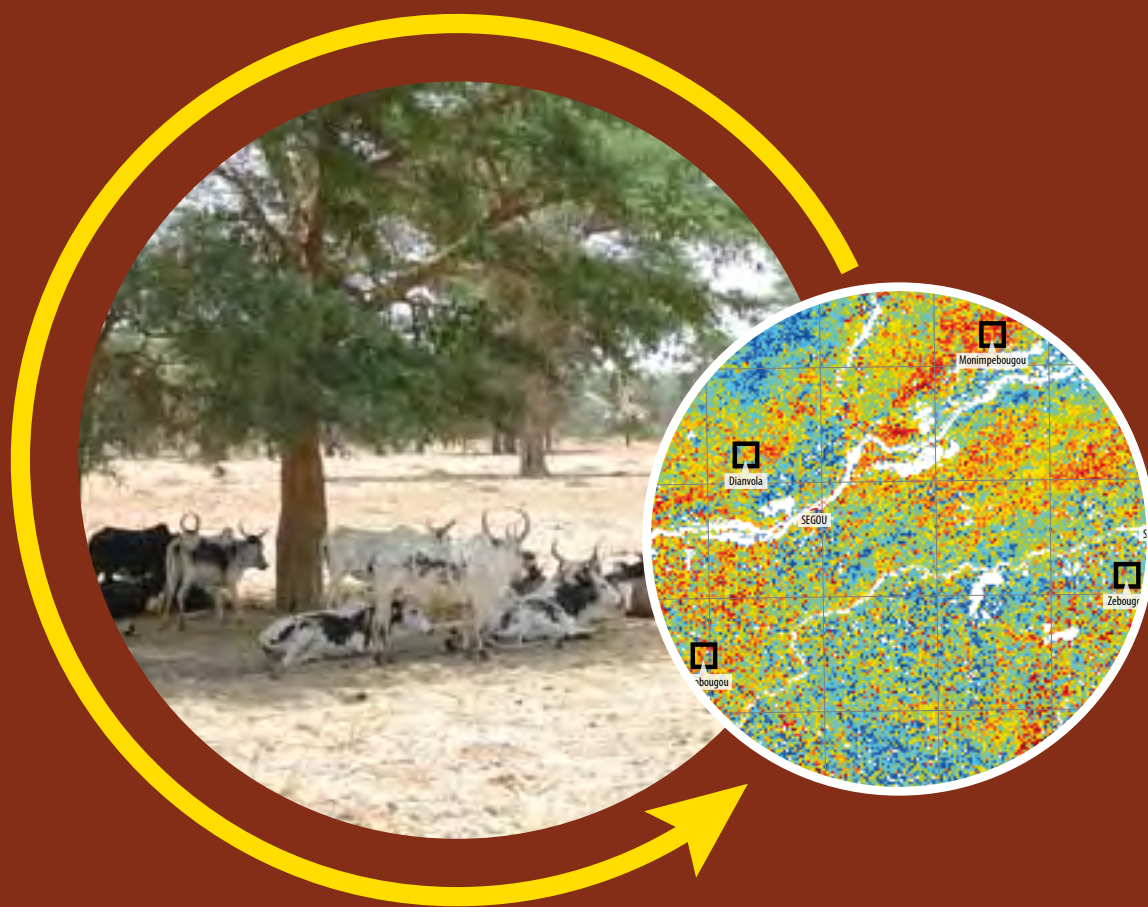


# LAND HEALTH SURVEILLANCE

an Evidence-based Approach to  
Land Ecosystem Management

*Illustrated with a Case Study in the West Africa Sahel*



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# LAND HEALTH SURVEILLANCE

## **An Evidence-based Approach to Land Ecosystem Management**

*Illustrated with a Case Study in  
the West Africa Sahel*



# Contents

Figure list	vii
Table list	x
Abbreviations and acronyms	xii
Foreword	xv
Preface	xvi
<b>Executive Summary</b>	<b>xvii</b>
Background	xvii
Land health surveillance concepts	xvii
Regional surveillance in West Africa Sahel	xviii
Sentinel site surveillance in Segou Region, Mali	xviii
Conclusions	xviii

## PART 1 GENERAL CONCEPTS AND ANALYTICAL APPROACHES

<b>Summary</b>	<b>22</b>
Surveillance principles	22
Surveillance implementation	22
Communicating surveillance data	23
<b>1 Land health surveillance concepts</b>	<b>24</b>
Land health, ecosystem services and human well-being	24
Evidence-based decision making on land health	26
Land health surveillance	27
<b>2 Overview of land health surveillance methods and tools</b>	<b>32</b>
Introduction	32
Regional surveillance system	32
Ground survey – sentinel site surveillance system	34
<b>3 Land health surveillance and decision making</b>	<b>37</b>
Communicating health surveillance information	37
Strengthening evidence-based decision-making	38
<b>References</b>	<b>44</b>

## PART 2 REGIONAL LAND HEALTH SURVEILLANCE: Synoptic Screening of Land Degradation in the West Africa Sahel

	<b>Summary</b>	<b>46</b>
	Desertification discourse	46
	Methods	46
	Rainfall and vegetation trends	47
	Conclusions	48
<b>4</b>	<b>The desertification debate</b>	<b>49</b>
	Background	49
	Assessments of land degradation in the Sahel	51
	Discourse during the Sahelian drought 1970–1985	52
	Discourse on Sahel vegetation recovery 1985 to present	52
	Conclusion	55
<b>5</b>	<b>The African Sahel and its climate</b>	<b>56</b>
	Introduction	56
	The climate system of the Sahel	58
	Sahel rainfall variation 1930–2006	60
	Rainfall station gauging data	61
	Geostatistical interpolation of rainfall station data	62
	Satellite-supported rainfall data	62
	Calculating annual rainfall and rainfall trends	65
	Trends in rainfall over the Sahel 1930–2006	66
<b>6</b>	<b>Sahel vegetation variation 1982–2006</b>	<b>67</b>
	Satellite vegetation mapping	67
	The GIMMS AVHRR-NDVI dataset	69
	NDVI preprocessing	70
	NDVI trends 1982–2006	70
	Methods for calculating annual vegetation growth and trends	75
	Trends in annual average NDVI 1982–2006	75
	Annual maximum NDVI 1982–2006	76
	Annual increment *NDVI 1982–2006	76
	Sahel vegetation changes 1982–2006 – comparison and summary	80
	Conclusions	81
<b>7</b>	<b>Sahel rain-normalized NDVI 1982–2006</b>	<b>84</b>
	Rain-normalized NDVI concept	84
	Rain-normalized *NDVI 1982–2006	85
	Trends in rain-normalized *NDVI 1982–2006	90
	Sahel RNNNDVI changes 1982–2006 – comparison and summary	90
	Rain-normalized *NDVI discussion	90
	Exploring the rain-normalized *NDVI	90
	RNNNDVI and spatial rainfall variations	91
	Consistency of responses across different rainfall patterns	91

RNNDVI and the previous year's rainfall	98
Conclusion	98
<b>8 Spatial ranking of vegetation index trends</b>	<b>99</b>
Introduction	99
Regional ranking of vegetation growth	100
Regional ranking of rain-normalized vegetation growth	100
Focal or neighbourhood ranking of vegetation growth	100
Conclusion	101
<b>9 Regional surveillance: overall discussion and conclusion</b>	<b>103</b>
Introduction	103
NDVI indicators of land degradation	103
Land degradation and the problem of scale	104
Ecological and technical data discrepancies	105
Sahel vegetation changes 1982–2006	106
Mauritania	107
Senegal	107
Mali	106
Burkina Faso	106
Niger	107
Overall conclusion	107
<b>References</b>	<b>110</b>
<b>Appendix 2.1</b>	<b>114</b>
Web links	114
Data and resources used in this study	114
Other data and resources	114
Millennium Ecosystem Assessment	114

## **PART 3 SENTINEL SITE SURVEILLANCE IN SEGOU REGION, MALI:** An evidence-based approach to assessing land degradation and targeting sustainable land management interventions

<b>Summary</b>	<b>116</b>
Background	116
Land Degradation Surveillance Framework (LDSF)	116
Case study	117
Vegetation condition	117
Soil physical constraints	117
Soil fertility constraints	117
Soil condition indicator	118
Mapping soil condition	118
Fertilizer response trials	118
Targeting interventions	118

	Socioeconomic conditions and tree planting preferences	119
	Prospects	119
<b>10</b>	<b>The Land Degradation Surveillance Framework</b>	<b>121</b>
	Background	121
	Field sampling procedures	122
	Land resource indicators	122
	Household indicators	123
	Analytical methods	123
<b>11</b>	<b>Case study background</b>	<b>124</b>
	Background	124
	Population density	124
	Climate and topography	124
<b>12</b>	<b>Vegetation health</b>	<b>129</b>
	Land use and vegetation cover	129
	Vegetation cover and structure	130
	Woody cover	131
	Remote sensing of woody cover	136
	Herbaceous cover	138
<b>13</b>	<b>Soil health</b>	<b>139</b>
	Soil physical constraints	139
	Fertilizer response trials	150
<b>14</b>	<b>Identification of priority intervention areas</b>	<b>159</b>
	Introduction	159
	Interventions in semi-natural areas	159
	Interventions in cultivated areas	160
<b>15</b>	<b>Human well-being and tree planting preferences</b>	<b>164</b>
	Socioeconomic profiles	164
	Household characteristics	164
	Agricultural systems	165
	Household well-being	167
	Tree planting preferences	168
	Costs	169
	Prospects	170
	<b>References</b>	<b>171</b>
	<b>Appendix 3.1</b>	<b>172</b>
	Land Degradation Surveillance Framework (LDSF) Field Guide	172
	<b>Appendix 3.2</b>	<b>184</b>
	Examples of LDSF statistical models and database	184
	Generalized linear models and generalized linear mixed-effects models	184
	Linear mixed-effects models	184

Non-linear mixed-effects models (NLME)	185
Plotting and visualizing data in R	185
The LDSF database	185

## **PART 4 SYNTHESIS AND IMPLICATIONS FOR POLICY, RESEARCH AND APPLICATION**

<b>16</b>	<b>Condition and trend in land health</b>	
	Implications for Sahelian food security, climate change mitigation and adaptation strategies, and ecosystem management	188
	Introduction	188
	Regional land health trends	188
	Land health status and trends in Segou Region, Mali	189
	Conclusion	191
<b>17</b>	<b>Land health surveillance research and practice opportunities and priorities</b>	<b>192</b>
	Land health surveillance concept	192
	Regional land health surveillance methods	194
	Sentinel site surveillance	195
	Conclusion	197
	<b>References</b>	<b>198</b>
<b>18</b>	<b>Policy recommendations</b>	<b>199</b>
	Introduction	199
	Regional priorities	199
	Priorities for Segou Region and similar areas	200
	<b>Index</b>	<b>201</b>



# Figure list

Figure 1.1	A soil health state-and-transition diagram.	25
Figure 1.2	Infrared spectroscopy as screening tool.	30
Figure 2.1	AVHRR-derived Normalized Difference Vegetation Index (NDVI) mapped for West Africa.	33
Figure 2.2	ASTER scene from Segou Region, Mali.	34
Figure 2.3	Sentinel site showing measurement plots.	35
Figure 2.4	Near-infrared spectrometer being used to scan air-dried soil samples.	35
Figure 4.1	MODIS satellite image over Africa highlighting the study area and countries included in this report.	50
Figure 4.2	Map of the Global Assessment of Human Induced Soil Degradation (GLASOD).	51
Figure 4.3	NOAA AVHRR images in natural colours for 1984 and 2004.	54
Figure 5.1	Annual average rainfall for West Africa 1982–2006.	57
Figure 5.2	Vegetation ecosystems in West Africa.	57
Figure 5.3	Typical ecosystems of the Sahel region.	58
Figure 5.4	Cloud patterns over West Africa in 1984 and 2004.	59
Figure 5.5	Rainfall stations used for spatial interpolation of rainfall, and zones used for analyzing latitudinal shifts in rainfall and vegetation.	62
Figure 5.6	Rainfall over West Africa for the month of August 1964.	63
Figure 5.7	Rainfall over West Africa for the month of January 2004.	63
Figure 5.8	Procedure for extraction of the latitude position of the 300 mm isohyet.	64
Figure 5.9	Variation in latitudinal position of the 300 mm isohyet in the Sahel.	64
Figure 5.10	Normalized trend in annual rainfall in the West African Sahel 1982–2006.	65
Figure 6.1	Deriving vegetation density satellite data.	68
Figure 6.2	NDVI pre-processing steps and results for the first decade of January 2004.	69
Figure 6.3	Average scaled NDVI (*NDVI) for the years 1982–2006.	69
Figure 6.4	Hovmoller diagrams of annual rainfall and *NDVI cycles for the Sahel region.	70
Figure 6.5	Hovmoller diagram showing the evolution of rainfall and *NDVI.	71
Figure 6.6	Annual rainfall and vegetation cycles for a transect through Mali.	74
Figure 6.7	Methods for calculating annual vegetation growth from satellite derived vegetation data.	75
Figure 6.8	Latitude shift in rainfall in the Sahel 1982–2006.	76
Figure 6.9	Normalized trend in annual average *NDVI for the period 1982–2006.	77
Figure 6.10	Average annual maximum *NDVI 1982–2006.	77
Figure 6.11	Latitudinal shift in rainfall and maximum NDVI.	78
Figure 6.12	Normalized trend in maximum annual *NDVI , 1982–2006.	79
Figure 6.13	Average increment *NDVI 1982–2006.	79

Figure 6.14	Latitudinal shift in rainfall and annual increment *NDVI in the Sahel 1980–2006.	80
Figure 6.15	Normalized trend in annual increment *NDVI, 1982–2006.	81
Figure 7.1	Rain-normalized *NDVI averaged for 1982–2006 using three different indices for vegetation growth.	86
Figure 7.2	Trends in rain-normalized *NDVI for the period 1982–2006.	88
Figure 7.3	Variation in annual RNNDVI as a function of rainfall around 5 long-term (1982–2006) isohyets.	92
Figure 7.4	Variation in annual RNNDVI as a function of rainfall around 5 short-term (1982–1987) isohyets representing drier conditions.	93
Figure 7.5	Variation in annual RNNDVI as a function of rainfall around 5 short-term (2000–2006) isohyets representing wetter conditions.	94
Figure 7.6	Variation in RNNDVI as a function of rainfall the previous year analyzed for five rainfall levels (isohyets) 1982–2006.	95
Figure 7.7	Variation in RNNDVI as a function of rainfall the previous year analyzed for five rainfall levels (isohyets) for the dry period 1982–1987.	96
Figure 7.8	Variation in RNNDVI as a function of rainfall the previous year analyzed for five rainfall levels (isohyets) for the wet period 2000–2006.	97
Figure 8.1	Relative regional ranking of increment *NDVI 1982–2006 for all terrestrial pixels in the Sahel Parklands.	100
Figure 8.2	Relative regional ranking of rain-normalized increment *NDVI 1982–2006 for all terrestrial pixels in the Sahel Parklands.	101
Figure 8.3	Relative focal or neighbourhood ranking of increment *NDVI 1982–2006 for all terrestrial pixels in the Sahel Parklands.	102
Figure 10.1	Land Degradation Surveillance Framework sampling plot layout.	122
Figure 11.1	Map of Mali showing regions.	125
Figure 11.2	Areas with >100 persons km <sup>-1</sup> in 1960 and 2000.	126
Figure 11.3	Rainfall isohyets for Mali, showing locations of sentinel sites in the Segou Region.	127
Figure 11.4	Distribution of 50-year (1951–2000) monthly rainfall estimates for the Segou Region.	127
Figure 11.5	Mean annual rainfall in the Segou Region, (average 1951–1991) and distribution of 50-year monthly rainfall estimates for individual blocks.	128
Figure 12.1	Areas having less than 75% NDVI in 1984 relative to median annually integrated NDVI for 1982–2004.	130
Figure 12.2	Vegetation dynamics for the five blocks.	131
Figure 12.3	Trend surface for RNNDVI between 1982 and 2004, with sentinel site boundaries and flowpaths.	132
Figure 12.4	The T-square sampling procedure.	133
Figure 12.5	Measurement of tree height, DBH and density in Zebougou.	133
Figure 12.6	Spatial distribution of woody vegetation in the five blocks.	134
Figure 12.7	Estimates of shrub density in cultivated and semi-natural areas.	136
Figure 12.8	Cluster-level estimates of shrub biovolumes in the five blocks.	137
Figure 12.9	Woody cover ratings and estimated relative woody cover abundance.	137
Figure 12.10	Block-level predicted herbaceous cover scores in semi-natural and cultivated or managed areas.	138
Figure 12.11	Panorama view from Dianvola, October 2007.	138

Figure 13.1	Predicted probability of root depth restriction within 0–20 cm soil depth in semi-natural and cultivated areas.	140
Figure 13.2	Predicted probability of root depth restriction within 0–50 cm soil depth in semi-natural and cultivated areas.	140
Figure 13.3	Infiltration testing using single rings.	141
Figure 13.4	Predicted versus measured infiltration rates for each block.	142
Figure 13.5	Infiltration curves showing average for all blocks and individual block averages.	143
Figure 13.6	Infiltration curves showing average for plots with and without root depth restriction within 0–20 cm soil depth.	143
Figure 13.7	Raw and 1st derivative plots of near infrared soil spectra.	144
Figure 13.8	Measured soil organic carbon contents in semi-natural and cultivated or managed areas.	145
Figure 13.9	Diagnostic plots for the soil organic carbon SIMPLS model, and measured vs. predicted SOC content for the model-building data set.	146
Figure 13.10	Cluster level median soil organic carbon contents and upper and lower quartiles.	147
Figure 13.11	Estimated soil organic carbon contents in semi-natural and cultivated or managed areas, by block.	148
Figure 13.12	Summary of selected soil properties by NIR spectral-based soil condition class.	149
Figure 13.13	Probability of having poor soil condition in cultivated versus semi-natural areas.	150
Figure 13.14	Estimated probability of being in poor soil condition class based on Quickbird reflectance.	150
Figure 13.15	Estimated risk of being in poor soil condition class based on Quickbird reflectance.	151
Figure 13.16	Landsat ETM+ scenes used in development of regional soil degradation hot-spot map.	152
Figure 13.17	Map of Segou Region showing areas with >75% probability of being in poor soil condition class.	153
Figure 13.18	NIR-based vs. ETM-based soil condition indices.	153
Figure 13.19	Estimated risk of being in poor soil condition class based on Landsat reflectance.	154
Figure 13.20	Millet variety used in fertilizer response trials.	155
Figure 13.21	Fitted versus measured biovolume production for blocks in the fertilizer response trials.	156
Figure 13.22	Average growth response curves expressed as estimated plant biovolume for fertilizer treatments.	155
Figure 13.23	Estimated grain yields for fertilizer treatments by block.	158
Figure 13.24	Estimated straw yields for the various fertilizer treatments by block.	158
Figure 14.1	Selected identified priority reforestation clusters in Sokoura and Zebougou.	159
Figure 14.2	Priority intervention areas in cultivated or managed clusters in Monimpebougou.	162
Figure 14.3	Priority intervention areas in cultivated or managed clusters in Dianvola and Zebougou.	162
Figure 15.1	Socioeconomic indicators in the Land Degradation Surveillance Framework.	165
Figure 15.2	Well in Zebougou.	166
Figure 15.3	Estimated daily water use per person in the five blocks.	167
Figure 15.5	Estimated number of trees planted under the three incentive structures.	168
Figure 15.4	Vitellaria paradoxa leaves, flowers and fruit.	168
Figure A3.2.1	Summary of content and structure of the LDSF database.	186

# Table list

Table 2.1	Satellite-derived vegetation indices used in this study.	33
Table 2.2	Satellite data used in this study for further investigation of regional land degradation trends.	34
Table 3.1	Steps in communication of surveillance data.	38
Table 3.2	Ways of enhancing use of surveillance data and findings.	38
Table 3.3	Types of land health surveillance data and findings and examples of their uses at different scales.	39
Table 3.4	Examples of mechanisms for disseminating land health surveillance information.	43
Table 5.1	Geographical baseline data for countries included in the present study (for the year 2005).	58
Table 6.1	Spatial vegetation changes from *NDVI data in five Sahelian countries, 1982–2006.	81
Table 6.2	Spatial vegetation changes from *NDVI data in five Sahelian countries, 1982–2006: areas with average rainfall below 900 mm per year.	82
Table 6.3	Spatial vegetation changes from *NDVI data in the Parklands region in five Sahelian countries 1982–2006.	82
Table 6.4	Spatial vegetation changes from *NDVI data in the Parklands region, 1982–2006: areas with average rainfall below 900 mm per year.	82
Table 7.1	Changes in rain-normalized *NDVI, 1982–2006 restricted to areas with less than 900 mm in annual rainfall.	87
Table 7.2	Changes in rain-normalized *NDVI (RNNDVI) in the Parkland areas, 1982–2006: areas with less than 900 mm in annual rainfall.	89
Table 11.1	Summary of mean annual rainfall estimates by Sentinel Site.	128
Table 12.1	Estimated area under cultivation or management in each cluster for each of the five blocks.	132
Table 12.2	Estimated tree density in each cluster for the five blocks.	135
Table 12.3	Estimated shrub density in each cluster for the five blocks.	135
Table 12.4	Block-level average estimated area under dense woody cover.	136
Table 12.5	Block-level woody cover estimates based on Quickbird image classification.	138
Table 13.1	Estimated cluster-level frequency of root depth restriction within 0–20 cm soil depth.	140
Table 13.2	Estimated cluster-level frequency of root depth restriction within 0–50 cm soil depth.	140
Table 13.3	Estimated cluster- and block-level proportion of areas predicted to have high inherent soil degradation risk.	141
Table 13.4	Summary of soil physicochemical properties by block.	144
Table 13.5	Correlation and partial correlations for topsoil samples.	145
Table 13.6	Estimated cluster- and block-level proportion of areas predicted to be in poor soil condition class.	148

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Table 13.7	Overview of fertilizer response trial treatments.	155
Table 13.8	Estimated average maximum biovolume production per plant for fertilizer treatments.	157
Table 13.9	Average grain and straw yields across blocks.	158
Table 14.1	Estimated priority reforestation intervention area.	160
Table 14.2	Priority conservation agriculture intervention area for each cluster.	160
Table 14.3	Estimated number of trees ha <sup>-1</sup> to be planted in cultivated areas within each cluster.	163
Table 15.1	Basic summary of households surveyed in each block.	165
Table 15.2	Age and sex distributions of household members for each block	166
Table 15.3	Tropical livestock units assigned to different types of livestock.	167
Table 15.4	Ratio of tropical livestock units (TLU) to human population.	167
Table 15.5	Food grain purchase in each of the surveyed clusters.	167
Table 15.6	Tree species ranked by farmers as important in the five blocks.	169
Table 15.7	Estimated costs for sentinel site characterization.	169

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# Abbreviations and acronyms

ADDS	African Data Dissemination Service
AEJ	African Easterly Jet
AMMA	African Monsoon Multidisciplinary Analysis
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BLUPs	Best Linear Unbiased Predictors
CCD	Cold Cloud Duration
CI	Confidence Interval
CIA	Central Intelligence Agency
CoV	Coefficient of variation
CRRA	"Cinzana Agronomic Research Station, Mali"
DBH	Diameter at Breast Height
DNCN	"Directorate for Nature Conservation, Mali"
DPSIR	Drivers-Pressures-State/Trends-Impact-Response
EM algorithm	Expectation-maximization algorithm
EMC	Environmental Modelling Centre
ETM	Enhanced Thematic Mapper
ETM+	Enhanced Thematic Mapper Plus
EVI	Enhanced Vegetation Index
FAO	Food and Agriculture Organization
fAPAR	fraction of Absorbed Photosynthetically Active Radiation
fCFA	Central African franc
FEWS	Famine Early Warning System
GCM	Global Circulation Models
GDAS	Global Data Assimilation System
GDP	gross domestic product
GHCN	Global Historical Climatology Network
GIMMS	Global Inventory Monitoring and Modeling System
GLASOD	Global Assessment of Human Induced Soil Degradation
GLMM	Generalized Linear Mixed-effects Modeling
GLMs	Generalized Linear Models
GOES	Geostationary Operational Environmental Satellite
GPCC	Global Precipitation Climatology Centre
GPCP	Global Precipitation Climatology Project
GPI	GEOSS Precipitation Index
GPS	Global Positioning System

GSFC	Goddard Space Flight Center
GTS	Global Telecommunication System
HIDR	high inherent soil degradation risk
IER	"Institut d'Economie Rural, Mali"
IPCC	Intergovernmental Panel on Climate Change
IR	infiltration rates
ISRIC	International Soil Reference and Information Centre
ITCZ	Intertropical Convergence Zone
K	potassium
LAI	leaf area index
Landsat TM	Landsat Thematic Mapper
LDSF	Land Degradation Surveillance Framework
LME	linear mixed-effects models
MA	Millennium Ecosystem Assessment
MAP	mean annual precipitation
MASS	a statistical package in R
MD	Mahalanobis distance
MDGs	Millennium Development Goals
ML	Maximum Likelihood
MODIS	Moderate Resolution Imaging Spectroradiometer
MSAVI	Modified Soil Adjusted Vegetation Index
MS	multispectral
MSC	Multiplicative Scatter Correction
MVC	Maximum Value Compositing
N	nitrogen
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
*NDVI	Scaled NDVI
NDVI <sub>0</sub>	bare soil value of NDVI
NIR	near-infrared diffuse reflectance spectroscopy
NLME	non-linear mixed-effects
NOAA	National Oceanographic and Atmospheric Administration
NP	N and P together
NPK	N, P and K together
NPP	net primary production
OLS	Ordinary Least Square
P	phosphorus
PC	principal component
PCA	PC analysis
PLS	partial least squares
PNT	a natural rock phosphate fertiliser in Mali
PPT	precipitation
PQL	Penalized Quasi-Likelihood
QB	Quickbird

RDR	root depth restriction
RMSEP	root mean squared error of prediction
RNNDVI	Rain Normalized NDVI
RUE	Rain Use Efficiency
SAVI	Soil-Adjusted Vegetation Index
SC	soil condition
SCI	soil condition index
SD	standard deviation
SE	standard error
SFF	spectral feature fitting
SIMPLS	an algorithm for partial least squares regression
SOC	soil organic carbon
TEJ	Tropical Easterly Jet
TLU	tropical livestock units
TN	total nitrogen
TRMM	Tropical Rainfall Measuring Mission
UN	United Nations
UNCBD	United Nations Convention on Biological Diversity
UNCCD	United Nations Convention to Combat Desertification
UNCED	United Nations Conference on Environment and Development
UNCOD	United Nations Conference on Desertification
UNDP	United Nations Development Program
UNEP	United Nations Environment Program
UNESCO	United Nations Educational and Scientific Organization
US\$	US dollar
USA	United States of America
USAID	United States Agency for International Development
USAID-FEWS	USAID Famine Early Warning Systems
VASCLimO	Variability Analysis of Surface Climate Observations
VI	vegetation indices
WHO	World Health Organization
WMO	World Meteorological Organization
WRS	World Reference System
WUE	Water Use Efficiency
ZAB	Zaire Air Boundary



# Foreword

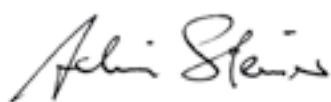
The land resource base supports many of the essential ecosystem services upon which mankind depends for survival and economic development. The Millennium Ecosystem Assessment and UNEP's Global Environment Outlook reports have provided strong evidence of the trade-offs between the ecosystem provisioning to meet immediate human needs, such as food and fibre, and the supporting and regulating services that are needed to support production and human well-being in the longer-term, such as climate and hydrological regulation and nutrient cycling.

The global dimensions of land degradation were recognized in the Rio+20 outcome document *The Future We Want*. Countries emphasized the economic and social significance of good land management, including soil, particularly its contribution to economic growth, biodiversity, sustainable agriculture and food security, eradicating poverty, women's empowerment, addressing climate change and improving water availability. There was deep concern expressed for the devastating consequences of cyclical drought and famine in Africa, in particular in the Horn of Africa and the Sahel region, with a call for urgent action through short-, medium- and long-term measures at all levels. Countries urged action

'to reverse land degradation' and "to strive to achieve a land degradation neutral world in the context of sustainable development'.

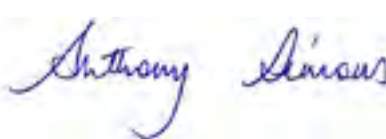
The publication makes a timely contribution towards *The Future We Want* by providing a framework for scientific, evidence-based land health assessment. The report lays down a set of scientific principles for land health surveillance, and illustrates how the principles can be translated into operational measurement systems using a wide range of technology from space platforms to the laboratory bench. A key strength of the framework is the use of standardized ground measurement protocols that are applied in the same way everywhere, and designed to work under the toughest conditions in Africa. The work is innovative in the way in which a range of scientific and technological tools is combined to provide rapid but reliable assessments of land condition.

We hope that the land health surveillance methods will be taken up as an integral part of development policy and practice. This would help to ensure that policy decision-making on sustainable land management is informed by a reliable evidence base on the state and trends in land health and on the impact of interventions.



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# Preface

Land degradation remains controversial because of the lack of scientifically objective and consistent methods for monitoring and assessing the problem. The lack of reliable data poses a fundamental bottleneck to sound development policy and for assessing progress towards goals throughout the developing world.

UNEP has been involved in land degradation assessment work for several decades and led the preparation of the *Handbook of Desertification Indicators*, published by the American Association for Advancement of Science in 1978. UNEP then published the *World Atlas of Desertification* in 1992, updated in 1997. Further synthesis and analysis of available data was provided under the Millennium Ecosystem Assessment (MA), published in 2006. However, the MA revealed a surprising lack of replicable data even at a basic level on changes in the condition of key ecosystems such as forests, croplands and wetlands. It concluded that one of the most critical needs for further information is an improved understanding of the factors governing the capacity of ecosystems to provide services, a message further reinforced by UNEP's Global Environment Outlook assessments. This report aims to help address this need, by illustrating a surveillance framework for science-based monitoring and assessment of land health—the capacity of land to sustain delivery of essential ecosystem services.

Land health surveillance borrows many scientific concepts and principles from the public health sector, where surveillance systems are well established and provide the main source of information for formulation and evaluation of public policy and practice. Many aspects of land degradation share similarities with chronic human disease problems, in terms of being persistent problems that are difficult and expensive to treat, and which emerge slowly in response to a complex web of proximal and distal drivers or risk factors. The intention has been to bring across much of the scientific rigour used in public health surveillance and apply it to land health.

A second key feature of this work has been to draw on latest developments in geoinformatics to build *operational* surveillance systems for systematic collection of data on land health and associated risk factors that can be applied in landscapes everywhere and replicated to national and regional

scales. While the emphasis of land health surveillance is to provide scientifically objective information on land health, the approaches and methods can complement and enhance efforts to develop local indicators that can be used by local communities to monitor land health.

Part 1 of this publication presents scientific concepts of land health surveillance and the methods and analytical approaches that are used to make surveillance operational. Part 2 presents a regional application of land health surveillance with a synoptic screening study of land degradation in the Sahel using historical changes in vegetation growth and rainfall patterns, based on remote sensing. Part 3, describes a sampling and measurement framework for field level assessment of land degradation based on a sentinel site surveillance scheme and illustrates its application in Segou Region in Mali. Part 4, draws out the implications of the methods and results for development policy and research and identifies priorities for further development and application of the land health surveillance framework. The final chapter provides succinct recommendations for policy action. The main findings of this report are illustrated in a separate summary for decision makers and further illustrated in *Sahel Atlas of Changing Landscapes: Tracing trends and variations in vegetation cover and soil condition*.

Systematic application of land health surveillance would provide a sound evidence base for planning intervention programmes aimed at improving land productivity while safeguarding the land resource base. Installing reliable surveillance systems now will be key to managing the increasing human pressures on land in developing countries. It is encouraging to see the methods being taken up by the Africa Soil Information Service and more recently the Ethiopia Soil Information System, as well as by an increasing number of agroforestry and other sustainable land management projects.



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# Executive summary

## BACKGROUND

Improving and maintaining land health – the capacity of land to sustain delivery of essential ecosystem services – is a prerequisite for wise ecosystem management and sustainable development. This is especially so in developing countries, where declining land health is threatening food security, poverty alleviation and national economies. However current information on land health and degradation is grossly inadequate for the task of planning and evaluating land management interventions. Policymakers and development agencies urgently need objective, quantitative, cost-efficient and practical assessments of land degradation and the associated risk factors to justify, target and prioritise investments. Land health surveillance is a science-based approach to land health assessment and monitoring designed to address this need. The approach is modelled on evidence-based approaches used in the public health sector, where surveillance is the main mechanism for determining public health policy and practice.

In Part 1 of this report, we present scientific concepts and analytical approaches of land health surveillance as a building block for operational systems that can generate and interpret data to inform decision-making for improved land health in developing countries. In Part 2 we illustrate a regional application of land health surveillance with a synoptic screening study of land degradation in the Sahel using historical changes in vegetation growth and rainfall patterns based on remote sensing. In Part 3 we describe a framework for field level assessment of land degradation based on a sentinel site surveillance scheme and illustrate its application in Segou Region in Mali. In Part 4 we draw out the implications of the methods and results for development policy and research and for further application of the land health surveillance framework.

## LAND HEALTH SURVEILLANCE CONCEPTS

Land health surveillance is a scientific conceptual framework and set of multiscale assessment tools aimed at enhancing land management as an integral component of development policy and practice. 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.

Land health surveillance places emphasis on acquiring statistically valid estimates of land health problems and quantification of key risk factors associated with land degradation. Scientific principles of land health surveillance include use of (i) case definitions of land health as a basis for diagnosis and management decision-making (ii) standardized measurement protocols so that results can be aggregated at different scales, (iii) random sampling schemes so that statistically valid statements can be made about populations of land sample units (e.g. prevalence of particular land degradation problems), including assessments of the uncertainty in results, (iv) an objective and documented method, which allows comparisons between times and places, and (v) a process that is open to criticism, rational assessment and improvement (unlike a subjective/expert opinion-based method, where differences of opinion just remain as that). This information is then used for targeting interventions to reduce and reverse risks. Surveillance systems are implemented as an integral part of policy and practice, and used to measure intervention outcomes. Surveillance systems adopting these principles are routinely used in the public health sector but have not yet been applied to land health management.

The implementation of land health surveillance harnesses 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 method places emphasis on rapid, systematic collection, analysis and interpretation of empirical data on land condition and human well-being, and the use of this information to guide decision making on land management at a range of scales. Surveillance includes strategies for active dissemination of surveillance findings to ensure their use and to assess their impact.

## **REGIONAL SURVEILLANCE IN WEST AFRICA SAHEL**

A land health surveillance study was conducted in the West Africa Sahel with the objectives to (i) synthesize existing knowledge from satellite-derived studies on land degradation in the Sahel, and (ii) develop a synoptic screening method to identify areas with anomalous vegetation degradation or recovery patterns from available satellite data for the period 1982–2006. The results are discussed in the context of previous studies and debates on desertification trends in the Sahel, including technical limitations associated with remote sensing and climate data.

Debates on the degree, extent and causes of desertification in the Sahel have persisted for almost a century and still remain unresolved. This uncertainty impedes policy development for sustainable land management. During the Sahel drought period in the 1970s and early 1980s, the “equilibrium” hypothesis on Sahelian desertification dominated, pointing to internally driven land degradation caused by human activities leading to loss of vegetation, particularly through over-grazing. From the mid 1980s a “non-equilibrium” hypothesis developed, based on dynamic ecological theories and better understanding of the climate system: the climate system was blamed for exerting abiotic external forcing, and depicting humans as more the victims responding to external changes. However from 2000, the idea of internally driven degradation has regained support and a merging of the two concepts has emerged, emphasizing feedback effects between climate change and land management. With the current understanding, while long-term climate fluctuations are recognized as inevitable, maintaining vegetation plays an important stabilizing role, by localizing rainfall and stabilizing rainfall levels between years, until a gradual change causes a new vegetation and rainfall regime to dominate. However, large decreases in vegetation can reduce resilience and lead to a change to a drier climate regime.

An indicator of land degradation was derived from an index of annual vegetation growth based on long-term (1982–2006) satellite-derived (Advanced Very High Resolution Radiometer) data, normalized for annual rainfall differences. The index was designed to minimize problems with previously reported indicators due to interference from soil signal and sensitivity to temporal and spatial

changes in vegetation type. Most recent previous studies using this type of data have concluded that vegetation cover has improved in the Sahel (a greening trend) in response to increased rainfall since the severe droughts that occurred in the early 1980s. Further studies have attributed greening in part to improvements in agricultural practice. Due to differences in methods, our results contrast with most previous studies: we found evidence for widespread land degradation in the Sahel, masked by the increase in rainfall and the general increase in vegetation growth since the early 1980s. Vegetation growth has not responded to the increases in rainfall as much as expected in most areas, indicating incipient desertification. In regions with average annual rainfall below 900 mm, 50% of the total area (2.0 million km<sup>2</sup>) showed a significant decrease in rainfall-adjusted vegetation index at a 95% certainty level. There was a trend for less degradation in the Parkland areas, located between 11° N and 18° N, than surrounding areas, indicating resilience of this tree-crop-livestock system and the importance of maintaining it for the environmental stability and economic development of the region.

There were indications of improved land health in agriculturally dominated areas in southern parts of Mali, Burkina Faso and Niger, which could be due to improved agricultural management, but there was little evidence to support large area impacts of agricultural innovation in the central plateaux of Burkina Faso. Other areas showing improvement in rainfall-normalized vegetation index are restricted to areas along the Senegal River in both Mauritania and Senegal, probably reflecting increase in irrigated agriculture. The indication of widespread land degradation in the Sahel raises a critical need for more detailed and systematic follow-up studies to validate and interpret the trends and establish causal factors, using higher resolution time-series satellite data and field survey.

## **SENTINEL SITE SURVEILLANCE IN SEGOU REGION, MALI**

A surveillance framework for field measurement of land health in landscapes is described and illustrated in Segou Region, in Mali. The Land Degradation Surveillance Framework is a standardized protocol for measuring vegetation, soil and socioeconomic conditions in landscapes, that follows the scientific surveillance principles laid down in Part 1. The framework employs a scale hierarchical sampling frame, designed to be logistically efficient in terms

of field sampling, with measurements taken on 100 m<sup>2</sup> sub-plots within 1,000 m<sup>2</sup> plots, which are randomized within 1 km<sup>2</sup> clusters, which are in turn nested within 100 km<sup>2</sup> sentinel sites. The standardized sampling and measurement protocol permits data on land degradation indicators and risk factors to be aggregated at various scales, including across sentinel sites, allowing statistically valid inferences to be made about land health. This is done using hierarchical statistical methods that provide powerful inference. Key indicators of land health, such as woody cover and soil condition, are also statistically calibrated to satellite imagery and digitally mapped at fine to medium spatial resolution (2–30 m). Simple rule models are then used to spatially target land management interventions to specific land health constraints. The sentinel site surveillance protocol can be used for assessing baselines and monitoring land health at regional, national, or sub-national levels, and for project impact assessment.

Application of the protocol in Segou Region in Mali used five sentinel sites to sample conditions from cultivated agro-ecosystems in the south of the region to predominantly pastoralist systems in the north. Population density in this area has more than doubled over the past 40 years, but 80% of the population between 15 and 65 years old are still illiterate and primarily depend on agriculture for their livelihoods.

Average woody cover (trees and shrubs) ranged from less than 4% in blocks with least cover to 15–40% in the block with most cover, tending to increase with increasing rainfall. There was large local variation in woody cover, indicating biophysical opportunity for targeted tree planting efforts to help maintain the Parkland system. The surveillance data provided a basis for establishing woody cover targets and identifying areas for reforestation. Contingency valuation surveys showed strong farmer interest in tree planting for a variety of uses, but that adoption levels are sensitive to the cost of seedlings.

Soil fertility levels are critically low for crop production in Segou Region. Soil tests indicate that about 80% of the samples have soil organic carbon lower than 5 g kg<sup>-1</sup>, 98% of the soils are P-deficient, while about 50% are potassium deficient. We provide statistical evidence that cultivation practices have depleted rather than improved soil fertility, posing a severe threat to food security in the region.

Crop responses to N-P-K fertilizers were found to be small, despite the acute nutrient deficiencies, and soil organic amelioration will be required for cost-effective fertilizer use in many cases. Scope for expanding cultivation into semi-natural areas is extremely limited without further damaging ecosystem services, especially water and erosion regulation. Farmers have already selected the better soils for cultivation and remaining areas have low saturated infiltration capacity and high soil erosion hazard, associated with a high prevalence of soil depth restrictions within the surface 50 cm.

There is potential for enormous increases in cost-effectiveness through spatial targeting and prioritization of land management interventions compared with blanket recommendations. Areas targeted for woody cover restoration in semi-natural area cover 19–42% of the landscape, but less than 5% of the area has high inherent soil degradation risk, which should be accorded highest priority for environmental protection. Cultivated areas with low soil fertility but free of inherent soil physical constraints, which should be prioritised for integrated soil fertility management, make up only between 7% and 21% of the area of the region. The sentinel site surveillance scheme demonstrated how multi-scale land health surveillance can be made operational and the potential of evidence-based land health surveillance for increasing efficiency through intervention targeting.

## CONCLUSIONS

Land degradation poses a very real threat to sustainable development in the West Africa Sahel. This study has revealed an incipient trend of land degradation across the region and a crisis in Segou Region in terms of the critically poor and degraded state of soil health in the areas most suited for agricultural production. If the conditions in Segou Region are found to be common across the Sahel, the prognosis for food security is dire. Evidence-based approaches for managing the land resource base are needed to target cost-effective interventions and assess outcomes, to speed reliable learning and increase efficiencies.

The multiscale land health surveillance methods demonstrated here provide a scientific approach for evidence-based decision making on land management and should be as an integral part of development policy and practice in tropical developing countries. Regional synoptic screening

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for early warning and outcome monitoring should take advantage of new, multi-spectral, multi-temporal, moderate spatial resolution imagery and hinge development of new land degradation indicators on systematically collected ground data.

Risk factor surveillance should be operationalized using the sentinel site surveillance scheme demonstrated here, to quantify the burden of land degradation attributable to major modifiable risk factors. These data will provide a sound basis for the design of population-wide preventive interventions targeted at reducing and reversing these risks. At the same time there is a need to begin systematic collection and standardized analysis of data on the cost-effectiveness of interventions for the

prevention and treatment of land health problems and their risk factors, so that policy makers and planning departments have a rational basis for resource allocation. Once intervention programmes are designed, sentinel site surveillance can provide a scientifically sound and efficient approach for systematic intervention testing and project impact assessment. Land health surveillance implies a new and revitalized role for land resource departments and requires capacity building in the new surveillance scientific concepts, technologies and tools. These investments must be made as an integral part of national and regional strategies for economic development, poverty reduction, environmental management, and climate change adaptation and mitigation.

# **PART 1**

## **GENERAL CONCEPTS AND ANALYTICAL APPROACHES**

*Keith D Shepherd, Tor-Gunnar Vågen,  
Thomas Gumbricht, and Markus G. Walsh*

# Summary

## **SURVEILLANCE PRINCIPLES**

We define land health as the capacity of land to sustain delivery of essential ecosystem services (the benefits people obtain from ecosystems). Improving and maintaining land health is a prerequisite for wise ecosystem management and sustainable development everywhere. However, especially in developing countries, declining land health is threatening food security, ecosystems management, climate change adaptation, and poverty alleviation. Unfortunately, essential information on land health needed to guide wise decision-making on trade-offs among ecosystem services is poorest where it is needed most, in developing countries. In Part 1 we lay out scientific concepts and analytical approaches of land health surveillance as a building block for operational systems that can generate and interpret data to inform decision-making for improved land health in developing countries.

Land health surveillance is a scientific conceptual framework and set of multiscale assessment tools aimed at enhancing land management as an integral component of development policy and practice. First conceived by the World Agroforestry Centre, the framework 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 improved ecosystem and climate management and 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.

Scientific principles of land health surveillance include an emphasis on the health of *populations* of sample units rather than on individual units; sampling designs to enable inferences to be made about populations; standardized protocols for data collection to enable statistical analysis of patterns, trends, and associations; case definitions based on diagnostic criteria; rapid low cost screening

tests to permit detection of cases and non-cases in large numbers of samples; measurement of the frequency of health problems in populations; measurement of association between health problems and risk factors using statistical models; meta-analysis of these data as the primary source of information of design of public policy and land health programmes; statistically rigorous evaluation of intervention impacts; and integration of these principles into operational systems as part of regular policy and practice.

## **SURVEILLANCE IMPLEMENTATION**

The implementation of land health surveillance harnesses 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 method places emphasis on rapid, systematic collection, analysis and interpretation of empirical data on land condition and human well-being, and the use of this information to guide decision making on land management at a range of scales. In this case study, land health surveillance is implemented at two main levels of scale: regional surveillance, employing long-term satellite data at coarse spatial resolution (8 km) over a regional extent (West Africa Sahel); and sentinel site surveillance, which employs ground sampling in conjunction with remote-sensing imagery at fine to medium spatial resolution (2–30 m pixel size).

Regional surveillance is designed to identify degraded areas and provide early warning of land degradation, so that these sites can be screened for further investigation. Vegetation indices extracted from remote-sensing data are used as an indicator of land degradation after controlling for temporal and spatial variations in rainfall. Differences in amount of vegetation are generally a good indicator of degradation in semi-arid areas, because vegetation growth is constrained by climatic potential and at the same time strongly influenced by management. Due to various limitations with remote-sensing data, ground observation and monitoring are required to validate and interpret trends.



Sentinel site surveillance is designed to provide accurate baseline data and monitoring of land health and factors affecting it. Sentinel sites are selected to represent the diversity or specific groups in a population. In this study, sentinel sites are 10 x 10 km blocks, within which randomized sample plots are used for characterization of vegetation and soil characteristics and as sample points for collecting data on people and livestock. A hierarchical, stratified random sampling scheme is used to avoid bias in locating plots or households within sentinel sites.

At sentinel sites, a standardized field measurement protocol is used, based on rapid, quantitative, repeatable, and interpretable measurements of indicators of land health and human well-being. Soil samples taken from the plots are analysed in the laboratory using a new low-cost, high-throughput technique: infrared spectroscopy. With this approach spectral signatures of light reflected off soil samples are used to provide estimates of soil fertility indicators and soil organic carbon. Soil fertility indices determined at the georeferenced sample points are calibrated to reflectance values derived from fine resolution satellite imagery at the same ground locations. The resulting statistical models are used to predict values for each pixel in the image and digitally map out soil fertility indicators. Woody vegetation cover and other environmental variables are also extracted directly from the images using specialized algorithms. Hierarchical statistical analytical methods are used to analyse risk factors at different levels of scale and to generalize findings for the population of sentinel sites. This allows wider area (e.g. 100 km) mapping in conjunction with satellite imagery at medium spatial resolution (30 m). Land management interventions are then spatially targeted, using simple rule-based models, in relation to land health indicators such as woody vegetation cover and inherent soil degradation risk.

The sentinel sites provide a spatial framework for systematic intervention testing and provide for powerful statistical inference on intervention

performance in relation to environmental and socioeconomic factors. The sentinel site surveillance scheme also provides a scientific framework for measuring impacts of interventions and projects through repeat sampling after a number of years (e.g. five to ten years).

## **COMMUNICATING SURVEILLANCE DATA**

Surveillance is intended to provide information for action and therefore data must be presented in a way that facilitates their use in practice. Experiences with communicating surveillance information in public health are reviewed to provide guidance on communicating land health surveillance information. The communication process, including involvement of target audiences and evaluation of impacts, is time-consuming and costly and requires a different set of skills from those needed to collect and analyse surveillance data. For this reason, it is best to have specialist knowledge brokers on surveillance teams to lead this vital component.

Communications research in the public health sector has shown that many of the most commonly used approaches to keeping practitioners informed have minimal impact or give mixed results, and that more active dissemination strategies are required to get guidelines used. How best to communicate surveillance and research findings in developing countries still needs much local research.

Information technology will play a pivotal role in land health surveillance systems in developing countries. There is increasing use of digital means for gathering and storing information coupled with the use of internet and mobile phone technology, which is transforming access to information in remote rural areas and educational establishments. These developments present a significant opportunity to catalyze progress through re-use and re-purposing of data. Examples of types of land health surveillance information, and their uses at different scales and dissemination mechanisms, are presented.

