle in the Sahel?

The last quarter century has seen increases in rainfall over large parts of the Sahel, with subsequent regreening. This atlas suggests that farmers in the Sahel have not been able to utilize the increases in rainfall fully. This could be attributed to a lag in the response of farmers to more favorable rainfall conditions, or underlying land degradation that is trapping these ecosystems in a less favorable state for food production. There is still debate on whether the dryland ecosystems of the Sahel have returned to their pre-drought functionality.

Future droughts are extremely likely to occur as the analysis of historical rainfall patterns indicate recurring droughts, the consequences of which can be catastrophic given less resilient societies and land degradation. Climate patterns are difficult to predict accurately, but if the 80-year rainfall cycle identified in this study continues, the next severe drought will hit the Sahel in only a decade or two.

A key question is how much influence man has had on climate through appropriation of vegetation. Is it possible that human caused changes in land cover, such as overgrazing and conversion of woodland to agriculture, have exacerbated the drought cycles by adversely reinforcing internal feedback processes?

The Great Green Wall initiative for re-greening of the Sahel in a corridor going from the Atlantic Ocean to the Red Sea is a potentially promising approach to increasing the resilience of these ecosystems to drought. Such initiatives also provide an opportunity for further studies to better understand the relationships between rainfall and vegetation on the one hand, and climate, land management and land degradation on the other.

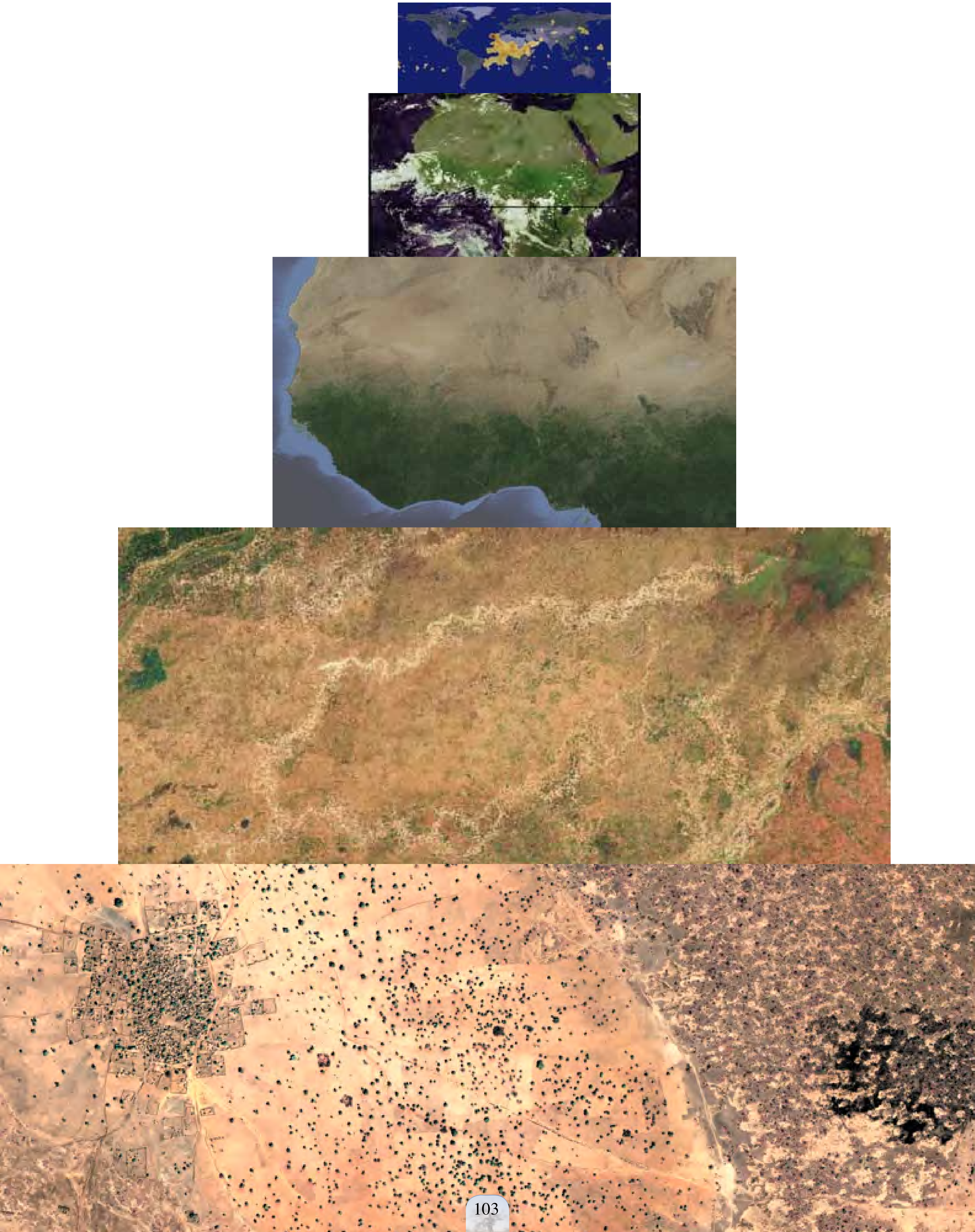
Therefore, the imperative now is for close and consistent monitoring of climate, vegetation and land degradation to develop systems for better early warning of droughts and for targeting land management interventions that can improve preparedness for future drought situations.

The atlas has demonstrated technology and tools for synoptic screening of vegetation changes at regional scale using rainfall normalized vegetation indices.

Continued monitoring using MODIS data offers good prospects for keeping a regional watch on greening and browning trends, to identify areas developing land degradation or its reversal, but this needs to be complimented with improved weather monitoring networks.

As demonstrated in this atlas, regional greening and browning trends are complex when investigated in more spatial and temporal detail. At coarse scales, several landscape elements compose one picture element (pixel), and a positive trend in in one ecosystem can be canceled out by changes in adjacent ecosystems. For instance a greening up of a floodplain might be out-shadowed by tree felling further ashore.

The only way to really understand what is going on is to build the picture bottom up through systematic statistical ground sampling, such as demonstrated here through use of scientific concepts of land health surveillance, implemented through the Land Degradation Surveillance Framework. Systematic sampling and observation of ground conditions can be combined with new technology for rapid soil characterization and with fine to moderate resolution satellite imagery to provide powerful inference about soil, vegetation and socioeconomic conditions at local to regional scales. Investments in regional application of this approach will provide a sound scientific basis for understanding and managing climate-vegetation-management processes and feedbacks in the Sahel and elsewhere.



This atlas aims to illustrate a rigorous scientific basis for understanding processes of landscape change in the Sahel and describes landscapes, climate, vegetation, and trends in vegetation and soil health.

The atlas provides a pictorial overview of the application of land degradation surveillance – a science-based approach to land health monitoring and assessment. Systematic sampling and observation of ground conditions are combined with new technology for rapid soil characterization and with fine to moderate resolution satellite imagery to provide powerful inference about soil, vegetation and socioeconomic conditions at local to regional scales.

Investments in regional application of this approach will provide a sound scientific basis for understanding and managing climate-vegetation-management processes and feedbacks in the Sahel and elsewhere.

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