# Land health surveillance concepts

## LAND HEALTH, ECOSYSTEM SERVICES AND HUMAN WELL-BEING

Human actions in the past 50 years have altered ecosystems on a global scale to an extent and degree unprecedented in human history, which has led to the decline in many ecosystem services with negative impacts on human well-being, especially in developing countries (UNEP, 2007; 2012). The resilience of many ecosystems is likely to be exceeded this century by an unprecedented combination of climate change, associated disturbances (e.g. flooding, drought, wildfire, insects, ocean acidification), and other global change drivers (e.g. land-use change, pollution, over-exploitation of resources) (IPCC, 2007).

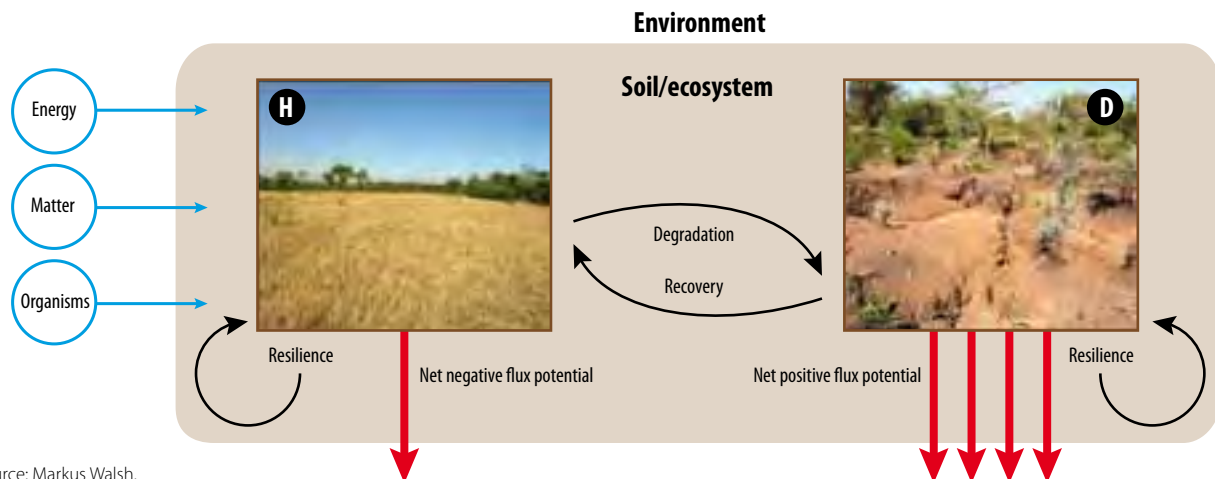
Land is a basic component of terrestrial ecosystems, and also strongly influences the health of inland water and marine ecosystems. We define land health as *the capacity of land to sustain delivery of essential ecosystem services* (the benefits people obtain from ecosystems). Ecosystem services are well described by the Millennium Ecosystem Assessment (MA 2003). Human well-being is directly dependent on provisioning services of land, such as food, fibre and fuelwood. Human well-being is also indirectly dependent on regulating and supporting services that underpin the functioning of terrestrial ecosystems, such as regulation of climate, water, and erosion; and support from primary production nutrient and water cycling. Freshwater quantity and quality, for example, is intimately linked to land health and management, to the degree that most land management decisions impact on water management decisions (Comprehensive Assessment of Water Management in Agriculture, 2007). Impairment of land health, or land degradation, is a long-term loss of ecosystem function and services, caused by disturbances from which the systems cannot recover unaided (UNEP, 2007). Resilient ecosystems are less likely to switch to a degraded state in response to variation in environmental and management conditions. State and transition models have been extensively used, for example in rangeland management (Bestelmeyer, 2006), to represent ecosystem state transitions and as an aid to management (Figure 1.1).

Land degradation ranks with climate change and loss of biodiversity as a global threat to habitat, economy and society and is the overarching environmental issue of concern in Africa (UNEP, 2007). It has both direct and indirect impacts on human well-being and

**FIGURE 1.1**

A soil health state-and-transition diagram. “Healthy” (H-type) soil systems are differentiated from “degraded” (D-type) systems on the basis of cumulative energy, matter and organisms flows across the system boundary up to a particular point in time. Both H & D states may be resilient (capable of maintaining internal structure and function over a finite range of environmental and management conditions before switching states). Switches between states are

designated as “degradation” or “recovery” processes, respectively. Management would seek to maintain or increase the resilience of H-state systems (prevention) and decrease the resilience of D-state systems (restoration). Downward arrows show relative magnitudes of losses of energy and matter from the systems. In practice there may be more than one state and the simplest case is shown.



Source: Markus Walsh.

human health through loss of essential ecosystem services. Local scale effects of land degradation include reduced plant production, and losses of soil organic matter, nutrients, and soil water infiltration and storage capacity. These are the result of land degradation processes, including degradation in vegetation cover and quality through over-use, and soil degradation, though erosion, nutrient depletion, physical degradation, salinity, and pollution. Higher-scale effects of land degradation include disruption of hydrological and nutrient cycles, leading to poorer water quality and supply; sedimentation causing siltation of dams, affecting electricity generation, and damage to irrigation schemes; and dust storms affecting human health in cities. Tropical deforestation and degradation of woodlands in dry tropical areas, rangeland degradation, and nutrient depletion in cropland pose serious problems for developing countries.

When land degradation processes combine to affect large areas of drylands, desertification occurs (UNEP, 2007). Over the next ten years, desertification could displace 50 million people, particularly in Sub-Saharan Africa and South Asia, resulting in additional pressure on adjacent ecosystems and on developed countries (Adeel et al, 2007). Land degradation is both a cause and consequence of climate change. Consequently, avoided land degradation and improved land

management are important strategies for climate change adaptation and mitigation (IPCC, 2005).

Poor countries and poor people are particularly vulnerable to land degradation because their livelihoods depend directly on the ecosystem services that land provides. Over the next several decades, rapid population growth and economic development in these regions will create much increased demands on ecosystems. For example, a doubling of global food production will be required by 2050 to meet the Millennium Development Goal on hunger, at a time when increased demand for land from urbanization, biofuel production and conservation will also occur (UNEP, 2007; 2012). These demands will drive rapid land use change and could result in unsustainable land management practices and widespread land degradation. On the other hand, improving agricultural productivity in developing countries has been identified as an essential strategy for poverty alleviation (World Bank, 2007). Thus, improving land health is a prerequisite for wise ecosystem management and sustainable development and poverty alleviation in developing countries. It is therefore imperative that adequate measurement systems are in place to guide and evaluate land policy and management interventions in developing countries.

## EVIDENCE-BASED DECISION MAKING ON LAND HEALTH

It is a striking fact that, at a time that mankind is exploring the solar system, current information and measurement systems on land health and land degradation are completely inadequate for the task of planning and evaluating land health policy and practice; this capability is least where land health problems are greatest – in developing countries. Billions of dollars of development aid and public funds have been spent on programmes and projects to improve land health in developing countries, but with limited targeting in relation to degree and extent of land degradation and the types of degradation processes operating; and mostly without scientifically sound evaluation of intervention outcomes. Science-based reliable learning processes can speed human development.

The only comprehensive global source of information has been the Global Assessment of Human-induced Soil Degradation (Oldeman et al, 1991), which has been widely cited but was compiled from expert judgement and is not reproducible (UNEP, 2007). The Millennium Ecosystem Assessment (MA, 2003) recognizes that one of the most critical needs for further information is an improved understanding of the factors governing the capacity of ecosystems to provide services, and the ability to provide advanced warning of when the capacity of ecosystems is beginning to be eroded or thresholds are likely to be reached, so that preventive action may be taken before significant adverse trade-offs have occurred. UNEP's Global Environmental Outlook (UNEP, 2007) recommends effective early warning, assessment and monitoring as one of the key responses for dealing with desertification. However, nothing comparable to the surveillance systems established by the World Health Organization exists for monitoring land health problems (e.g. WHO, 2003).

Currently few if any developing countries have operational systems that are capable of answering basic questions such as:

- Where is degraded land located and what are the specific degradation processes to be overcome?
- Which areas are at risk of degradation that could lead to a sudden decline in ecosystem services and should be targeted for preventive action?
- What are the socioeconomic and biophysical determinants of land degradation that may point to effective intervention levers?
- Which areas should receive priority for

land rehabilitation in relation to ecosystem vulnerability and what types of intervention strategies are required?

- What is the cost-effectiveness of alternative intervention strategies to reduce and reverse land health risks?
- What are the costs and benefits of land rehabilitation under different circumstances?
- Where are there opportunities for avoiding land degradation as a climate change mitigation strategy?
- What are the national trends in land degradation and what impact are intervention programmes achieving?

At a more detailed level, examples of relevant questions are:

- What proportion of the watershed should be under protective vegetation cover to stabilize the system?
- What is the prevalence of key soil constraints in an area for crop and pasture production?
- Where are semi-natural areas located and which areas have high priority for reforestation in terms of degradation risk?
- Which areas are unsuitable for cropping due to inherent soil physical constraints?
- How much carbon could be sequestered through improved land use and where are the biggest gains to be made?
- How much cultivated area is critically deficient in soil available phosphorus, and what measurable project target could be set for overcoming the deficiency? How will we measure degree of achievement of this target?
- Where are soil organic matter levels critically low for efficient use of mineral fertilisers?

Our currently inability to answer these types of questions stems from a lack of scientific rigour integrated into current land health practice. Lack of well-designed and systematic data collection on land health has resulted in limited information on which to base evidence-based decision-making on policies, programmes and practice related to land health. This problem is endemic across fields such as natural resource management, agronomy and soil science. For example, broad scale land resource surveys were conducted during the 1950s–1970s in many developing countries but there has not yet been a move to soil monitoring systems centred on properties that are relevant to soil management (Young, 2000). As a result it has been impossible

to assess prevalence of land health problems and quantitatively assess socioeconomic and biophysical determinants of land degradation. The lack of consistent historic data on land condition has also compromised our ability to forecast future trends in land degradation. In agronomic programmes, field trials to test land management interventions are rarely conducted at multiple locations using standardized protocols, precluding use of meta-analysis to combine evidence across studies, for example to establish factors associated with risk of success or failure. Few development projects aimed at land improvement have acquired baselines on land condition at the start of the project and monitored subsequent project impacts in a scientifically defensible manner. Consequently there is little reliable learning on what has worked, or not worked, and why.

This situation contrasts sharply with the situation in the public health sector, where health surveillance provides the information base for public health decision-making (Teutsch and Churchill, 2000). In public health, accurate measuring and monitoring of changes and improvements in the health of populations is closely integrated with statistical methods to form a scientific basis for policy development, priority setting and management (Stroup and Teutsch, 1988). Land health is just as important as human health in determining future human well-being, and therefore there is a public responsibility to apply the same degree of scientific rigour to land health. Many of the same complexities of quantifying land health problems also exist in public health, and so degree of complexity is not a valid excuse for lack of scientific rigour. For example, like land health problems, human health problems are associated with a range of social and environmental (physical, biological, social and economic) determinants, by personal health behaviour, health care services, etc. Many public health problems are also typified by long time lags between cause and effect, and are due to a complex web of proximal and distal risk factors. This complexity has not prevented quantification of the effects of behaviour, health status and policies on public health risk. To help close the gap between scientific rigour in public health practice and land health practice we have developed the concept of land health surveillance. The scientific conceptual and statistical approaches in land health surveillance are closely modelled on those employed in public health, although the concept of land health itself is not directly equated with human health.

## LAND HEALTH SURVEILLANCE

Our definition of surveillance is modelled on the definition used by the Centre for Disease Control (described in Brookmeyer and Stroup, 2004).

*Land health surveillance is the ongoing, systematic collection, analysis, and interpretation of data essential to the planning, implementation, and evaluation of land management policy and practice, and application of these data to promote, protect, and restore land and ecosystem health. A surveillance system includes a functional capacity for data collection, analysis, and dissemination linked to land health programmes.*

Emphasis is placed on data collection as an ongoing and systematic activity integrated into practice, as opposed to ad hoc external assessment conducted by scientists. The definition requires an ability to identify land units in the population that are at risk of experiencing preventable or controllable land degradation outcomes and not just degraded land. Surveillance explicitly includes the application of the data to prevention and control of land degradation, so that the responsibility does not end with information dissemination. We take environment and development policy and practice to include aspects such as improving ecosystem management, increasing agricultural productivity for poverty alleviation and food security, and strategies for climate change adaptation and mitigation through improved land management. Surveillance aims to ensure that information is provided in a form that addresses the needs of various environment and development stakeholders. However, surveillance excludes actual research and implementation of delivery programmes.

The surveillance framework incorporates the critical need to ensure functional capacity to generate relevant and specific information on land health and degradation *as an integral part* of national planning processes. Environmental assessments are commonly based on published scientific literature and international data sets and are conducted by organizations and scientists that are external to the decision-making processes of national public policy. Because decision makers are not directly connected to the assessment, they often make limited use of the information. In addition, because the data are not collected on the ground in the countries concerned they are usually inadequate for practical and effective planning for prevention and control of land degradation. Establishment of surveillance systems could provide an effective pathway to

closing the widely acknowledged science-policy gap, by integrating science with practice to provide evidence-informed policy making.

In broad terms land health surveillance information tells us:

- Where land problems exist.
- Whom they affect.
- Where programmatic and prevention activities should be directed, and
- How well they are working.

In more specific terms, land health surveillance has several functions, including to:

- Identify land health problems.
  - Assess and monitor land health status.
  - Quantify determinants of land degradation and sustainable land management.
  - Provide early warning of land degradation.
- Establish quantitative objectives for land health promotion.
  - Specify immediate control objectives for prevention of land degradation.
  - Specify longer-term objectives for land rehabilitation.
- Provide information for the design and planning of land management intervention programmes and resource allocation priorities.
  - Spatially target land management interventions.
  - Prioritise intervention areas in terms of risk and vulnerability.
- Determine the impact of specific interventions.
  - Establish baselines and measurement protocols.
  - Monitor outcomes.
- Identify research, service and training needs for different stakeholder groups.

Some essential aspects of methods employed by health surveillance are:

- A focus on the health of *populations* rather than individuals.
  - Surveillance is concerned with the health of the population, measured by health status indicators. A population is a collection of units from which a sample may be drawn. In public health sampling, units are normally people, but can also be institutions, records or events (Last, 2001). In land health surveillance we generally define the sampling unit is a fixed area of land

(e.g. satellite pixel, field sampling plot, or soil auger hole of fixed area). This concept is a departure from most previous land assessment work, where sampling units are often not rigorously defined, or are of inconsistent size, which causes problems in statistical analysis. However, the fixed area sample unit concept can be extended to sample other types of land units (such as watersheds, river basins, agro-ecological zones, districts, or countries).

- Target sub-populations may be defined, such as a population of land units that are at high risk or etiology of a specific land health problem. Interventions may, however, also target specific land user groups or institutions.
- Sampling designs.
  - A sample of units that make up the target population is used and is taken to be representative of that population. The goal is to make inferences from the sample to the population. Surveillance commonly uses different types of sampling design. Probability (random) sampling designs are used to avoid bias, but convenience designs may be used to take advantage of data collected for other purposes (e.g. data from testing laboratories). Probability sampling allows standard errors and Confidence Intervals to be calculated and hypotheses to be tested.
  - Sentinel surveillance uses selected samples chosen to represent the diversity in a population. Case definition and protocols are used to ensure validity of comparison across times and sites despite lack of statistically valid sampling.
  - Standardized protocols for data collection.
    - The application of standardized protocols and methods for measuring health problems that are consistently applied over locations and time is fundamental for statistical analysis of health patterns, trends and associations. This has rarely been achieved in land assessment.
  - Case definitions of health problems.
    - A case definition is a set of diagnostic criteria that must be fulfilled in order to identify a sample unit as a case of a particular problem. Health problems generally exist as a continuum of severity, and for practical reasons the diagnostic continuum is dichotomized into 'cases' and 'non-cases', or 'affected' and 'non-affected' to aid decisions on interventions.

Case definitions may be based on observations, laboratory criteria, a combination of both, or a scoring system with points for each criterion that matches the features of the health problem. This is probably the area that land assessment has fallen down on the most: rigorous case definitions for what is or is not degraded have rarely been applied beyond specialist studies (e.g. salinity problems). Averages alone, the summaries so often presented, offer little to decision guidelines. Recent trends towards community-based monitoring using local indicators, while worthwhile for local understanding, have reduced attention on application of standardized case definitions.

- Dichotomising a continuous variable necessarily involves information loss. So a principle should be to keep the continuous indicators in the analysis as long as possible, only converting to the dichotomous definition at final presentation, and then only if it is necessary.
- There is a widely held perception that land health problems are more difficult to define and diagnose than human health problems. In fact, in surveillance the 'normal' case is rarely known, and most attention is directed to detect passing limits based on observed or expected patterns (Lawson and Kleinman, 2005). These limits may be fixed or may depend on the status of ancillary variables (e.g. time of year). Too little attention has been paid to establishing expected patterns in land health based on systematic measurement. For example, it is currently impossible to establish, say, an average infiltration capacity for crop lands in Africa, let alone to show how values are influenced by factors such as vegetation type, soil type and presence of cultivation. Land health surveillance gets away from use of vaguely defined concepts and expert opinion assessment of land health.
- Screening tests.
  - Rapid, low cost screening tests are needed to allow rapid assessment of large sample numbers in surveys and assign samples as affected (case) or non-affected by a particular health problem. An example is use of infrared spectroscopy as a screening tool for assessing soil health (Figure 1.2). Socioeconomic variables will often be included in the schema.
  - Further diagnostic tests are commonly applied to confirm a diagnosis. Screening tests are

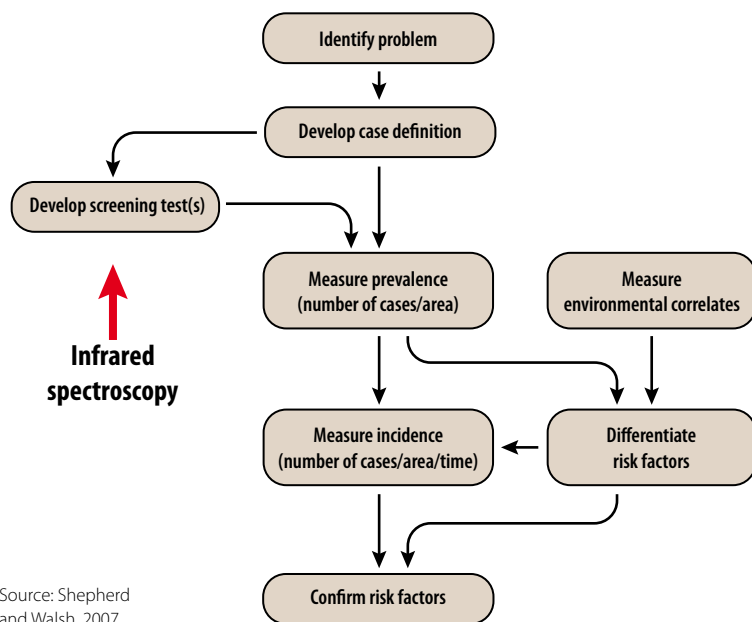
designed to sort out apparently unhealthy samples (i.e. suspected cases) that probably are affected by a particular problem from samples that probably are not affected (suspected non-cases). Error associated with the screening test may produce false positives (or false negatives), and samples screened as affected may be subjected to further tests or bioassays to confirm a diagnosis (confirmed case). For example, a soil infrared spectral scan may indicate available soil phosphorus deficiency, but a crop response trial may be required to confirm the diagnosis.

- Screening tests may be used to provide an operational case definition for some health problems, whereby an arbitrary cut-off value of the screening test is used as a decision threshold for treatment.
- Measurement of frequency of health problems in populations, such as prevalence and incidence.
  - Prevalence is the number of instances of a particular health problem in a population at a given time. Few unbiased prevalence data exist on land health problems (e.g. prevalence of strong soil acidity or degraded rangeland in a country). Prevalence (or cross-sectional) studies examine the relationship between health problems and other variables, as they exist in a defined population at one particular time (see Figure 1.2).
  - Incidence is the number of new instances of a particular health problem during a given period in a specified population. Incidence data is needed to confirm risk factors for the development of a problem (see Figure 1.2).
- Measurement of association between health problems and risk factors using statistical models, including significance testing and Confidence Interval estimation.
  - Association between occurrence or development of a health problem and risk factors (or determinants<sup>1</sup>) are established quantitatively, and this is a key goal of many surveillance systems (e.g. behavioural risk factor surveillance systems). Establishing the distribution and determinants of risks to health in a population is the key to prevention and is used to guide population-based strategies that lower risk in the entire population. Assessing

1 Alternative terms include: explanatory variables, predictors, covariates, independent variables, and exposure variables.

**FIGURE 1.2**

Example of use of infrared spectroscopy as screening tool for surveillance of soil health problems.



Source: Shepherd and Walsh, 2007.

Steps in surveillance approach:

- The specific agricultural or environmental problem is identified.
- A rigorous case definition to define 'affected' and 'non-affected' states is developed.
- A screening test (or set of tests) is developed to be able to rapidly assign subjects to 'affected' or 'non-affected' states. Infrared spectroscopy can play a key role as a screening tool for identification of cases.
- The screening test is applied to subjects in randomized sampling schemes designed to provide unbiased prevalence data on the specified problem.
- Simultaneous measurement of environmental and socio-economic correlates permits problem risk factors to be identified. Controllable risk factors point to the main management levers for controlling the problem.
- Risk factors are confirmed through follow-up surveys that measure changes in the problem over time (incidence) and assess intervention impacts. Assessment of impacts may lead back to a new or refined problem definition.

the distribution of health risk factors by poverty level is an important goal.

- Risk factors are attributes that are associated with an increased probability of a specific health problem or outcome, but do not necessarily imply a causal link. Risk factors can be biophysical or socioeconomic factors or exposures, and can include behavioural as well as inherent characteristics. Protective as well as hazardous risk factors are also considered. As an example from the public health sector, the World Health Report 2002 has identified the risk factors that are most important for predicting future disease burden. We do not yet have an equivalent analysis for land health.
- Modifiable risk factors, which are factors that can be controlled or influenced, are of most interest as they identify areas for action to overcome a health problem. They include health behaviours (e.g. type of land management), health status (e.g. state of degradation), and policies (e.g. land tenure policy). Non-modifiable risk factors are often important conditioning variables (e.g. climatic zone, soil type).
- Distal determinants or risk factors are remote or far in position, time or resemblance to the health problems; whereas proximal determinants are nearest in time and/or distance to the occurrence of a health problem and more

likely to have well-defined causal linkage to the problem. There is equivalence with 'drivers' and 'pressures' in the Drivers-Pressures-State/Trends-Impact-Response (DPSIR) assessment framework used by UNEP (2007) and 'indirect' and 'direct' drivers used in the MA (2003).

- Spatial and syndromic surveillance.
  - There are new method developments in spatial and syndromic surveillance (Lawson and Kleinman, 2005). Spatial surveillance combines geographical information with traditional surveillance monitoring data to identify spatial clustering of outbreaks and other spatial associations (with ecological factors), and to provide spatial targeting of interventions. Advances in remote sensing and geographical information technology are also providing unprecedented opportunities in land assessment and monitoring. However, currently few georeferenced field-based observations on land health exist.
  - Syndromic surveillance groups symptoms together into 'syndromes', which provides opportunity for identification of common causes of different health problems that would normally be treated separately. This aids early detection of emerging problems, even before formal symptoms are detectable, and design



of more efficient intervention programmes. Land degradation problems are commonly syndromic, with several land degradation processes operating together, caused by one or more common factors (e.g. reduction in pasture quality and soil erosion may both be caused by over-grazing). With the increased availability of temporal and spatial data, health surveillance is increasingly drawing on analytical advances in areas such as multivariate statistics, process control, database mining, and probabilistic (Bayesian) methods. Bayesian approaches hold promise for future development as they allow (i) realistic incorporation of multiple types of uncertainty and (ii) integration of qualitative and expert opinion data with quantitative data.

- Meta-analysis is used as the primary source of information for design of public policy and health programmes.
  - Meta-analysis refers to the statistical analysis of data from separate but similar studies, leading to a quantitative summary of the pooled results (Last, 2001). Meta-analysis is only feasible when consistent measurement protocols have been used in different studies, which has rarely been achieved in land-related studies. Use of consistent measurement protocols is an essential feature of surveillance systems.
- Evaluation of intervention impacts.
  - Intervention surveillance is used to evaluate the health impact of specific interventions and of public policy. For example the actual reduction in incidence of a health problem resulting from an intervention is assessed.
  - Case-control and cohort studies are often used in conjunction with surveillance to measure intervention impact and to establish causality of risk factors (Schlesselman, 1982). They are used to help ensure proper controls and guard against confounding factors such as baseline drift. In case-control studies sample units with and without an intervention or health problem are selected for study. In cohort studies individual sample units are selected for observation and followed over time.
  - Because health surveillance is by definition oriented towards action, the surveillance system itself is also evaluated, for example in terms of whether surveillance information has been communicated to those who need to know, and whether the information has had a beneficial impact on the health problem

(Teutsch and Churchill, 2000).

- Projection of future needs (forecasting).
  - Forecasting is a method used to predict future events using mathematical models to detect patterns in data collected over time (time series analysis). Once appropriate models are determined to fit existing observations, these models can be used to forecast future values for the series.
  - Causal models are more important for predicting the future than 'time series analysis', which project trends into the future and rely on serial correlations.
  - Spatial modelling can be used to predict areas where health problems have a high risk of developing, based on existing spatial patterns of health problems in relation to risk factors. Spatio-temporal modelling includes both spatial and temporal components simultaneously (Lawson and Kleinman, 2005).
- Building operational surveillance systems.
  - For a surveillance system to be effective, the above components must be integrated and put into operation as part of regular health policy and practice. Considerations in building surveillance systems are: (i) the people and organizations involved, (ii) tools for data collection, analysis and dissemination, (iii) mechanisms for information flow, reporting and feedback, and (iv) quality control (Teutsch and Churchill, 2000). The World Health Organization has a number of guidelines on making surveillance work (WHO, 2001).
  - In public health many different types of surveillance systems are in operation. These may be grouped according to the progression from hazard to outcome (Stroup et al, 2004): (i) Hazard Surveillance or Risk Factor Surveillance Systems identify early opportunities for intervention by obtaining data on risk factors and preventive behaviours; (ii) Intervention Surveillance Systems gather data on intervention impacts; and (iii) Outcome Surveillance Systems collect data on final outcomes in terms of frequency and distribution of health in a population. Recently emphasis is being placed on the development of integrated surveillance to help better describe the webs of causation that result in health problems (e.g. Sopwith and Regan, 2004).

# Overview of land health surveillance methods and tools

## INTRODUCTION

The land health surveillance concepts described in Chapter 1 are put into operation through the combined application of a set of science and technology methods and tools that collectively can be termed *geoinformatics*. These include: (i) multiscale and multitemporal remote sensing, (ii) georeferenced ground survey, (iii) infrared spectral analysis of soils in the laboratory, (iv) hierarchical and spatial statistical analytical methods, and (v) geographical information systems and digital mapping. Recent developments in geoinformatics provide unprecedented opportunities for putting land health surveillance concepts into operation over large areas of land. Earth observation through remote sensing using satellites is a crucial component for large area surveillance, but needs to be underpinned by rigorous *in situ* (measured on the surface) data for understanding. Ground-based monitoring has traditionally received insufficient attention (e.g. Nisbet, 2007). Therefore in our implementation of land health surveillance we have placed special emphasis on systematic ground measurement of land condition and its linkage to remote sensing data through statistical models. Innovations in this approach include the use of infrared spectroscopy for low cost, rapid soil characterization, which has enabled large area soil assessment (Shepherd and Walsh, 2007) and linkage of spectrally-derived soil fertility indicators to remote sensing data through statistical models (Vagen et al, 2006).

Land health surveillance in this study is implemented through two types of surveillance system, corresponding with different levels of scale: (i) Regional Surveillance, which employs long-term satellite data at coarse spatial resolution over a regional extent to identify the wider picture of land degradation, and (ii) Sentinel Site Surveillance, which employs ground sampling and satellite imagery at fine spatial resolution to provide more accurate data on land condition and human welfare at sentinel sites.

## REGIONAL SURVEILLANCE SYSTEM

The Regional Surveillance System is designed to monitor land health at regional extent to identify degraded areas and provide early warning of land degradation, so that these sites can be screened for further investigation and preventive or rehabilitation action as necessary. The Regional Surveillance System can be classified as an outcome surveillance system. Outcomes are all the identified changes in the status of land health arising as a consequence of land health management, or the

lack of it. At this level the indicators of land health are restricted to vegetation and soil attributes that can be readily observed or extracted from remote sensing imagery. Potentially the system can also analyse land degradation or improvement, as measured by these indicators, in relation to conditioning factors, such as climate, elevation, soils, population, poverty, and infrastructure.

In this study, vegetation indices extracted from remote sensing data are used as an indicator of

land degradation (Table 2.1; Figure 2.1). Vegetation indices indicate the relative abundance and activity of green vegetation. The assumption is that at broad, regional level, serious land degradation will result in reduction in vegetation index values; and dramatic improvement in land condition will result in increased values of vegetation index. Changes in vegetation index can be evaluated either over time or spatially relative to neighbouring areas. However, some forms of land degradation may not result in a change in vegetation index (e.g. degradation of

**TABLE 2.1**

Satellite-derived vegetation indices used in this study.

Satellite	Sensor	Spatial resolution	Temporal resolution used	Length of record	Vegetation index
NOAA	AVHRR	8 km	10 days	1982–2006	NDVI
Terra	MODIS	250 m	16 days	2000–2006	EVI

NOAA: National Oceanographic and Atmospheric Administration

AVHRR: Advanced Very High Resolution Radiometer

MODIS: Moderate Resolution Imaging Spectroradiometer

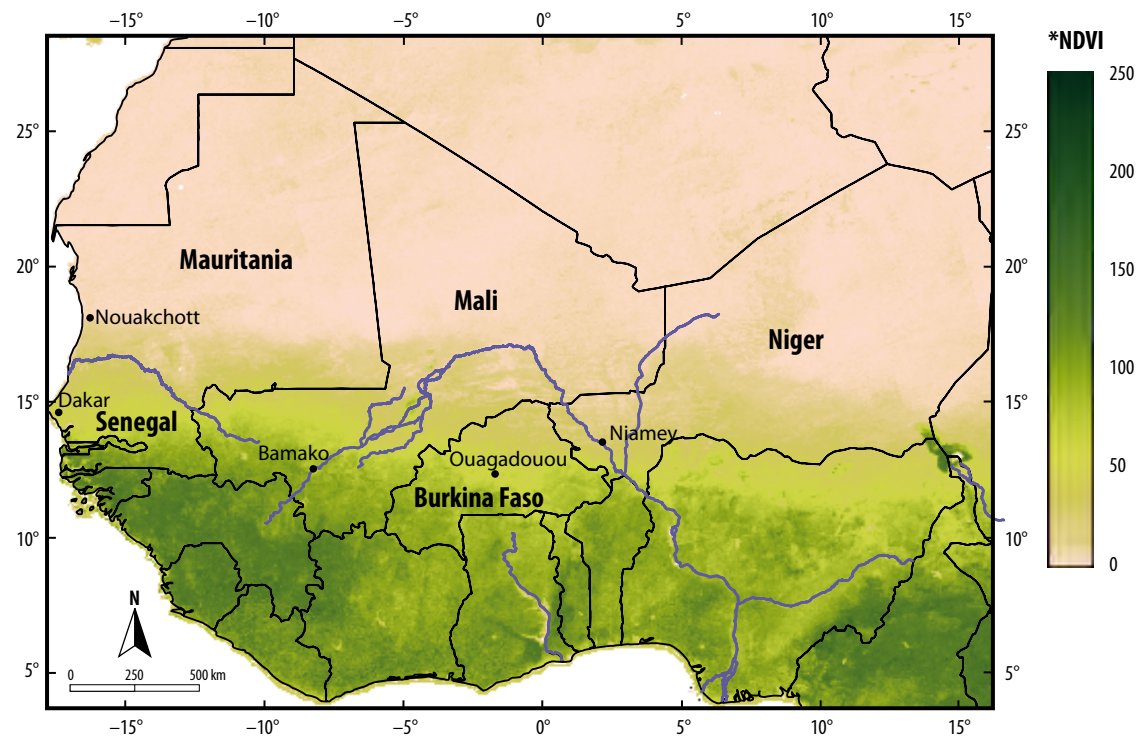
NDVI: Normalized Difference Vegetation Index

EVI: Enhanced Vegetation Index

**FIGURE 2.1**

AVHRR-derived Normalized Difference Vegetation Index (NDVI) mapped for West Africa. Data is average scaled NDVI for the

years 1982–2006, based on decadal (10-day) maximum value composition observations.



**TABLE 2.2**

Satellite data used in this study for further investigation of regional land degradation trends.

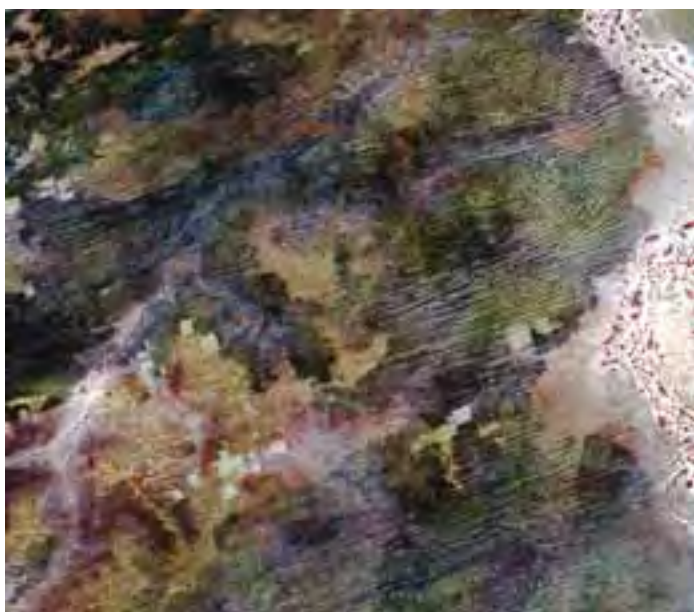
Satellite	Sensor	Spatial resolution	Time periods used	Spectral bands used	Swath width
Landsat 5	Landsat TM	30 m	1986, 2001	6	185 km
Terra	ASTER	15–30 m	2007	9	60 km

Landsat TM: Landsat Thematic Mapper

ASTER: Advanced Spaceborne Thermal Emission and Reflection Radiometer

**FIGURE 2.2**

ASTER scene from Segou Region, Mali. Scale 1:29,000.



pasture quality) and changes in vegetation index may not always be a result of land degradation or improvement (e.g. due to rainfall changes, land use conversions, or flooding). There are also a number of limitations due to other technical factors, such as non-linearity between vegetation indices and vegetation abundance, and sensor drift over time. In this study, attempts are made to control for rainfall changes in interpreting changes in vegetation indices. The limitations of the data are discussed in more detail in Part 2. Due to these various limitations, changes in vegetation indices can only be viewed as a first-level screening of land degradation, and ground observation and monitoring are required to validate and interpret the trends.

Satellite imagery of moderate spatial resolution (Table 2.2; Figure 2.2) is also used in this study to investigate current land cover classes and major

land use changes at selected sites where land degradation or improvement is indicated by trends in rainfall-normalized vegetation index.

### GROUND SURVEY – SENTINEL SITE SURVEILLANCE SYSTEM

Sentinel surveillance uses selected sites chosen to represent the diversity of specific groups in a population. Sentinel sites in this study are designed to provide accurate baseline data and monitoring of land health and factors affecting it. The sites serve several objectives, to:

- Quantify determinants of risks to land health (risk factor surveillance).
- Precisely target management interventions in relation to the types of land degradation problems and inherent constraints (spatial targeting).
- Provide a spatial framework for systematic testing of interventions and evaluation of their impacts (intervention surveillance).
- Provide consistent data for the development and testing of forecasting, simulation, remote sensing and other types of models.

### Sentinel site protocol

In this study sentinel sites are 10 x 10 km blocks, within which random sampling strata are used for characterization of the vegetation, soils, people, and livestock. The size of the block is chosen to be large enough to sample essential landscape elements, but small enough to be logistically efficient for field operations (e.g. walking distances). Sampling units within blocks are 1,000 m<sup>2</sup> (about 35 m diameter) plots for land health measurements and nearest households for human well-being measurements. A hierarchical, stratified random sampling scheme is used to avoid bias in locating plots or households within sentinel sites (although if households are clustered then selecting the nearest house to a random sampling point is biased in favour of isolated houses). The blocks are divided into 16 tiles, each of 2.5 x 2.5 km, and plots are randomly located within

1 km clusters, which are themselves randomly located within tiles (Figure 2.3). The sampling plans are generated in advance and field teams navigate to the pre-assigned sampling locations using a Global Positioning System (GPS). Prior information on factors that influence relationships of interest would help to increase the precision of the estimates (or increase the efficiency of the sampling design), however such information is often not uniformly available. Rather than making assumptions associated with prior stratification, the hierarchical randomized sampling scheme provides unbiased prevalence data, while allowing ancillary information to be included as covariates at the analysis stage.

A standardized protocol is used, emphasizing use of rapid, quantitative, repeatable, and interpretable measurements of indicators of land health and human well-being. Land health measurements include spatial information, topography and landform, land cover and use, environmental condition, and socioeconomic conditions (see Part 3). Vegetation and soil observations and soil samples are taken from 100 m<sup>2</sup> sub-plots. Standardized data entry forms are used to ensure consistency of field observations.

### Soil analysis

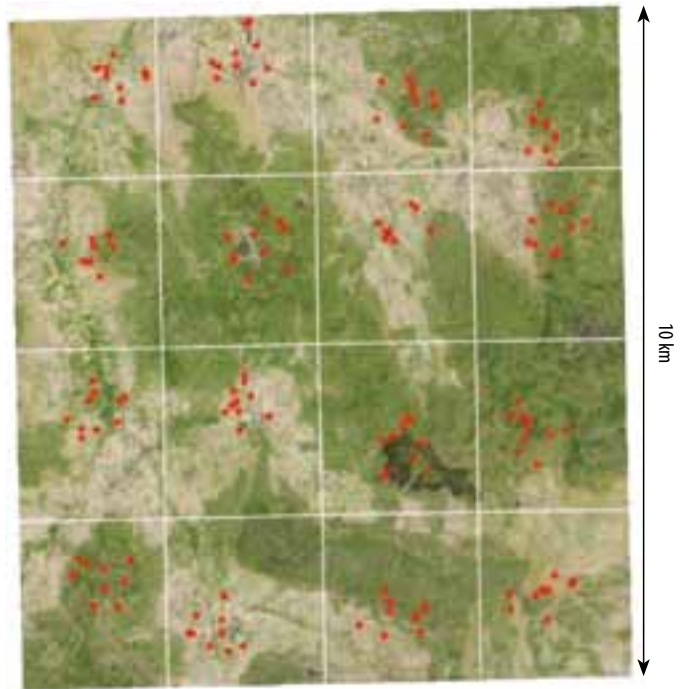
Soils are analysed in the laboratory using a new low-cost, high-throughput technique: infrared spectroscopy. The technique is widely used for quality control in the pharmaceutical industry and is considered to be one of the most cost-effective and reproducible technologies for the 21st century. The principle is simple: light is directed on to a soil sample and the reflected light is collected and measured at different wavelengths in the infrared region (Figure 2.4). The resulting spectral signature provides a fingerprint of the soil from which information on many different physical, chemical and biological properties can be derived (Shepherd and Walsh, 2007). The emphasis in this study has been on the use of infrared spectroscopy to provide estimates of soil fertility indicators and soil organic carbon on large numbers of soil samples based on calibrations to conventional reference measurements made on a small set of samples.

### Fine resolution satellite imagery

Satellite imagery with fine spatial detail is acquired for the sentinel site area as part of the standard data set. In this study we use QuickBird imagery (DigitalGlobe Inc), which has a panchromatic band

**FIGURE 2.3**

Sentinel site showing measurement plots (red dots) randomized within 1 km diameter clusters, within 2.5 km x 2.5 km tiles. The background is a fine resolution, QuickBird satellite image.



**FIGURE 2.4**

Near-infrared spectrometer being used to scan air-dried soil samples. Air-dried soil samples in glass dishes are placed on top of a light source. The instrument collects the reflected light at different wavelengths and stores the resulting spectral signature on a computer. A single operator can scan 400 samples per day.



with spatial resolution of 0.6 m and four multispectral bands with a resolution of 2.4 m. Soil fertility indices determined at the georeferenced sample points are calibrated to the corresponding reflectance values from the QuickBird imagery. The resulting statistical model is used to predict values for each 2.4 m pixel in the image and digitally map out the soil fertility indicator. Woody vegetation cover and other variables are also extracted directly from the images using specialized algorithms (see Part 3).

### **Statistical analysis**

The standardized protocols used ensure validity of comparison across times and sites despite lack of statistically valid sampling of the sentinel sites themselves. This provides for powerful statistical inference, as things are measured in the same way using the same sample areas everywhere. Hierarchical statistical analytical methods are used (mixed effects models) to analyse risk factors at different levels of scale and to generalize findings for the population of sentinel sites (see Part 3). A key advantage of mixed effects models for surveillance is that they allow population level estimates of variables while providing flexibility to incorporate information on local effects. For example the risk of land degradation can be related to a modifiable risk factor at one scale (e.g. tree density at cluster level), conditioned on a non-modifiable risk factor at another scale (e.g. mean annual rainfall at sentinel block level).

### **Targeting and testing land management interventions**

A key innovation in land health surveillance is the ability to use the sentinel site information to target land health interventions at fine spatial resolution. Using simple rule-based approaches, measurable targets for development projects can be provided in terms of what interventions to extend where (e.g. target tree densities for semi-

natural areas) and priority areas identified, based on criteria such as inherent soil degradation risk. This level of specificity, together with the ability to quantitatively track progress towards well-defined targets, provides a science-based approach to land management that has potential considerably to enhance learning processes.

There is scope for inference beyond the sentinel sites by building statistical models that combine data from a number of sentinel sites with higher scale information, for example, using data acquired from Landsat imagery, climate databases and other geographical information. The opportunity for building such models, and using them for forecasting, has been hampered until now by the lack of systematic data collection that the sentinel site surveillance system provides.

The sentinel sites provide a spatial framework for intervention testing, helping to ensure that interventions are systematically tested across a wide range of conditions, and can be linked to baseline data on conditions. We exemplify this in Part 3, where a multi-location crop fertiliser trial was distributed across clusters within blocks. A mixed effects statistical modelling approach is used to estimate average, population-level crop growth curves, which are then adjusted for sentinel block and fertiliser treatment effects.

Intervention surveillance systems, designed to establish quantitatively the impact of interventions, can be readily overlaid on the sentinel sites, as they are large enough to include control areas (e.g. use of case-control designs). Because the sentinel sites are well-characterized and sample a wide range of conditions, they also provide a basis for testing and validating land degradation indicators derived from regional-level remote-sensing information and for testing of other remote-sensing algorithms.

## COMMUNICATING HEALTH SURVEILLANCE INFORMATION

In developing concepts for communication of land health surveillance information we again draw on experience in public health surveillance, which has a long history of engagement with governments and individuals to bring about change in policy, practices and individual behaviours. Surveillance is intended as a process that provides information for action. Therefore data must be presented in a way that facilitates their use in practice (Goodman et al, 2000; Churchill, 2000).

The communication process, which basically takes facts and packages them to convey meaning, involves several basic steps (Table 3.1). Surveillance data are simply values and need first to be translated into information, by analyzing and interpreting them to provide meaning and context. Information is then translated into 'actionable' messages – units of communication science that tell their audiences how to respond to particular pieces of information. There is a need to identify who is the most appropriate or credible person or institution to convey the message, to what target audience and through which channel. Target audiences may include top-down initiatives focused on public policy-making and bottom-up initiatives that focus on land users and extension providers. When selecting communication channels, timing of messages in relation to needs and opportunities for maximum effect can sometimes be an important consideration, including phasing of messages to prevent information overload.

Following marketing of the message, it is critical to evaluate the impact. Feedback on the effectiveness of the information dissemination is vital for effective communication (a two-way process) and improvement in delivery. After all, the objective is to evoke a response. Involvement of target audiences in the design of the dissemination process can provide valuable early feedback on relevance and effectiveness, making the cycle more of an iterative than a linear process (e.g. Mitchell et al, 2006). Target audiences are also more likely to be responsive if involved in the design and if efforts are undertaken to build their capacity to be able to understand and use surveillance information. Examples of mechanisms to bring researchers and policy makers together to informally discuss a body of research and its implications include 'rapid reaction evidence seminars' and 'safe harbour policy forums' (WHO, 2004). At community level, special

# CHAPTER 3

# Land health surveillance and decision making

events that bring together researchers, village elders and traditional healers have proved to be an effective way of conveying evidence-based health information to communities (WHO, 2004). There are similar experiences in agricultural extension (Roling and Wagemakers, 1998). In many of these

contexts, an 'actionable message' forms the starting point of the discussion.

The communication process, including involvement of target audiences and evaluation of impacts, is time-consuming and costly and requires a different set of skills to those needed to collect and analyse surveillance data. For this reason, it is best to have specialist knowledge brokers on surveillance teams to lead this vital component (WHO, 2004). There is currently much interest in new and evolving paradigms in knowledge management and translation, such as 'boundary-spanning organizations' (Guston, 2001) and 'knowledge to action' (Cash et al, 2003). How best to communicate surveillance and research findings in developing countries still needs much local research. Surveillance itself has an important role in evaluating the impact of communication initiatives.

**TABLE 3.1**

Steps in communication of surveillance data. Two-way communication processes at all levels are also encouraged.

Steps	Example
Acquire data	Systematic soil survey shows 80% prevalence of extreme deficiency of soil available phosphorus in food-cropped areas of the country.
Convert data into information	Phosphorus deficiency is a basic constraint and major threat to national food security.
Establish message	The government must establish programmes to supply phosphorus fertilisers to food production areas and extend information to farmers.
Identify sender	Head of Soil Survey; Minister of Agriculture
Define the audience	Minister of Planning; international donors
Select the channel	Policy brief
Market the message	Briefing seminar and discussion with Planning ministry; disseminate message to local press and web-based international science and development media.
Evaluate the impact and iterate	Monitor government and donor plans; elicit additional information needs for planning.

**TABLE 3.2**

Ways of enhancing use of surveillance data and findings.

**Planning**

- Identify needs of different users and stakeholders
- Involve intended users and stakeholders in design
- Set objectives and clarify expectations on intended use
- Identify incentives for use
- Promote multiple ownership of surveillance data

**Implementation**

- Organize feedback from users during early stages of implementation
- Involve users in data collection and interpretation

**Communication**

- Make a dissemination plan for different user groups
- Use intermediaries to translate data into messages for stakeholders and users
- Market findings to segments of users and stakeholders
- Link findings to key problems and interventions
- Educate users and stakeholders in objectives and use of surveillance data

**Evaluation**

- Assess whether and how surveillance findings are being used
- Gather user's suggestions for improving surveillance systems
- Develop capacity for responding to user suggestions and new demands

Modified from Ottoson and Wilson, 2003.

**STRENGTHENING EVIDENCE-BASED DECISION-MAKING**

A principle objective of health surveillance is that decision-making and action are based on solid scientific evidence, directly provided by relevant and timely data collection and analysis (as distinct from being based on expert opinion, or a review of scientific literature from work done in other settings). However, surveillance is only one of many influences on decision-making and therefore it is vital that surveillance is put into the context of its use. Thus, while the activity of high quality data collection and analysis is the building block of surveillance, this focus must be embedded in a system perspective, whereby interactions with other influences on decision-making are considered. Effective surveillance systems do not simply make the assumption that data will be used, but purposively plan use of surveillance findings. Thus the design of surveillance systems must revolve around the recognition that the value of surveillance data comes from their use and the framing question: "who will use the data and how?" (Tables 3.2 and 3.3).

Groups with an interest in surveillance data and information can be categorized into stakeholders, a subset of direct users, and those who have principal responsibility for defining and establishing the surveillance system (Ottoson and Wilson, 2003). Stakeholders and users may span a number of organizations including policy, research, academic, practitioners, community groups, private sector, and



media. Successful surveillance systems find ways to manage the collaboration among these groups and ensure enduring partnerships. Although there has to be some centralized coordinating body or design team, involvement of target audiences in the design of surveillance systems is critical for effective utilization of results (e.g. Mitchell et al., 2006).

Different users may have different incentives that prompt use and tapping them can enhance

use. Policy-level decision-makers are more likely to want to use surveillance findings in a highly synthesized form to make high-level strategic decisions, whereas a programme manager may be seeking more specific information on the benefits and costs of alternative interventions. Policies are often impeded in areas where there is still scientific uncertainty over the importance of a problem and surveillance findings supplied to fulfil this need have a high chance of being used. Representing

**TABLE 3.3**

Types of land health surveillance data and findings and examples of their uses at different scales.

Scale	Audience	Information products	Uses
Farm or range unit	Farmers and pastoralists; Community-based organizations	<ul style="list-style-type: none"> <li>● Prevalence data and maps of land health constraints in a locality</li> <li>● Proximal, behavioural risk factors for land degradation</li> <li>● Evidence-based evaluation of performance and risks for specific land management interventions</li> </ul>	<ul style="list-style-type: none"> <li>● Develop individual and community knowledge of predominant land health constraints and hazards in the locality to help mobilise action</li> <li>● Guide screening of appropriate management interventions for testing by individual land users or communities</li> <li>● Guide good preventive practice by individuals and communities</li> <li>● Develop individual and community knowledge on trade-offs and risks associated with different management interventions</li> </ul>
District	Agricultural extension providers	<ul style="list-style-type: none"> <li>● Prevalence and incidence data and maps of land health constraints in a district</li> <li>● Information on proximal, behavioural risk factors for land degradation</li> <li>● Maps targeting intervention strategies and priorities in relation to constraints</li> <li>● Early warning of land degradation outbreaks</li> <li>● Evidence-based evaluation of performance and risks for specific land management interventions</li> <li>● Standardized operational norms or case definitions and screening tests for assessing good/poor land health</li> </ul>	<ul style="list-style-type: none"> <li>● Develop extension knowledge of predominant land health constraints and hazards in the district to mobilize appropriate action</li> <li>● Guide preparation of extension materials on best preventive practice for prevalent hazards</li> <li>● Guide preparation of extension messages and materials on rehabilitation of degraded land for prevalent land health constraints</li> <li>● Guide preparation of extension materials on performance and risk of specific management interventions</li> <li>● Use of standardized screening tests to identify land health constraints in the field</li> </ul>
	Local government planners; development assistance organizations	<ul style="list-style-type: none"> <li>● As above</li> </ul>	<ul style="list-style-type: none"> <li>● Plan public information and awareness campaigns on prevalent land health problems, best preventive practice and rehabilitation interventions</li> <li>● Knowledge of land health status in district; assess needs of different groups and areas</li> <li>● Plan land health intervention programmes; target priority areas; define and monitor measurable objectives and targets</li> <li>● Take early action in relation to new land degradation outbreaks</li> <li>● Prepare funding proposals to central government and donors based on evidence of problems</li> <li>● Adjust surveillance programmes in light of user feedback, evaluation of interventions and new emerging threats</li> </ul>
	Local stockists	<ul style="list-style-type: none"> <li>● Prevalence of major constraints by land use type and matching recommendations on input-based management recommendations</li> </ul>	<ul style="list-style-type: none"> <li>● Project input requirements (type, amounts, packaging) and potential market</li> <li>● Develop knowledge of prevalent constraints and management recommendations to be able to advise customers</li> </ul>

**TABLE 3.3** *continued*

Types of land health surveillance data and findings and examples of their uses at different scales.

Scale	Audience	Information products	Uses
National	National research organizations (agriculture, livestock, forestry, environment, etc)	<ul style="list-style-type: none"> <li>● Prevalence and incidence data and maps of land health constraints in country</li> <li>● Information on proximal, behavioural risk factors for land degradation</li> <li>● Maps targeting intervention strategies and priorities in relation to constraints</li> <li>● Early warning of land degradation outbreaks</li> <li>● Evidence-based evaluation of performance and risks for specific land management interventions</li> <li>● Standardized operational norms or case definitions and screening tests for assessing good/poor land health</li> <li>● Standardized protocols for monitoring land health nationwide</li> </ul>	<ul style="list-style-type: none"> <li>● Priority setting for agricultural, forestry and environmental research programmes (constraints, spatial targeting)</li> <li>● Systematic evaluation of impact of land management interventions</li> <li>● Target land management strategies for climate change adaptation and mitigation</li> <li>● Identify opportunities for schemes for payments for ecosystem services</li> <li>● Operational systems for land health surveillance</li> <li>● Evaluation and modification of national land health surveillance system</li> <li>● Frameworks for systematic design of national crop, tree and livestock trials linked to surveillance data.</li> </ul>
	Ministries of agriculture, livestock, forestry, environment, etc	<ul style="list-style-type: none"> <li>● As above</li> </ul>	<ul style="list-style-type: none"> <li>● Develop extension knowledge of predominant land health constraints and hazards in different districts to mobilize appropriate action</li> <li>● Guide preparation of extension materials on best preventive practice for prevalent hazards</li> <li>● Guide preparation of extension messages and materials on rehabilitation of degraded land for prevalent land health constraints</li> <li>● Guide preparation of extension materials on performance and risk of specific management interventions</li> <li>● Use of standardized screening tests to identify land health constraints in the field</li> </ul>
	Planning and finance ministries	<ul style="list-style-type: none"> <li>● Identification of priority risk factors for prevention of land degradation at national level</li> <li>● Information on time trends in land health and associated risk factors</li> <li>● Reliable and comparable estimates of the burden of land degradation in relation to factors such as poverty, region</li> <li>● Cost-effectiveness analysis to identify high, medium and low priority interventions to prevent or reduce land health risks</li> <li>● Evaluation of targeting strategies: population-wide versus high-risk individuals; distal versus proximal risks; primary versus secondary prevention; prevention vs rehabilitation</li> </ul>	<ul style="list-style-type: none"> <li>● Formulate risk prevention and rehabilitation policies for land health management and set priorities and targets</li> <li>● Formulate concrete and specific action plans and monitor impacts</li> <li>● Evidence-based reporting of progress on land health management in fulfilment of commitments to UN and other conventions and international agreements (e.g. UNCCD, UNCBD, MDGs)</li> <li>● Improve public awareness and understanding of risks to land health</li> <li>● Identify opportunities for combining risk reduction strategies, including those with other sectors (e.g. human health)</li> <li>● Identify priorities for investments in land health surveillance systems to strengthen the scientific evidence base</li> </ul>
	Development assistance and conservation organizations; bilateral donors	<ul style="list-style-type: none"> <li>● As above</li> </ul>	<ul style="list-style-type: none"> <li>● Formulate development assistance strategies and priorities for land health management and in relation to other sectors, poverty reduction strategies, environmental management plans</li> <li>● Identify and spatially target interventions</li> <li>● Assess impacts of interventions on land health and human welfare</li> </ul>

**TABLE 3.3** *continued*

Types of land health surveillance data and findings and examples of their uses at different scales.

Scale	Audience	Information products	Uses
	Universities and colleges	<ul style="list-style-type: none"> <li>● Training and educational materials on land health surveillance approaches and methods</li> <li>● Identification of research needs and priorities</li> <li>● Information on risks to land health and cost-effectiveness of alternative intervention strategies</li> </ul>	<ul style="list-style-type: none"> <li>● Curriculum development</li> <li>● Identification of research priorities and topics for MSc and PhD programmes and research departments</li> </ul>
	Private sector input suppliers	<ul style="list-style-type: none"> <li>● Information on priority intervention strategies, technology, inputs, and information products for land health care (e.g. fertilizers, germplasm, implements, extension products)</li> <li>● Information on land health surveillance research priorities</li> </ul>	<ul style="list-style-type: none"> <li>● Projection of potential markets for technology, inputs and information products</li> <li>● Planning for manufacture or importation of appropriate products, product formulations (e.g. fertilizer types) and quantities</li> <li>● Identification of future technology needs for research and development</li> <li>● Formulation of reliable information products for private sector extension services</li> </ul>
Regional	Regional scientific bodies	<ul style="list-style-type: none"> <li>● Regional level information on land health status and risks and their spatial distribution and time trends</li> <li>● Information on cost-effectiveness of alternative land health intervention strategies</li> <li>● Information on land health surveillance approaches and methods</li> <li>● Priority research needs in land health management and surveillance</li> </ul>	<ul style="list-style-type: none"> <li>● Identification of common land health problems and solutions, including trans-boundary issues, where regional coordination on policy or research may be beneficial</li> <li>● Early identification of emerging land health issues that may have regional impacts</li> <li>● Development of harmonized land health surveillance and intervention testing approaches so that results can be compiled at regional level</li> </ul>
	Regional economic development bodies	<ul style="list-style-type: none"> <li>● As above</li> </ul>	<ul style="list-style-type: none"> <li>● Development of harmonized regional policies and intervention strategies for land health management based on scientific evidence</li> <li>● Coordinated efforts to improve public awareness and understanding of risks to land health</li> </ul>
International	Development assistance organizations	<ul style="list-style-type: none"> <li>● Multiscale (continental to sub-national) data on land health status and risks</li> <li>● Information on priority intervention strategies and their cost-effectiveness for different countries and regions</li> <li>● Information on priority research and training needs in land health care and surveillance</li> </ul>	<ul style="list-style-type: none"> <li>● Priority setting and targeting of support programmes based on scientific evidence on land health status and cost-effectiveness of alternative intervention strategies</li> <li>● Assessment of impacts of intervention strategies on land health based on scientifically sound information</li> <li>● Formulation of capacity building programmes based on systematic appraisal of needs and bottlenecks</li> </ul>
	Scientific community	<ul style="list-style-type: none"> <li>● Scientifically sound multiscale data and information on land health status and risks over time</li> <li>● Priority research and training needs in land health care and surveillance</li> </ul>	<ul style="list-style-type: none"> <li>● Scientifically credible and systematic assessments of land health status and risks at different scales</li> <li>● Consistent data sets on land health and risks for development and testing of new hypotheses and theory on ecosystem health and links to human well-being (e.g. resilience, tipping points)</li> <li>● Development of new scientific methods and technology for land health assessment and management (e.g. remote-sensing algorithms, diagnostic tools, statistical methods)</li> </ul>

**TABLE 3.3** *continued*

Types of land health surveillance data and findings and examples of their uses at different scales.

Scale	Audience	Information products	Uses
	UN bodies, Conventions	<ul style="list-style-type: none"> <li>● Scientifically sound multiscale data and information on land health status and risks over time</li> <li>● Priority research and training needs in land health care and surveillance</li> <li>● Information on priority intervention strategies and their cost-effectiveness</li> </ul>	<ul style="list-style-type: none"> <li>● Scientifically credible and systematic assessments of land health status and risks at different scales, including early warning</li> <li>● Evidence-based information on land health intervention priorities as a basis for policy development, advocacy, science coordination, and capacity building</li> <li>● Scientifically credible monitoring and impact assessment with respect to achieving goals of international conventions related to land management</li> </ul>
	International donors	<ul style="list-style-type: none"> <li>● Reliable information on intervention priorities and strategies for land health management, including in relation to other sectors (e.g. poverty reduction strategies, food security, human development)</li> <li>● Information on research and training needs in land health management and surveillance</li> </ul>	<ul style="list-style-type: none"> <li>● Formulation of development assistance plans and priorities related to land management based on scientifically sound data and information</li> <li>● Formulation of well-targeted capacity building assistance programmes for land health care</li> </ul>
	International private sector	<ul style="list-style-type: none"> <li>● As above</li> </ul>	<ul style="list-style-type: none"> <li>● Assess markets for technology, inputs, information products related to land management and surveillance</li> <li>● Identify technological opportunities for research and development</li> <li>● Development of land health surveillance strategies within agricultural industries (e.g. for auditing of environmentally sound practices, monitoring impacts on land quality)</li> </ul>

uncertainty in surveillance data in presenting findings should be strongly encouraged and is increasingly being done, but there is also need for capacity building of decision-makers in how to interpret and use this information.

Communications research in the public health sector has shown that many of the most commonly used approaches to keeping practitioners informed (e.g. guidelines, reports, education programmes) have minimal impact or give mixed results, and that more active dissemination strategies (e.g. delivery of messages to health professionals through medical representatives and key opinion leaders) are required to get guidelines used (WHO, 2004). However, research on such aspects in developing countries is still limited. The situation in land health is perhaps even more difficult as decisions on land management are spread among different ministries (e.g. forestry, agriculture, livestock, water, environment) and agricultural and forestry extension infrastructure is mostly very weak. Table 3.4 gives examples of mechanisms for disseminating different types of land health surveillance information.

Information technology is having a major impact on both dissemination strategies and user demands for information. The increasing use of digital means for gathering and storing information coupled with the use of internet and mobile phone technology is transforming access to information in remote rural areas and educational establishments in developing countries. This presents a significant opportunity to catalyze progress through re-use and re-purposing of data and is changing how individuals interact and collaborate. The digital products of research are also rich resources for science-based learning and for outreach programmes to engage and inform the general public. Information technology will thus play a pivotal role in land health surveillance systems in developing countries.

**TABLE 3.4**

Examples of mechanisms for disseminating land health surveillance information.

Communication objective	Audience	Channel	Form	Expected impact	Evaluation mechanism
Alert smallholder farmers to key soil constraints to increased food crop production	Smallholder farmers growing food crops in a defined locality	Local extension agents and village chiefs; local web-based agricultural service enterprises	Extension leaflet with maps showing prevalence of soil constraints and describing management alternatives to alleviate constraints	Farmers in affected areas conduct own trials to test management options to overcome key constraints	Surveys indicate increase in number of farmers in affected areas testing recommended management alternatives.  In long-term, reduction in prevalence of soil constraints detected by soil surveillance surveys
Direct agronomic research efforts for tackling a national strong soil acidity problem	National agricultural research services	Direct distribution to national agricultural researchers	Assessment report with electronic maps and tables showing areas affected and describing intervention options and ameliorant dose ranges	Systematic, spatially targeted programme of agronomic trials testing soil amelioration and tolerant germplasm alternatives leading to recommendations for tackling national soil acidity problem including analysis of cost-effectiveness and adoption potential	Testing programmes are based on surveillance data. In long-term, surveillance surveys indicate reduction in prevalence of strong soil acidity at national level
Advise fertilizer companies on regional formulations and projected demands	Regional/international fertilizer companies	Direct distribution to fertilizer companies via web	Assessment report with electronic maps and tables showing prevalence of soil constraints, major cropping systems, and fertilizer recommendations, disaggregated at national and sub-national levels	Fertilizer companies supply appropriate types, formulations and amounts of fertilizers to regions and at national and sub-national levels	Survey of changes in supply policies by fertilizer companies
Advise planning and finance ministries on cost-effective land health intervention programmes	Senior planners and advisors in finance ministries	Direct distribution and seminars to senior planners and policy advisors in finance ministries; involvement of same in analysis	Assessment report based on systematic surveillance data giving information on priority risk factors for prevention of land degradation at national level; reliable and comparable estimates of the burden of land degradation in relation to factors such as poverty, region; cost-effectiveness analysis to identify priority interventions to prevent or reduce land health risks	Cost-effective national programmes launched to reduce and reverse risks to land degradation.	Monitoring of national policies and plans. In the long-term surveillance surveys show reduction in land health risk factors and improvement in land health at national level
Promote increased awareness among general public on land health risks	General public at national level	National TV	Documentary providing data on major land health problems and risks illustrated with examples and case studies	Improved public awareness of land health risks and interventions needed to reduce risks	Surveys of changes in public awareness. In long-term, surveillance surveys show changes in levels associated with modifiable behavioural risk factors

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# **PART 2**

## **REGIONAL LAND HEALTH SURVEILLANCE:**

### **Synoptic screening of land degradation in the West Africa Sahel**

*Thomas Gumbricht and Keith D Shepherd*

# Summary

Part 2 illustrates a regional application of land health surveillance with a synoptic screening study of land degradation in the Sahel using historical changes in precipitation and vegetation. The objectives of the study were to (i) synthesize existing knowledge from satellite-derived studies on land degradation in the Sahel, and (ii) develop a synoptic screening method to identify areas with anomalous vegetation degradation or recovery patterns from available satellite data, with the aim of providing a sampling frame for more detailed studies.

## DESERTIFICATION DISCOURSE

Debates on the degree, extent and causes of desertification in the Sahel have persisted for almost a century and still remain unresolved. This uncertainty impedes policy development for sustainable land management. During the Sahel drought period in the 1970s and early 1980s, the “equilibrium” hypothesis on Sahelian desertification dominated, pointing to internally driven land degradation caused by human activities leading to loss of vegetation, particularly through over-grazing. From the mid 1980s a “non-equilibrium” hypothesis developed, based on dynamic ecological theories and better understanding of the climate system: the climate system was blamed for exerting abiotic external forcing, and depicting humans as more the victims responding to external changes. However from 2000, the idea of internally driven degradation has regained support and a merging of the two concepts has emerged, emphasizing feedback effects between climate change and land management. With the current understanding, while long-term climate fluctuations are recognized as inevitable, maintaining vegetation plays an important stabilizing role, by localizing rainfall and stabilizing rainfall levels between years, until a gradual change causes a new vegetation and rainfall regime to dominate. However, large decreases in vegetation can reduce resilience and lead to a change to a drier climate regime.

The review of previous remote-sensing studies revealed that the vast majority of studies find no evidence for land degradation in the Sahel. On the

contrary, several studies report a greening trend that is stronger than expected from rainfall increases alone. However, some recent reports, using more detailed datasets, that take into account transient changes and vegetation ecological responses to rainfall variation, indicate that there has been a degradation trend that is actually reflected in lower biomass than what could be expected from the rainfall increase. Our analysis sought to help resolve these contradictions.

## METHODS

Rainfall records going back to around 1900 were assembled and used for creating monthly rainfall maps over the Sahel for the period 1931–1996. For the period 1996–2006 rainfall maps produced by a blend of rainfall station and satellite imagery were used. Vegetation data was obtained from the Advanced Very High Resolution Radiometer (AVHRR) flown on a series of satellites operated by the National Oceanic Atmospheric Administration (NOAA) of the United States of America (USA). The Normalized Difference Vegetation Index (NDVI) was used as an indicator of vegetation productivity. The annual vegetation growth was then compared with annual rainfall for the period 1982–2006 to derive an annual index of Rain Normalized NDVI (RNNDVI). This index is a modification of Rain Use Efficiency (RUE) used in many previous studies. The RNNDVI disentangles the temporal and spatial variation in vegetation due to rainfall variation from other factors, and can hence be used as a proxy for screening studies identifying areas with potential land degradation.

We used different methods than used in previously reported studies of long-term vegetation and rainfall changes in the Sahel, to help overcome several problems with the use of vegetation data from satellite images. To overcome the influence of soil signal at low vegetation densities we applied a previously published soil adjustment factor. The soil adjustment factor is a post-processing procedure whereby the vegetation signal recorded for bare soil conditions is used to adjust the vegetation signal when the ground is not fully covered by green vegetation. We also developed an algorithm to



neutralise artificial spatial and temporal differences in satellite derived vegetation indexes between different ecosystems such as rangelands, croplands and parklands. Changes in vegetation properties occur from transitions such as from rangeland to agriculture, and through tree-planting. Instead of measuring vegetation growth as the accumulated or maximum vegetation over an annual or seasonal cycle, as done in previous studies, we calculated the vegetation increments in 10-day intervals over an annual cycle. In this way we should theoretically be able to better capture the vegetation growth in both rangelands (where intermittent grazing leads to less standing biomass than in croplands) and tree interspersed agriculture (where woody biomass distorts the satellite derived vegetation estimates). The increment index has the further advantage of neutralizing initial effects at the start of the growing season stemming from woody biomass and soil colour. NDVI and RNNDVI were also scaled using Z-scores to reduce the influence of outliers. Furthermore we used improved data sets for estimating rainfall compared with earlier studies and an updated version of the Global Inventory Monitoring and Modeling System (GIMMS) NDVI database. To identify anomalous areas, a spatial ranking approach for regional and local scale analyses of changes in vegetation was developed. This approach also has the advantage that errors stemming from sensor degradation and atmospheric disturbances are avoided. Trend analysis of rainfall, vegetation growth, RNNDVI and spatial ranking were then applied in order to identify land degradation risk domains.

## **RAINFALL AND VEGETATION TRENDS**

The rainfall trend found in this study confirmed the variations in the rainfall over the Sahel reported in previous studies. The period 1950–1965 had high and stable rainfall. Rainfall then started to decrease during the late 1960s to the early 1980s, followed by a rainfall increase from the late 1980s to present. Also, as observed in previous studies, we noted a strong greening trend in vegetation over the Sahel over the period 1982–2006 in response to the rainfall recovery following the droughts that persisted in the 1970s to early 1980s. However, we observed a weaker greening trend than found in most previous remote-sensing studies. Vegetation cover in the five project countries (Burkina Faso, Mali, Mauritania, Niger, and Senegal) during 1982–2006 increased by about 42% of the total area (1.8 million km<sup>2</sup>), although the increase was statistically significant with 95%

certainty for only 19% of the area. The Parklands region (11° N–18° N) of all five countries showed a dominant trend of increasing vegetation growth over about 70% of the Parklands area (1.5 million km<sup>2</sup>) with a significant increase over 45% of the area with 95% certainty. Thus most of the greening that has taken place over the last 25 years has taken place in the Parklands area, whereas areas to the north and south of the Parklands have mostly experienced a browning. Mauritania and Niger showed an overall trend of decreasing vegetation cover due to negative trends north of 18° N. The strongest greening trends were in Senegal and Burkina Faso as these are predominantly Parklands. However, vegetation recovery has however not been as strong as the rainfall recovery. The increment NDVI closely follows the rainfall, with vegetation trending northward at half the pace of the rainfall. This reveals that vegetation has not been able to harvest the increase in rainfall, indicating land degradation. The Parkland areas displayed greater resilience to degradation than surrounding areas.

Previous regional remote-sensing studies have indicated no decrease or even an increase in Rain Use Efficiency over the period 1982–2006, indicating full recovery of vegetation growth following the droughts of the early 1980s, and no net land degradation. In contrast, our results indicate a decrease in RNNDVI over 80% of the total area of the project countries. The trends in rain-normalized annual vegetation growth for 1982–2006 reveal that for areas with average rainfall below 900 mm per year, for which the index is most robust, the RNNDVI has increased on only 10% of the area (0.4 million km<sup>2</sup>) and almost none of the area showing a statistically significant increase at a 95% certainty level. On the other hand, rainfall-adjusted vegetation growth has decreased over 90% (3.3 million km<sup>2</sup>) of the area with average rainfall below 900 mm per year, with 50% of the total area (2.0 million km<sup>2</sup>) showing a statistically significant decrease at a 95% certainty level. Although trends of increasing RNNDVI were stronger in the Parklands region than surrounding areas, the area with a statistically significant increase in RNNDVI was negligible. Overall the results indicate that vegetation has not been able to harvest the increases in rainfall since the early 1980s and in most areas over the Sahel there has been extensive incipient desertification. Some other recent studies using fine resolution NDVI imagery and rainfall data support our conclusions.

From a detailed analysis of alternative approaches for calculating vegetation growth, we conclude that choice of index for portraying annual vegetation growth has an important effect on the results obtained. Average (or integral) NDVI used in most previous studies of this type was found to be the least suitable for studying vegetation changes in transient environments (i.e. where spatial or temporal variation in vegetation type or land use exists), and more reflects underlying soil and vegetation types, rather than vegetation growth. Our analysis suggests that the rain normalization based on the scaled increment NDVI gives consistent and logical results and is the best-suited index for analyzing changes in transient environments.

The results of the rank trend analysis highlight the areas that have performed relatively better or worse vis-à-vis all other areas in the region under analysis. Areas with a stronger relative increase in RNNDVI performance seem to be clustered along the major rivers and along international boundaries. Explanations for this could be irrigation development along waterways, and a lower population density in peripheral areas. A potential use of the ranking trend maps is for identifying interesting areas for further studies. Another use is as a complementary tool for analyzing ground sampled data, where the ranking trend maps

could be used for setting a threshold, and hence identifying the spatial distribution of areas with a ground-based definition of vegetation changes.

## **CONCLUSIONS**

Overall our results do not support reports of large area impacts of agricultural innovation, for example in the central plateaux of Burkina Faso. However, increases in RNNDVI, indicating land restoration, were observed along the Senegal River in both Mauritania and Senegal, possibly reflecting irrigated agriculture; and in agriculturally-dominated areas in southern parts of Mali, Burkina Faso and Niger, which could be related to improved agricultural management.

The results indicate widespread land degradation in the Sahel and therefore there is a critical need for more detailed and systematic follow-up studies to validate and interpret the RNNDVI trends and establish casual factors, using higher resolution time-series satellite data and field survey. Systematic field baselines are needed to make further progress towards informing policy on the extent of land degradation and strategies for sustainable land management. The trends reported here can be used to indicate land degradation risk and as a sampling frame for such studies.

## BACKGROUND

Land degradation in arid and semi-arid regions (desertification) is a major global environmental problem (World Bank, 2003). Desertification in the African Sahel, a semi-arid region in West Africa between the Sahara Desert and the Guinea moist savannah (Figure 4.1), has been studied and debated for almost a century (see Harrison Church, 1966; Herrmann and Hutchinson, 2005) and yet remains a highly controversial topic. A better understanding of the dynamics of the Sahel rangeland and cropland systems is crucial to remove this controversy and identify sustainable policy and management options.

The strong spatial dependence of the Sahelian vegetation system on rainfall is widely accepted. Less understood is the large interannual variation in rainfall over the Sahel, giving rise to large temporal fluctuations in vegetation type, growth and cover. Studies of the Sahel rainfall records over the last 100 years show long-term variations: the period 1950–1965 had higher rainfall, followed by drier conditions culminating in severe droughts in the early 1970s and 1980s. The droughts led to a decline in vegetation cover. Over the last 20 years there has been an increase in rainfall that has driven a vegetation recovery (Tucker and Nicholson, 1999; Hulme, 2001; Eklundh and Olsson, 2003; Dai et al, 2004; Anyamba and Tucker 2005; Olsson et al, 2005), but average rainfall is still below the 1950–1965 level. The observed fluctuations in vegetation and rainfall, coupled with development in scientific concepts on ecosystem-human interactions over the same period, have precipitated an ongoing debate on whether the dryland ecosystems of the Sahel have returned to their pre-drought functionality, or whether irreversible land degradation has trapped these ecosystems in a less favourable state for food production. The development of this discourse is summarized in the following sections.

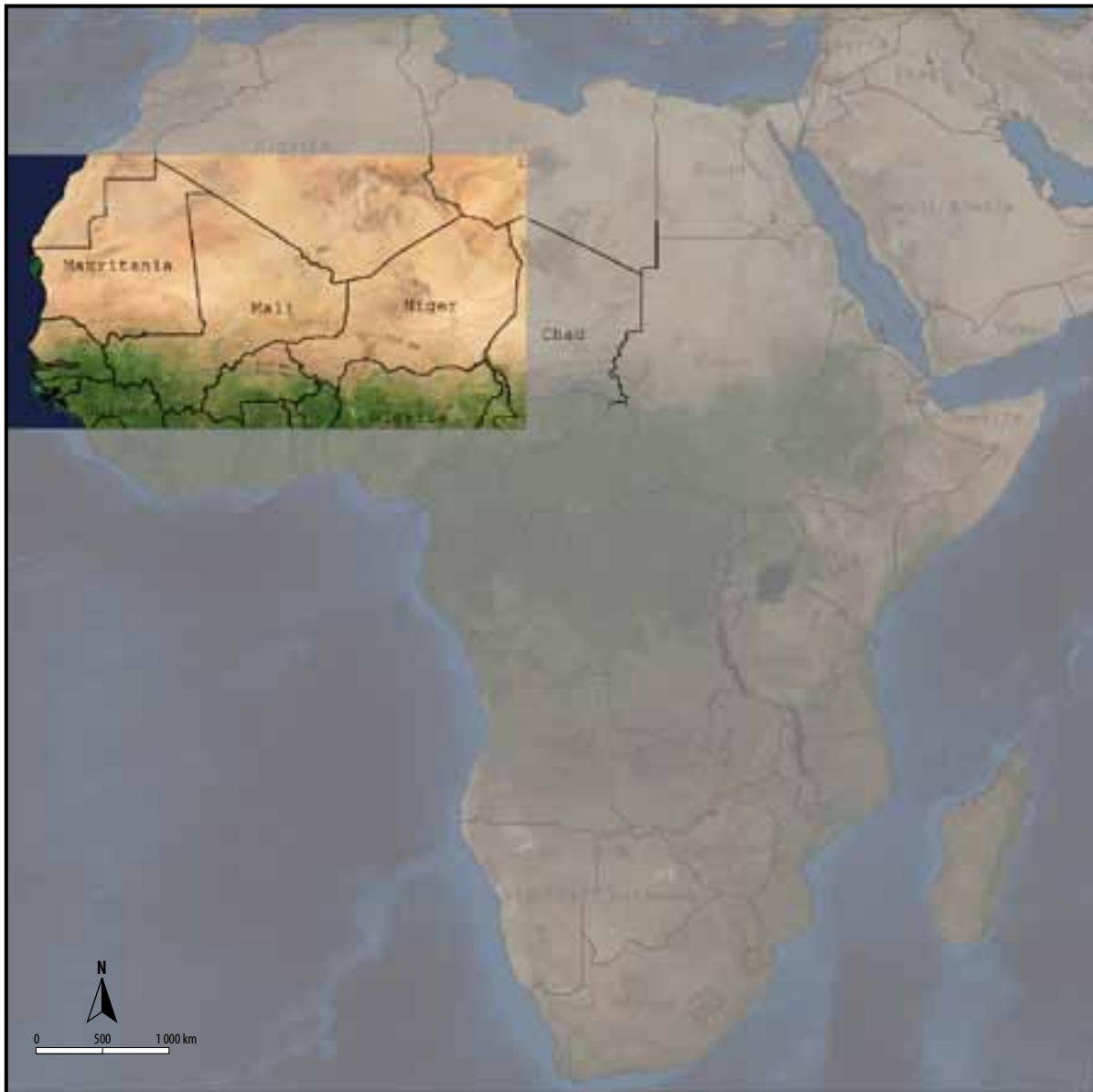
Lack of rigorous case definitions and objective indicators of desertification, and their consistent measurement using scientifically-rigorous sampling and monitoring over time and space have until now hampered a much-needed understanding of land degradation processes and desertification. The lack of a scientifically sound approach precludes the development of sound and specific action plans for sustainable land management. Many studies have been able to draw conclusions about soil and vegetation changes (or their absence) in the Sahel, but many have also recognized the fragmented

# CHAPTER 4

# The desertification debate

**FIGURE 4.1**

MODIS satellite image over Africa highlighting the study area and countries included in this report. Image mosaic from April 2004.

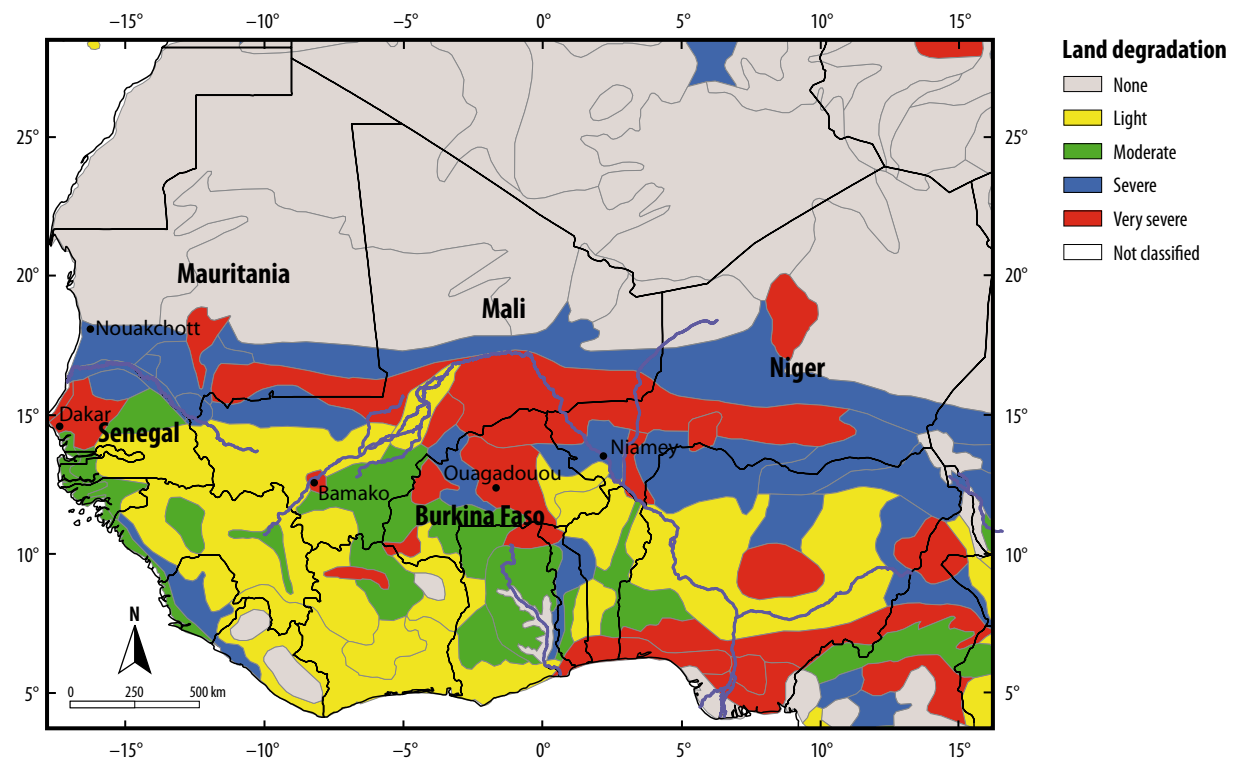


and diverse picture that these studies portray (e.g. Helldén, 1991; Niemeijer and Mazzucato, 2002; Reynolds and Stafford Smith, 2002a). Several authors have pointed at a lack of separation between causes and effects of land degradation on one hand, and the environmental problems and societal response to such biophysical changes on the other (summarized in Agnew and Warren, 1996). Different stakeholders and institutions have different perspectives on land degradation (Reynolds and Stafford Smith, 2002b), also reflected in the

extreme variation in the estimates of global land degradation and desertification. Despite almost a century of research on desertification, the term itself is largely misused and a cause of much debate, both among scientists and policy makers. More than 100 definitions have been suggested (Glantz and Orlovsky, 1983; Verstraete, 1986; Reynolds and Stafford Smith, 2002b). One of the most widely used definition is by UNCCD “land degradation in arid, semi-arid and sub-humid areas resulting from various factors, including climate variations

**FIGURE 4.2**

Map of the Global Assessment of Human Induced Soil Degradation (GLASOD).



and human activities”, where land degradation refers to the UN (1994) definition “reduction of loss of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns”. Faced with such large uncertainty among the scientific community, perhaps we should not be surprised that decisive policy is wanting.

### **ASSESSMENTS OF LAND DEGRADATION IN THE SAHEL**

The first attempt to map global soil degradation in the spatial domain was the Global Assessment of Human Induced Soil Degradation (GLASOD). GLASOD was prepared between 1987–1990 by scientists from the International Soil Reference and Information Centre (ISRIC) on behalf of UNEP (Oldeman et al, 1991). GLASOD contains information on soil degradation within map units (as reported by numerous soil experts around the world on the basis of a questionnaire. The GLASOD map (Figure 4.2) has been extensively used as a base map for estimating

global and regional soil degradation, including the UNEP World Atlas of Desertification (UNEP, 1992 and 1997). These studies reported that approximately 20% of the world’s drylands (excluding hyper-arid areas) suffer from human-induced degradation, mainly associated with soil erosion by wind and water. However, according to the GLASOD project leader “the GLASOD map and accompanying statistics do not allow assessment of soil degradation on a country by country basis” (Oldeman, 1994, quoted in Niemeijer and Mazzucato, 2002). In a more recent effort, Dregne and Chou (1992) mapped both vegetation and soil degradation, based on a synthesis of secondary sources. They estimated that 70% of global drylands (excluding hyper-arid areas) were degraded (soil plus vegetation degradation). The lack of adequate data prompted the Millennium Ecosystem Assessment to commission yet another desk study (Lepers, 2003; Lepers et al, 2005) that compiled regional data with 70% coverage of global drylands. The report by Lepers and others (2005) estimates 10% of global drylands (including hyper-arid areas) to be degraded. In contrast to the GLASOD map and the study by Dregne and Chou (1992), the latter assessment found few areas in the

Sahel to be degraded. The Millennium Ecosystem Assessment hence concluded that the degradation in the Sahel is negligible (Safriel and Adeel, 2005). More recently, as part of the Land Degradation Assessment in Drylands (LADA), Bai et al (2008) have conducted a global analysis of changes in satellite-derived vegetation and rainfall over the past 25 years, which indicates little evidence for degradation over the Sahel. These contradicting views emphasize the need for reconsideration with more appropriate data and development of appropriate indices, as already recommended 15 years ago (Helldén, 1991; Rubio and Bochet, 1998), and as long as 30 years ago by Reining (1978). The lack of adequate ground data has led to most recent studies utilizing the growing archives of satellite data for mapping vegetation changes in the Sahel.

### **DISCOURSE DURING THE SAHELIAN DROUGHT 1970–1985**

The concept of land degradation as a processes of deteriorating capacity for biomass production has its roots in the theory of Thomas Robert Malthus (1803), who stated that population growth tends to be exponential and would therefore outpace linear growth in food production. The Club of Rome report *Limits to Growth* (Meadows et al, 1972) was modelled after Malthus' theory, and established a framework of thinking that came to dominate the discourse on land degradation at the time. The extended droughts in the African Sahel culminating in the 1970s and 1980s, gave support to the doomsday scenarios presented by the Club of Rome. However, a few opposing voices, notably Boserup (1965) suggested that the increase in pressure on land resources would give rise to adoption of improved agricultural practices and institutional adjustments (see Wilkinson, 1973). The 1970s repetition of the debate on population growth and limited resources, first set forth by Thomas Malthus and David Ricardo (1817), became a platform for the proponents of the Malthusian theory. The Malthusian perspective was corroborated by the early responses to the drought and famine of the 1970s and 1980s, which resulted in migration and extensification rather than adoption of land management innovations (e.g. Wickens, 1997; Reij et al, 2005). Wickens (1997) suggested that such responses were probably sustainable in earlier centuries with lower population densities, but that population densities in the 1970s had become too high for this to occur.

Consequently the 1970s agenda became dominated

by reports on desertification, a term coined already in colonial times (Aubreville, 1949), following earlier reports on desiccation and vegetation decline in the Sahel (e.g. Bovill, 1921; Stebbing, 1935). The concept was reinforced after a study of desertification in the Sudan sponsored by the United Nations Educational and Scientific Organization (UNESCO) and the United Nations Environment Program (UNEP) by Lamprey (1975 – republished in 1988) which projected the popular image of spreading deserts leaving behind barren and sterile land; an image that re-occurs in the media to this day.

The researchers' main explanation for desertification in the 1970s was that it was caused by land degradation leading to changes in rainfall (internal forcing or "equilibrium" theory). The equilibrium view blamed human mismanagement (overgrazing) for irreversible land degradation (LeHouerou, 2002; Hein and de Ridder, 2006; Hein, 2006). The classic paper by Charney (1975) suggested that overgrazing and subsequent exposure of high-albedo soil may have altered the radiation balance and thus caused the Sahel drought (cf. Otterman, 1974).

The scientific and popular reports on land degradation and desertification emanating in the 1970s, combined with media reports of the drought and famine in the Sahel and exacerbated by political instability and unrest, led to an upsurge in public and political interest in desertification. In response, UNEP took primary responsibility for preparing the United Nations Conference on Desertification (UNCOD), which was held in Nairobi in 1977 (UNCOD Secretariat, 1977). UNEP subsequently played a major role in international efforts to combat desertification, most notably in the negotiating process leading to the United Nations Convention to Combat Desertification (UNCCD), which entered into force in 1996.

### **DISCOURSE ON SAHEL VEGETATION RECOVERY 1985 TO PRESENT**

During the 1980s several different factors contributed to a paradigm shift in the views on land degradation and desertification. The Sahelian drought reached its climax in the early 1980s (Nicholson et al, 2000; Hulme, 2001; Dai et al, 2004). The theoretical framework in rangeland ecology shifted from an equilibrium concept to emphasize non-equilibrium and multiple meta-stable resilient states (Holling, 1973 and 1986; Wiens, 1989; Westoby et al, 1989; Oba et al, 2000). Researchers started to accumulate more accurate field data using methods that were

relevant for the study of arid and semi-arid rangeland ecosystems (Olsson, 1983; Helldén, 1984). In contrast to colonial and post-colonial research, studies of the agroecological systems in the Sahel included work with local people and started recognizing the adaptive behaviour in the farmers' and herders' responses to external climate forcing (Mortimore, 1989; Mortimore and Adams, 2001). Over the same period, the accumulation of climate data and the emerging understanding of the global climate system played a key role in reformulating concepts on the driving forces of the ecology in the Sahel (Lamb, 1978 and 1980). The view hence shifted from that of an internally driven degradation process, to one that emphasized external forcing by the global climate system as the causative agent (Olsson, 1983, 1985, 1993; Helldén, 1988). The abiotic driving force of the non-equilibrium system was largely thought to control livestock density at a level that naturally prevented land degradation (Westoby et al, 1989; Vetter, 2005; Retzer, 2006).

The non-equilibrium theory considered responses in both vegetation and human management to be rainfall-driven and emphasized sustainable adaptive capacity (Tucker and Nicholson, 1999; Eklundh and Olsson, 2003; Retzer, 2006). This is supported by several recent local scale studies, which report a high degree of managerial adaptation to rainfall changes (Mortimore and Adams, 2001; Tiffen and Mortimore, 2002; Niemeijer and Mazzucato, 2002; Reij et al, 2005). However, other recent studies tend to draw more cautious conclusions and even hypothesize that ongoing land degradation is disguised under the veil of increases in rainfall. These studies include time-series analysis of vegetation change derived from (i) satellite data (Hein and de Ridder, 2006), (ii) medium- to high-resolution satellite data in combination with better rainfall data and ground surveys (Diouf and Lambin, 2001; Hountondji et al, 2006), and (iii) ground data from paired studies of controlled and uncontrolled grazing fields (Hein, 2006).

The increase in availability of satellite-derived information on vegetation since the early 1980s (Figure 4.3) has been one of the most crucial components for explaining the vegetation dynamics in the Sahel and its response to variation in rainfall (e.g. Tucker et al, 1983, 1985 and 1991). Many studies of post-drought vegetation changes in the Sahel show that at a broad scale the vegetation increase is well correlated with the increase in rainfall (Prince, 1991; Prince et al, 1998; Tucker and Nicholson, 1999;

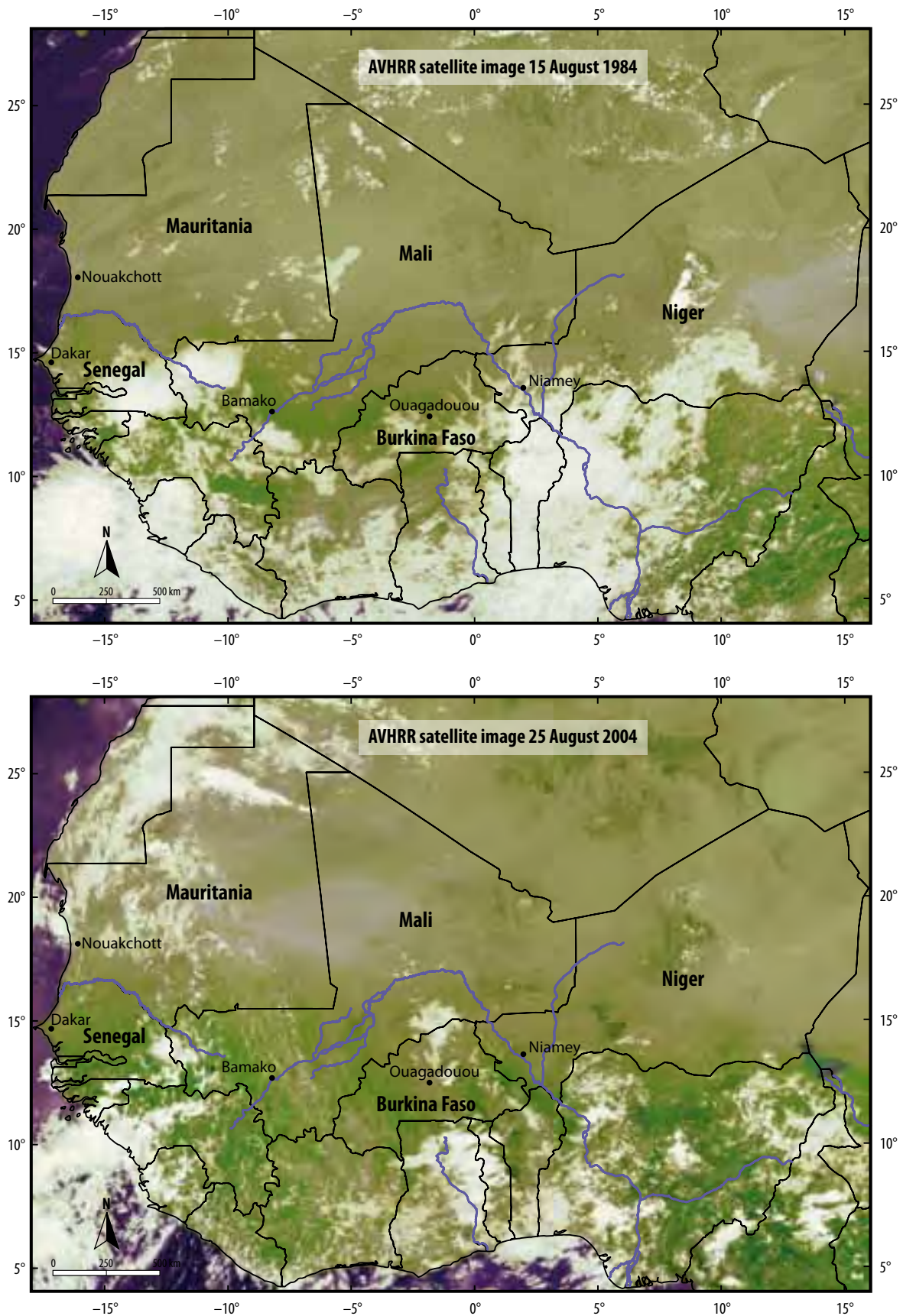
Eklundh and Olsson, 2003; Herrmann et al, 2005a; Anyamba and Tucker, 2005; Olsson et al, 2005; see also Chapter 5). However, the vegetation increase in the Sahel has not been uniform, and there are large discrepancies between rainfall and vegetation trends over different parts of the Sahel as well as over different time-periods (see Chapters 6–8). Hence, the growth in archives of satellite imagery has sparked reassessments of the nature, scale and extent of the concept of desertification.

A vast majority of the remote-sensing studies find no evidence for land degradation in the Sahel. On the contrary, several studies report a greening trend that is stronger than expected from rainfall increases alone (Prince et al, 1998; Anyamba and Tucker, 2005; Herrmann et al, 2005a, 2005b; Olson et al, 2005). Only recent reports since 2000, using more detailed datasets (Diouf and Lambin, 2001; Hein and De Ridder, 2006; Hein 2006; Hountondji et al, 2006) and, taking into account transient changes and vegetation ecological responses to rainfall variation, indicate that there has been a degradation trend that is actually reflected in lower biomass than could be expected from the rainfall increase. These more detailed studies support the arguments of researchers such as Charney (1975), Xue and Shukla (1993) and Wang and others (2004) that anthropogenic land cover changes have contributed to the Sahelian droughts. In addition, the present Global Circulation Models (GCM) can explain only around 25–30% of the total variation in the Sahelian rainfall from sea surface temperature data (Folland et al, 1986; Giannini et al, 2003), further suggesting that processes other than external climate variation are involved. Although the processes on the ground have not yet been firmly established, the satellite-observed greening trend following the drought has challenged notions of irreversible damage inflicted on the Sahelian ecosystem during the drought.

Research during this period has also provided clearer insights into the climate-land surface feedback mechanisms, which can both stabilize climate and, with larger perturbations, reinforce transitions between wet and dry conditions (Wang and Eltahir, 2000; Wang et al, 2004). The feedback processes operate primarily through evapotranspiration due to soil moisture and vegetation effects (Flohn, 1987; Zheng and Eltahir, 1998; Nicholson, 2000b and 2002; Xue and Shukla, 1993; Xue and Fennessy, 2002; Wang and Eltahir, 2000; Wang et al, 2004), and are not associated with albedo as suggested in the 1970s.

**FIGURE 4.3**

NOAA AVHRR images in natural colours for 1984 and 2004.





Furthermore, at the local scale, patches that receive rainfall early in the season are reported also to attract more precipitation later in the season compared with adjacent patches (Xue and Fennessy, 2002). The increase in evapotranspiration associated with dense vegetation leads to the formation of an atmosphere boundary layer near the land surface where the air trapped in the lower layer becomes saturated with water vapour as temperature falls after noon, often leading to localized rainfall and a local recycling of water (cf. Avissar, 1993 and 1995). This vertically closed water cycle is scale dependent and lost when vegetation is cleared or vegetation density decreases below some threshold.

Since 2000, the combined knowledge on (i) the recovery of the Sahel vegetation as seen in satellite imagery, (ii) the non-equilibrium theory of rangeland ecology and (iii) better understanding of the responses in human and ecological systems to external forcing, has led to a new paradigm on land degradation and desertification. This new paradigm of a coupled human-environmental system is consistent with the broader concept of “sustainable development” adopted by both the scientific and political community (Brundtland, 1987; Vogel and Smith, 2002). This paradigm shift is also consistent with Chapter 12 of Agenda 21 arising from the Earth Summit (United Nations Conference on Environment and Development – UNCED) in Rio de Janeiro in 1992. This more divergent and adaptive view of desertification is also at the core of the UNCCD (United Nations Convention to Combat Desertification), which was signed in 1994 and came into force in 1996 (see <http://www.unccd.int>). A more detailed review of the role of international institutions in the desertification discourse is given by Chasek and Corell (2002).

## CONCLUSION

Two main hypotheses for the cause of rainfall and vegetation variation over the Sahel have been proposed (see Briske et al, 2003; Vetter, 2005). The

older “equilibrium” hypothesis points at internally driven degradation, where loss of vegetation through human activities, particularly grazing, is emphasized. The “equilibrium” hypothesis inherited ideas from theories of ecological successions and Malthusian ideas of resource depletion. It was the dominating idea during the droughts in the 1970s and early 1980s. The conclusion was that the ecology of the drylands was being forced out of a more desirable and productive climax state and into a poor sub-climax state. Both scientists and policy makers consequently saw the people of the Sahel as causing a desertification process through poor land management, which was inflicting irreversible damage on the Sahelian ecosystem and climate (e.g. Charney et al, 1975; Dregne, 1983; Leonard, 1989). Discourse from the mid 1980s favoured a “non-equilibrium” hypothesis, whereby vegetation changes were considered to be a response to abiotic external forcing exerted by the climate system, and depicting humans as more the victims responding to external changes (Westoby et al, 1989; Vetter, 2005). The “non-equilibrium” hypothesis grew out of dynamic ecological theories and better understanding of the climate system, which coincided with the start of a period of rainfall increase over the Sahel. From 2000, however, the idea of internally driven degradation has regained support and a unified view of desertification in the Sahel has emerged (Reynolds 2007; Vetter 2005). With this current understanding, while long-term climate fluctuations are recognized as inevitable, maintaining vegetation plays an important stabilizing role, by localizing rainfall and stabilizing rainfall levels between years, until a gradual change causes a new vegetation and rainfall regime to dominate. However, large decreases in vegetation can reduce resilience and lead to a change to a drier climate regime. Research on the climate system will hopefully contribute to the new emerging view, assisted for example by the international project – African Monsoon Multidisciplinary Analysis (AMMA) (<http://amma.mediafrance.org>).

# The African Sahel and its climate

## INTRODUCTION

The name 'Sahel' refers to the region fringing the Sahara desert in West Africa and was first used by Chevalier (1900; quoted in Wickens, 1997). The origin of the word is from the Arabic sahel, meaning shore or coast.

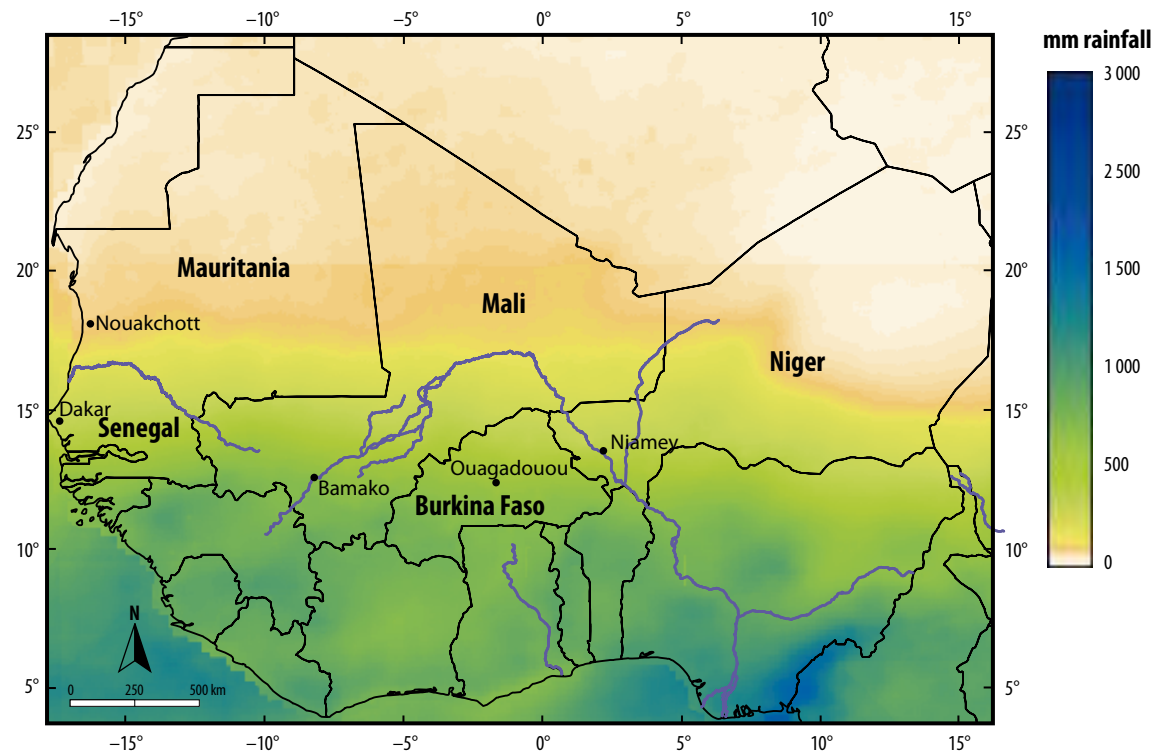
The Sahel is a semi-arid region, predominantly grassland and shrubland, located approximately between 11° N and 18° N with a steep north-south gradient in annual rainfall. The Sahel stretches almost 5,000 km from the Atlantic Ocean in the west to the Red Sea in the east. The Sahara desert bounds it to the north, and Guinea wet savannah (coastal rain forests) to the south. There is no exact boundary of the Sahel but usually it is considered as the rainfall transition region bounding the 100–200 mm per year isohyet (rainfall isoline) in the drier north, up to the 500–800 mm per year isohyet in the wetter south (Figure 5.1).

The Sahelian rainfall gradient is reflected by a continuum of change in vegetation and ecosystems (Le Houerou, 1980; White, 1983; Figure 5.2); the wetter south has denser ground cover and a greater coverage of woody species (*Acacia* spp.) than the drier areas to the north. The central region is characterized by parkland ecosystems – agricultural fields in which trees are maintained (e.g. *Faidherbia albida*, *Vitellaria paradoxa*, *Adansonia digitata*) allowing diverse agroecological production. Further north, thorny shrubs interspersed between annual and perennial grasses dominate (e.g. *Aristida siebriana* in disturbed grazing areas, *Cenchrus biflorus* in areas with less grazing pressure, and *Leptademia pyrotechnica* and *Cenchrus procera*, which are pioneer species after droughts). Figure 5.3 illustrates some typical ecosystems of the Sahel region. The grass and shrub land gradually grades into the Sahara desert. The agroecological zones follow the same gradient, with agriculture in the south (sorghum, *Sorghum bicolor*; millet, *Panicum* sp; cotton; and irrigated rice in river flood plains), the tree-interspersed parklands in the centre, and pastoral rangelands dominating in the north. The boundary between the parklands and rangelands is at around 300 mm of annual rainfall. In the northern part, livestock is the main income earner for the local population. The dominant culture whereby there is open access to grazing (also in agroecological regions during the dry season) tends to favour high stocking densities (Le Houerou, 1989).

**FIGURE 5.1**

Annual average rainfall for West Africa 1982–2006 derived from interpolation of rainfall gauge data (1982–1995), and satellite

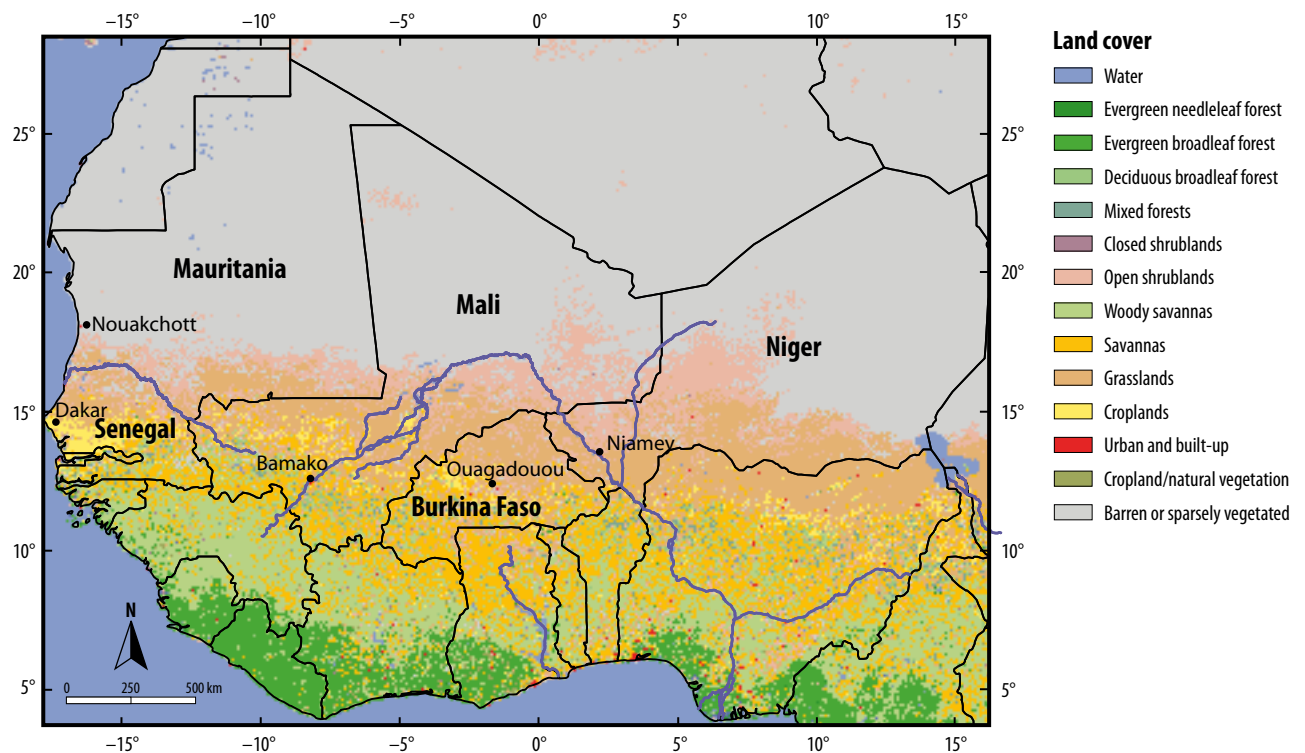
supported estimates updated with gauge data and other ancillary data (1996–2006).



**FIGURE 5.2**

Vegetation ecosystems in West Africa based on a classification made from the Moderate Resolution Image Spectroradiometer

(MODIS) (Friedl et al, 2002). Countries included in this study: Burkina Faso, Mali, Mauritania, Niger and Senegal.



**FIGURE 5.3**

Typical ecosystems of the Sahel region, (top) Laterite plateaux, (middle) parkland agriculture, and (bottom) small mango tree plantation. All images are taken close to the Niger River in Mali.



The Sahel is characterized by interannual fluctuations in vegetation, typical of rangeland ecosystems (e.g. Tucker et al, 1991; Goward and Prince, 1995). Despite the reports of recovery in vegetation density and production in many recent studies (see Chapters 4 and 6), there is strong evidence for deforestation and

loss of both tree cover and tree species variations in the Sahel over the last century (FAO, 1993; Gonzalez, 2001; Wardell et al, 2003). Concerns have been raised that deforestation in the Guinea coastal rain forest to the South of the Sahel will negatively impact the rainfall in the Sahel (Zheng & Eltahir 1998; Semazzi and Song, 2001). Wickens (1997) has presented a historical overview of land use and management history in the Sahel.

The study area in this report includes the countries of Burkina Faso, Mali, Mauritania, Niger and Senegal (Figure 5.2; Table 5.1).

### THE CLIMATE SYSTEM OF THE SAHEL

The Sahel climate is characterized by a marked annual cycle with a long dry season (9–10 months) and a short humid season (2–3 months), coinciding with the northern hemisphere summer. As much as 80% or more of the annual precipitation in the Sahel falls between July and October, with a maximum in August (Lamb, 1978 and 1980; Hulme, 2001; Nicholson, 2005). Much controversy still exists over the causes of the seasonality (for recent reviews see Nicholson, 2001 and 2005).

The overall climate of Africa is dependent on several factors; first its size and position – it is almost symmetrically divided by the equator, and secondly it is the most elevated of the world's continents. The circulation of air masses over Africa follows the general global tropical pattern; low latitude air-movement near the surface is towards the equator, with a slight westerly direction of the incoming winds. Near-surface converging air meets at the low-pressure zone (the Inter Tropical Convergence

**TABLE 5.1**

Geographical baseline data for countries included in the present study (for the year 2005).

Country	Area (km <sup>2</sup> )	Population (millions) <sup>1</sup>	Average population growth (%) <sup>1,2</sup>	GDP/capita <sup>1</sup>	Human Development Index <sup>1</sup>	Soil degradation index (1990) <sup>3</sup>
Mali	1,252,245	13.5	3.0	930	0.326	1.40
Mauritania	1,038,441	3.1	3.0	2,220	0.465	No data
Niger	1,181,959	14.0	3.6	800	0.292	1.55
Senegal	196,006	11.7	2.4	1,580	0.437	2.12
Burkina Faso	272,327	13.2	3.0	1,100	0.302	2.77

<sup>1</sup> UNEP-GRID (<http://globalis.gvu.unu.edu>)

<sup>2</sup> Annual population growth rate (%) 1975–2005

<sup>3</sup> Severity of Human Induced Soil Degradation index as calculated by the World Economic Forum (2001) on the basis of GLASOD data (<http://sedacciesin.columbia.edu/es/esi/>). High values denote higher levels of human induced soil degradation (world country average = 1.84).

Zone – ITCZ), which girdles the Earth along the solar equator. At the ITCZ, the moist air from above and below the equator is forced to ascend, a process mainly driven by the convective activity of thunderstorms. The rising air produces rainfall and the resulting dry airflows towards the North and South Poles in the higher atmosphere. The airflow loses heat as it travels, and at about 30° north and south of the equator, it begins to descend. As it descends the air is compressed and increases in temperature from adiabatic heating resulting in a decrease in relative humidity. The descending air forms a dry high-pressure zone approximately at the tropics, and is the origin of the sub-tropical deserts in Africa (see Figure 4.1). The semi-enclosed

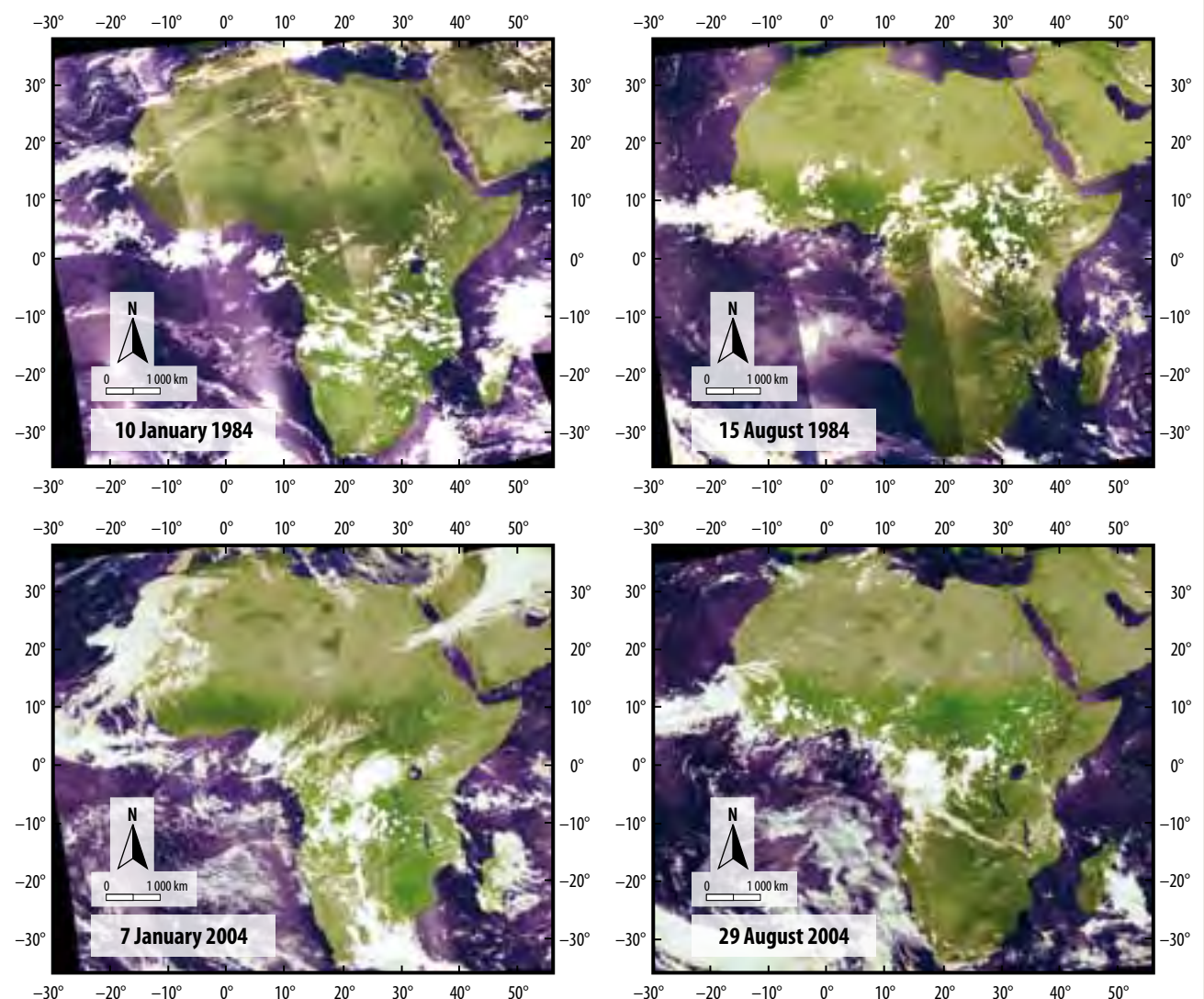
cells of circulating air masses are referred to as Hadley cells (Figure 5.4).

Over Africa the ITCZ is shifted towards the north of the equator, due to the large, dry land mass of West Africa. A second convergence zone, the Zaire Air Boundary (ZAB), separates the airflows of the Atlantic and Indian Ocean. The positions of the Hadley cells and the ITCZ and ZAB vary with season, related to the tilt of the Earth's axis and the annual circuit around the sun. When solar input is high in the northern region, the ITCZ moves northwards, and vice versa. Hence during the northern hemisphere summer, the ITCZ migrates northward to about 10° N, where it stays during the month of August (Gu and Adler, 2004). To the north

**FIGURE 5.4**

Cloud patterns over West Africa in January and August 1984 and January and August 2004, illustrating the shift in the position of the Intertropical Convergence Zone (ITCZ). The low pressure formed

under the solar zenith positions generates lifting air masses and leads to convective precipitation.



the dry NE trade winds, the Harmattan, dominate the climate, whereas to the south the humid southwest monsoons bring precipitation.

The upper air movements also shift with the seasons. In the northern hemisphere summer, the high altitude flow is easterly over most of Africa, embedding several jet streams. The African Easterly Jet (AEJ) and the Tropical Easterly Jet (TEJ) are both important for the development of precipitation as they provide energy for development and maintenance of rain-bearing disturbances (Long et al, 2000; Nicholson, 2000a; Gu and Adler, 2004).

The reversal takes place in the northern hemisphere winter; the ITCZ crosses the equator to the southern hemisphere and the Sahel comes under the influence of the Harmattan. The dryness of the Harmattan is primarily related to the general circulation pattern described, as it originates from dry, sinking air masses. But the dryness of Africa is also related to the low moisture content of the air masses penetrating the African continent from the sea. Currents in the Atlantic Ocean contribute to the relative air masses over Africa. In southern Africa, the Benguela stream feeds cold water along the coasts to South Africa, Namibia and Angola; and along the West African coast the Canary stream does the same for Senegal and Mauritania. The elevated topography, especially of southern Africa, further dries out the air masses before they reach the interior of the continent. The geological development of Africa, both its drifting apart from Antarctica, opening up for cold currents, and the more recent uplifting, are the fundamental causes of the drying trend that Africa has experienced over millions of years.

Early attempts to explain the droughts in the Sahel in relation to external factors suggested a southward shift and/or a weaker ITCZ as the cause. More recent research, however, indicates that the position of ITCZ is relatively stable. The indications are that it is displacement of the East African Jet (AEJ), lessening the necessary energy and instability levels critical for precipitation, that is causing the rainfall variation over the Sahel (Nicholson, 2000a and 2005; Grist and Nicholson, 2001).

The low-frequency variability of the Sahelian climate cannot be explained solely by external forcing. Giannini and others (2003), using an ensemble of scenarios from a global circulation model, found that only around 25–30% of the variation could be

explained by sea surface temperature forcing alone. An obvious candidate for a more full explanation is internal forcing, as suggested by a number of researchers, including Charney (1975), Wang and Eltahir (2000), and Wang and others (2004) (see Section 1.1). Using coupled biosphere-atmosphere models, these studies indicate that vegetation responds more slowly to rainfall changes than expected and that the vegetation situation is a reflection of rainfall in previous years, not only in the current season. As vegetation assists in localizing rainfall, it has the capacity to stabilize rainfall levels between years, until a gradual change causes a new vegetation and rainfall regime to dominate. The vegetation-rainfall system hence displays meta-stable states acting as attractors for high and low regimes of rainfall. Within a more narrow range the vegetation will act as a negative feedback, stabilizing agent; but with large perturbations, positive feedback flips the vegetation and climate system to another meta-stable state. This flip-flop behaviour could help to explain the low frequency alternation between prolonged periods of wet and dry conditions over the last century (Wang and Eltahir 2000; Wang et al, 2003).

A recent study using precipitation data from the Tropical Rainfall Measuring Mission (TRMM) has revealed that there are two monsoons over West Africa, both associated with the seasonal movement of the ITCZ (Gu and Adler 2004): an early monsoon (June) centred around 5° N, mainly influenced by sea surface temperature, and a later monsoon (August) centred around 10° N and driven by the AEJ. The Sahel region is mainly influenced by the latter monsoon, with August also being the wettest month. And in a recent study Nicholson (2005) found rainfall variability in the Sahel to be largely related to August rainfall, when the ITCZ is stationary, positioned at around 10° North. Several studies have attempted to establish a link between El Niño and rainfall in the Sahel (Anayamba et al, 2001; Lotsch et al, 2003). Until now, however, there is no clear evidence for an influence of El Niño events on Sahelian rainfall.

## **SAHEL RAINFALL VARIATION 1930–2006**

The rainfall over the Sahel is characterised by large interannual variations superimposed on low-frequency alternations between prolonged wet and dry periods. The climate of West Africa has changed dramatically over the last 20,000 years. During the Ice Age the climate was much drier than at present, but was followed by the African Humid Period, when the

Sahel was much greener than at present and reached further into the Sahara Desert. The Africa Humid Period came to an end about 5,000 years ago.

Studies of the Sahel rainfall records over the last century also show long-term variations (Nicholson, 2000a and 2001). The period 1950–1965 had higher than average rainfall, followed by drier conditions culminating in severe droughts in the early 1970s and early 1980s. Over the last 20 years there has been a recovery in rainfall (Tucker and Nicholson, 1999; Hulme, 2001; Eklundh and Olsson, 2003; Dai et al, 2004; Nicholson, 2005; Nicholson et al, 2005), but average rainfall is still below the 1950–1965 level. Nicholson and others (2000) provide a detailed summary of rainfall variability in the Sahel during the 20th century mainly based on gauging data, and Nicholson (2005) presents an update for the period 1998–2003 based on remotely sensed precipitation, estimated from the Tropical Rainfall Measuring Mission (TRMM).

The reconstruction of precipitation over the Sahel is plagued by several problems (Dai et al, 2004; Nicholson, 2005); the gauge network has changed significantly over time, and, more seriously, the number of stations having readily accessible data has decreased significantly over the last 20–30 years. In this study, rainfall station gauging data were used to reconstruct the monthly and annual rainfall over the entire Sahel using geostatistical interpolation. Data density prior to 1930 and after 1996 do not allow geostatistical interpolation of rainfall over the entire study area and were hence omitted. Rainfall data for the period 1996–2006 were instead taken from satellite supported rainfall maps distributed by the African Data Dissemination Service (ADDS). Alternative sources of historical precipitation over the Sahel include the two NOAA datasets: (1) Global Precipitation Climatology Project (GPCP) (Adler et al, 2003), and (2) the Global Historical Climatology Network (GHCN) (see Appendix 2.1); the Hamburg-based Global Precipitation Climatology Centre (GPCC) dataset (Rudolf et al, 1994); the Variability Analysis of Surface Climate Observations (VASCLIMO) project; and data from the Tropical Rainfall Monitoring Mission (TRMM) satellite that was launched jointly by the United States and Japan in 1997 (Kummerow et al, 2000). All these data sets suffer quality problems to varying degrees, arising from a lack of consistent gauging data, errors made in the transmission of data, and the small number of stations with data actually available at reasonable cost (see Nicholson, 2005). To derive a spatially and

temporally distributed rainfall dataset that would allow comparison with existing satellite derived vegetation data, we revisited the original rainfall datasets available, and generated consistent monthly rainfall maps going back to 1930.

### **RAINFALL STATION GAUGING DATA**

Three separate sources of publicly available rainfall station data were assembled into a single dataset (Figure 5.5).

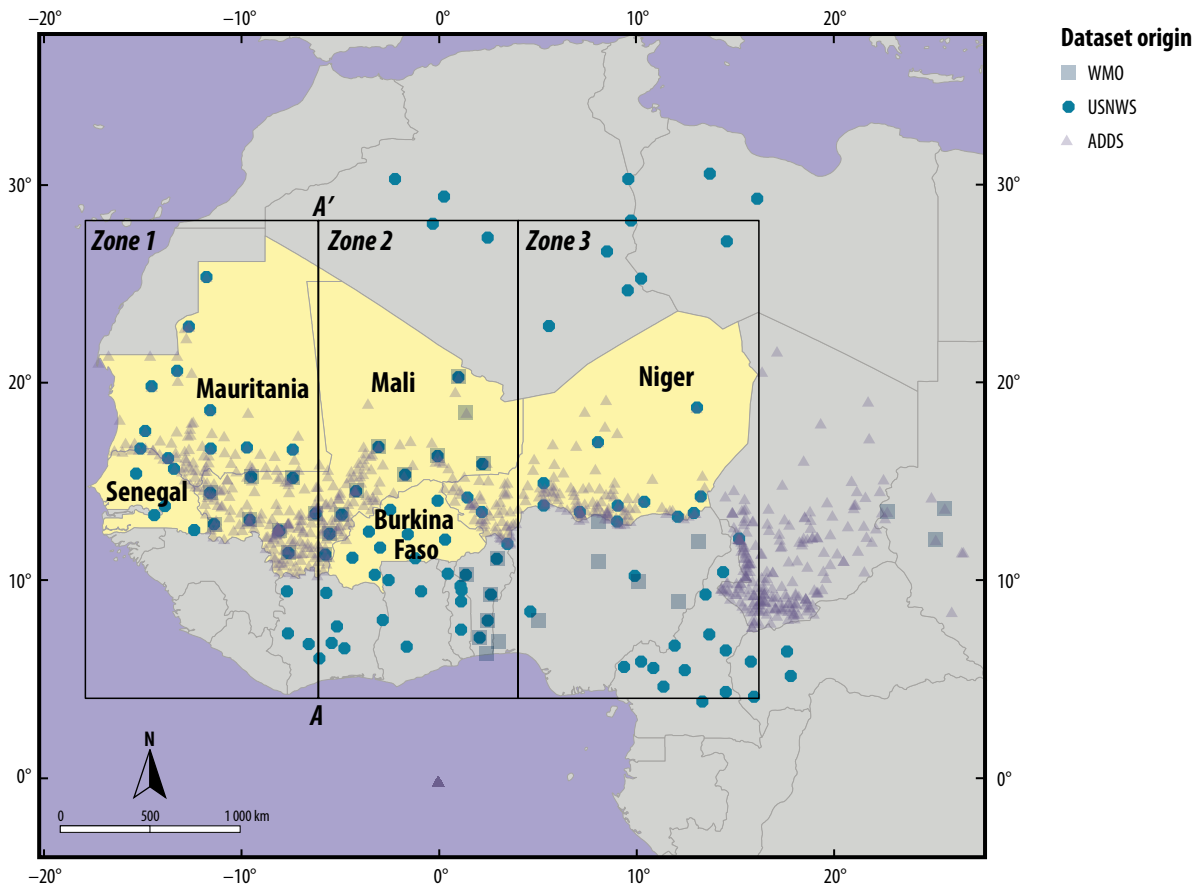
1. World Meteorological Organization (WMO) daily station data available via the Global Telecommunications System (GTS), dating back to October 1997 (57 stations);
2. A CD compiled by the United States National Weather Service (1996) with daily station data for the period 1987–1995 (110 stations); and
3. Data deposited on the website of the African Data Dissemination Service (ADDS), provided by the United States Agency for International Development (USAID), Famine Early Warning System (FEWS) (834 stations).

All station data was recalculated to represent monthly rainfall. Large gaps in the data and inadequate documentation about missing data necessitated an approach with generous acceptance of missing data. Separate levels of acceptance were used for missing data during the dry season (November to March) than the wet season. For the dry season, days with missing readings were assumed to be “nil”, whereas in the wet season missing records were retained as “missing”. If more than 50% of the monthly data records had valid readings during the dry season, then that station was included in the geostatistical interpolation. For the wet season at least 75% of the monthly records had to have valid readings in order for the station to be included. The data assembly and selection was done using purpose-written software.

In a few cases the same station was represented in two or all three of the available datasets. If the entered value was not identical, the average value was used. The station positions were given in all datasets, but if the positions given for the same station were not identical, a sequential approach was taken to adjust the position, following the sequence above (1 – WMO station position, 2 – United States National Weather Service CD station position, and 3 – ADDS station position). All input data were projected to Albers conical equal area projection before interpolation.

**FIGURE 5.5**

Rainfall stations used for spatial interpolation of rainfall 1930–1996, and zones used for analyzing latitudinal shifts in rainfall and vegetation.



### GEOSTATISTICAL INTERPOLATION OF RAINFALL STATION DATA

All stations with valid data were used as input for geostatistical interpolation. First the variogram of rainfall for each month was analyzed. During the rainy season the variogram is linear up to around 1,000 km, hence a linear variogram with no nugget was chosen to represent the rainfall for all months. The maximum search radius was set to 1,000 km. As the rainfall relation is much stronger in an East-West direction compared with North-South, double weights were given to E-W relations compared with N-S. The resulting grid was set to a resolution of 8 by 8 km to fit the satellite-derived precipitation and vegetation data.

The number of stations with acceptable data was highly variable: before 1925 and after 1996 fewer than 30 stations were recorded in the available datasets. Closer analysis of the results revealed that data prior to 1930 was not sufficient for generating

reliable results in the eastern part of the study area. The last year with sufficient data for spatial interpolation was 1996. Figure 5.6 shows the interpolated rainfall for August 1964.

### SATELLITE-SUPPORTED RAINFALL DATA

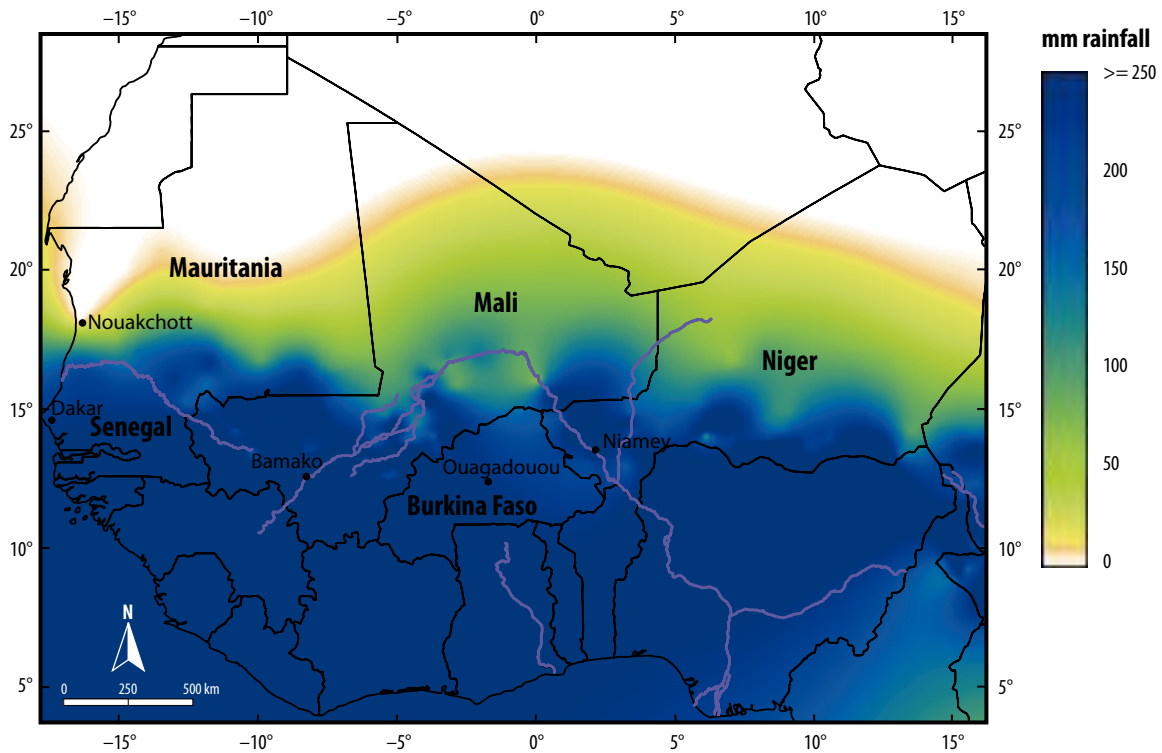
Rainfall grid maps at 8 x 8 km resolution, representing decadal (10-day) rainfall from June 1995 until December 2006, were taken from the FEWS-ADDs web site (see Appendix 2.1). These rainfall grid maps are derived from an initial estimate of precipitation based on the Geostationary Operational Environmental Satellite (GOES) Precipitation Index (GPI) (Arkin and Meisner, 1987). The GPI uses Cold Cloud Duration (CCD) for determining precipitation by assigning 3 mm of precipitation for each hour that CCD is measured at temperatures of less than 235 K. The GPI estimate is then adjusted using near-real time official rain gauge data communicated via the Global Telecommunications System (GTS). The result is an estimate of convective precipitation.



**FIGURE 5.6**

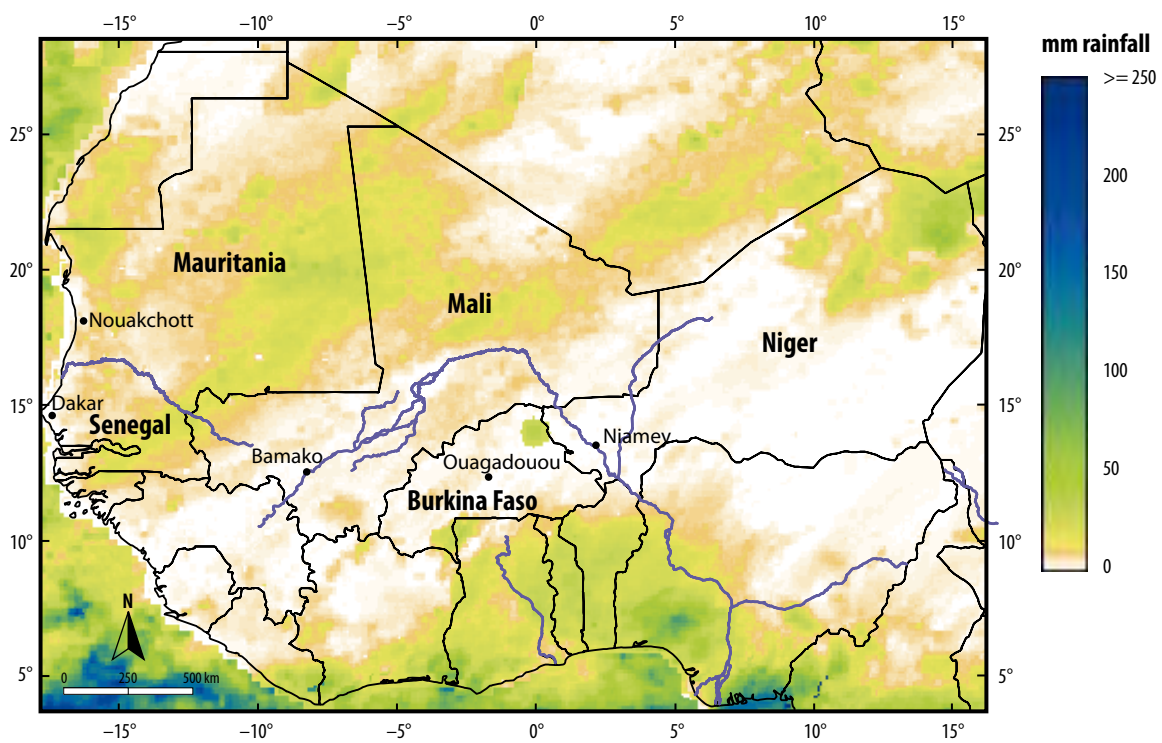
Rainfall over West Africa for the month of August 1964, created by geostatistical interpolation (variogram fitted kriging) of rainfall

gauging data. August is normally the most rainy month of the year.



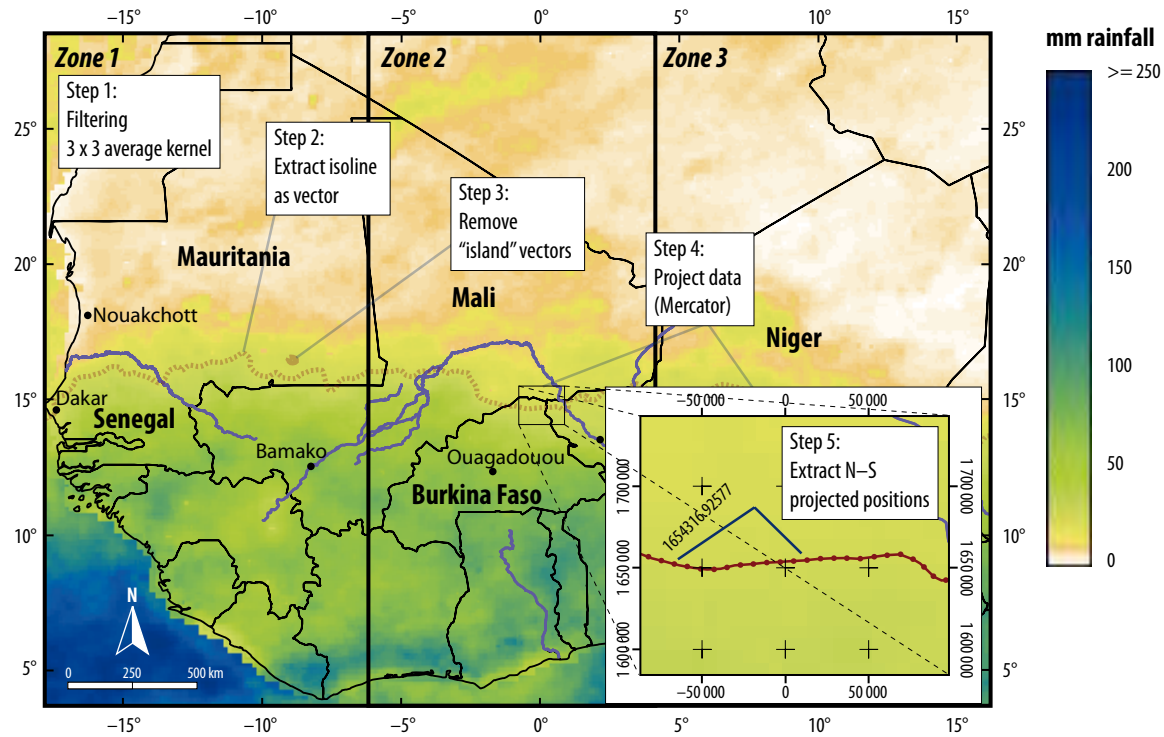
**FIGURE 5.7**

Rainfall over West Africa for the month of January 2004, created from a blend of satellite data and gauging station data (ADDS rainfall dataset); January is in the middle of the dry season.



**FIGURE 5.8**

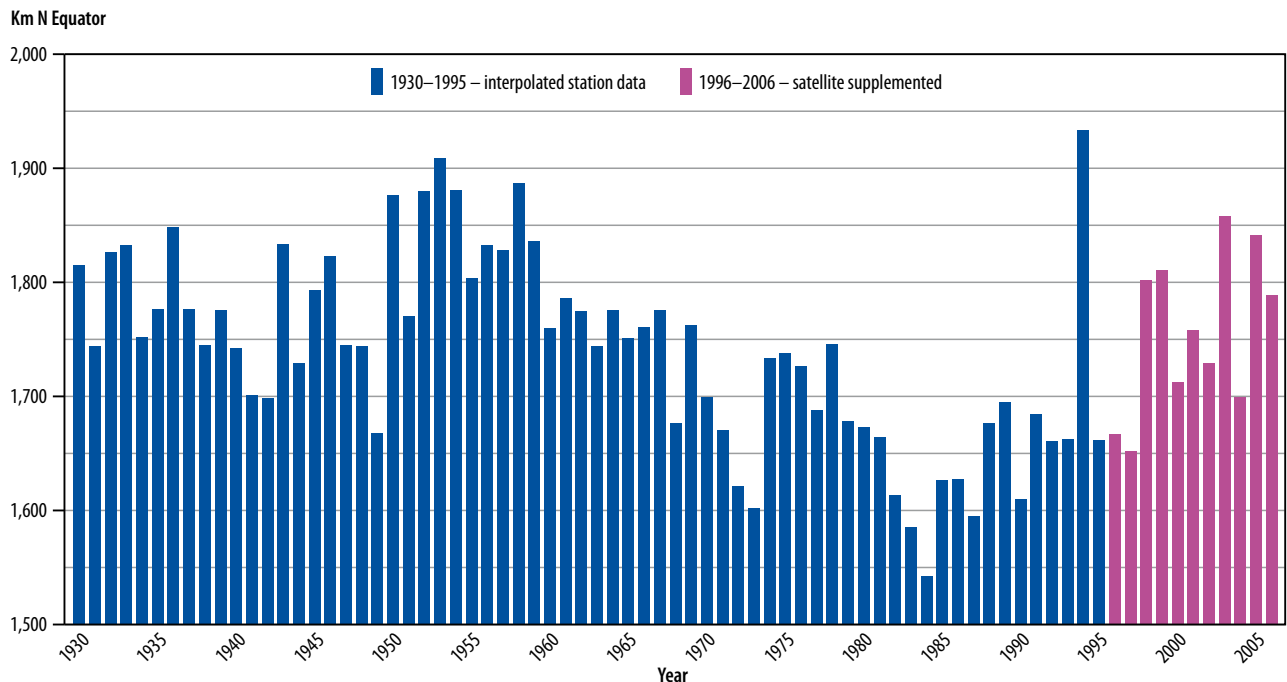
Procedure for extraction of the latitude position of the 300 mm isohyet, illustrated for the year 2004.



**FIGURE 5.9**

Variation in latitudinal position of the 300 mm isohyet in the Sahel for 1930–2006. Data for the period 1930–1995 are based on spatial interpolation of rainfall station data, whereas data for the 1996–2006 period are based on a combination of rainfall station

data and satellite data. The North-South position is in km north of the equator (Mercator projection using a spherical ellipsoid and the equator as latitude of origin for Y-coordinates).



For orographic precipitation, caused by lifting of air masses over elevated terrain with relatively warmer clouds, precipitation is estimated using a process that combines terrain slope, wind direction and the relative humidity. Wind and relative humidity are taken from the analyses of the one degree horizontal resolution data of the Environmental Modelling Centre (EMC) Global Data Assimilation System (GDAS). The convective and orographic precipitation estimates are combined to provide a distributed estimate of total precipitation (Herman et al, 1997). Figure 5.7 shows the rainfall for January 2004, a typical example of the rainfall situation during the Sahel dry season. For the years 1996–2000, the FEWS rainfall dataset lacks rainfall estimates for the region approximately north of 10° N.

### CALCULATING ANNUAL RAINFALL AND RAINFALL TRENDS

For all the years in the period 1930–2006, the decadal/monthly rainfall maps were summed to create annual rainfall maps (see Figure 5.8). The latitudinal shift in Sahel annual rainfall over this period was calculated by extracting the rainfall level

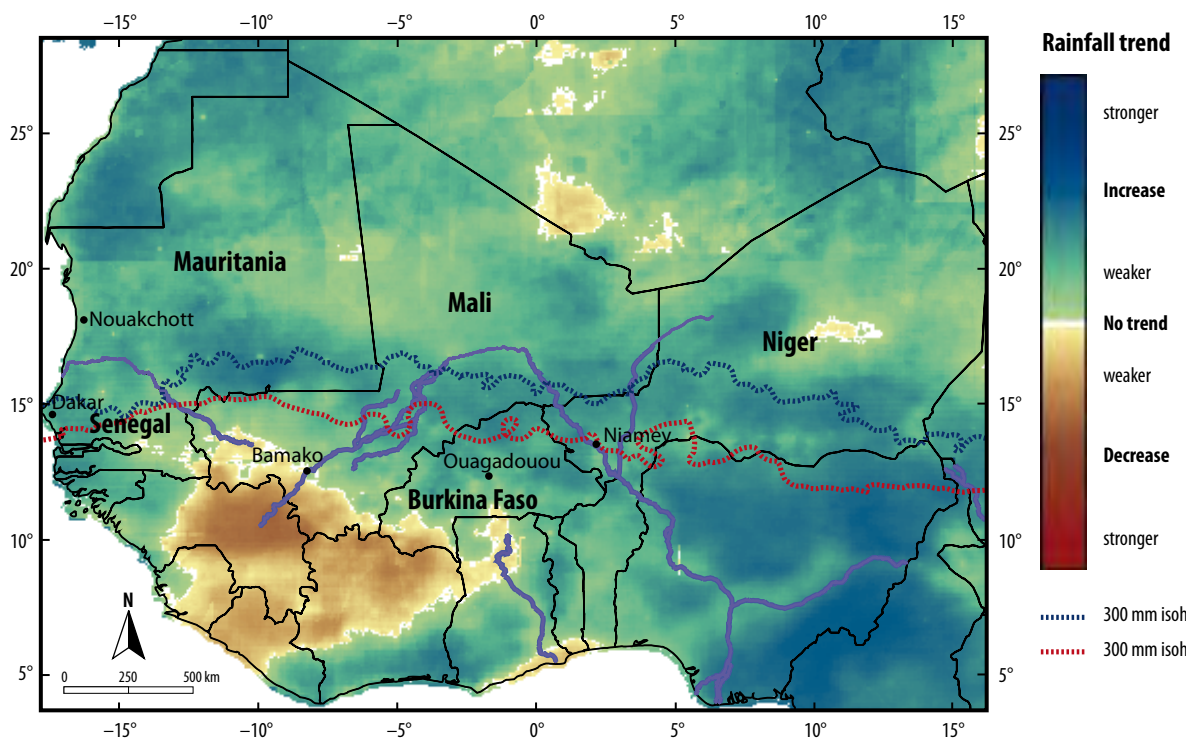
of 300 mm. The 300 mm rainfall boundary roughly corresponds with the limit for rain-fed agriculture in the Sahel (limit for growing pearl millet). The 300 mm boundary is not a desert boundary in an ecological sense, but it illustrates the relative movement of an agroecological boundary. Tracking this boundary also gives an idea of the environmental stress imposed upon the farmers and pastoralists in the region as a result of rainfall variations.

The isohyet (precipitation isoline) for 300 mm was extracted from the annual precipitation grid maps. To obtain a smooth isoline, the grid maps were first filtered with a 3 x 3 kernel using an average filter. The isolines were then extracted and all rainfall “islands” were eliminated: only the isohyet stretching the entire Sahel was kept for further analysis. The latitudinal position was then extracted for points of equal distances of about 8 km along the isohyet, and projected to Mercator projection using a spherical ellipsoid with the equator as the origin for the Y-coordinate. The derived latitudinal position is hence in km north of the equator (Figure 5.8).

**FIGURE 5.10**

Normalized trend in annual rainfall in the West African Sahel 1982–2006; rainfall data derived from spatial interpolation of point data (1982–1995) and satellite data adjusted with weather station data

(1996–2006); the 300 mm isohyets for 1984 (dry year) and 2001 are included to illustrate the change in rainfall between the droughts in the 1980s and the situation after the recovery in rainfall.



The average North-South position of the 300 mm isohyet was calculated for the whole Sahel and for three sub-regions (Figure 5.8): 1 = Mauritania, Senegal and West Mali; 2 = Burkina Faso, East Mali and West Niger; 3 = Nigeria and Niger. For each region the trend in the latitude shift of the 300 mm isohyet was calculated using least squares regression for the periods 1930–2006 and 1982–2006 (the latter period is the period for which also vegetation data is available – see Chapter 6). The North-South trend in the 300 mm isohyet was calculated using time-series Ordinary Least Square (OLS) regression.

### **TRENDS IN RAINFALL OVER THE SAHEL 1930–2006**

Figure 5.9 shows the North-South variation in the position of the 300 mm isohyet over the Sahel for 1930–2006. It has a range of 380 km. The North-South trend in rainfall for 1930–2006 shows a slightly southward (or negative) trend. The 300 mm isohyet trend in the period 1982–2006 is strongly northward, with an average of 9.0 km per year over this 25-year period. The strongest increase in rainfall since the droughts in the early 1980s has been over southern Mauritania, central Mali, the central plateau in Burkina Faso, and southern Niger (Figure 5.10). North and

south of the Sahel, rainfall has shown little or no increase from 1982–2006, and has even reduced over some areas (southern Mali and southern Burkina Faso).

The rainfall patterns over the Sahel found in this study are in agreement with those reported in previous studies. The period 1950–1965 saw high and stable rainfall, which then started to decrease during the 1960s to the early 1980s, followed by a rainfall increase from the late 1980s to the present (Nicholson, 2000a and 2005; Hulme et al, 2001; Dai et al, 2004). The driving forces for these variations are debated but recent research indicates that global circulation patterns connected to shifts in sea surface temperature, and variations in the jet streams over the Sahel in the rainy season act as an external force. With large shifts in external forcing, vegetation is hypothesized to act as an attractor through positive feedback effects and trigger flip-flop changes in climate. Within meta-stable states, however, vegetation seems to act as a negative feedback system that traps the climate in prolonged wet or dry periods – a possible explanation for the rainfall variation recorded over the last century (Figure 5.9).

## SATELLITE VEGETATION MAPPING

The greening of the Sahel after the droughts that culminated in the early 1980s has been documented both by local ground surveys (e.g. Mortimore and Adams, 2001; Niemeijer and Mazzucato, 2002; Reij et al, 2005; Hein, 2006) and regional studies using remote-sensing data (see below). The focus in this review is on studies employing remotely sensed data.

Earth observations from satellite images enable synoptic mapping of vegetation over large areas with high time frequency. This is because green vegetation strongly absorbs visible light (wavelengths 500–700 nm) for driving photosynthesis, but reflects most of the electromagnetic radiation in the near infrared range (700–1300 nm) (Figure 6.1). The difference in reflection between these bands is a sensitive indicator of green vegetation (Gausman, 1974; Tucker, 1979, Tucker and Sellers, 1986).

The longest consistent time series of satellite-derived vegetation indices available is from the Advanced Very High Resolution Radiometer (AVHRR) instruments operated by the National Oceanic and Atmospheric Administration (NOAA) in the United States of America (USA). From 1981 until today AVHRR instruments have been carried on board NOAA-7, NOAA-9, NOAA-11, NOAA-14, NOAA-16, and NOAA-17. The AVHRR sensor records electromagnetic radiation in five bands or channels: visible, near infrared, middle infrared and two thermal bands. The resolution at nadir (straight down) is 1.1 km. The spectral bands used for monitoring vegetation are the visible (580–680 nm) and the near infrared (725–1100 nm). Reflectance in these two bands are combined to calculate the Normalized Difference Vegetation Index (NDVI):

$$\text{NDVI} = (\text{near infrared} - \text{visible}) / (\text{near infrared} + \text{visible})$$

(Eq. 6.1)

Figure 6.1 illustrates the difference in vegetation reflection in the visible and near-infrared wavelengths, and the construction of NDVI using satellite AVHRR satellite data. NDVI was one of the first vegetation indices (VI) that were developed. NDVI has several shortcomings, including sensitivity to soil colour, atmospheric effects, and illumination and observation geometry. Alternative vegetation indices, include the Soil-Adjusted Vegetation Index (SAVI) (Huete, 1988), the Modified Soil Adjusted Vegetation Index (MSAVI) (Qi et al, 1994), and the Enhanced Vegetation Index (EVI) (Huete et al,

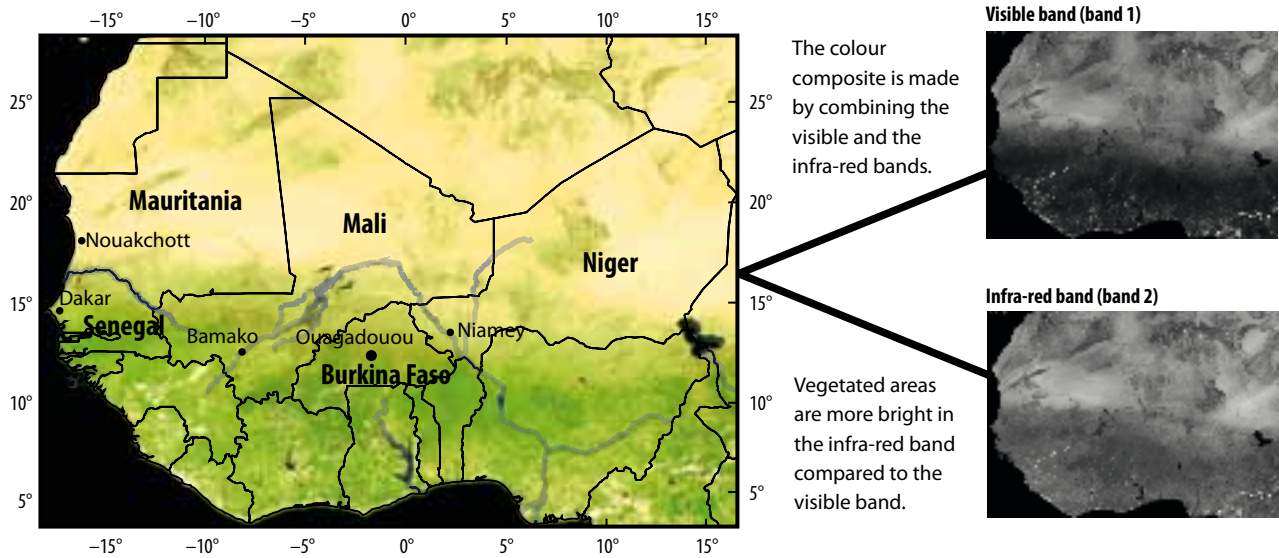
# Sahel vegetation variation 1982–2006

**FIGURE 6.1**

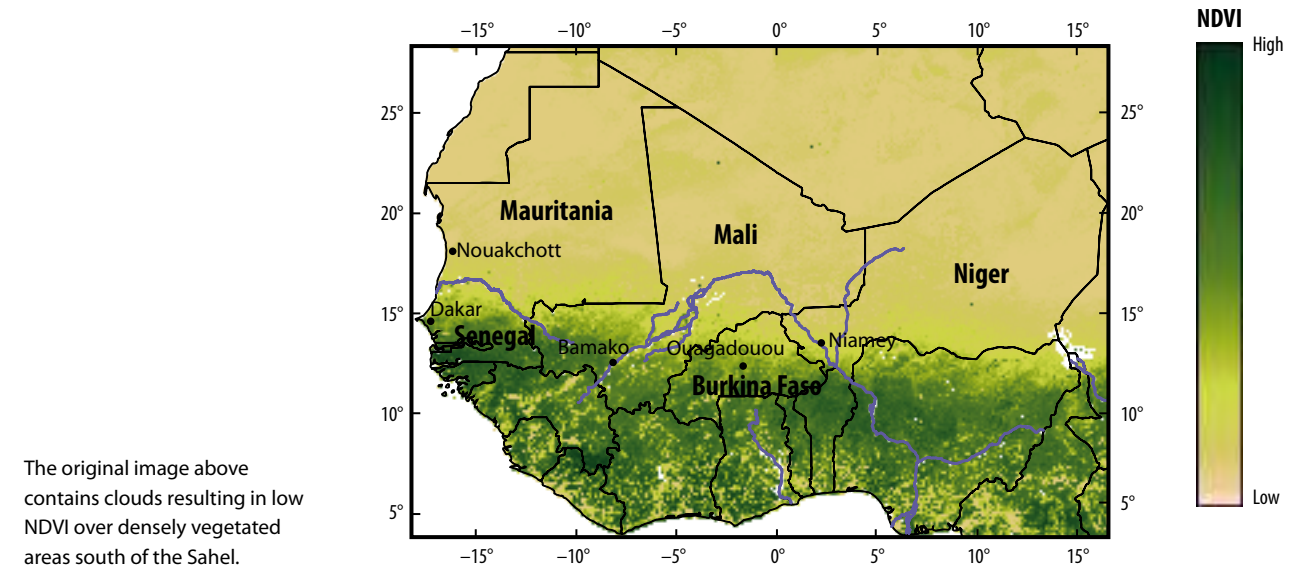
Illustration of deriving vegetation density (Normalized Vegetation Difference Index – NDVI) from NOAA-AVHRR satellite data – the illustration is made from uncalibrated AVHRR data at 1 km

resolution acquired in October 1995, with some cloud cover in the southern parts.

Calculation of NDVI from NOAA-AVHRR satellite images  
 NOAA-AVHRR image from October 1995 (1 km original resolution)



$$NDVI = \frac{B2 - B1}{B2 + B1}$$



The original image above contains clouds resulting in low NDVI over densely vegetated areas south of the Sahel.

2002; Wang et al, 2003). These more advanced and accurate vegetation indices demand additional information about surface reflectance and atmospheric conditions, not possible to obtain with the AVHRR sensor.

NDVI provides a good spectral contrast from most background materials, with restrictions in some arid and semi-arid areas where bare soil reflectance may cause large NDVI variations (Huete, 1985; Huete and Tucker, 1991; Farrar et al, 1994). NDVI has been demonstrated to be a good proxy for various vegetation parameters, including leaf area index (LAI), biomass, vegetation cover, vegetation net primary production, and fraction of Absorbed Photosynthetically Active Radiation (fAPAR) (Tucker, 1979; Asrar et al, 1984; Sellers, 1985; Myneni et al, 1997). In arid to semiarid regions, problems with sensor saturation and cloud cover are usually small. The AVHRR sensor was not explicitly constructed for vegetation mapping, and the visible and near infrared channels are not optimal for vegetation studies (see e.g. Steven et al, 2003; Gallo et al, 2005). Different studies have adopted various methods to overcome the shortcomings with AVHRR-derived NDVI measures. In this study we applied a correction for adjusting the NDVI dependent on vegetation cover and per pixel soil conditions. To neutralize the effect of soil conditions and woody biomass at the start of the growing, we further developed an index based on the annual increment in NDVI, rather than annual maximum or average (integral) NDVI.

Many studies have used AVHRR-derived NDVI to study vegetation conditions in Africa (e.g. Tucker et al, 1983, 1985 and 1991; Gray and Tapley, 1985; Justice et al, 1986; Hiernaux and Justice, 1986; Justice and Hiernaux, 1986; Townshend and Justice, 1986, Malo and Nicholson, 1990; Nicholson et al, 1998; Diallo et al, 1991; Prince, 1991; Tucker and Nicholson, 1999; Davenport and Nicholson, 1993; Nicholson and Farrar, 1994; Rasmussen, 1998; Symeonakis and Drake, 2004). The compiled NOAA-AVHRR time series is now exploited to study the linkages between climate variations and vegetation dynamics associated with El Niño/Southern Oscillation phenomenon (Anyamba and Eastman, 1996; Myneni et al, 1996; Anyamba et al, 2001; Lotsch et al, 2003) and more recently to study long-term trends in vegetation (Eklundh and Olsson, 2003; Slayback et al, 2003; Nemani et al, 2003; Anyamba and Tucker, 2005; Olsson et al, 2005). These studies show that the temporal variations in NDVI are closely linked to rainfall, both seasonally and

interannually. There is strong evidence for a linear relation between rainfall and NDVI up to a saturation threshold (Malo and Nicholson, 1990). The threshold is reported to vary from 500 mm year<sup>-1</sup> (Botswana), to 1,000 mm year<sup>-1</sup> (Sahel and East Africa) (Davenport and Nicholson, 1993; Nicholson and Farrar, 1994). However, there is typically a lag between precipitation and NDVI response. The best correlation between rainfall and NDVI is reported to be provided by using data from the concurrent month plus two previous months (Malo and Nicholson, 1990; Davenport and Nicholson, 1993; Schmidt and Karniele, 2000; Herrmann et al, 2005b).

Most of the NDVI studies reported above detected no indication of land degradation in the Sahel. The link between NDVI and ecosystem/agroecosystem processes is however reported to be weak (e.g. Hutchinson, 1991). Beck and others (1990) found little difference in NDVI when comparing two semi-arid grasslands with different ground conditions across the border of Mexico and the United States. Karniele and others (2002) found differences in the NDVI derived from semi-arid grasslands and woodlands, not reflected by ground measurements of vegetation. Bush encroachment in grazing lands (usually taken as a sign of over-grazing and degradation) is difficult to distinguish using NDVI, and can even lead to increased NDVI values (Pearce, 1992). Semiarid pastures with moderate grazing pressure are reported to be more productive compared to ungrazed fallow (*ibid*; Oba, 1994) but will show up as areas with reduced NDVI (see e.g. Bénié 2005; Kawamura et al, 2005). These problems need to be considered in regions that have gone through transient changes, e.g. due to changes in grazing pressure or climate. The incremental NDVI-index (as a proxy for net primary production) developed herein is hypothesized to partly neutralize transient changes in ecosystems/agroecosystems, and hence give a more objective evaluation of land degradation processes.

### THE GIMMS AVHRR-NDVI DATASET

The NDVI used in this analysis is processed by the Global Inventory Monitoring and Modeling System (GIMMS) group at NASA Goddard Space Flight Center (GSFC) (see Tanre et al, 1992; Tucker et al, 2005; Pinzon et al, 2005; Los et al, 1994; Los, 1998; Vermote et al, 1995 for processing details). Near-real time data processing for Africa is carried out to support the activities of the Famine Early Warning System (FEWS) project of the United States Agency for International Development (USAID). The data, at 8 x 8 km spatial

resolution, are first processed as 10-day composites using a Maximum Value Compositing (MVC) procedure to minimize effects of cloud contamination, varying solar zenith angles and surface topography (Holben, 1986; Tucker and Newcomb, 1994). To further minimize the effects of sensor degradation, calibration based on stable desert targets is applied to minimize the effects of sensor degradation (Los et al, 1994). Stratospheric aerosol corrections are applied to remove the effects of the eruptions of El Chichon from 1982–1984 and Mt. Pinatubo from 1991–1993 (Vermote and El Saleous, 1994). In a recent accuracy evaluation the GIMMS NDVI dataset was shown to have consistent quality, and was concluded to be the best source for historical vegetation studies

(Fensholt et al, 2006). The ADDS NDVI data used in this study are version 'g', where all cloud data have been filled in using average values from the preceding and following decades (Gutman et al, 1994). The NDVIg data are scaled to fit the range 0–255. Conversion to original NDVI values is given by:

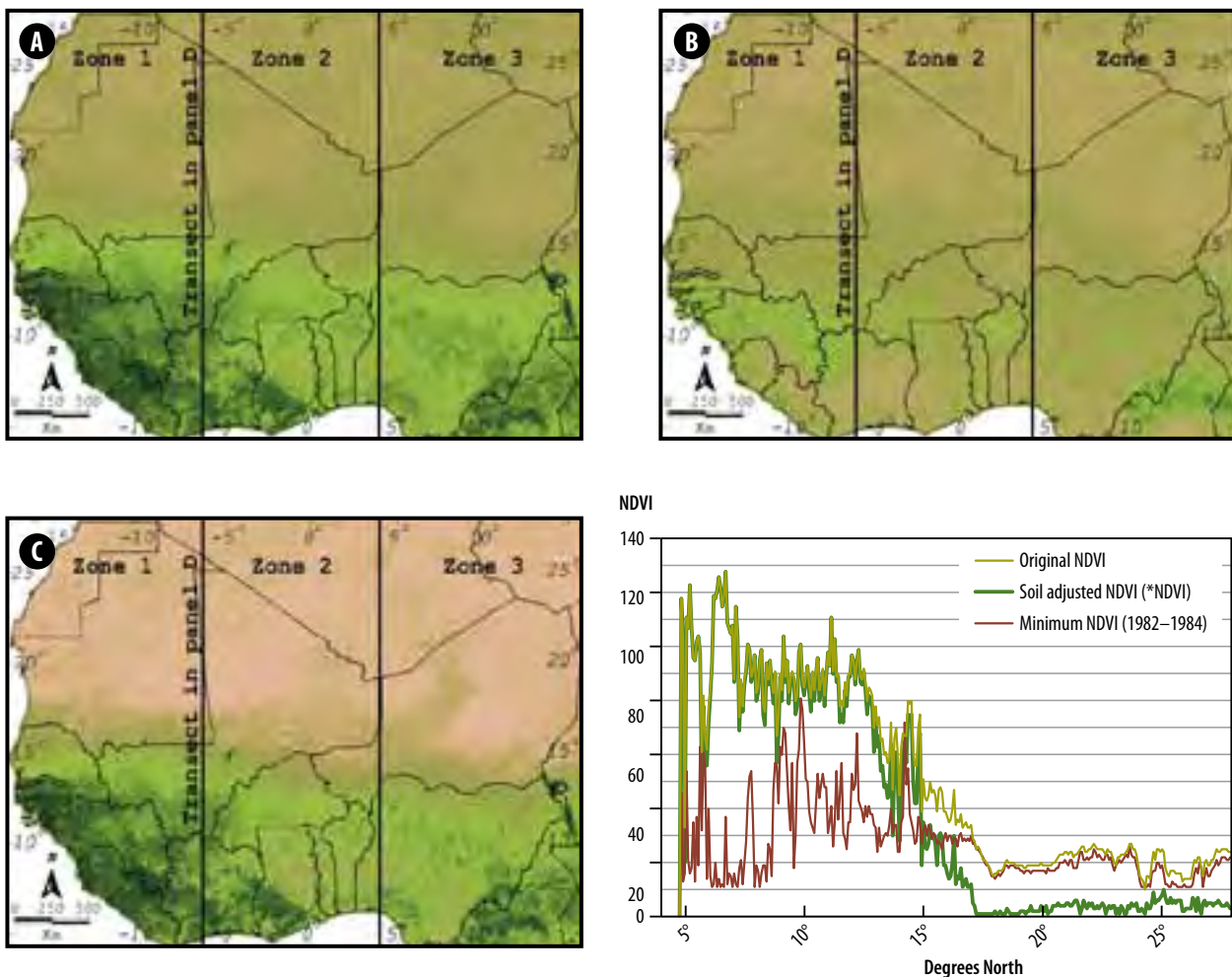
$$\text{NDVI} = \text{NDVIg} / 255 \text{ (Eq. 6.2)}$$

The data used here is derived from 6 generations of AVHRR sensors, carried on board NOAA -7, -9, -11, -14, -16 and -17. The most notable residual problem is decreasing NDVI trends for individual satellites at low latitudes caused by increased solar zenith angles following satellite orbital drift (Eklundh and Olsson,

### FIGURE 6.2

Example of the NDVI pre-processing steps and results for the first decade of January 2004, showing A) unadjusted NDVI, B) the minimum NDVI extracted from images acquired in February to

March in the years 1982–1984, C) adjusted image, and d) the difference between the adjusted and unadjusted NDVI along the transect shown in images (A) to (C).





2003; Slayback et al, 2003). These problems are well known and studies that have utilized the NOAA-AVHRR NDVI data have used different approaches to minimizing the problems, for instance excluding one or several years of data. The presently available NDVI data from GIMMS (version 'g') is, however, corrected for orbital drift (Pinzon et al, 2005). In this study we have hence chosen to use the complete time series, covering the period July 1981 to December 2006. A goal-driven approach that eliminates the inter-annual distortions in the NDVI data is presented in Chapter 8. We also chose to use the original decade (10-data maximum) data. Most other studies chose to rely on monthly maximum NDVI, in order further to reduce errors stemming from cloud contamination. Monthly data is, however, too sparse to allow a correct analysis of the vegetation phenology in the Sahel (e.g. Tucker et al, 1983), and hence fails to capture annual vegetation growth in rangelands with intermittent grazing.

### NDVI PREPROCESSING

The GIMMS NDVI data is not linearly related to vegetation cover or biomass, and overestimates vegetation cover over bare and sparsely vegetated soil (cf. Huete, 1985; Huete and Tucker, 1991). Several

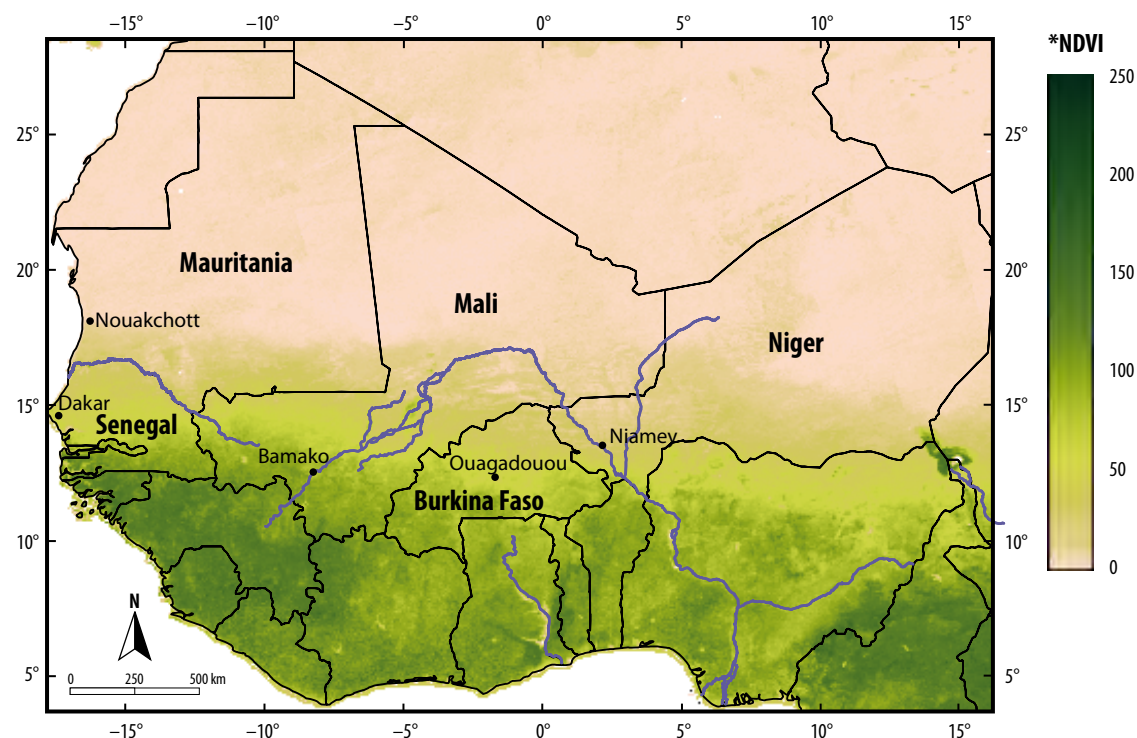
algorithms have been developed to adjust NDVI for soil conditions and for low vegetation densities. In this study a linear NDVI correction process following Maselli and others (2000) was adopted for adjusting the GIMMS NDVI data. The scaled NDVI (or \*NDVI) method used by Maselli and others (2000) does not demand any data other than the original NDVI data. The method assumes that the soil influence decreases as vegetation increases, and becomes negligible at full vegetation coverage:

$$*NDVI = (NDVI - NDVI_0) / (NDVI_S - NDVI_0) \text{ (Eq. 6.3)}$$

where  $NDVI_S$  is the value of NDVI at 100% vegetation cover and  $NDVI_0$  is the value for bare soil (Choudhury et al, 1994; Carlson et al, 1995).  $NDVI_0$  was estimated by finding the lowest NDVI in the driest period of the available time series (See Figure 6.2). For the Sahel we used the February to March data for the years 1983–1985 to estimate the bare soil NDVI ( $NDVI_0$ ) value. Values higher than  $NDVI = 25$  were assumed to be contaminated by vegetation, and values lower than  $NDVI = 10$  were assumed to be contaminated by clouds. Hence  $NDVI_0$  values falling outside the range 10–25 were set to these threshold values. NDVI

**FIGURE 6.3**

Average scaled NDVI (\*NDVI) for the years 1982–2006, based on decadal (10-day) maximum value compositions.



values at 100% vegetation coverage (NDVIS) were set to 94, following Maselli and others (2000). \*NDVI of bare dark soil was set to 1 and water areas to 0. Figure 6.2 illustrates the processing steps, and the resulting NDVI adjustment.

### NDVI TRENDS 1982–2006

The overall average scaled NDVI for the period 1982–2006 is shown in Figure 6.3.

The \*NDVI data set was used for extracting an average annual vegetation cycle over the Sahel Parklands (11° N–18° N) using the decadal values for the period 1982–2006 (Figure 6.4). The rainfall maximum occurs in August, with the maximum vegetation growth lagging into September and October.

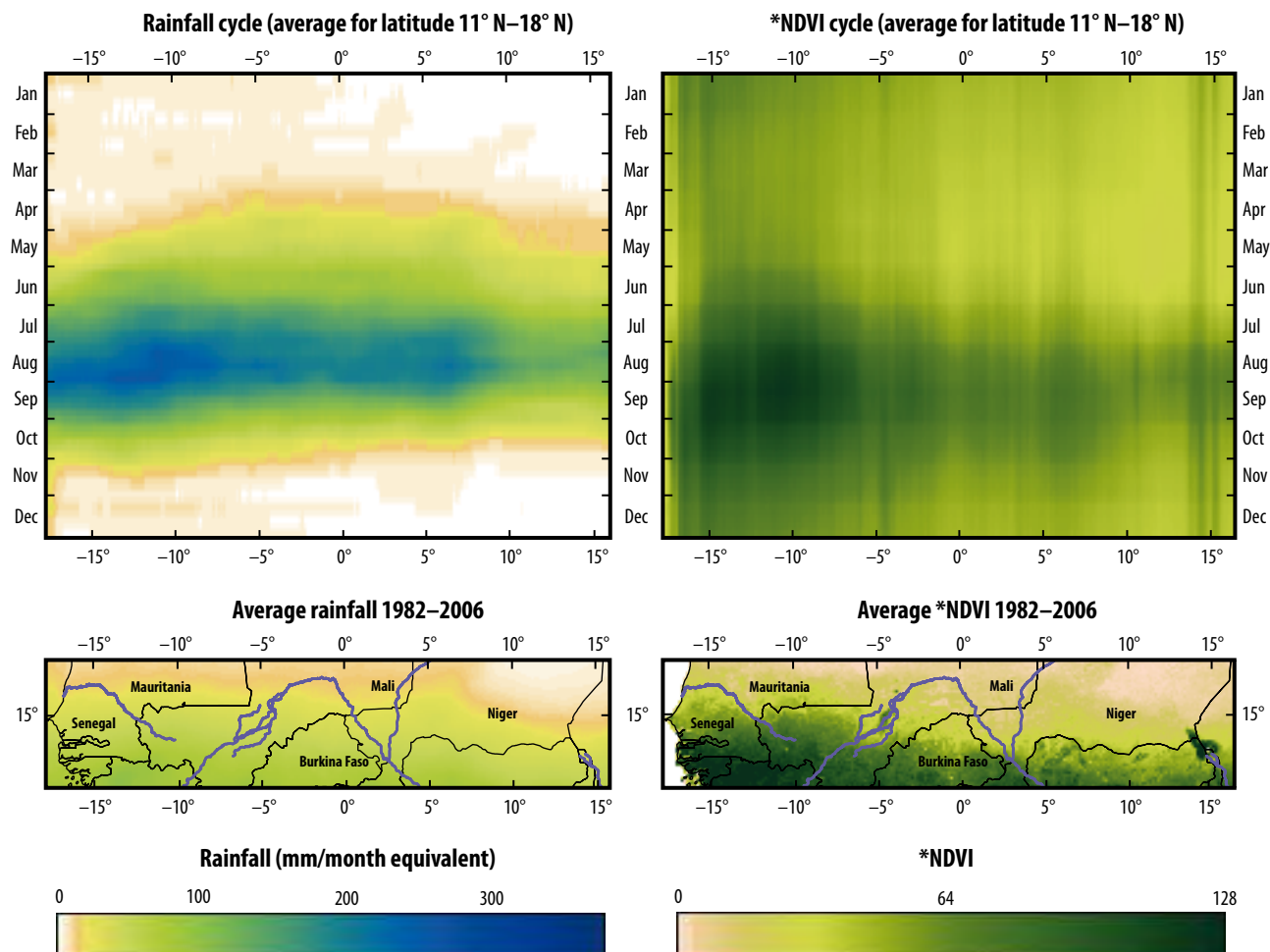
The evolution of vegetation for the Sahel Parklands region (11° N–18° N) from July 1981 to December 2006 is shown in Figure 6.5. Rainfall data after 1995 is for 10-day periods, whereas rainfall from 1982–1995 has been converted from monthly data to 10-day data by interpolation and averaging.

Figure 6.6 illustrates variations in rainfall and vegetation production in space and time by comparing the annual rainfall and vegetation cycles for a transect through Mali (Figure 6.2), showing three selected years: 1984 (dry), 1994 (wet) and 2004 (recent year with more “normal” rain). The rainfall data for 1984 and 1994 were derived from monthly interpolation of rainfall station data, and then interpolated and averaged to 10-day interval data – the rainfall pattern

**FIGURE 6.4**

Hovmoller diagrams of annual rainfall and \*NDVI cycles for the Sahel region spatially averaged between 11° N and 18° N and temporally averaged for the period 1982–2006. The rainfall occurs from July–October, with a maximum in August, while the rest of the year is mostly dry (left panel); the annual NDVI cycle

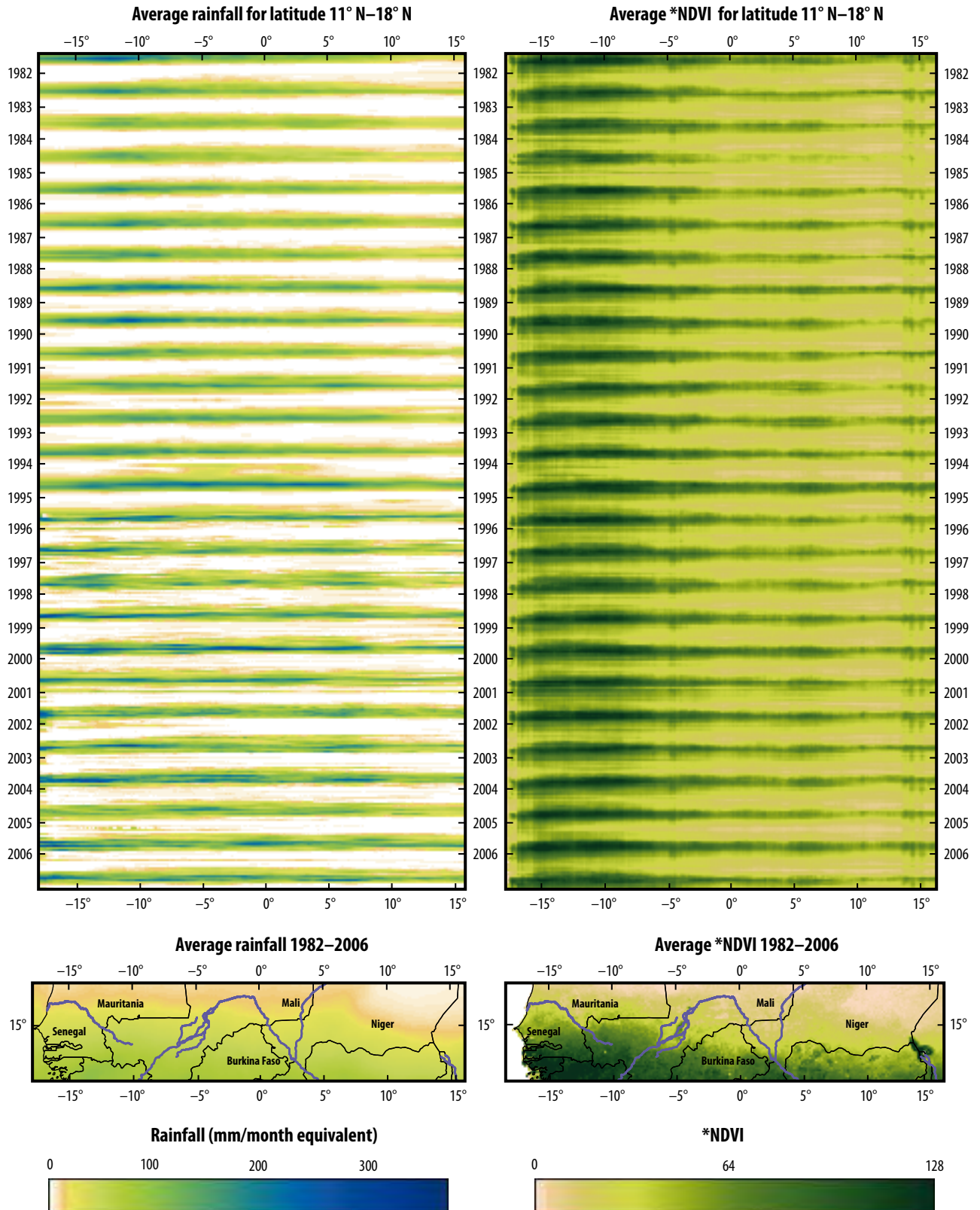
lags behind the rainfall, with the larger water bodies (the Niger inland delta in Mali and Lake Chad) sustaining longer growth periods (right panel). Note that the \*NDVI in this figure is rescaled compared with other figures.



**FIGURE 6.5**

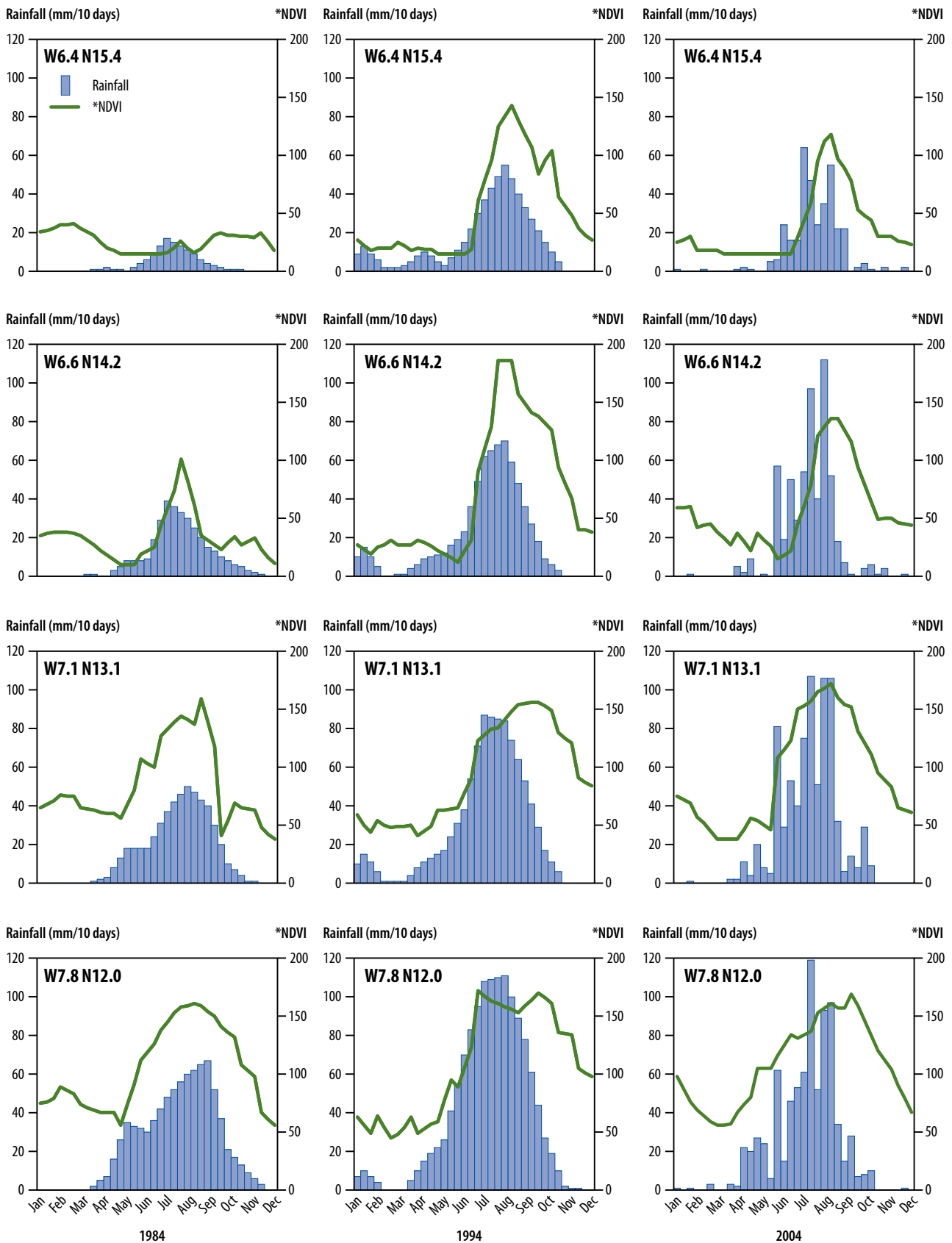
Hovmoller diagram showing the evolution of rainfall (left) and \*NDVI (right) for each 10-day period (decade) from July 1981–December 2006 across the Sahel Parklands region between 11° N and 18° N. The low rainfall in the early 1980s (especially 1984) is seen, as is the higher rainfall in e.g. 1994 and 1998. The change

in the rainfall pattern before and after 1995/96 is affected by a change in rainfall mapping method. The evolution of NDVI over the 25 years closely follows the rain, with the lowest NDVI in 1984 and the highest in 1994. Note that the \*NDVI in this figure is rescaled compared with other figures.



**FIGURE 6.6**

Annual rainfall and vegetation cycles for a transect through Mali (Figure 6.2) showing annual cycles for 1984 (dry), 1994 (wet) and 2004 (recent year with more “normal” rain).



hence has a more smooth appearance compared to the 2004 rainfall data which is based on satellite-supported 10-day original values.

The diagrams in Figure 6.6 clearly illustrate the increase in rainfall going from north to south, and how rainfall has varied largely between dry (1984), wet (1994) years compared with more “normal” years (2004). The lag in vegetation response following rainfall is also seen. The variation in the vegetation growth pattern is likely to be dependent on both rainfall and land management: in farmland a unidirectional increase in growth is followed by one or two abrupt decreases indicating harvest, whereas in grazing land growth can be expected to be more intermittent as a result of extensive grazing. As the area of each pixel represented in the diagrams is 64 km<sup>2</sup>, it is most probable that land management in varying within the pixel and hence the recorded \*NDVI cycle is also showing the pattern of a mixed landscape. Another observation that can be made from the diagrams is that despite the adjustment of the original NDVI to \*NDVI (Figure 6.2) the diagrams indicate substantial vegetation cover even during the drought in 1984, and dry seasons.

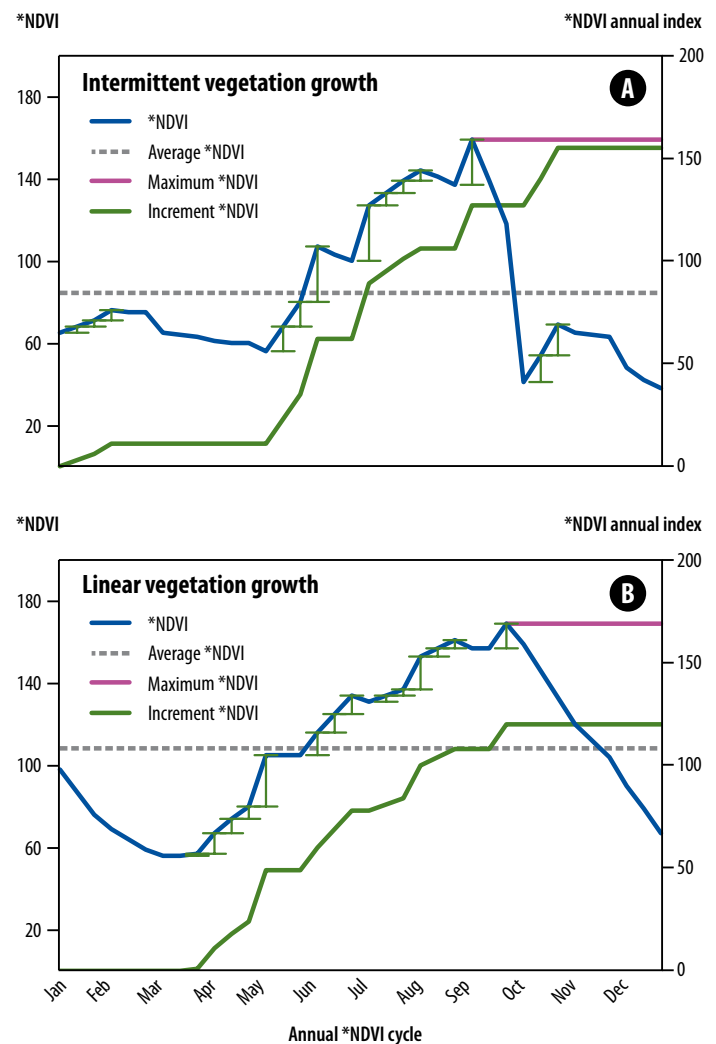
### METHODS FOR CALCULATING ANNUAL VEGETATION GROWTH AND TRENDS

To calculate the annual vegetation growth from time series of satellite-derived vegetation data, several different approaches can be used. The most commonly used approach is to calculate the annual or growing season integral (equivalent to sum or average) of vegetation growth (Figure 6.7). Another common approach is to use the annual (growing season) maximum vegetation index for representing growth, especially in agro-ecological landscapes (Figure 6.7). In this study we developed an alternative index, calculated as the annual increment in vegetation growth (Figure 6.7). The increment index calculates annual vegetation growth as the accumulated positive difference between \*NDVI recordings in an annual sequence of recordings. Compared with the other indices it hence neutralizes initial \*NDVI values at the beginning of the growing season, and it captures vegetation growth in intermittently grazed pastoral landscapes, as illustrated in Figure 6.7.

Each approach for calculating annual vegetation growth from time-series of NDVI data has its merits and drawbacks. Hence all approaches were tested

**FIGURE 6.7**

Illustration of methods for calculating annual vegetation growth from time series of satellite derived vegetation data; a) NDVI cycle with intermittent vegetation growth, and b) NDVI with linear vegetation growth.

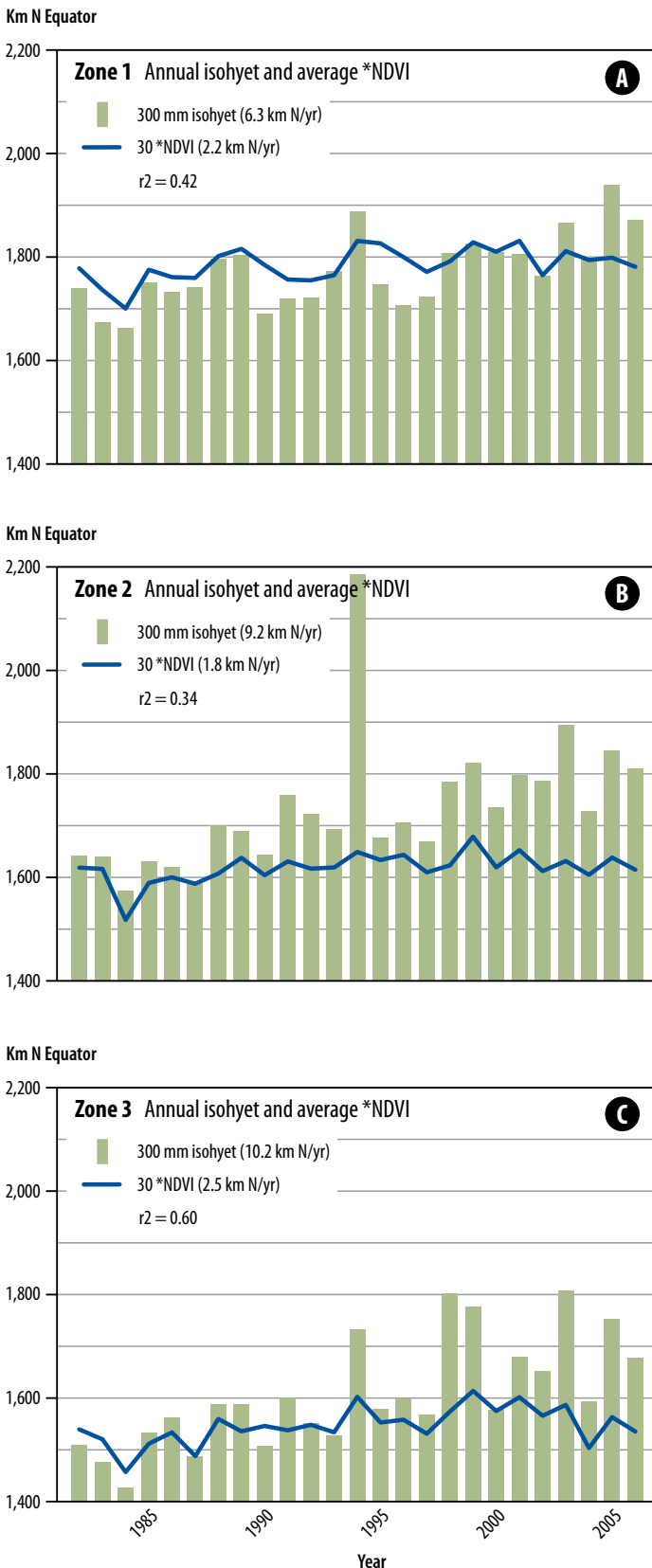


and compared for analyzing both absolute and rain-adjusted vegetation changes in this study.

For calculating spatial trends in rainfall, vegetation growth and RRNDVI data was normalized using z-scores. The z-score (or normal or standard score) is a dimensionless quantity derived by subtracting the population mean from an individual raw score (annual rainfall, \*NDVI or RRNDVI) and then dividing the difference by the population standard deviation. The standard score derived from the normalization indicates how many standard deviations an observation is above or below the mean. It allows comparison of observations from different normal distributions, and reduces the influence of outliers.

**FIGURE 6.8**

Latitude shift in rainfall (isohyet = 300 mm) and average NDVI (iso \*NDVI = 30) in the Sahel 1982–2006, a = zone 1, b = zone 2, and c = zone 3 (see Figures 4.1 and 4.4); the northward trends of rainfall and vegetation growth are indicated in the legend.



## TRENDS IN ANNUAL AVERAGE NDVI 1982–2006

The annual average (equivalent to annual sum or annual integral) \*NDVI for the Sahel was calculated from the scaled NDVI dataset. For analyzing the annual latitude shift of vegetation in the Sahel, an arbitrary value of \*NDVI = 30 was chosen, simply for the reason that it falls closely to the rainfall level of 300 mm used in the rainfall analyses. The isoline for \*NDVI = 30 was extracted from the vegetation maps, excluding the coastal strip (which shows a more erratic behaviour related to coastal rainfall that is not well captured in the rainfall dataset). All “islands” of \*NDVI = 30 were excluded and only the continuous isoline transgressing the entire Sahel was selected for further analysis (method as illustrated in Figure 5.8). The latitudinal shifts in the average \*NDVI for the entire study area and for three separate zones (see Figure 5.5 and Figure 5.8) were calculated by extracting a position point every 8 km along the isoline for \*NDVI = 30. The correlation between the northward shifts in rainfall (isohyet = 300 mm) and annual average vegetation (\*NDVI isoline = 30) was calculated using OLS regression (Figure 6.8). The northward trend in \*NDVI = 30 was also calculated using time-series regression (Figure 6.8). The trend in average \*NDVI for each pixel over the period 1982–2006 was calculated by first normalizing the data and then using OLS regression (Figure 6.9). The significance of the pixel-wise trend was calculated by comparing the observed normalized trend with 999 randomized permutations.

## ANNUAL MAXIMUM NDVI 1982–2006

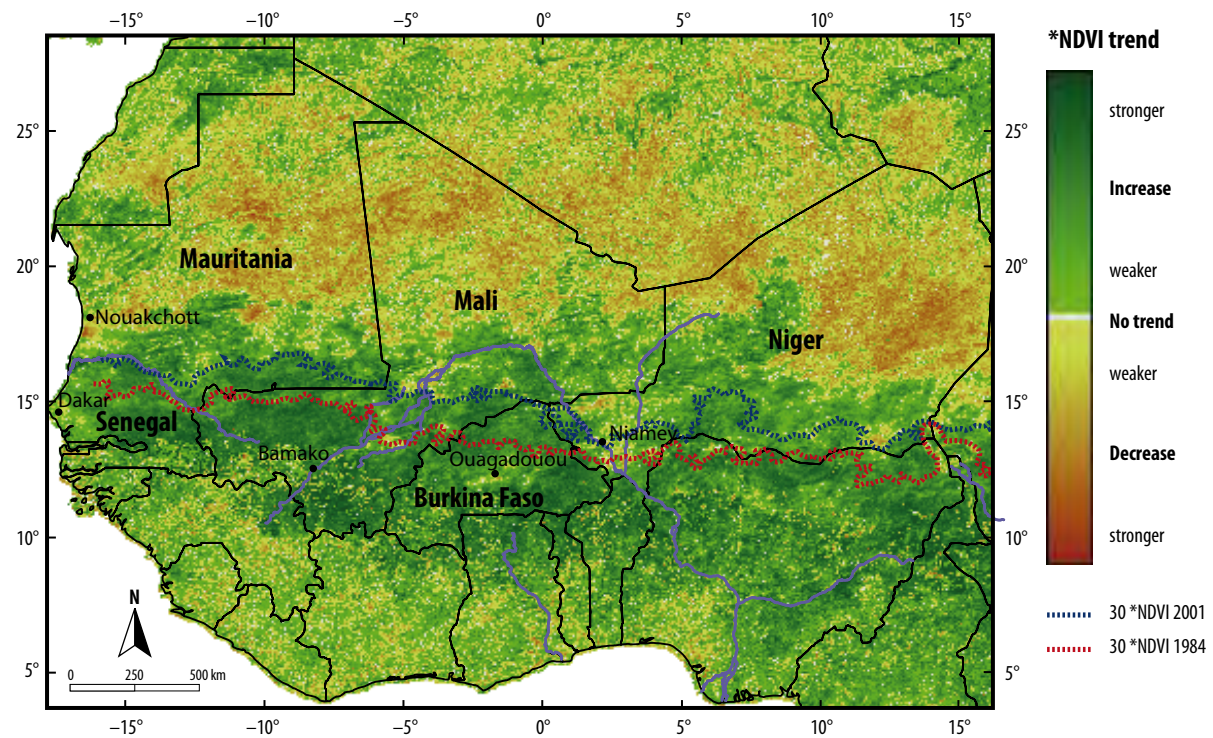
The annual maximum NDVI value is less affected by clouds compared with the average NDVI, and frequently used as a measurement of primary production in farmlands (Hiernaux and Justice, 1986; Hobbs, 1995; Fuller, 1998) (Figure 6.10).

To study the latitudinal shifts in maximum NDVI, the isoline for maximum \*NDVI = 70 was extracted in the same way as the average annual \*NDVI = 30 and the 300 mm rainfall isohyet (see Figure 5.8). The latitudinal shifts in the annual maximum \*NDVI for the entire study area and for three separate zones (see Figures 5.5 and 5.8) were calculated by extracting a position point every 8 km along the isoline for \*NDVI = 70. The correlation between the northward shifts in rainfall (isohyet = 300 mm) and maximum vegetation (\*NDVI isoline = 70) was also calculated using OLS regression (Figure

**FIGURE 6.9**

Normalized trend in annual average \*NDVI for the period 1982–2006. The map also shows the latitudinal movement of vegetation

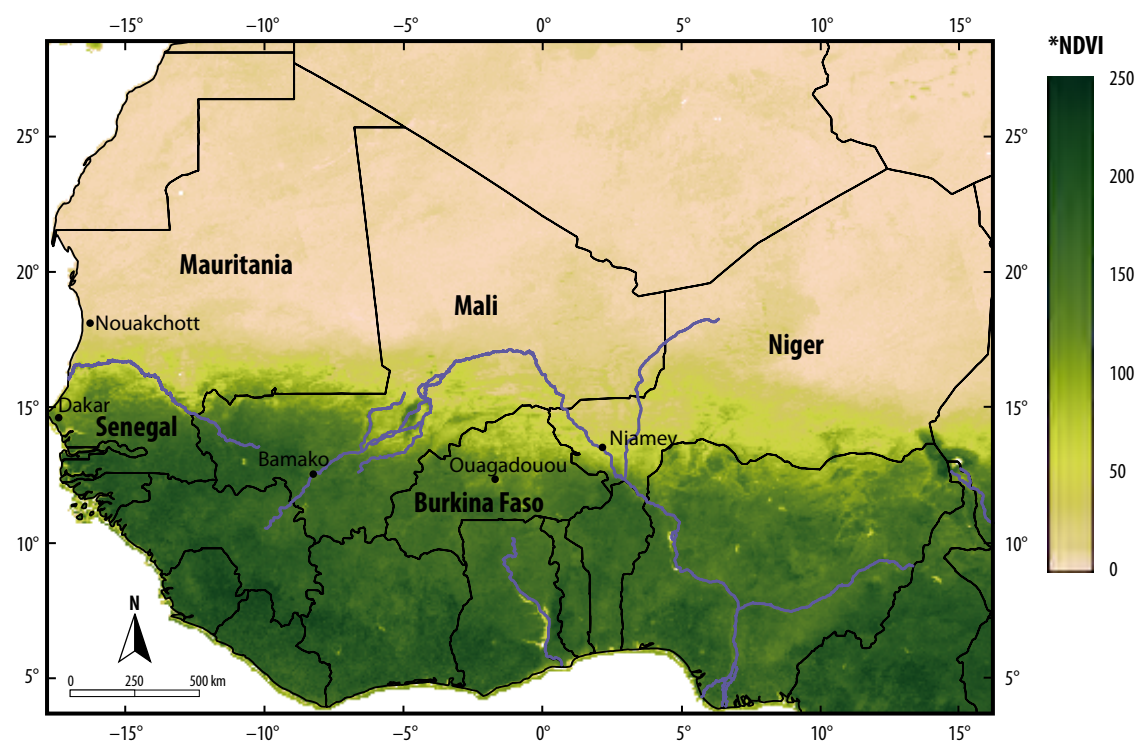
illustrated by the isolines for annual average \*NDVI = 30 for the years 1984 (dry) and 2001 (wet).



**FIGURE 6.10**

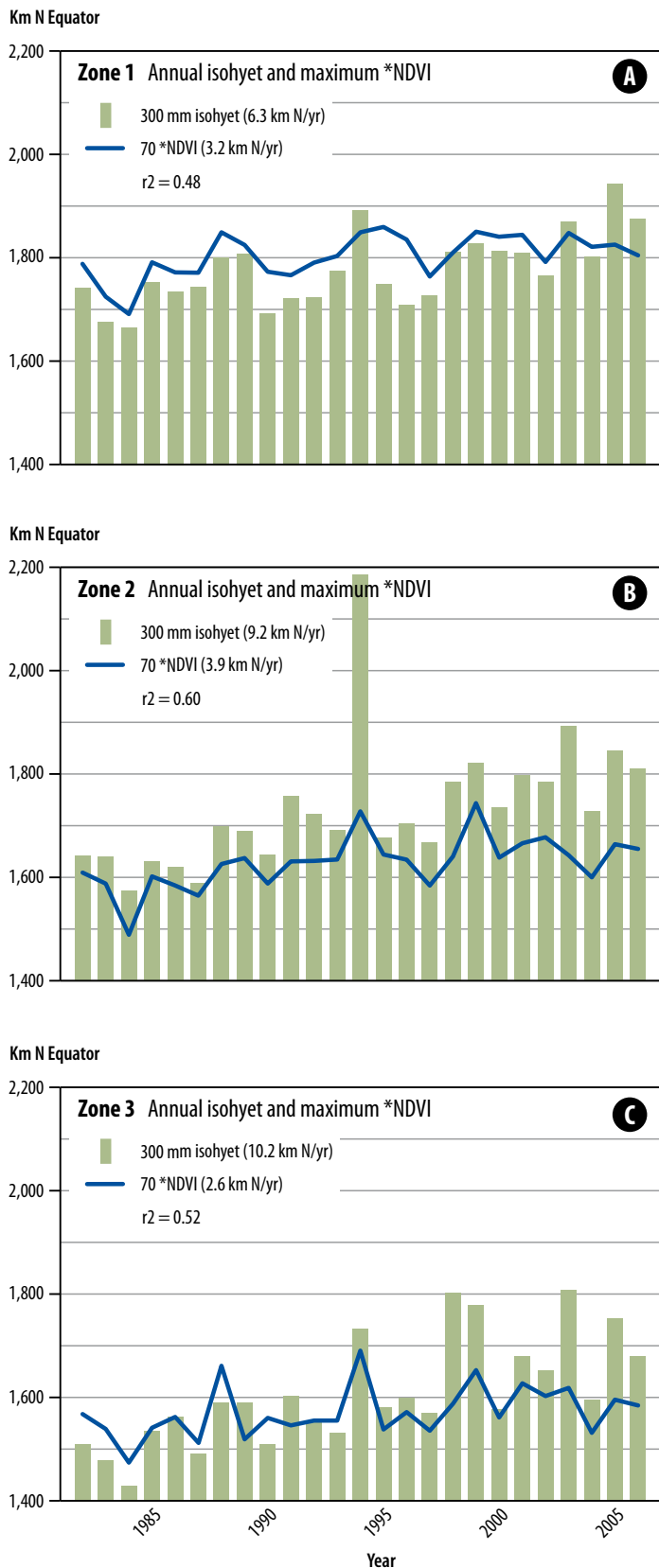
Average annual maximum \*NDVI 1982–2006; the maximum NDVI (\*NDVI) is sometimes used as a proxy for estimating net primary production in agricultural systems, under the assumption that the

maximum value represents standing crop biomass before annual harvest.



**FIGURE 6.11**

Latitudinal shift in rainfall (isohyet = 300 mm) and maximum NDVI (iso \*NDVI = 70) in the Sahel 1980–2004; a = zone 1, b = zone 2, and c = zone 3 (see Figures 5.5 and 5.8); the northward trends of rainfall and vegetation growth are indicated in the legend.



6.11). The northward trend in \*NDVI = 50 was also calculated using OLS time-series regression (Figure 6.11). The trend in annual maximum \*NDVI for each pixel over the period 1982–2006 (Figure 6.12) and its statistical significance was calculated as for average \*NDVI.

### ANNUAL INCREMENT \*NDVI 1982–2006

A drawback with using the average or annual maximum NDVI in arid and semi-arid pastoral regions is that NDVI is a biased indicator of production. Intermittent grazing reduces the values of both the average and maximum NDVI (see Figures 6.6 and 6.7) even though biomass production may be higher compared to other systems such as fallows (e.g. McNaughton et al, 1988; Pearce, 1992; Oba, 1994).

To deal with this problem we developed a theoretically neutral index for annual vegetation growth, defined as the increment in NDVI between each of the individual 36 decades (i.e. difference in \*NDVI between current and previous decade if positive) and then summed these increases over the whole year (see Figure 6.7). For the Sahel, the starting decade was set to the December 21st–31st decade of the preceding year, also eliminating initial differences stemming from soil properties and woody biomass. In an ideal case, with zero vegetation at the start of the growing season, continuous accumulation of vegetation density until harvest and no further vegetation growth, the increment index estimate would equal the maximum NDVI. By summing the increments we hypothesize that the increment index better captures the productivity of rangelands, and neutralizes the differences between rangelands, croplands and parklands. It further has the advantage of neutralizing initial background effects (e.g. soil moisture conditions, influence of woody biomass) at the start of an annual growing cycle (cf. Figure 6.7). The developed increment index should hence be more suitable when comparing vegetation in landscapes with transient temporal and spatial changes, compared with either the annual average or maximum indices.

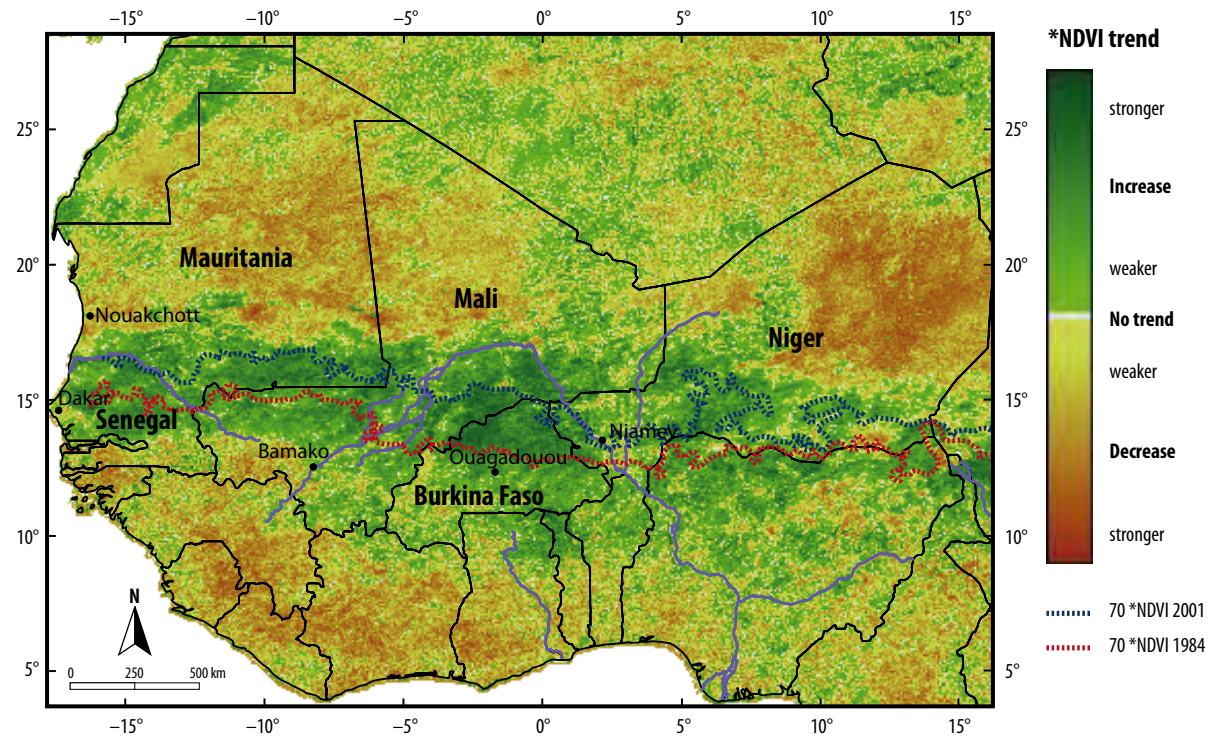
Figure 6.13 shows the increment index averaged for the years 1982–2006, which can be compared with the average and maximum annual indices for the same period shown in Figures 6.3 and 6.10 (note, however that the scales of \*NDVI differs in these images).



**FIGURE 6.12**

Normalized trend in maximum annual \*NDVI for the period 1982–2006. The map also shows the latitudinal movement of vegetation

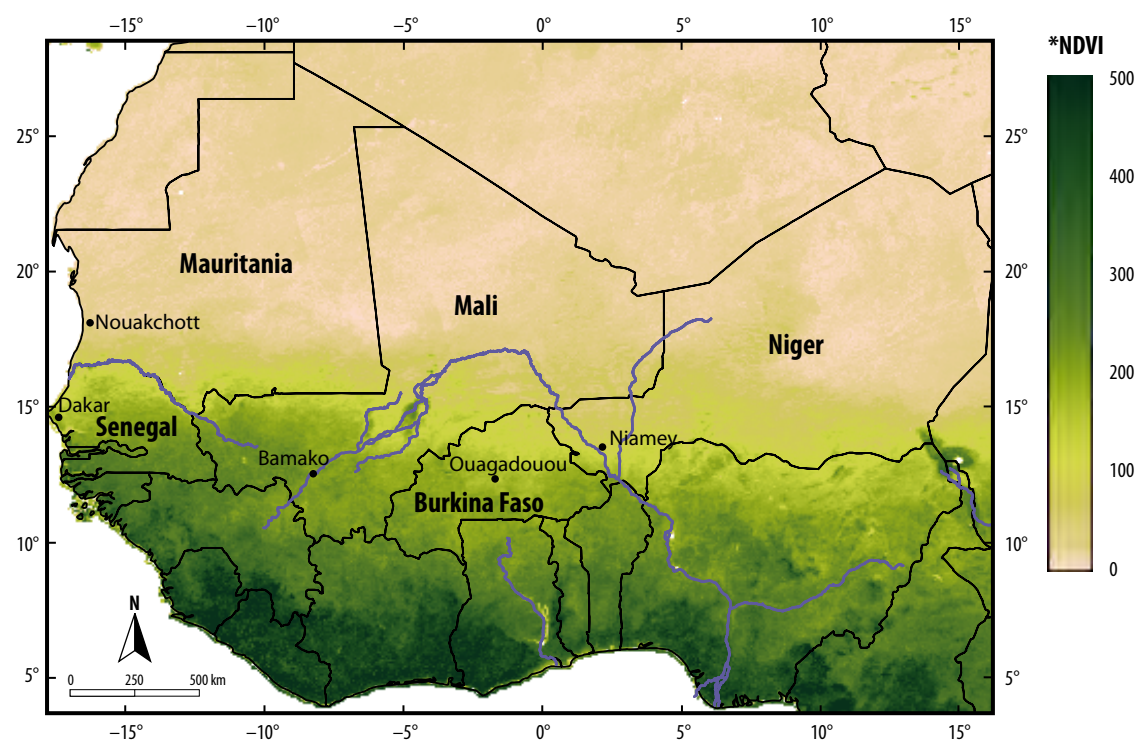
illustrated by the isolines for annual maximum \*NDVI = 70 for the years 1984 (dry) and 2001 (wet).



**FIGURE 6.13**

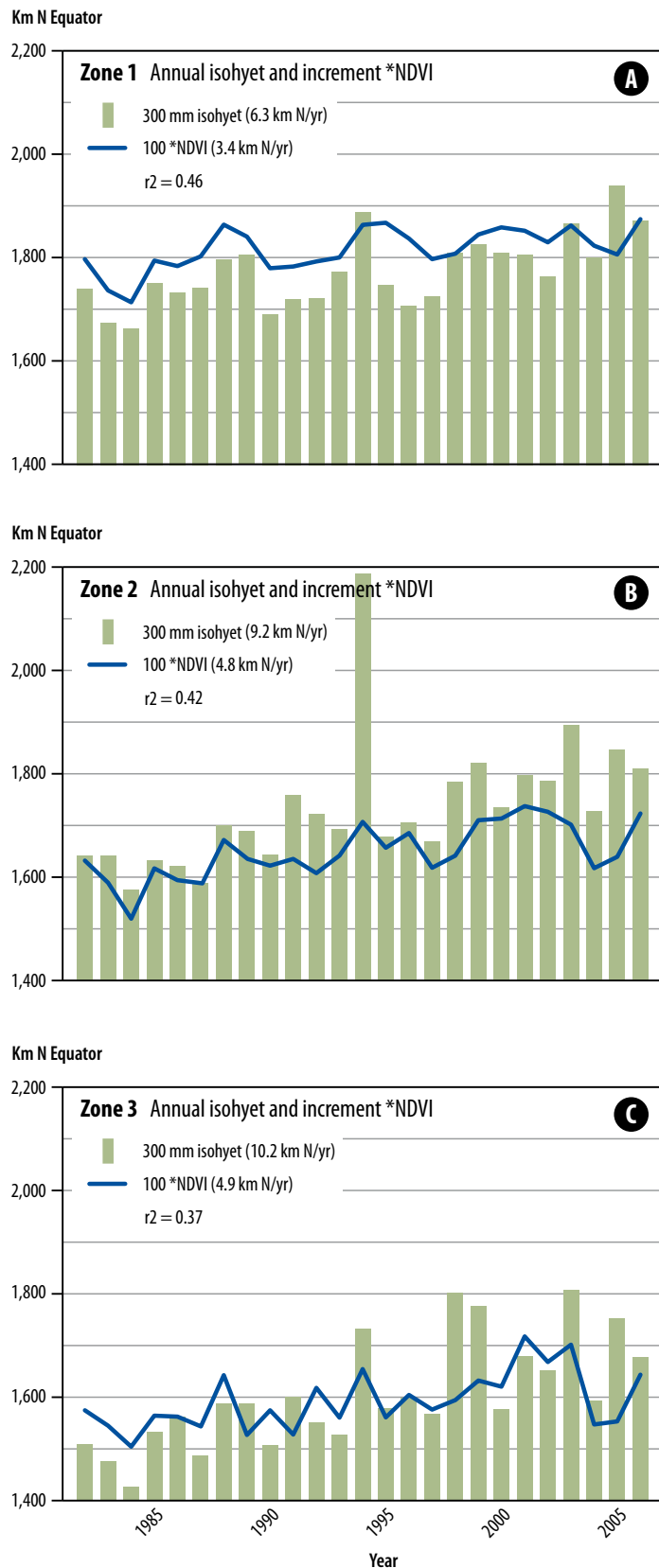
Average increment \*NDVI 1982–2006; the increment index is calculated as the accumulated positive difference in \*NDVI

between the present and previous \*NDVI recording over an annual cycle (see Figure 5.7).



**FIGURE 6.14**

Latitudinal shift in rainfall (isohyet = 300 mm) and annual increment \*NDVI (\*NDVI = 100) in the Sahel 1980–2006, a = zone 1, b = zone 2, and c = zone 3 (see Figures 5.5 and 5.8); the northward trends of rainfall and vegetation growth are indicated in the legend.



The annual latitudinal position in the increment \*NDVI index was calculated by extracting the isoline for \*NDVI = 100 (arbitrary value), in the same way as described for the average annual \*NDVI = 30 (see Figure 5.8). The latitudinal shifts in the annual increment \*NDVI index for the entire study area and for three separate zones (see Figures 5.5 and 5.8) were calculated by extracting a position point every 8 km along the isoline for \*NDVI = 100. The correlation between the northward shifts in rainfall (isohyet = 300 mm) and annual increment \*NDVI (\*NDVI = 100) was calculated using OLS regression (Figure 6.14). The northward trend was also calculated using OLS time-series regression (Figure 6.14). The trend in annual increment \*NDVI for each pixel over the period 1982–2006 (Figure 6.15) and its statistical significance was calculated as for average \*NDVI.

### SAHEL VEGETATION CHANGES 1982–2006 – COMPARISON AND SUMMARY

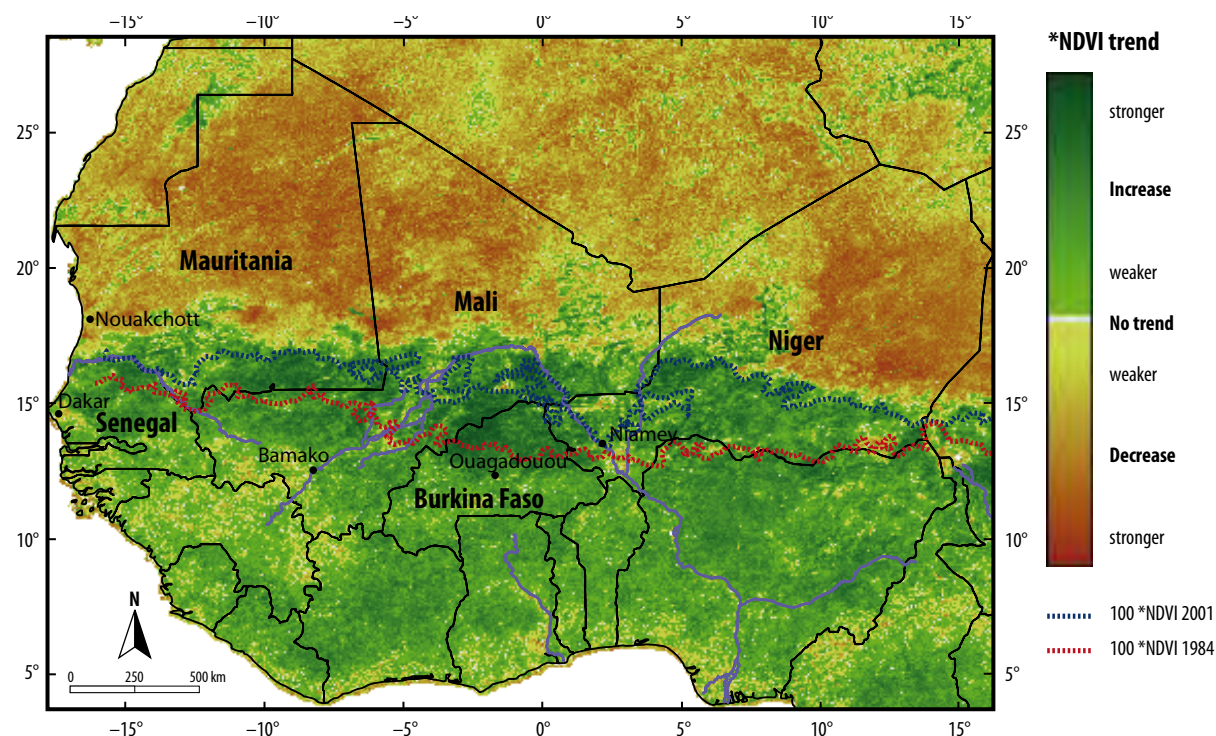
The changes in vegetation growth as captured from regional scale \*NDVI data from 1982–2006 are summarized in Table 6.1 for each of the five countries in this study. Table 6.2 summarizes vegetation growth restricted to regions of each country with a long-term (1930–2006) annual rainfall below 900 mm (see Chapter 7). This was done to so as to be able to compare the absolute vegetation growth with rain-adjusted growth in Chapter 7. Tables 6.3 and 6.4 summarize vegetation growth in the Parklands region (defined as the region between 11° N and 18° N) of the five countries, with Table 6.4 restricting the analyses to regions with rainfall lower than 900 mm per year.

The trends in annual vegetation growth 1982–2006 reveal that the total area (Table 6.1) where vegetation growth has increased in the five countries is between 1.8 (increment \*NDVI) and 2.2 (average \*NDVI) million km<sup>2</sup>, (42–56% of the total area). To a large extent this increase is statistically significant (0.8–1.1 million km<sup>2</sup>). For the Parklands regions (11° N–18° N; Table 6.3) the greening area in the five countries is between 1.5 (increment \*NDVI) and 1.7 (average \*NDVI) million km<sup>2</sup>, (70–82% of the Parklands area). The corresponding statistically significant area is about 0.9 million km<sup>2</sup> or 47% of the Parklands. This means that most of the greening over the last 25 years has taken place in the Parklands area, whereas areas to north and south of the Parklands have mostly experienced a decrease in vegetation growth (browning).

**FIGURE 6.15**

Normalized trend in annual increment \*NDVI for the period 1982–2006. The map also shows the latitudinal movement of vegetation

illustrated by the isolines for annual increment \*NDVI = 100 for the years 1984 (dry) and 2001 (wet).



**TABLE 6.1**

Spatial vegetation changes as recorded from soil adjusted NOAA-AVHRR NDVI (\*NDVI) data in five Sahelian countries 1982–2006. Figures in parentheses are significant values ( $p < 0.05$ ).

Country	Total area km <sup>2</sup>	Average *NDVI		Maximum *NDVI		Increment *NDVI	
		Increase	Decrease	Increase	Decrease	Increase	Decrease
		%					
Mali	1,252,352	61 (35)	39 (11)	54 (22)	46 (13)	50 (28)	50 (31)
Mauritania	1,039,808	46 (18)	54 (16)	31 (13)	69 (29)	23 (13)	77 (61)
Niger	1,182,784	47 (19)	53 (20)	38 (13)	61 (35)	38 (22)	62 (45)
Senegal	195,648	92 (60)	8 (1)	74 (40)	26 (8)	89 (41)	11 (1)
Burkina Faso	272,000	96 (75)	4 (1)	84 (44)	16 (2)	97 (61)	3 (0)

All countries in the study have had dominant trends of increasing vegetation growth in the Parklands region. Mauritania and Niger have seen slightly negative vegetation growth development north of 18° N and hence these countries as a whole are spatially dominated by a browning trend. In Mali vegetation increase has been strong in the Parklands region: around half of the country has experienced increases and half decreases in vegetation growth over the 25-year period 1982–2006. The strongest greening

trends found in the data are in Senegal and Burkina Faso. Much of the area of these two countries is under Parklands compared with the others.

### CONCLUSIONS

We analysed spatial vegetation changes in the Sahel using the GIMMS NDVI (version g) time-series decadal (10-day) data from 1982–2006. Three different annual indices of vegetation growth were compared: average (or integral) \*NDVI, maximum \*NDVI and increment

**TABLE 6.2**

Spatial vegetation changes as recorded from soil adjusted NOAA-AVHRR NDVI (\*NDVI) data in five Sahelian countries 1982–2006 restricted to areas with average rainfall below 900 mm per year. Figures in parentheses are significant values ( $p < 0.05$ ).

Country	Area km <sup>2</sup>	Average *NDVI		Maximum *NDVI		Increment *NDVI	
		Increase	Decrease	Increase	Decrease	Increase	Decrease
		%					
Mali	1,124,224	58 (31)	42 (12)	55 (23)	45 (12)	47 (28)	53 (34)
Mauritania	1,039,808	46 (18)	54 (16)	31 (13)	69 (29)	23 (13)	77 (61)
Niger	1,182,784	47 (19)	53 (20)	38 (13)	61 (35)	38 (22)	62 (45)
Senegal	176,064	93 (62)	7 (1)	77 (40)	22 (7)	89 (44)	11 (1)
Burkina Faso	205,760	98 (78)	2 (0)	92 (55)	8 (1)	98 (69)	2 (0)

**TABLE 6.3**

Spatial vegetation changes as recorded from soil adjusted NOAA-AVHRR NDVI (\*NDVI) data in the Parklands region (11° N–18° N – see Figure 5.3) in five Sahelian countries 1982–2006. Figures in parentheses are significant values ( $p < 0.05$ ).

Country	Parklands area km <sup>2</sup>	Average *NDVI		Maximum *NDVI		Increment *NDVI	
		Increase	Decrease	Increase	Decrease	Increase	Decrease
		%					
Mali	708,928	88 (57)	12 (1)	75 (35)	24 (6)	82 (48)	18 (4)
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 (27)
Senegal	195,648	92 (60)	7 (1)	74 (37)	26 (8)	89 (41)	11 (1)
Burkina Faso	236,224	97 (76)	3 (1)	86 (49)	14 (2)	97 (64)	3 (0)

**TABLE 6.4**

Spatial vegetation changes as recorded from soil adjusted NOAA-AVHRR NDVI (\*NDVI) data in the Parklands region (11° N–18° N – see Figure 5.3) in five Sahelian countries 1982–2006 restricted to areas with average rainfall below 900 mm per year. Figures in parentheses are significant values ( $p < 0.05$ ).

Country	Parklands area km <sup>2</sup>	Average *NDVI		Maximum *NDVI		Increment *NDVI	
		Increase	Decrease	Increase	Decrease	Increase	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)

\*NDVI. The annual average \*NDVI is probably the most widely used index, but is reported to be a rather poor estimator of vegetation growth (e.g. Milich and Weiss, 2000; Diouf and Lambin, 2001). The average \*NDVI shows the strongest greening trend of the three indices used in the study. The maximum \*NDVI is the index least affected by cloud contamination, and is

frequently used as proxy for net primary production in farmlands. The maximum \*NDVI is, however, rather similar, moving from the Guinea coastal rain forest well up into the Sahel, after which it abruptly goes down (cf. Figure 6.10). This pattern does not reflect the continuum in rainfall and in vegetation cover and growth seen on the ground (see Figures 5.1–5.3).

Analysis of a transect through Mali revealed that maximum \*NDVI can be high at low rainfall, and that the peak is not representative of the annual vegetation growth. We suspect that despite the adjustment of NDVI to \*NDVI there is still an overestimation of vegetation density at low vegetation cover, affecting both the average and maximum \*NDVI in dry periods. The abrupt change in the maximum \*NDVI may be partly reflect the division between agriculture and grazing land. In agricultural land the maximum \*NDVI is high before the annual harvest, whereas in the rangelands continuous grazing suppresses the maximum \*NDVI, even though the net primary production can be high. We conclude, therefore, that maximum \*NDVI is a poor index for estimating annual biomass growth in rangelands.

To counter the above problems, we developed the increment \*NDVI index, defined as the \*NDVI increments over an annual cycle. This index should theoretically capture vegetation production both in agricultural and pastoralist systems, avoiding the problems of using average or maximum \*NDVI in grazed ecosystems. The increment index has the further advantage of neutralizing initial effects at the start of the growing season, stemming from woody biomass and soil colour (as illustrated in Figures 6.6 and 6.7). But the increment \*NDVI will be plagued by cloud-contamination, in theory leading to an overestimation of annual vegetation growth. Clouds will suppress the \*NDVI value (see Figure 6.1) and cause a more intermittent pattern of vegetation growth, hence increasing the increment index and decreasing the average index, but not affect the maximum index. The increment \*NDVI index shows a weaker greening trend compared to the average \*NDVI and maximum \*NDVI indices. The stronger increase in the average and maximum \*NDVI indices could partly be explained by transient changes from rangeland to cropland to parkland, leading to a higher biomass accumulation on the ground (woody biomass will be higher), but most likely not attributable to increases in net primary production. We hence conclude that the incremental \*NDVI is the better indicator of change in vegetation net primary production, and should be the preferred index to use in landscapes with transient space-time changes in vegetation.

The increment \*NDVI approach reveals a stronger browning effect south of the Sahel. A browning effect in the increment \*NDVI is caused by a lower annual increment in NDVI. Increased cloud contamination can

cause this, as the GIMMS NDVI(g) data used a cloud mask and temporal adjacent values for filling gaps in cloudy dates. As the filling uses an average value, cloud contamination can only lead to a decrease in the annual increment. As rainfall (and cloudiness) increases towards the south, the decrease in increment \*NDVI might be an artefact of cloud contamination. In the wetter south it is also more probable that factors other than rainfall limit vegetation growth. We cannot, however, rule out the possibility that the decrease is related to an actual loss in vegetation production.

From the analysis of the latitudinal shifts in rainfall (isohyet = 300 mm) and \*NDVI, it is obvious that the northward trend in rainfall has been much stronger than the vegetation response to this rainfall (Figures 6.8, 6.11 and 6.14). The response in increment \*NDVI more closely follows the rainfall than the other indicators, with vegetation trending northward at half the pace of the rainfall. The average \*NDVI response is lagging the most, only going a quarter as far north as the rainfall over the 25-year study period. This reveals that vegetation has not been able to harvest the increase in rainfall, an indication of land degradation. It also indicates that the three annual vegetation indices (average, maximum and increment \*NDVI) perform differently. The figures also show a generally lower vegetation response to rainfall in the central part of the region (Zone 2), compared to the fringes (Zones 1 and 3). On the other hand, the analyses of the pixel-wise trends instead show that average annual \*NDVI (Figure 6.9 and Tables 6.1–6.4) has increased the most, and increment \*NDVI (Figure 6.15 and Tables 6.1–6.4) the least. This inconsistency is most probably caused by shortcomings in using the annual average \*NDVI as a proxy for vegetation growth. The annual average (and to a lesser degree the annual maximum) \*NDVI is more related to site-specific conditions, including soil, vegetation type and woody biomass. Average and maximum \*NDVI are hence not reliable for studying vegetation in transient environments.

The overall conclusion of the analysis of vegetation changes in the Sahel 1982–2006 is that vegetation growth has increased significantly throughout the central Parklands region (approximately 13° N–17° N), but not to the north of the Parklands region. In general, vegetation recovery over the 25-year period has not been as strong as the rainfall recovery, indicating degradation.

# Sahel rain-normalized NDVI 1982–2006

## RAIN-NORMALIZED NDVI CONCEPT

To overcome the shortcomings of using annual vegetation indices for tracking land degradation, the concept of Rain Use Efficiency (RUE), which combines rainfall and vegetation information, has been proposed by Le Houerou (1984, 1989), and subsequently used in many studies (e.g. Prince et al, 1998, Diouf and Lambin, 2001; Huxman et al, 2004; Symeonakis and Drake, 2004; Hountondji et al, 2006; Hein and de Ridder, 2006). The concept was developed for arid and semi-arid regions where rainfall variations tend to obscure trends in biomass production that are related to other factors (Le Houerou, 1984). It is an attractive index in regions where growth is limited by rainfall, and where there is a linear relation between rainfall and vegetation. RUE is reported to be lower in degraded arid lands compared to equivalent non-degraded areas (Le Houerou, 1984, 1989; Tyson 1996) and is hence a useful index for separating the effects of rainfall from human factors on temporal changes of vegetation in rangeland ecosystems. As RUE is calculated using seasonal or annual time-steps it is also hypothesized to bridge short-term fluctuations in vegetation dynamics. It, however also means that RUE is not sensitive to short-term droughts or heavy storms, and thus might be biased by such events.

Several studies have noted that soil moisture conditions (including field capacity and wilting point) provide the actual linkage between rainfall and vegetation primary production (e.g. Prince et al, 1998; Hein, 2006). Studies attempting to calculate soil moisture conditions (or effective rainfall) from climate and soil data also reported better results with Water Use Efficiency (WUE) compared to RUE. Most synoptic studies covering larger regions, however, use total rainfall as the estimation of evaporation, especially as estimating runoff is difficult in data-poor regions.

RUE is usually expressed as the primary production (dry biomass) per unit of rainfall (depth), over a given area. Many studies have examined both the spatial and temporal variation in RUE (summarized in Le Houerou et al, 1988). Spatial variation in RUE can be attributed to variations in rainfall, soil type, drainage, runoff pattern, and vegetation type. Temporal variation in RUE can typically occur following changes in rainfall, vegetation, soil properties and drainage patterns (*ibid*; Prince et al, 1998).

In the Sahel plant production is reported to be linearly related to irrigation or rainfall up to a threshold of

around 1,000 mm/yr (Davenport and Nicholson, 1993; Nicholson and Farrar, 1994). Le Houerou and Host (1977) report a vegetation production (translated to RUE) of 0.3 g/m<sup>2</sup>/mm at 200 mm of rainfall that decreased to 0.25 g/m<sup>2</sup>/mm at 800 mm. Other studies report RUE in the Sahel to average between 0.1 g/m<sup>2</sup>/yr/mm and 0.25 g/m<sup>2</sup>/yr/mm (Le Houerou et al, 1988; Le Houerou, 1989). For grassland the water (irrigation) use efficiency is reported to vary from 0.37 g/m<sup>2</sup>/mm to 1.25 g/m<sup>2</sup>/mm (Webb et al, 1978). Generally, in arid zones, the water use efficiency for grasses (1.3 g/m<sup>2</sup>/mm) is greater than for shrubs and trees (0.65 g/m<sup>2</sup>/mm) (Coughenour, 1992).

Data on vegetation growth are usually derived from ground surveys, or by using NDVI data from satellite imagery as a proxy. Prince and others (1998) and Nicholson and others (1998) used the latter approach, and concluded that there were no signs of extensive degradation in the Sahel, even though local regions were identified as being affected by decreases in RUE. Anyamba and Tucker (2005) and Olsson et al (2005) also used vegetation data from NOAA-AVHRR and concluded that RUE had actually increased in the Sahel since the droughts in the 1980s. Herrmann and others (2005a) studied the NDVI residual after a statistical normalization against rainfall data, and found a stronger than expected greening over large parts of the Sahel. A local scale study in Senegal, Diouf and Lambin (2001) compared RUE derived from both ground-surveyed biomass data and 10-day Maximum Value Compositing (MVC) of AVHRR data at the original resolution of 1.1 km resolution (used in Figure 6.1 above). It found that the spatial scale of variation was not captured by the AVHRR data, and that the apparent resilience of vegetation in dry years, as interpreted from RUE analysis based on remote sensing data, might be erroneous.

Rain Use Efficiency is not linearly dependent on rainfall, but is shown to be higher close to the average annual rainfall than near maximum or minimum rainfall values for a particular site (Le Houerou, 1984; Wylie et al, 1992; Diouf and Lambin, 2001; O'Connor et al, 2001; Huxman et al, 2004; Hein, 2006; Hein et al, 2006). At lower rainfall amounts, a larger portion of the rainfall is intercepted and evaporated, and consequently the plant accessible fraction is smaller. At higher than average rainfall, factors other than water become limiting for plant growth. RUE hence decreases as rainfall increases over some threshold level (cf. Hooper and Johnson,

1999). Thus RUE is reported to be quadratic with respect to rainfall, with maximum RUE around the average annual rainfall for a particular location. Under the assumption that RUE increases with rainfall when recovering from drought to normal conditions, Hein and De Ridder (2006) speculate that the lack of any increase in RUE over the past 20 years in the Sahel is actually a signal of land degradation. Rain Use Efficiency is further reported to be lower in a normal year following a drought year, compared with a normal year following a normal year, probably because of insufficiencies in the seed pool after drought, which leads to slow vegetation recovery (Diouf and Lambin, 2001; Milich and Weiss, 2000).

The concept of Rain Use Efficiency was developed for estimating net primary production in dryland ecosystems. This study focuses on identifying areas with potential soil degradation (or soil improvements). Thus we do not use the ratio between vegetation and rainfall for primarily forecasting vegetation growth, but rather as an index for studying changes and trends in time. Thus we use the term "Rain-normalized NDVI" instead of "Rain Use Efficiency".

### **RAIN-NORMALIZED \*NDVI 1982–2006**

In this study the Rain-normalized \*NDVI (RNNDVI) is calculated as the ratio of an annual \*NDVI vegetation production index over rainfall amount for a given period:

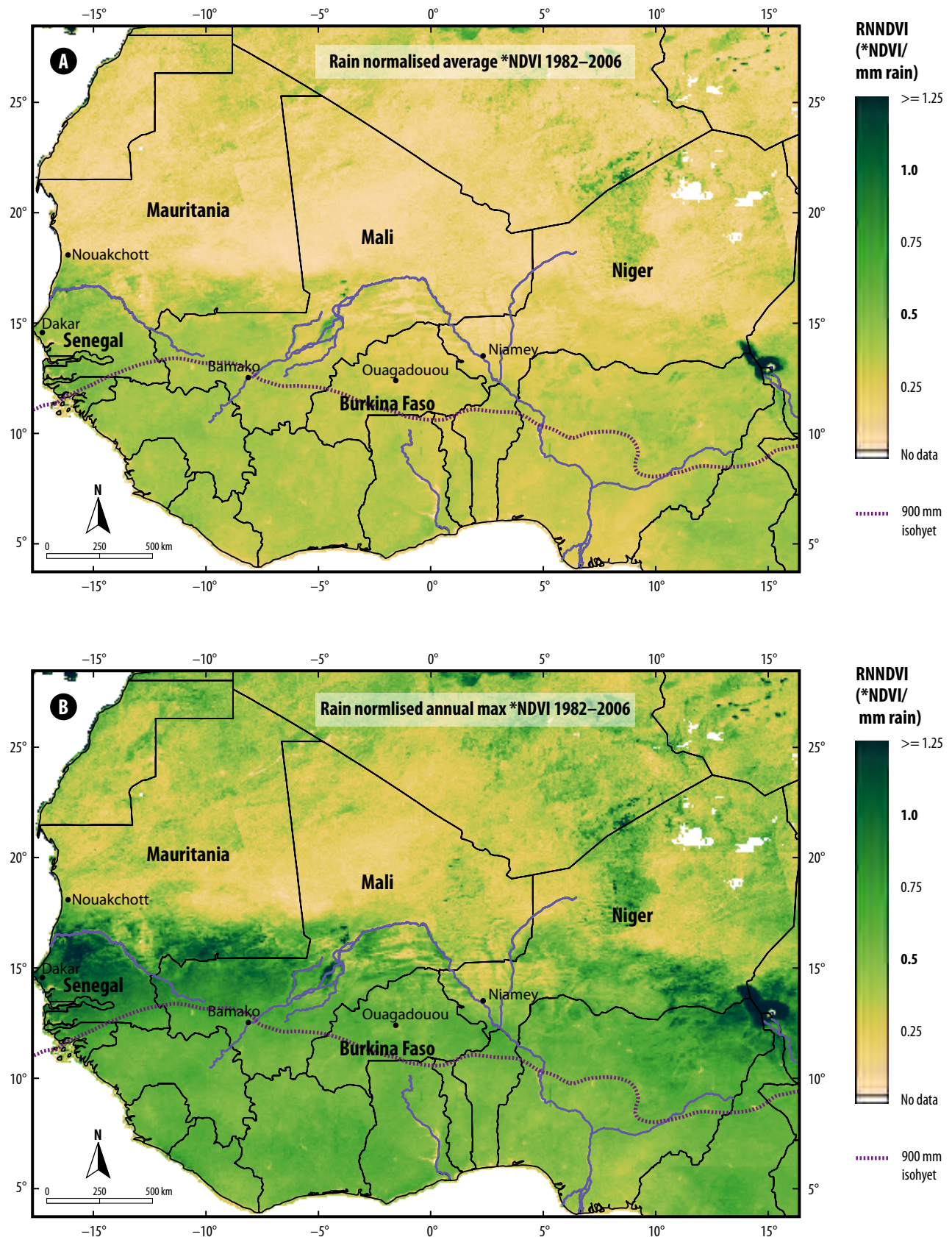
$$\text{RNNDVI} = \text{annual *NDVI index} / \text{rainfall} \quad (\text{Eq. 7.1})$$

We calculated RNNDVI on a per-pixel basis with annual time-steps representing January to December, as this marks the middle of the dry season in the Sahel and NDVI /\*NDVI is assumed to be at its minimum. We used all our derived annual indices of vegetation (average \*NDVI, maximum \*NDVI and increment \*NDVI) to study and compare RNNDVI. This also gave us the opportunity of evaluating the performance of the different indices. Other studies employing RUE use either the integral (average) of NDVI and rainfall over an annual cycle or the growing season, or maximum NDVI at the end of the growing season compared with the growing season rainfall. As discussed in Chapter 6, we believe that average and maximum vegetation indices are biased when analyzing systems that have gone through transient changes in vegetation ecosystems and agro-ecological management regimes. We also found that the use

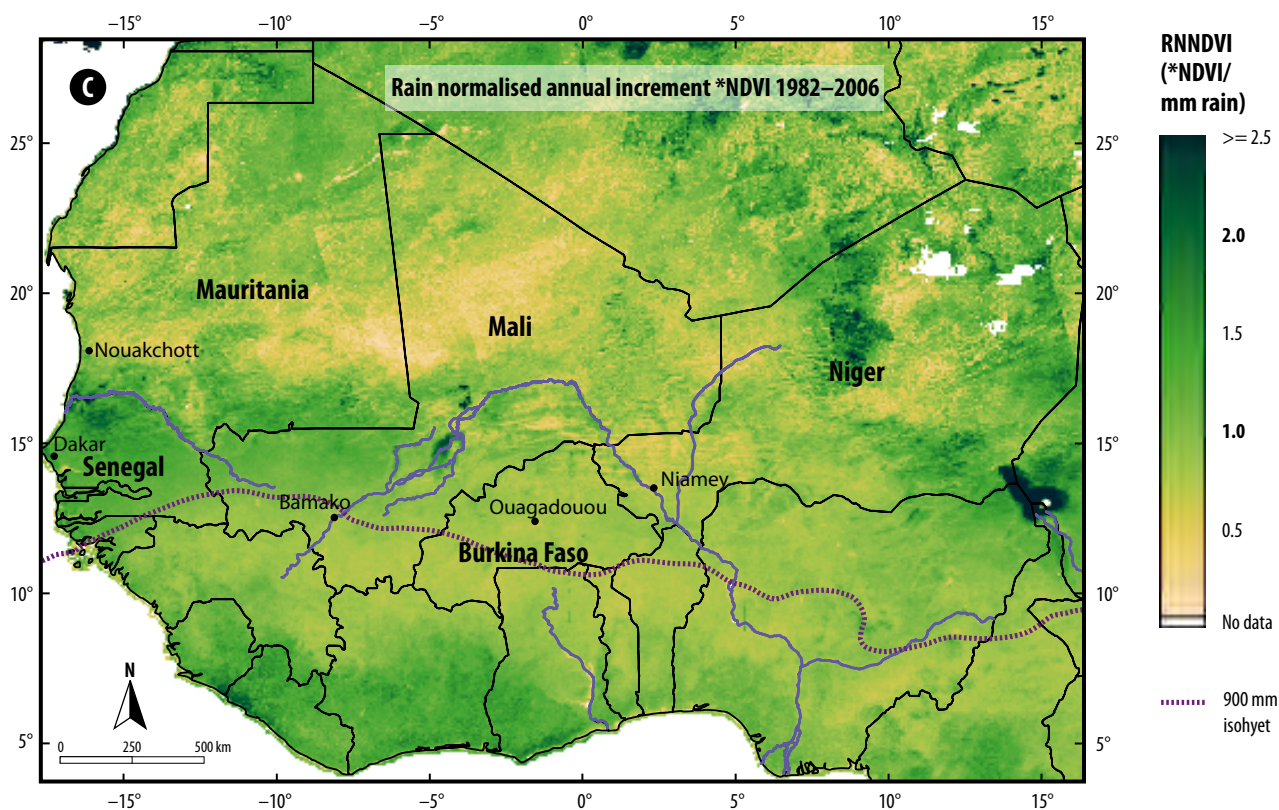
**FIGURE 7.1**

Rain-normalized \*NDVI averaged for the period 1982–2006 using three different indices for vegetation growth; a) annual average \*NDVI, b) annual maximum \*NDVI, and c) annual increment \*NDVI;

RNNDVI is calculated as the annual ratio between a vegetation index and annual rainfall.







**TABLE 7.1**

Changes in rain-normalized \*NDVI (RNNDVI) in five Sahelian countries 1982–2006 restricted to areas with less than 900 mm in annual rainfall. Figures in parentheses are statistically significant values ( $p < 0.05$ ). Areas with no change occur, and hence the increase and decrease does not always add up to 100%.

Country	Area km <sup>2</sup>	Average RNNDVI		Maximum RNNDVI		Increment RNNDVI	
		Increase	Decrease	Increase	Decrease	Increase	Decrease
Mali	1,124,224	12 (1)	88 (44)	12 (0)	88 (54)	13 (0)	87 (54)
Mauritania	1,039,808	5 (0)	95 (56)	6 (0)	94 (78)	4 (0)	96 (78)
Niger	1,182,784	10 (0)	89 (35)	12 (0)	88 (40)	7 (0)	91 (40)
Senegal	176,064	33 (2)	67 (37)	30 (0)	70 (29)	36 (0)	64 (29)
Burkina Faso	205,760	12 (0)	88 (35)	21 (0)	79 (16)	27 (0)	73 (16)

of unadjusted NDVI data biases the RUE /RNNDVI analysis by overestimating RUE/RNNDVI in years with low vegetation coverage (the NDVI signal is artificially increased by the reflectance of the underlying soil – see Figure 6.2). Applying unadjusted NDVI will give high RUE values to the regions with least vegetation

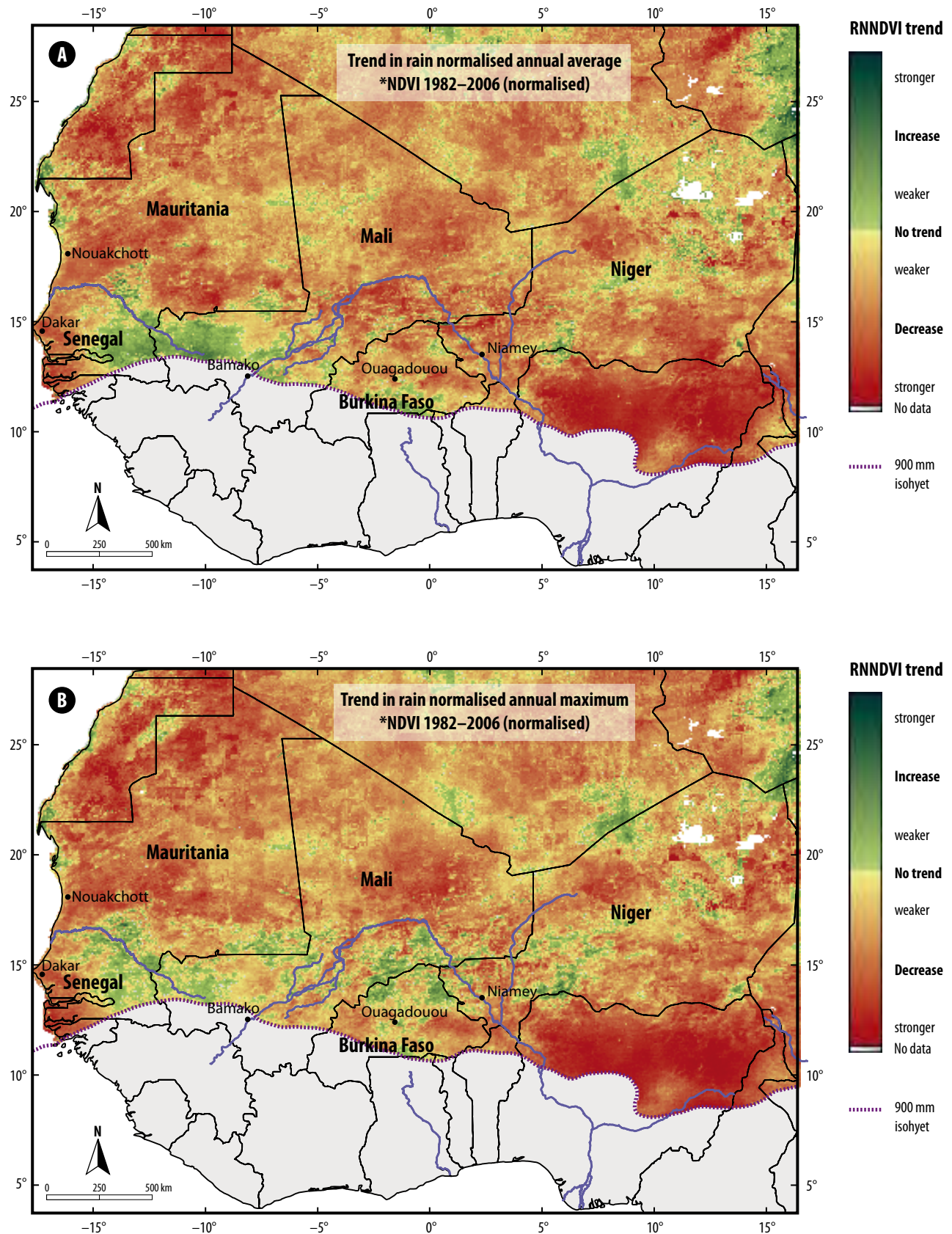
(e.g. the fringes of the Sahara Desert). In this study a minimum annual rainfall of 25 mm was used as a threshold for calculating RNNDVI.

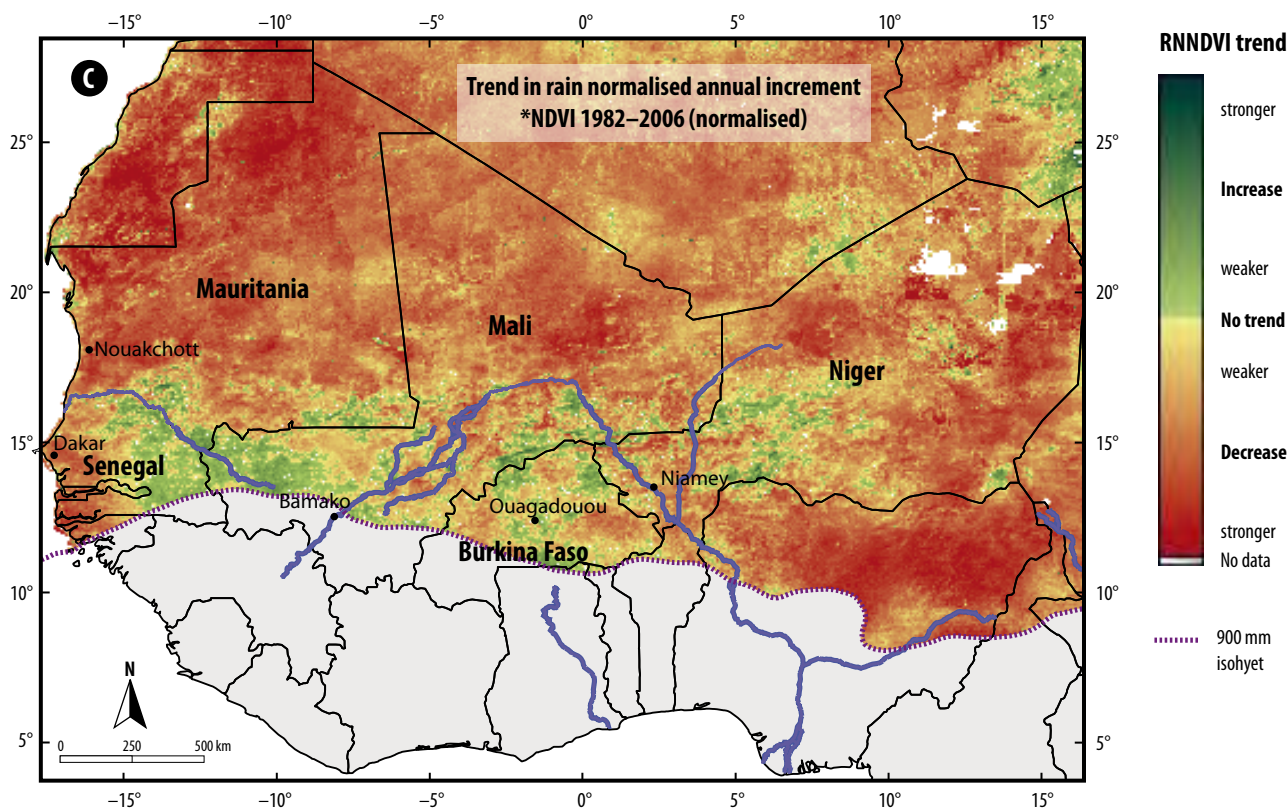
Figure 7.1 compares the average RNNDVI for the period 1982–2006 derived from a) annual average \*NDVI,

**FIGURE 7.2**

Trends in rain-normalized \*NDVI for the period 1982–2006 calculated using three different indices for vegetation growth; a) annual average \*NDVI, b) annual maximum \*NDVI, and c) annual increment

\*NDVI; RNNNDVI is calculated as the ratio between a vegetation index for annual vegetation production and annual rainfall.





**TABLE 7.2**

Changes in rain-normalized \*NDVI (RNNDVI) in five Sahelian countries 1982–2006 restricted to the Parkland areas (11° N–18° N) with less than 900 mm in annual rainfall. Figures in parentheses are statistically significant values ( $p < 0.05$ ). Areas with no change occur and hence the increase and decrease does not always add up to 100%.

Country	Area km <sup>2</sup>	Average RNNDVI		Maximum RNNDVI		Increment RNNDVI	
		Increase	Decrease	Increase	Decrease	Increase	Decrease
Mali	601,344	20 (2)	80 (39)	21 (1)	79 (32)	24 (1)	76 (31)
Mauritania	290,944	10 (0)	90 (60)	18 (0)	82 (50)	14 (0)	86 (50)
Niger	688,768	6 (0)	94 (49)	10 (0)	90 (46)	11 (0)	89 (46)
Senegal	176,064	33 (2)	67 (37)	30 (0)	70 (29)	36 (0)	64 (29)
Burkina Faso	205,760	12 (0)	88 (35)	21 (0)	79 (16)	27 (0)	73 (16)

b) annual maximum \*NDVI and c) annual increment \*NDVI. The scale of the integral \*NDVI in (c) is double compared to (a) and (b). The maps in Figure 7.1 reveal the influence of drainage patterns on RNNDVI, with Lake Chad and the Niger Inland Delta in Mali having the highest RNNDVI values. These water bodies

derive water from sources other than rainfall and hence vegetation can grow better than expected from rainfall alone. As vegetation growth is reported to be directly related to rainfall up to 800–1,000 mm of annual rainfall, the long-term (1930–2006) isohyet for 900 mm rainfall is indicated in the maps.

## **TRENDS IN RAIN-NORMALIZED \*NDVI 1982–2006**

The trend in Rain-normalized \*NDVI (RNNDVI) for each pixel over the period 1982–2006 was calculated by first normalizing the time-series of RNNDVI annual indices and then using Ordinary Least Square (OLS) regression, eliminating pixels that had fewer than 6 observations (Figure 7.2). The normalized trends were calculated using all three annual indices of vegetation growth; annual average \*NDVI (Figure 7.2a), annual maximum \*NDVI (Figure 7.2b) and annual increment \*NDVI (Figure 7.2c). The significance of the pixel-wise trend for each index was calculated by comparing the observed normalized trend with 999 randomized permutations.

## **SAHEL RNNDVI CHANGES 1982–2006 – COMPARISON AND SUMMARY**

The changes in rain-normalized vegetation growth (RNNDVI) as captured from regional scale \*NDVI and rainfall data for 1982–2006 are summarized in Table 7.1 for each of the five countries in this study. As RNNDVI is a valid concept only below around 800–1,000 mm in annual rainfall, the data in Table 7.1 is restricted to areas with annual average rainfall (1930–2006) below 900 mm. The results of Table 7.1 can be compared with the results of vegetation change in Table 6.2. Table 7.2 summarizes vegetation growth in the Parklands region (defined as the region between 11° N and 18° N) of the five countries, also restricting the analyses to regions with rainfall lower than 900 mm per year. Table 7.2 can be directly compared with Table 6.4.

The trends in rain-normalized annual vegetation growth (RNNDVI) for 1982–2006 reveal that the area with average rainfall below 900 mm per year in the five countries where RNNDVI has increased (Table 7.1) is around 0.4 million km<sup>2</sup> (10% of the area). However, almost none of this increase is statistically significant ( $p < 0.05$ ). Large parts of the project countries have instead experienced a decline in rain-normalized vegetation growth over the period 1982–2006. The area with average rainfall less than 900 mm where rainfall-adjusted vegetation growth has decreased is 3.3 million km<sup>2</sup> (90%), of this a large fraction, or approximately 2.0 million km<sup>2</sup> (50% of the total area) is statistically significant ( $p < 0.05$ ). The Parklands regions of the five countries (Table 7.2) have seen a slightly more positive development compared with regions further north.

## **RAIN-NORMALIZED \*NDVI DISCUSSION**

The general decrease in rain-normalized vegetation growth over the Sahel over the period 1982–2006 shown by our results contradict most other regional-

scale studies employing the AVHRR derived NDVI data set. Most other studies (e.g. Prince et al, 1998; Nicholson et al, 1998; Anyamba and Tucker, 2005; Olsson et al, 2005) conclude that RUE has increased since the droughts that culminated in the early 1980s. This is also what would have been expected on the basis of studies that show that RUE is higher closer to average rainfall conditions and is therefore expected to increase during recovery from drought. The discrepancies in the results can be attributed to several factors including 1) the use of different versions of the AVHRR NDVI dataset or other NDVI datasets, 2) the use of different rainfall datasets, 3) differences in pre-processing of the NDVI data, 4) different methods used for calculating annual vegetation growth, and 5) different time-steps used for calculating RUE or RNNDVI (e.g. annual or seasonal). Most other studies use the annual (or seasonal) average NDVI (NDVI integral) for estimating vegetation growth. Our results indicate that the average NDVI method gives a stronger greening trend when studying the same pixel (local position) compared with using the annual maximum or increment indices for estimating vegetation production. As discussed above, the annual (seasonal) average NDVI is shown to be a rather poor index of vegetation growth, especially in regions that have gone through changes in vegetation composition.

A review of the recent literature focusing on more local-scale studies and employing higher resolution remote-sensing data in combination with ground surveys, give support to our findings of a decline in rain-normalized vegetation growth in the Sahel over the last two decades. Our findings therefore challenge the conclusions from earlier regional remote-sensing studies on RUE.

## **EXPLORING THE RAIN- NORMALIZED \*NDVI**

In order to explain the observed changes and differences in rain-normalized \*NDVI the dataset was used to explore two of the concepts developed from the idea of Rain Use Efficiency (RUE). RUE (and hence RNNDVI) is hypothesized to peak around the average rainfall level for a particular location (see above). This is both due to the vegetation ecosystem at a particular site that has evolved as a response to the average rainfall situation, and to physical factors. At lower rainfall a larger portion of the rainfall is intercepted and evaporated and consequently the plant-accessible fraction is smaller; at higher than average rainfall, more water forms surface runoff and eventually factors other than water become

limiting for plant growth. A second concept is that in drier areas, rainfall in a given year influences RUE in the following year. As grasses usually dominate vegetation, the seed pool produced in one year will influence vegetation growth the next. A year with more rain can also recharge soil and groundwater, to be harvested by vegetation for growth the following year.

## **RNNDVI AND SPATIAL RAINFALL VARIATIONS**

Figures 7.3–7.5 show RNNDVI as a function of rainfall deviation from the average rainfall. For all figures the analysis was done using five rainfall levels (isohyets): 300 mm, 400 mm, 500 mm, 600 mm and 700 mm. Figure 7.3 shows the variation of RNNDVI as a function of rainfall around the longer term average isohyets for the period 1982–2006. The graphs show the variation using all three annual vegetation production indices; a) RNNDVI based on average \*NDVI, b) RNNDVI based on maximum \*NDVI, and c) RNNDVI based on increment \*NDVI. The map (Figure 7.3d) shows the position of the five isohyets for the average rainfall 1982–2006. Figure 7.4 instead uses the shorter period 1982–1987, with the lowest rainfall in the time series, for the same analysis. Figure 7.5 shows the situation for the shorter period 2000–2006, with higher rainfall levels. The maps show the rainfall increase as shift in isohyet positions from the droughts in the 1980s (Figure 7.4d) to the present situation (Figure 7.5d), with Figure 7.3d showing the average situation over the last 25 years.

The analysis of RNNDVI as a function of deviation from the average rainfall does show a weak pattern of RNNDVI peaking at the average rainfall for the more stable rainfall period 2000–2006 (Figure 7.5). For the longer period 1982–2006 (Figure 7.3) all rain normalized \*NDVI indices show that RNNDVI is higher at lower rainfall (i.e. each drop of rainfall produces more vegetation at lower than average rainfall) at a particular location (i.e. all data points in the same series show a declining trend with increases in rainfall). Especially for the 300 and 400 mm isohyets, this is a surprising result – at low rainfall it would be expected that an increase in rainfall would lead to higher RNNDVI. One plausible explanation, suggested by Milich and Weiss (2000) is that very dry conditions cause migration of rangers and/or animal die-off, hence allowing vegetation to recover during very dry conditions.

The analysis also indicates a stepwise behaviour in vegetation response to rainfall (the black vertical bars indicate the jumps at 350 mm, 450 mm, 550 mm and

650 mm of rainfall) when transgressing from drier to wetter (i.e. from north to south) conditions. The relative jump is largest for average \*NDVI and lowest for increment \*NDVI. The upward jump in RNNDVI when transecting towards higher rainfall contradicts the result that at a particular location RNNDVI increases as rainfall decreases. The interpretation of these results would be that at a particular rainfall level, locations normally receiving more rainfall have a better response compared with locations normally receiving less rainfall (points at the same vertical position receive the same rainfall amount but have different average rainfall). We think that this is not a logical or expected explanation, and the index must be erroneous.

The increment \*NDVI response is more consistent than the case for average \*NDVI in that the RNNDVI response to rainfall is more linear all the way from 200–800 mm of annual rainfall. The increment index also shows a more similar response to the same amount of rainfall when deviating from the long-term average (the vertical jumps are relatively smaller). The pattern captured by the increment \*NDVI index (decreasing RNNDVI with increasing rainfall) is consistent with other studies (see above). One explanation for these differences in responses is that land-management changes (e.g. from rangelands to parklands to croplands and woodlands) bias the average and maximum indices more than the increment index. The average and maximum indices reflect vegetation and soil compositions more than vegetation growth.

## **CONSISTENCY OF RESPONSES ACROSS DIFFERENT RAINFALL PATTERNS**

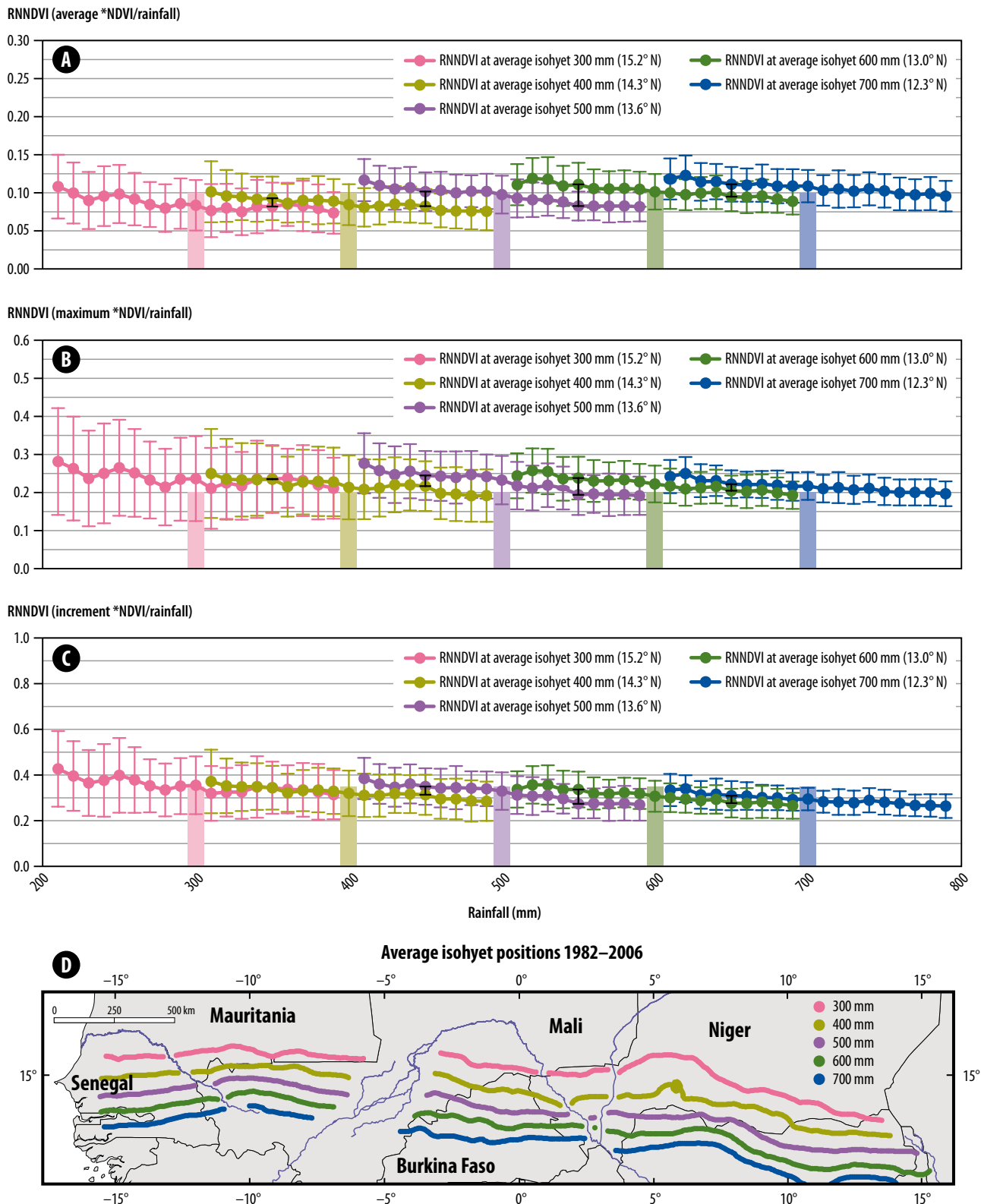
The period 1982–2006 has a strong underlying trend of increasing rainfall, and so the average rainfall level for this transient period might not be representative for analyzing the relationship between RNNDVI and rainfall. The period 1982–1987 had a lower (and less varying) rainfall compared with any other period in the time series (Figure 7.4). At this lower rainfall situation, the isohyets for 300–700 mm used in the analyses are strongly shifted to the south. The results of the analysis of RNNDVI related to rainfall deviation at average isohyets for the period 1982–1987 show the same general pattern as the analysis for the longer period 1982–2006.

The more wet period 2000–2006 (Figure 7.5) is closest to the expected pattern, with a peak in RNNDVI at the average rainfall. The isohyets for this wetter period are shifted northwards, and the general values of average- and maximum-derived RNNDVI are shifted

**FIGURE 7.3**

Variation in annual RNNDVI ( $\ast\text{NDVI}/\text{rainfall}$ ) as a function of rainfall around 5 long-term (1982–2006) isohyets; the vertical bars indicate average rainfall, and the circles show actual rainfall and RNNDVI (mean and standard deviation grouped for  $\pm 5$  mm of rainfall) for locations along the five average rainfall isohyet over the period

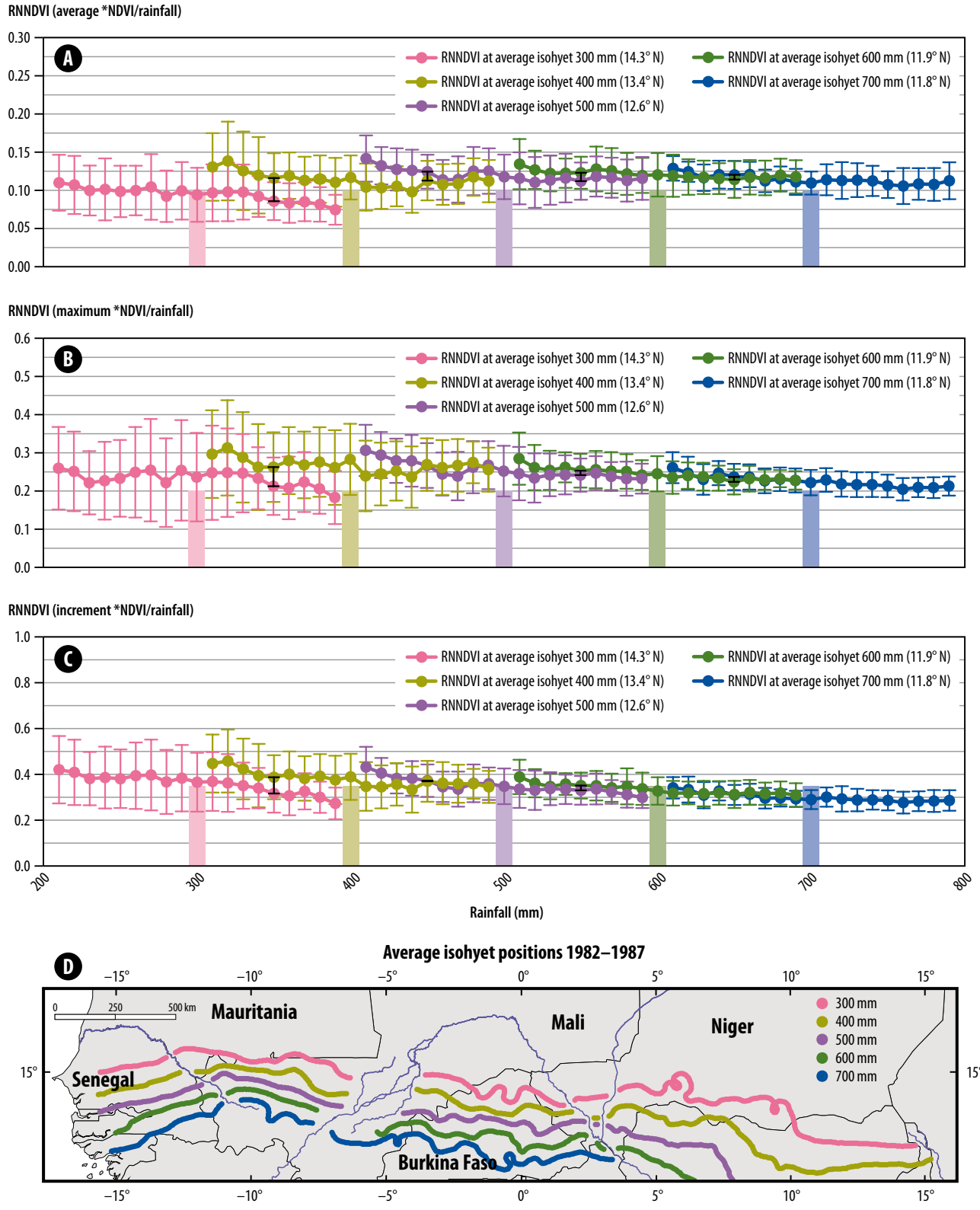
1982–2006; a) RNNDVI based on annual average  $\ast\text{NDVI}$ , b) RNNDVI based on annual maximum  $\ast\text{NDVI}$ , c) RNNDVI based on annual increment  $\ast\text{NDVI}$ , and d) map showing the positions of the five isohyets. Note that the Y-scales are normalized to show relative variations of the different RNNDVI indices.



**FIGURE 7.4**

Variation in annual RNNDVI ( $\ast\text{NDVI}/\text{rainfall}$ ) as a function of rainfall around 5 short-term (1982–1987) isohyets representing drier conditions; the vertical bars indicate average rainfall, and the circles show actual rainfall and RNNDVI (mean and standard deviation grouped for  $\pm 5$  mm of rainfall) for locations along the five average rainfall isohyet over the period 1982–1987; a) RNNDVI

based on annual average  $\ast\text{NDVI}$ , b) RNNDVI based on annual maximum  $\ast\text{NDVI}$ , c) RNNDVI based on annual increment  $\ast\text{NDVI}$ , and d) map showing the positions of the five isohyets. Note that the Y-scales are normalized to show relative variations of the different RNNDVI indices.

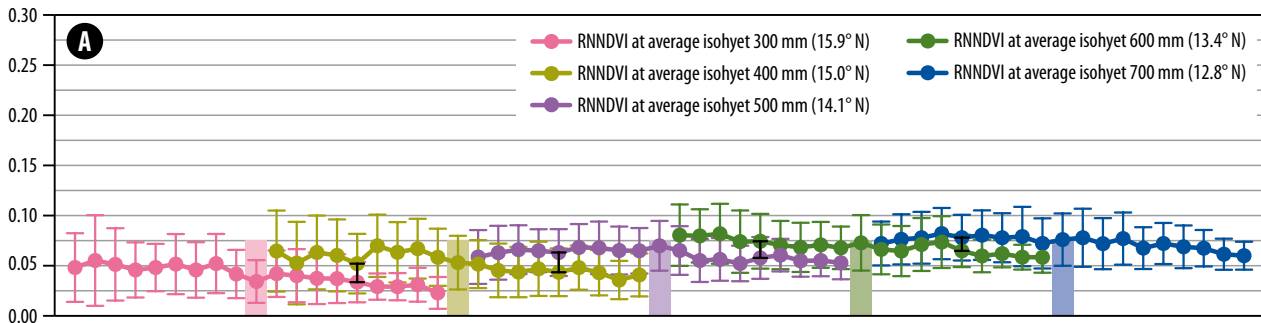


**FIGURE 7.5**

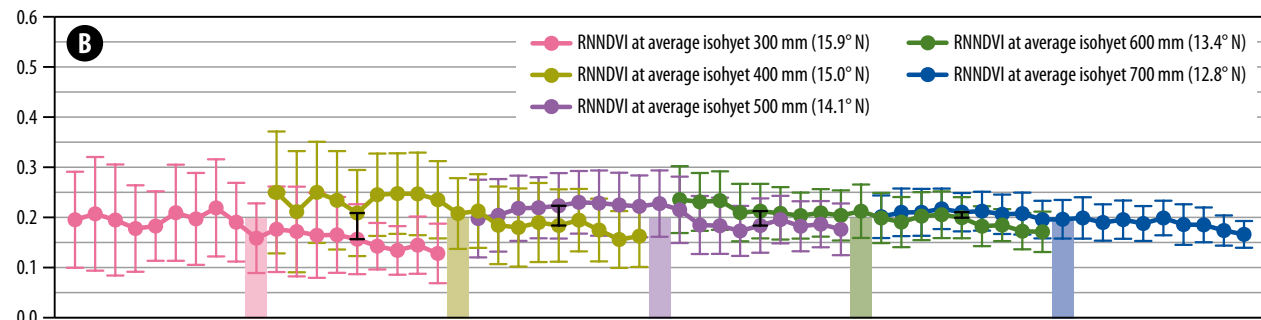
Variation in annual RNNDVI ( $\ast\text{NDVI}/\text{rainfall}$ ) as a function of rainfall around 5 short-term (2000–2006) isohyets representing wetter conditions; the vertical bars indicate average rainfall, and the circles show actual rainfall and RNNDVI (mean and standard deviation grouped for  $\pm 5$  mm of rainfall) for locations along the five average rainfall isohyet over the period 2000–2006; a) RNNDVI

based on annual average  $\ast\text{NDVI}$ , b) RNNDVI based on annual maximum  $\ast\text{NDVI}$ , c) RNNDVI based on annual increment  $\ast\text{NDVI}$ , and d) map showing the positions of the five isohyets. Note that the Y-scales are normalized to show relative variations of the different RNNDVI indices.

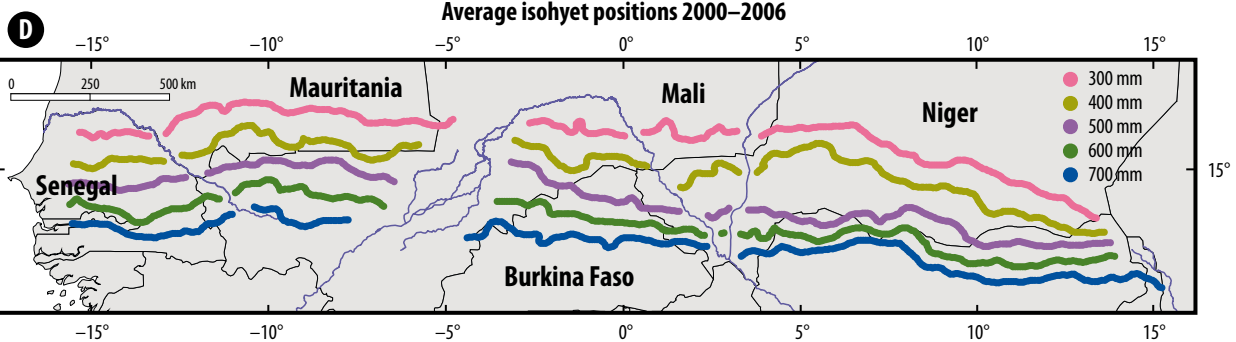
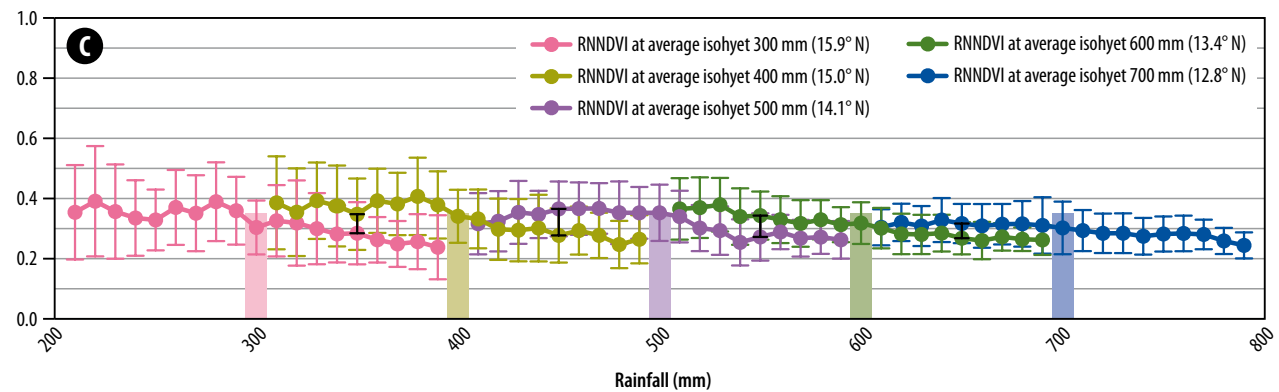
**RNNDVI (average  $\ast\text{NDVI}/\text{rainfall}$ )**



**RNNDVI (maximum  $\ast\text{NDVI}/\text{rainfall}$ )**



**RNNDVI (increment  $\ast\text{NDVI}/\text{rainfall}$ )**



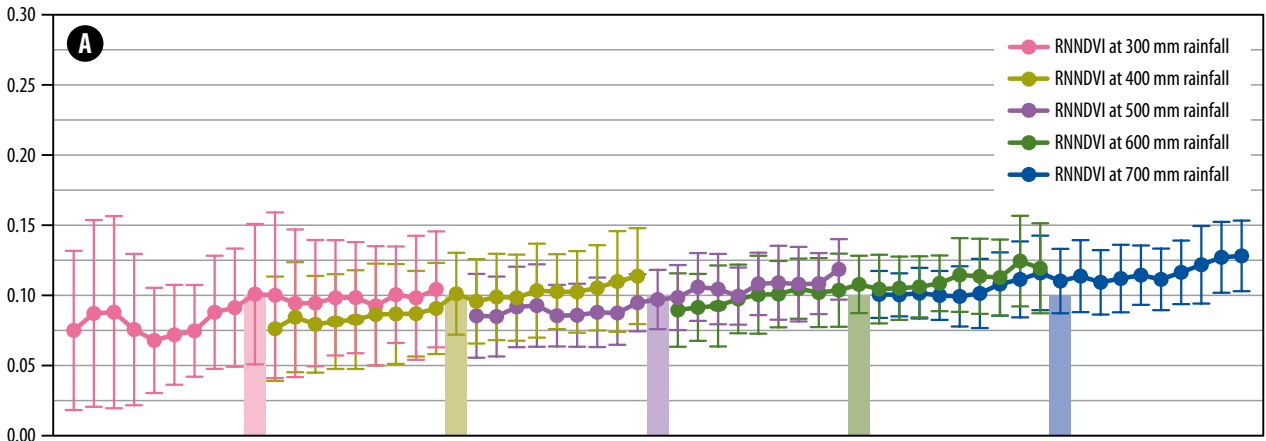


**FIGURE 7.6**

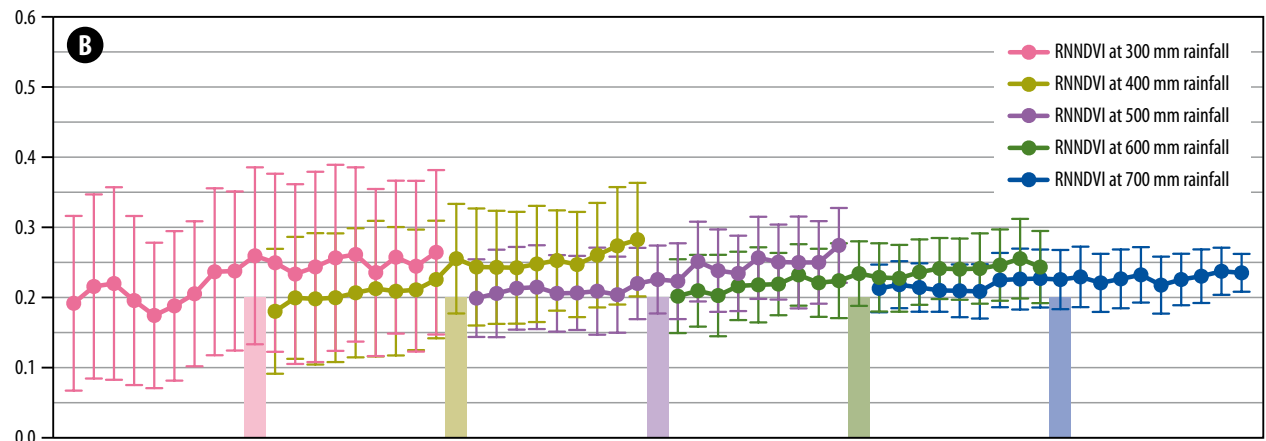
Variation in RNNNDVI ( $\ast\text{NDVI}/\text{rainfall}$ ) (mean and standard deviation grouped for  $\pm 5$  mm of rainfall) as a function of rainfall the previous year analyzed for five rainfall levels (isohyets) 1982–2006; the vertical bars indicate the rainfall levels used in the analysis (current year), and the circles show the previous year's rainfall (all

RNNNDVI values are recorded at rainfall levels 300, 400, 500, 600 and 700 mm  $\pm 5$  mm, but with varying rainfall the previous year); a) RNNNDVI based on annual average  $\ast\text{NDVI}$ , b) RNNNDVI based on annual maximum  $\ast\text{NDVI}$ , and c) RNNNDVI based on annual increment  $\ast\text{NDVI}$ .

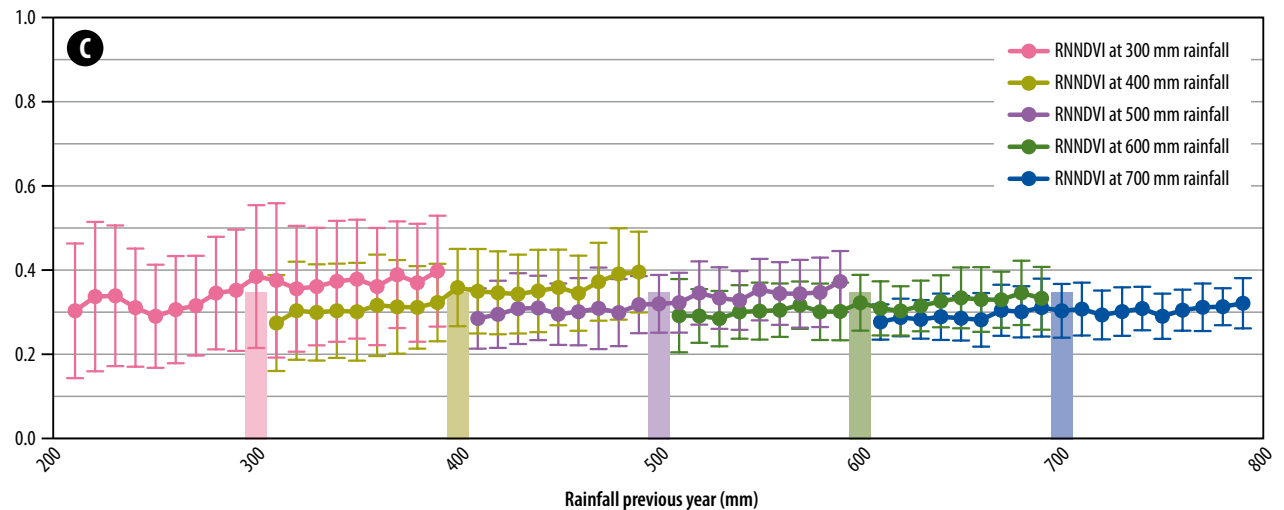
RNNNDVI (average  $\ast\text{NDVI}/\text{rainfall}$ )



RNNNDVI (maximum  $\ast\text{NDVI}/\text{rainfall}$ )



RNNNDVI (increment  $\ast\text{NDVI}/\text{rainfall}$ )

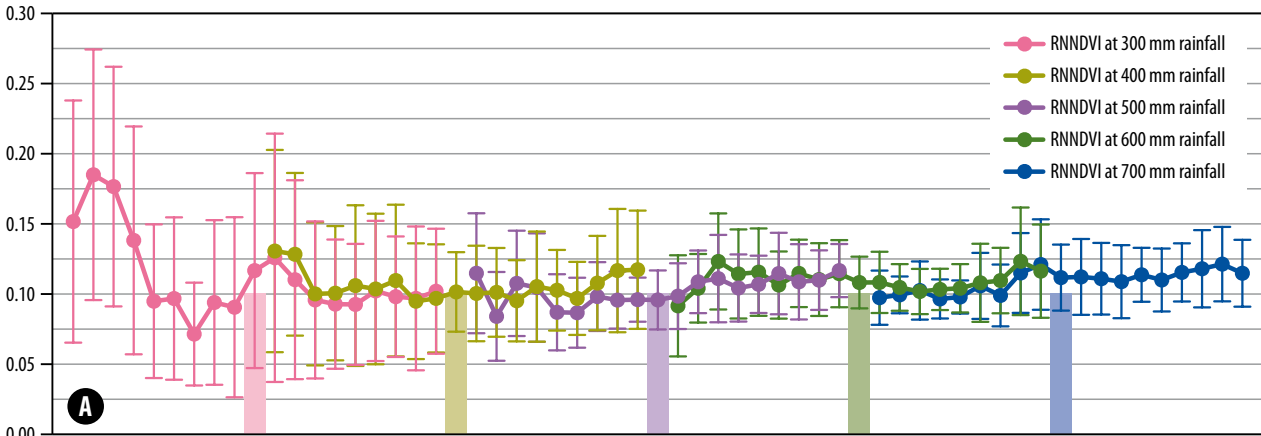


**FIGURE 7.7**

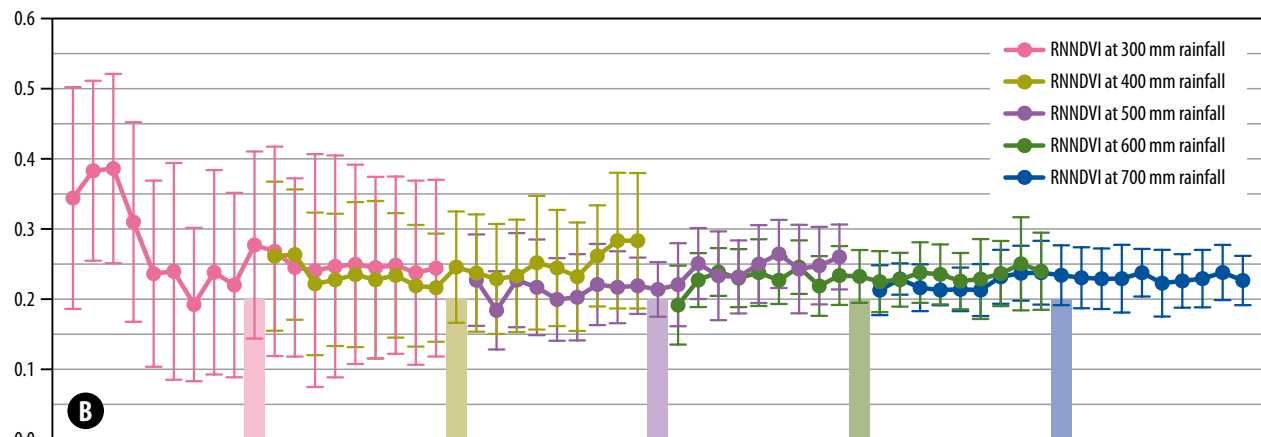
Variation in RNNNDVI ( $\ast\text{NDVI}/\text{rainfall}$ ) (mean and standard deviation grouped for  $\pm 5$  mm of rainfall) as a function of rainfall the previous year analyzed for five rainfall levels (isohyets) for the dry period 1982–1987; the vertical bars indicate the rainfall levels used in the analysis (current year), and the circles show the previous

year's rainfall (all RNNNDVI values are recorded at rainfall levels 300, 400, 500, 600 and 700 mm  $\pm 5$  mm, but with varying rainfall the previous year); a) RNNNDVI based on annual average  $\ast\text{NDVI}$ , b) RNNNDVI based on annual maximum  $\ast\text{NDVI}$ , and c) RNNNDVI based on annual increment  $\ast\text{NDVI}$ .

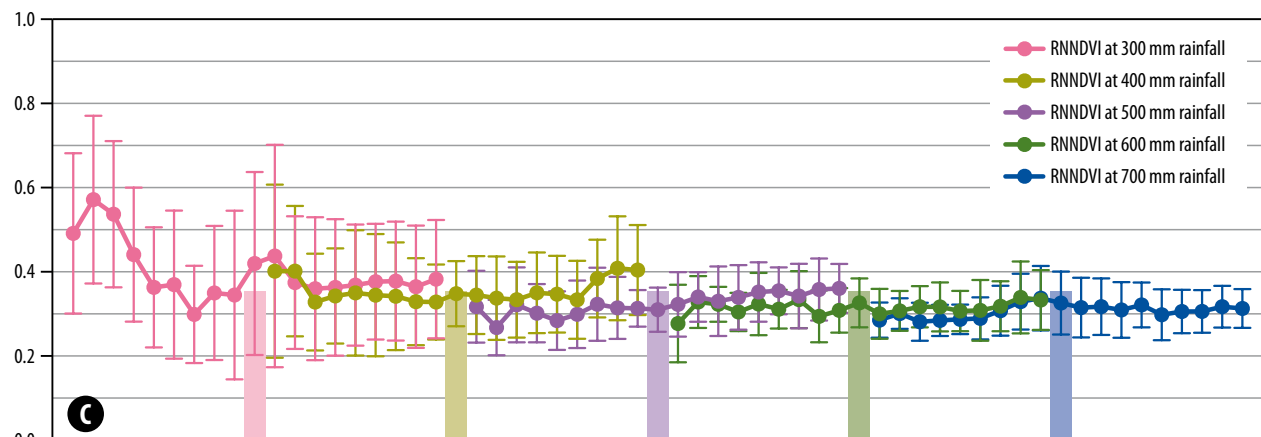
RNNNDVI (average  $\ast\text{NDVI}/\text{rainfall}$ )



RNNNDVI (maximum  $\ast\text{NDVI}/\text{rainfall}$ )



RNNNDVI (increment  $\ast\text{NDVI}/\text{rainfall}$ )



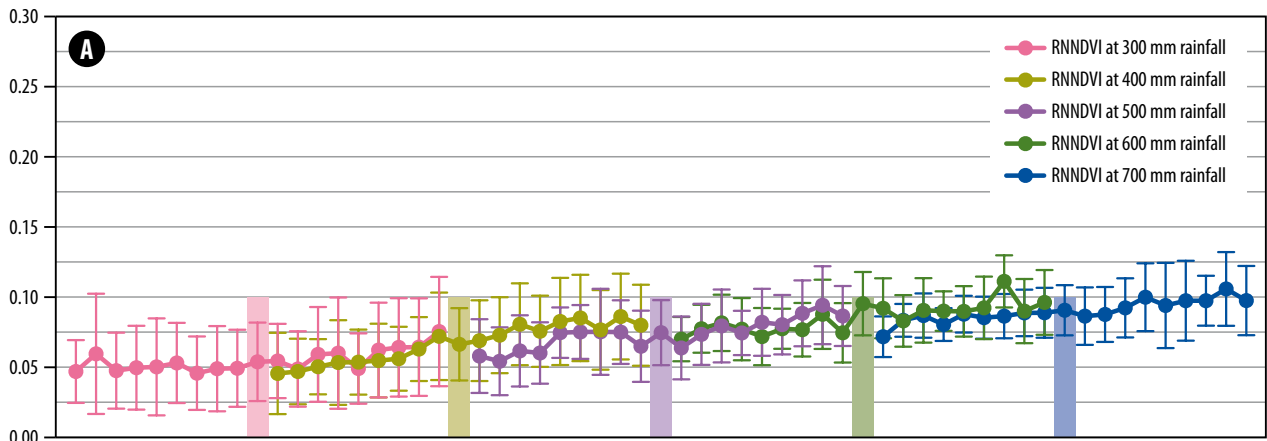
Rainfall previous year (mm)

**FIGURE 7.8**

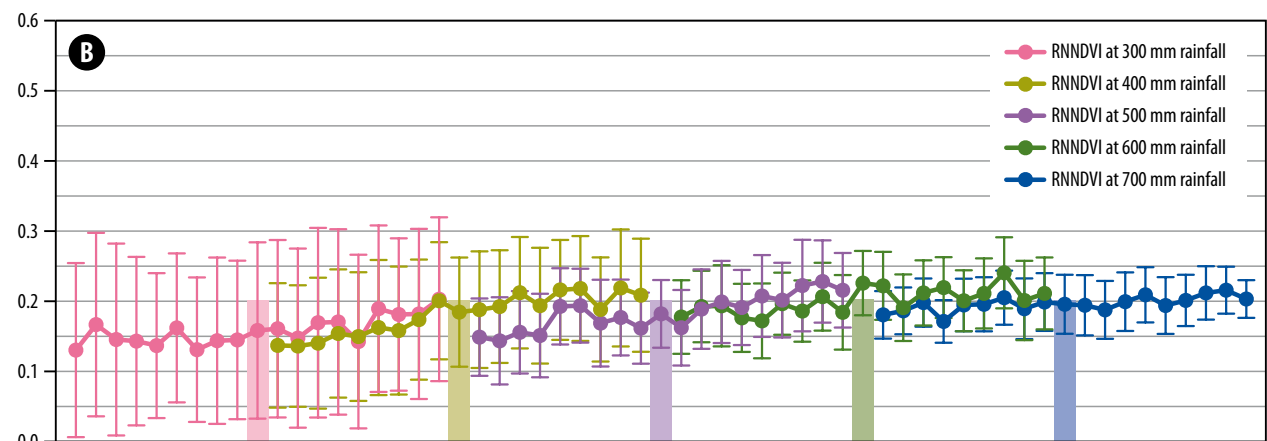
Variation in RNNDVI ( $*NDVI/rainfall$ ) (mean and standard deviation grouped for  $\pm 5$  mm of rainfall) as a function of rainfall the previous year analyzed for five rainfall levels (isohyets) for the wet period 2000–2006; the vertical bars indicate the rainfall levels used in the analysis (current year), and the circles show the previous

year's rainfall (all RNNDVI values are recorded at rainfall levels 300, 400, 500, 600 and 700 mm  $\pm 5$  mm, but with varying rainfall the previous year); a) RNNDVI based on annual average  $*NDVI$ , b) RNNDVI based on annual maximum  $*NDVI$ , and c) RNNDVI based on annual increment  $*NDVI$ .

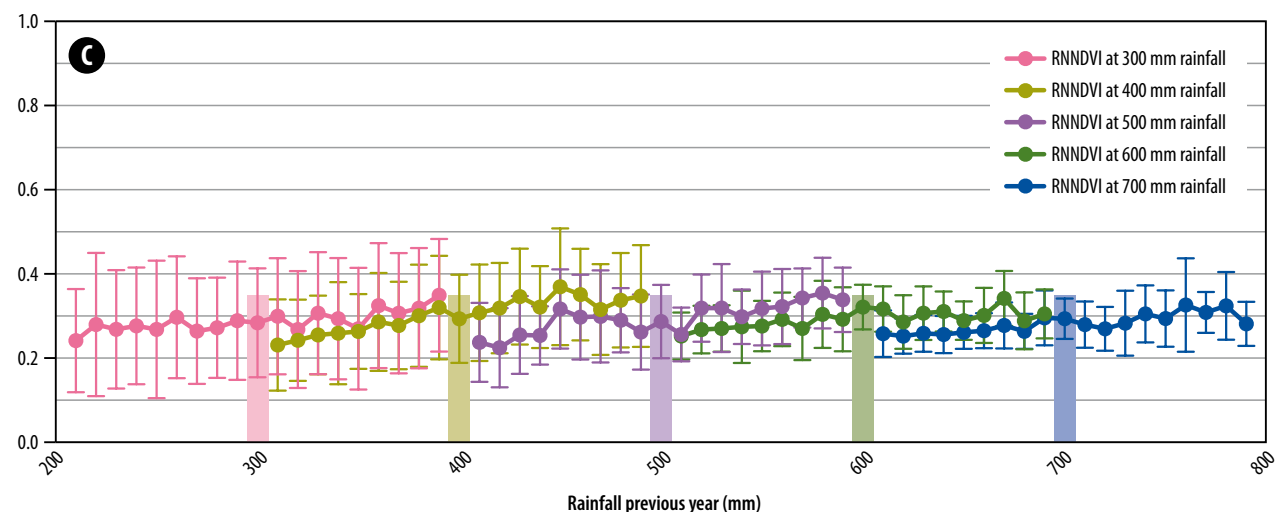
RNNDVI (average  $*NDVI/rainfall$ )



RNNDVI (maximum  $*NDVI/rainfall$ )



RNNDVI (increment  $*NDVI/rainfall$ )



to lower values (compare Figures 7.3a, 7.4a and 7.5a), whereas increment-derived RNNDVI is more stable. The relative jump between different isohyets in Figure 7.5 (showing wetter conditions) does not, however, differ between the different \*NDVI indices (the black vertical jump bars are of similar relative length in panels Figures 7.5a, 7.5b and 7.5c).

Exploring the changes in RNNDVI for the same index but comparing the three time periods used (e.g. Figures 7.3a, 7.4a, and 7.5a), all RNNDVI indices show a decline from the 1982–1987 period to the 2000–2006 period. This tendency is strongest for the average index and weakest for the increment index. This can either indicate an underlying degradation in the vegetation production system, or be the result of the shifting positions of the isohyets (transgressing further north) together with biases in the average and maximum indices. As all indices show the tendency of declining RNNDVI over time, we believe that it is an indication of ongoing land degradation. We also think that the stronger tendency in the average and maximum indices is due to biases, and depends on underlying soil conditions and vegetation type. Average and maximum NDVI-derived indices trends analyzed by pixel will hence also be biased, and reveal a less strong trend than the increment index, due to the influence of underlying factors on the annual signal. Such a bias in using the average \*NDVI for estimating vegetation production also explains why the northward trend in vegetation recovery is lower for average \*NDVI compared with the increment \*NDVI, as seen when comparing Figures 7.8 and 7.14.

### **RNNDVI AND THE PREVIOUS YEAR'S RAINFALL**

Vegetation growth may respond to rainfall conditions in the previous year. For example, pasture seed stocks or animal numbers may be low after a dry year and there may be a lag in recovery. To examine this, the dependence of RNDVI on the preceding year's rainfall was examined for locations with different rainfall amounts (isohyets) and for the whole period, a dry period and a wet period. Figures 7.6–7.8 show analysis of the relationship between rainfall the previous year and RNNDVI (mean and standard deviation) in the current year for five rainfall levels (isohyets): 300 mm, 400 mm, 500 mm, 600 mm and 700 mm (all using a range of +/- 5 mm of rainfall). Figure 7.6 shows the RNNDVI dependence on the previous years' rainfall for the whole period 1982 (rainfall from 1981) to 2006. Figure 7.7 shows the dependency of RNNDVI on the previous year's rainfall

for the dry period 1982–1987, and Figure 7.8 for the wet period 2000–2006.

Figure 7.6 reveals a small tendency for better vegetation response when rainfall is stable (i.e. at a rainfall level of 400 mm, vegetation growth is good if rainfall was also around 400 mm the previous year). But the general trend shows that the higher the rainfall the previous year, the better the growth in the current year. Consequently if rainfall at two sites was similar in the previous year, the RNNDVI in the current year will be higher for the location receiving less rain in the current year.

The analysis of the dry period RNNDVI dependency on the previous year's rainfall (Figure 7.7) shows highly varying results for the effects of very low rainfalls the previous year (a previous year's rainfall less than 280 mm). At very low rainfall the RNNDVI goes up. Again, herders migrating out (or cattle die-off) during extremely dry conditions could explain this. The tendency for vegetation to harvest more from rainfall the previous year is strongest when analyzing the full time-series (Figure 7.6) and could be a reflection of the more transient situation over the longer term. RNNDVI derived from annual average \*NDVI (Figures 6.6a, 6.7a and 6.8a) show a positive trend when going from 300–700 mm of rainfall. This is not an expected pattern, as a drop of rainfall should be equally or more effective at lower rainfall than at higher rainfall, and as rainfall approaches 800–1,000 mm per year factors other than rainfall become limiting for vegetation growth. Hence only the increment \*NDVI index shows the expected pattern of a decrease in RNNDVI as rainfall increases.

### **CONCLUSION**

The conclusion of the analysis of rain-normalized vegetation changes in the Sahel for 1982–2006 is that vegetation has not been able to harvest the increases in rainfall. This contradicts conclusions from most of the earlier studies analyzing rain-adjusted vegetation growth in the Sahel. Analyzing the different approaches for calculating vegetation growth, we conclude that average (or integral) NDVI (\*NDVI) is the least suitable for studying vegetation changes in transient environments, and more reflects underlying soil and vegetation types, rather than vegetation growth. Our analyses indicate that rain normalization based on the increment \*NDVI gives the most consistent and logical results and is the best-suited index for analyzing changes in transient environments.

# Spatial ranking of vegetation index trends

## INTRODUCTION

From a technical perspective, all the above vegetation analyses are driven by the AVHRR NDVI data and the results of the trends might be biased because of systematic errors over time (see Chapter 6). Several other authors have hence omitted data from certain years in their studies of vegetation change in the Sahel. Some studies omitted 1994, when the atmospheric transparency was influenced by the Pinatubo volcanic eruption. There have also been reports on systematic shifts in the remotely-sensed vegetation data from the AVHRR sensor, starting in 2000 as a result of shifting solar zenith angles (Eklundh and Olsson, 2003; Slayback et al, 2003). Errors introduced by such factors will plague all forward driven approaches.

In an effort to overcome errors originating in systematic shifts and variations in sensor and atmospheric conditions, a goal-driven approach for identifying the best and worst performing areas with regard to both absolute and rain-adjusted vegetation growth was developed. Under the assumption that sensor and atmospheric variations would have a consistent spatial influence but vary over time, the vegetation growth for each year in the time-series was spatially ranked from highest to lowest growth to provide yearly maps of relative vegetation performance over a given spatial domain. The change in ranking position for each pixel was then analyzed as a normalized time-trend regression for the period 1982–2006. The resulting map lacks any physical meaning, but the relative vegetation performance of all pixels vis-à-vis each other in the spatial domain used in the analysis can be identified. Systematic degradation in sensors or global atmospheric variations will have no, or a negligible, influence on the results, as such effects are assumed to have equal influence on all NDVI captured at a particular date.

The goal-driven ranking approach was applied at two separate different spatial scales: 1) a regional ranking encompassing the Sahel Parklands (bounded by 11° N–18° N) where all pixels were compared with each other, and 2) a focal or neighbouring ranking where the vegetation growth of each pixel was compared with the growth of its eight closest neighbours. The analysis was done only for incremental \*NDVI (as only relative growth is interesting, all indices will generate very similar results), and excluded the anomalous areas along the coast and around Lake Chad.

## REGIONAL RANKING OF VEGETATION GROWTH

The core of the Sahelian parkland area bridges the transition from agriculture to pastoral agro-ecology, and stretches from about 11° N–18° N. The regional ranking analysis was restricted to this Parklands area, excluding the coastal strip and Lake Chad (see Figure 8.1). For each year the annual increment \*NDVI of each pixel in this sub-region was ranked according to its index value, establishing ordinal maps for each year for 1982–2006 (Figure 8.1 – top panel). The normalized trend in the ranking position of each pixel for the period 1982–2006 was then calculated using OLS regression (Figure 8.1 – bottom panel).

## REGIONAL RANKING OF RAIN-NORMALIZED VEGETATION GROWTH

Relative regional ranking was also undertaken using

the rain-normalized increment \*NDVI as input (Figure 8.2). Areas showing greatest relative browning generally concur with the areas that had greatest browning in the analysis of absolute trends in rain-normalized annual increment \*NDVI (Figure 7.2c).

## FOCAL OR NEIGHBOURHOOD RANKING OF VEGETATION GROWTH

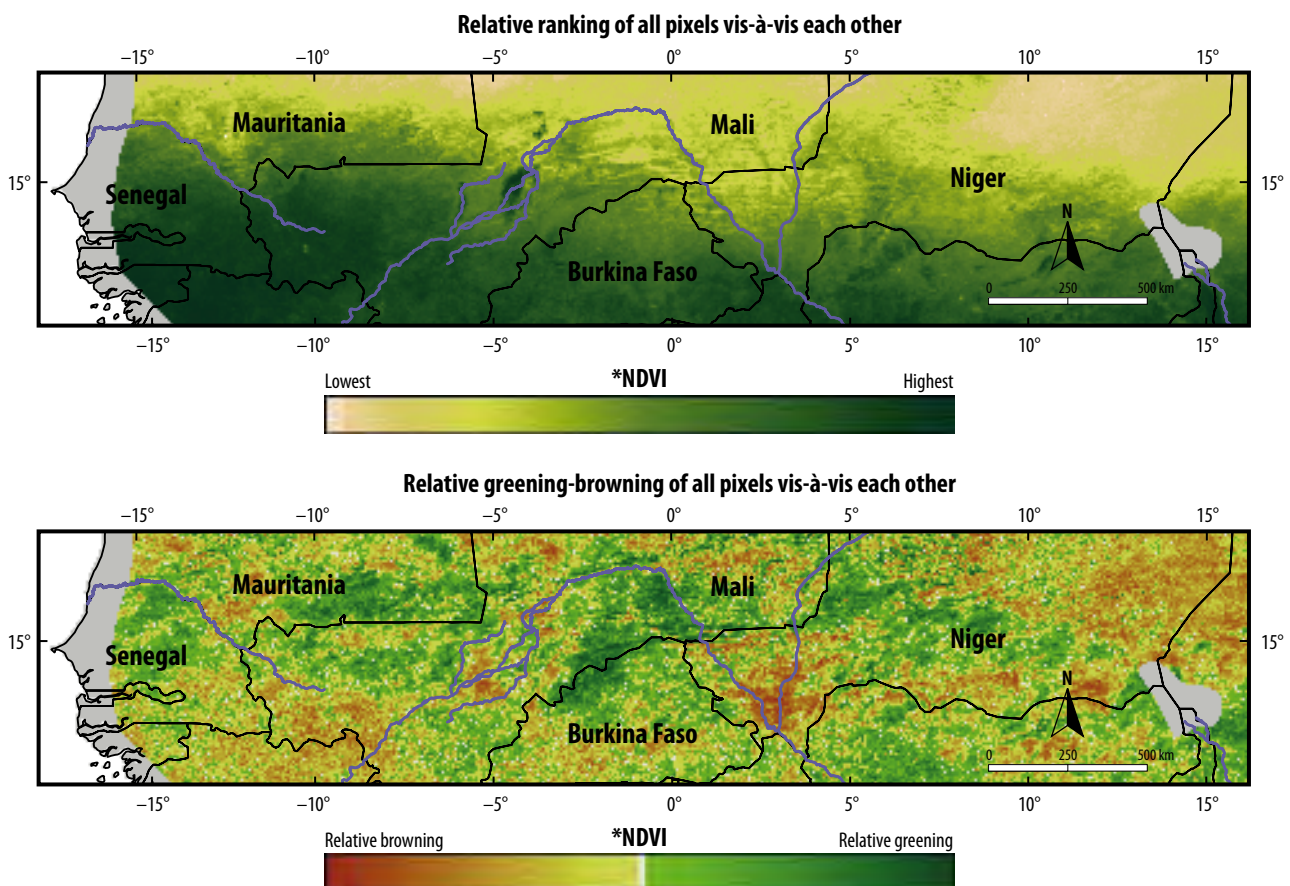
The regional ranking was complemented with a focal, or neighbouring ranking. The focal ranking was done only for vegetation data, as the rainfall variation between neighbouring pixels can be assumed to be negligible compared to variations in vegetation growth.

For each kernel of a size of 3 x 3 pixels the average increment \*NDVI for each window (3 \* 3 pixels) year was first calculated. Then the difference between the original \*NDVI value of the central pixel in the

**FIGURE 8.1**

Relative regional ranking of increment \*NDVI 1982–2006 for all terrestrial pixels in the Sahel Parklands (11° N–18° N); (top) average relative regional ranking, and (bottom) trend in relative regional ranking. The relative ranking compares all pixels vis-à-vis all others, and establishes an ordinal relation showing greenest

(mostly vegetated) to brownest (least vegetated) pixels; the values represent no physical property but can be used to identify best and worst performing areas; the ranking has the advantage of neutralizing all systematic errors stemming from sensor degradation and atmospheric disturbances.



kernel and the average kernel value for that particular year was calculated and saved as the relative focal (neighbourhood) vegetation performance indicator for that pixel. This was repeated for each year in the time-series, and the trend and standard deviation of the neighbourhood relative vegetation growth was analyzed using OLS regression (Figure 8.3).

## CONCLUSION

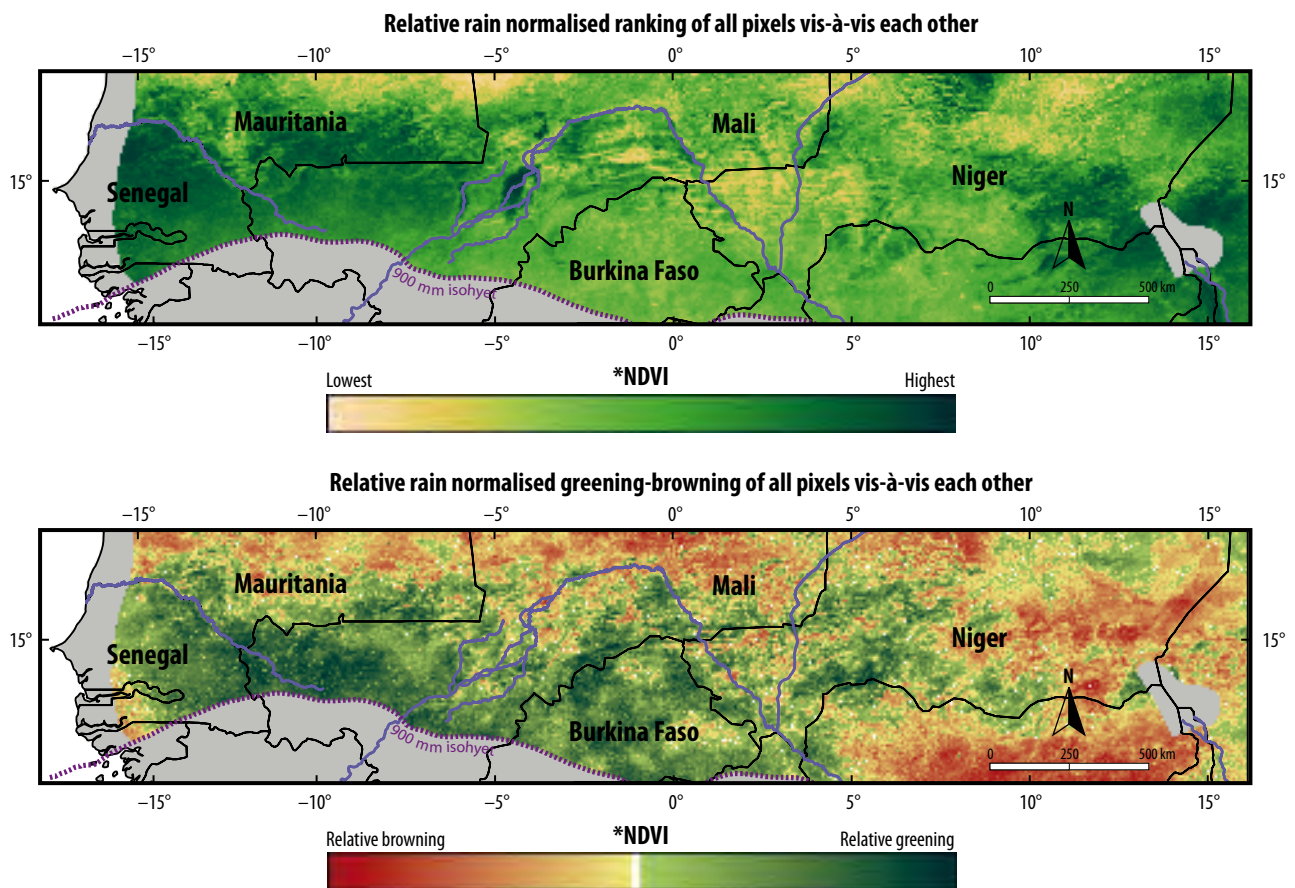
The relative regional ordinal ranking was undertaken in order to rule out temporal influence of biases in rainfall estimates, atmospheric disturbances, and errors and degradation stemming from the use of several generations of AVHRR sensors. The result of the ranking position trend analysis is dependent on the area selected for the ranking. In this study we chose to include all terrestrial areas between 11° N–18° N, also including areas outside the five project countries.

The results of the rank trend analysis highlight the areas that have performed relatively better or worse vis-à-vis all other areas in the region under analysis. The patterns of spatial changes in vegetation performance are similar for vegetation growth (Figure 8.1) and rain-normalized vegetation growth (Figure 8.2), but with a generally reinforced pattern in the rain-normalized analysis. The most notable difference between the trends is in the ranking positions outside the core countries of this study. Areas with a stronger relative increase in RNNDVI performance seem to be clustered along the major rivers and along international boundaries. Explanations for this could be irrigation development along waterways, and a lower population density in peripheral areas. The local ranking results in a forced fragmented pattern, which will however allow the identification of areas with homogeneous and

**FIGURE 8.2**

Relative regional ranking of rain-normalized increment \*NDVI (RNNDVI) 1982–2006 for all terrestrial pixels in the Sahel Parklands (11° N–18° N); (top) average relative regional ranking, and (bottom) trend in relative regional ranking. The relative ranking compares all pixels vis-à-vis all others, and establishes an ordinal relation showing pixels from the highest RNNDVI to the lowest RNNDVI in the

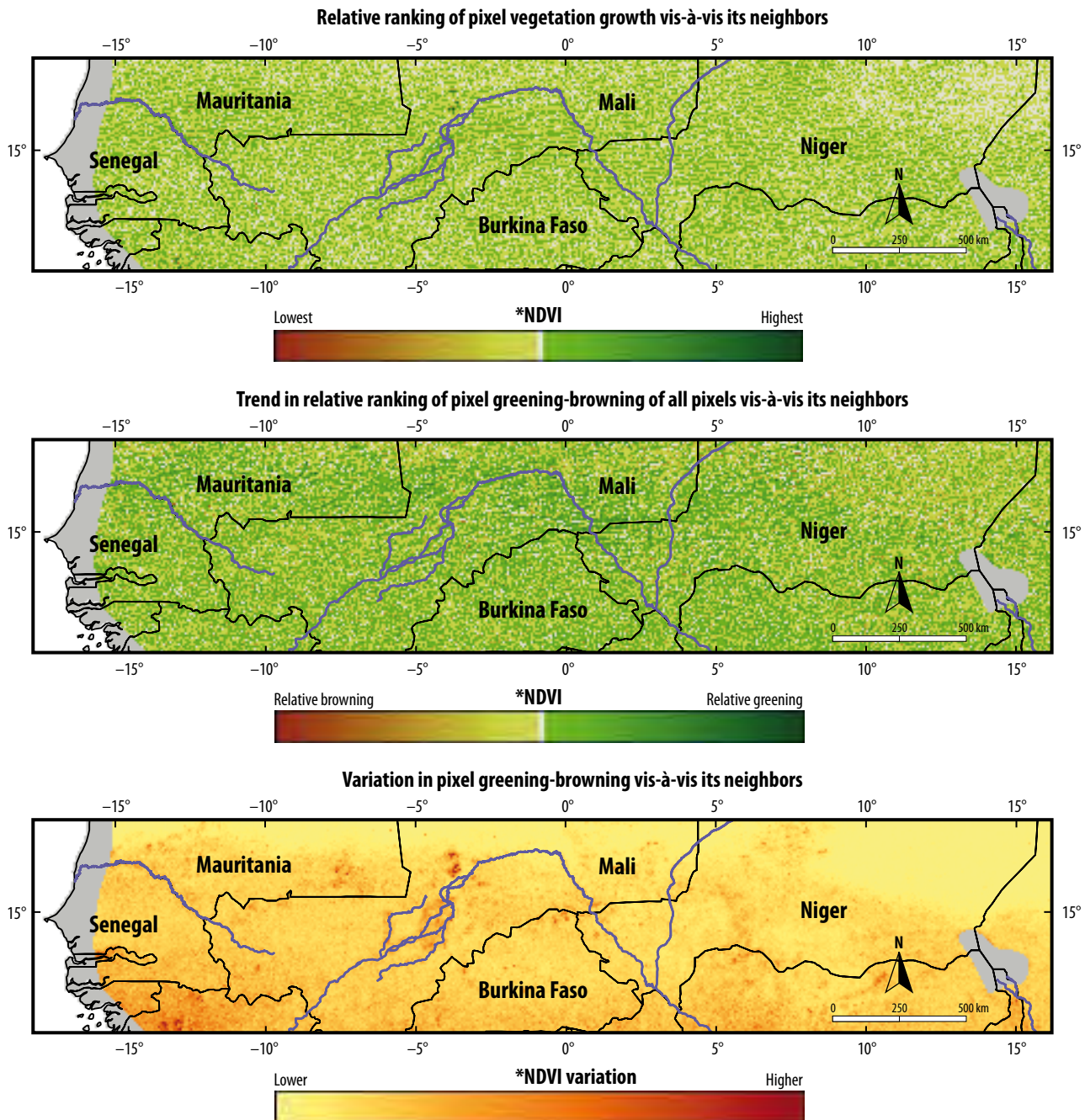
Parklands region; the values represent no physical property but can be used to identify best and worst performing areas; the ranking has the advantage of neutralizing all systematic errors stemming from sensor degradation and atmospheric disturbances, as well as from biases derived from using different rainfall datasets.



**FIGURE 8.3**

Relative focal or neighbourhood ranking of increment \*NDVI 1982–2006 for all terrestrial pixels in the Sahel Parklands (11° N–18° N); (top) average relative neighbourhood ranking, (middle) normalized trend in relative neighbourhood ranking, and (bottom) standard deviation in relative neighbourhood ranking. The relative ranking compares all pixels vis-à-vis its eight nearest neighbours, and establishes a relative neighbourhood relation showing greenest

(mostly vegetated) to brownest (least vegetated) pixels at a focal scale; the values represent no physical property but can be used to identify areas with high and low focal variation in vegetation performance; the focal vegetation growth analysis has the advantage of neutralizing all systematic errors stemming from sensor degradation and atmospheric disturbances.



heterogeneous vegetation dynamics over the last 25 years. A potential use of the ranking trend maps is for identifying interesting areas for further studies. Another use is as a complementary tool for analyzing ground-sampled data, where the ranking trend maps

could be used for setting a threshold, and hence identifying the spatial distribution of areas with a ground-based definition of vegetation changes.



# Regional surveillance: overall discussion and conclusion

## INTRODUCTION

Debates on the degree, extent and causes of desertification in the Sahel have been ongoing for almost a century but still have not been resolved. This uncertainty impedes policy development for sustainable land management. During the Sahel drought period in the 1970s and early 1980s, the dominant viewpoint was that the equilibrium of the Sahelian climate and ecosystem had become disturbed by an internal self-reinforcing (equilibrium) process that resulted from loss of vegetation through human activities, particularly overgrazing, leading to drought and desertification. Post-1980, when the Sahel recovered from the drought, a non-equilibrium hypothesis emerged in which external forcing exerted by the climate system was seen as the cause of drought and desertification, and in which humans were more the victims responding to external changes than the cause of the problem. Both the resilience of the natural ecosystem and human management of the agro-ecological system were regarded as sustainable at the prevailing grazing pressure. Recently, however the idea of internally driven degradation has regained support, and the debate is still ongoing whether irreversible land degradation has occurred or not in the Sahel. To settle this debate and for the development of concrete and specific action plans there is need for objective definition and indicators of desertification, and of their consistent measurement using scientifically-rigorous frameworks for sampling and monitoring over time and space.

The aim of the study was to synthesize existing knowledge on land degradation in the Sahel, and to develop a synoptic screening method to identify areas with anomalous vegetation degradation or recovery patterns. The results lend support to the idea that the Sahel vegetation system has not recovered to its pre-drought production capacity, and hence suggests that extensive land degradation has occurred.

## NDVI INDICATORS OF LAND DEGRADATION

Several recent studies on mapping of soil or land degradation have used the AVHRR derived NDVI time series data. Hulme and Kelly (1993) analyzed the temporal trend of residual vegetation variability after rain adjustment, but concluded that longer time-series were needed. Prince and others (1998) and Nicholson and others (1998) analyzed Sahel Rain Use Efficiency (RUE), and concluded that there were no signs of extensive degradation in the

Sahel, even though local regions were identified as affected by decreases in RUE. Symeonakis and Drake (2004) drew the same conclusion, using RUE together with vegetation cover, runoff and erosion to create a compounded index of land degradation. They concluded that land degradation was a local phenomenon, and singled out areas in East and Southern Africa as the worst hit areas, with virtually no degradation in the Sahel. Milich and Weiss (2000) used the coefficient of variance (CoV) applied to an earlier version of the GIMMS NDVI dataset. After eliminating pixels with known external influence on CoV, they hypothesized that pixels with a high CoV embedded in a more stable neighbourhood could indicate land degradation. Using this approach they found little evidence for regional land degradation in the Sahel. Olsson and others (2005) studied the time-integrated values and the amplitude values of smooth NDVI time-series 1982–1999. They also compared national population growth with population growth in cities, and suggested that migration to urban regions might be a contributing factor in land-use changes. They concluded that vegetation recovery in the Sahel had been stronger than would have been expected from rainfall increases alone. This view is supported by other studies using the GIMMS NDVI dataset (e.g. Anyamba and Tucker, 2005; Herrmann et al, 2005a) and local field studies in e.g. Burkina Faso (Mortimore and Admas, 2001; Niemeijer and Mazzucato, 2002; Nemani et al, 2003 Reij et al, 2005). Some studies (e.g. Hulme and Kelly, 1993; Goward and Prince, 1995) found a time lag in the vegetation recovery after drought, indicating a cumulative effect of a few dry-years, but they did not identify any irreversible land degradation. As part of a Global Land Degradation Assessment, ISRIC, using the GIMMS NDVI data set, also indicated little change in RUE over the past 25 years (Bai et al, 2008). With a few exceptions, these studies used the unadjusted NDVI data from the AVHRR sensors and an annual or seasonal integral of NDVI for estimating vegetation growth.

A majority of earlier studies of Sahelian vegetation from remotely-sensed data have focused on croplands, or assumed a spatial steady state in ecosystems. Transient changes, driven by increases in both rainfall and population, and by politically driven sedentarization of pastoralists (see Reynolds and Stafford Smith, 2002a) have, however been strong in the Sahel since the 1950s. Vegetation changes following in the wake of climatic and socioeconomic drivers will influence the NDVI in various ways.

In this study we developed an alternative method for calculating annual vegetation production from NDVI data – the annual increment index. This annual index estimates vegetation production as the accumulation of growth increments over an annual vegetation cycle. We developed the index hypothesising that it would be more robust than previously developed indices when analyzing vegetation trends across pastoral, agricultural and natural landscapes and in transitional landscapes. Our results clearly show the increment index to be more consistent compared with the results derived from the hitherto used indices based on average (integral) or maximum NDVI. The average annual (or seasonal) NDVI used by most other researchers is shown to be the least accurate for estimating vegetation growth. The average NDVI is sensitive to soil conditions and captures total above-ground standing biomass (green + woody) and hence tends to decrease when moving from woodlands to croplands to pasture lands (see Figures 7.3–7.8). This is especially so in ecosystems with inter-annual changes and with transient changes over longer time periods: both factors that have strongly affected the Sahel parklands over the last 25 years. The shortcomings of the annual average NDVI as an estimate for vegetation growth is also reflected in the results of comparing the northward trend in rainfall and vegetation over the last 25 years (Figures 6.8, 6.11 and 6.14), where average NDVI is lagging further behind the other indices. In our view this is caused by underlying soil condition and vegetation type changes when transgressing northwards, which influence the average NDVI to a larger extent than the other indices and cause an underestimation of vegetation increase when transgressing different ecosystems and management regimes.

## **LAND DEGRADATION AND THE PROBLEM OF SCALE**

It is obvious that the temporal and spatial scales used in a land degradation study influence the results obtained. Analyzing the rainfall trend in the Sahel for the period 1930–2006 reveals weaker trends than for more recent periods (Figure 5.10), but both long- and short-term variations are evident (Figure 5.11 shows the strong upward trend in rainfall 1982–2006). The start of accumulation of remotely sensed vegetation data more or less coincides with the climax of the drought, and the available records hence show an increase in vegetation (see Chapter 6). There are also inconsistencies in the rainfall time series data, stemming from a highly varying network of gauging stations and dwindling access to data.

In the spatial domain the correlation between rainfall and vegetation is stronger over larger areas because trends in rainfall are more evident. Coarse-resolution satellite images are not able to capture the large spatial variation that often occurs on the ground (Diouf and Lambin, 2000; Milich and Weiss, 2000). This is even truer when the geographical variation in underlying properties is considered. For example, Foody (2003), using eight years of data from the Sahel (1986–1993), found a much stronger relationship between NDVI and rainfall with geographically weighted regression ( $r^2 > 0.96$ ) than with Ordinary Least Square regression ( $r^2 = 0.67$  to  $0.73$ ), which is the method used almost universally in NDVI studies in relation to environmental factors. This demonstrates the high spatial correlation in NDVI response in different vegetation ecosystems. Thus, even though rainfall controls a large part of the spatial and temporal variation in biomass at the regional scale, it is clear that at the local scale there is considerable variation in the response of vegetation to rainfall. This is due to the effect of factors such as soil type, terrain, inter-annual variations in rain-use efficiency, presence of plant seeds, vegetation communities and floristic composition, land-use practices, and seasonal distribution of rainfall.

## **ECOLOGICAL AND TECHNICAL DATA DISCREPANCIES**

We believe that it is premature to conclude that a resilient vegetation recovery has occurred in the Sahel since the droughts in the early 1970s and 1980s. Rather, most studies using NDVI time-series data may be flawed, and it appears that ongoing land degradation is being hidden underneath the rain-driven increase in NDVI.

The flaws in previous studies are related to several factors, both ecological and technical. On the ecological side, most studies assume that Rain Use Efficiency (RUE) is constant with respect to rainfall. The review of the available information (Chapter 7), however, suggests that the relationship between RUE and annual rainfall is quadratic, with RUE reaching a maximum value around the annual average rainfall. Hence an increase in RUE, with factors other than rainfall remaining constant, would have been expected for the Sahel in view of the strong recovery in rainfall since the drought in the early 1980s. The lack of any increase in RUE (or Rain-normalized vegetation growth) in the Sahel could stem from changes in the vegetation ecosystem (e.g. changes in species composition leading to better adaptation

to lower rainfall, so that RUE reaches a maximum at lower annual rainfall), or from soil degradation. The exploration of RNNDVI versus rainfall (Chapter 7; Figures 7.3–7.5) indicates that the choice of index for portraying annual vegetation growth is important. Our analysis reveals that the most commonly used annual average NDVI is a poor index for portraying vegetation changes in a transient environment. The annual average \*NDVI, and to a lesser degree also the annual maximum \*NDVI, is influenced by the underlying soil and vegetation composition. These indices hence fail to identify transient changes in both time and space.

A second ecologically related flaw is that changes in vegetation composition may have taken place over the period of study, which would have changed the relationship between vegetation growth and NDVI. The increase in rainfall has driven an increase in tree planting, in conversion of fallow and pastoral land into agriculture, and a change in grassland species (e.g. from annual to perennial species). Most of these changes tend to increase the standing biomass, and hence the average \*NDVI integral, and to a lesser degree the annual maximum \*NDVI. As most studies have used the average (integral) or maximum NDVI as a proxy for vegetation growth, they will capture a mix of standing biomass (woody plus green) and soil composition, but not net primary production (NPP). The increment \*NDVI index developed in this study is shown to be less sensitive to such biases, and better capture net primary production compared with the more commonly used indices. The annual increment \*NDVI will capture intermittent grazing pressure in rangelands, and also eliminate over-estimation of vegetation growth in tree-based agroecological systems, where otherwise woody biomass will contribute to higher NDVI values. Local studies restricted to croplands reporting no decline in RUE will not suffer from the second flaw, but will probably be influenced by the first.

A technical flaw in most of the NDVI studies presented in the literature is the fact that the soil influence on NDVI at low NDVI values is ignored (see Chapters 6.1–6.3). With some exceptions (e.g. Prince et al, 1998; Maselli et al, 2000), most previous studies have used the available NDVI data sets without any soil adjustment. As vegetation cover decreases, soil influence in the spectral bands becomes greater, increasingly over-estimating NDVI at lower vegetation cover, with the result that vegetation resilience is over-estimated. Using the scaled (soil

adjusted) NDVI, as we did, results in lower NDVI values in drought years in proportion to the lower vegetation density in such years. Ignoring this soil effect will lead to over-estimation of vegetation production and RUE/RNNDVI in regions with low vegetation cover. The exploration of the spatial and temporal \*NDVI signal along a transect in Mali (Figure 6.6) indicates rather that despite the soil adjustment, \*NDVI probably still over-estimates vegetation cover at low densities.

The largest flaw, however, is related to the use of annual or seasonal average (integral) NDVI for estimating vegetation growth. Few studies have evaluated the effect of site-specific (edaphic) conditions on NDVI. The analysis of such influences undertaken in this study clearly shows that average NDVI, and also to large degree maximum NDVI, to be strongly influenced by edaphic conditions, and hence not to be very useful for studying vegetation changes in transient environments.

The different results in this study compared with most other regional remote-sensing-based studies employing the AVHRR-derived NDVI data set, are presumed to relate to the handling of the above ecological and technical flaws. However, discrepancies between different studies may also be partly due to continuous improvement (also backdating) of the GIMMS NDVI database, and use of different rainfall datasets.

## **SAHEL VEGETATION CHANGES 1982–2006**

As found in previous studies, we observed a strong greening trend in vegetation over the Sahel from 1982–2006, in response to rainfall recovery following the droughts that persisted in the 1970s to early 1980s. However we observed a weaker greening trend than found in previous remote-sensing studies. The total area of greening over the period 1982–2006 in the five countries in this study is around 2 million km<sup>2</sup> (50% of total area of the five countries). About half of this increase (equal to a quarter of total area) was identified as statistically significant ( $p < 0.05$ ). The greening mostly took place in the Parklands region of these countries (11° N–18° N). Normalizing the increase against the increases in rainfall, only about 0.4 million km<sup>2</sup> (10% of the total area of the five countries) have had an increase in vegetation growth efficiency. This increase is almost completely restricted to the Parklands region, but even so is not statistically significant ( $p < 0.05$ ).

The Parklands show a stronger greening than both the wetter and the drier areas of the countries in this study. The rainfall increase over the last two decades has also been stronger in the Parklands region than in adjacent regions. This could also explain the stronger increase in Rain-normalized Vegetation Growth (RNNDVI) in the Parklands compared with adjacent areas because of: (1) a stronger ecological recovery and more complete return to pre-drought (average) rainfall conditions, and (2) conversion in land use from pastoral and fallow to farmland, including the introduction of tree-based systems. Further to the south, such changes appear to be less pronounced. The greater resilience displayed by Parkland areas relative to surrounding areas, indicates the importance of maintaining and restoring this ecosystem. The stronger recovery along international borders (Figure 7.2) and along the major rivers in the region support the hypothesis that land management practices may have influenced the greening trend, both positively and negatively. Potentially, the restocking of more remote rangeland areas may also have been slower after the droughts, leading to a better recovery in vegetation growth.

These results contrast with those obtained from previous remote-sensing studies. Although there are a number of differences in the data and methods used between studies, we attribute the difference in conclusions to be mainly due to the use in our study of soil-adjusted NDVI, more detailed rainfall records and an improved estimate of annual vegetation production. Explanations of the discrepancies between the trends in absolute and rain-adjusted vegetation dynamics also include variation in natural conditions such as topography, soil conditions and vegetation. RUE/RNNDVI will normally increase down slope and in valley bottoms due to increased soil wetness, and in soils with higher infiltration capacity and water holding capacity. Several studies have suggested land use changes, including fuel-wood consumption, being responsible for secular change in vegetation. Olsson and others (2005) speculated that population migration and rapid urbanization might have influenced land use changes, which would be reflected in the NDVI data. At local scales, expansion of irrigation is reported to have led to increases in NDVI (Fuller, 1998), which we would expect to see mostly along the valleys of the major rivers in this region.

Recent local scale studies employing high-resolution remote-sensing data in combination with ground surveys give support to our findings of a decline

in rain-normalized vegetation growth in the Sahel since the droughts in the early 1980s. In fact an increase in RNNDVI would have normally been expected for the Sahel in response to the strong increase in rainfall since the early 1980's; but this was not the case, pointing to changes towards poorer vegetation composition and/or soil degradation. Diouf and Lambin (2001) showed that RUE from 1.1 km resolution AVHRR-NDVI data over Senegal under-estimated vegetation in dry years compared with ground-sampled biomass data, thus tending to overestimate greening trends following drought. Hountondji and others (2006) revisited the data from earlier studies in Burkina Faso and identified land degradation. Hein and de Ridder (2006) conducted a re-analysis of data on RUE from global drylands, including two sites in the Sahel, and proposed that land-degradation has prevented an expected increase in vegetation following the rainfall increase over the last 20 years. Hein (2006) did a re-analysis of a paired experiment with medium- and high-pressure grazing in Senegal, and found net primary production to be affected by intensive grazing in drought years. However, his conclusions were challenged by Retzer (2006), who argued that resilience after drought was equally high when grazing pressure was high.

Field studies also support the case that management-induced changes have caused increase in RUE/RNNDVI in the Parklands. Milich and Weiss (2000) surveyed species compositions and vegetation ground cover along several transects in Sahelian rangelands. They concluded that Sahelian NDVI follows rainfall more closely in agro-ecological systems compared with the drier rangeland ecosystems. A major reason put forward for this is that ecological and grazing pressures restrict development of seed pools, especially due to overgrazing in dry years and in years following good rains. This is then expressed in erratic patterns in the ratio of vegetation growth to rainfall in pastoral regions. The analysis of the influence of the rainfall the previous year on RNNDVI in the current year gives support to the idea of fluctuations in vegetation growth exerted by a varying climate (Figures 7.5–7.8). Cattle die-off during droughts gives the seed pool time to recover when the rains return (cf. Hein, 2006), which may have influenced the results of Figure 7.7, where very low rainfall during the drought years led to a higher RNNDVI the following year. It is also notable that the 300 mm isohyet used in this study coincides with the

boundary between agro-ecological and rangeland ecosystems, and so changes in management between pastoral and agricultural management may have tracked its movement.

Overall, the findings in this study lend support to the arguments of Charney (1975), Xue and Shukla (1993), Wang and others (2004) and others, that human-caused land degradation has negatively affected vegetation growth in the Sahel. Therefore, recent claims that the Sahel is greening because of improved land management (Mazzucato and Niemeijer, 2000; Rasmussen et al, 2001; Niemeijer and Mazzucato, 2002; Pearce, 2002; Eklundh and Olsson, 2003, Anyamba and Tucker, 2005; Herrmann et al, 2005a; Reij et al, 2005) may be overstated.

## **MAURITANIA**

Most of Mauritania has an average rainfall of less than 300 mm, and the Sahelian region only covers the southern part of the country. In the agro-ecological regions of Mauritania (along the Senegal River and the southern border with Mali) vegetation recovery and increase in RNNDVI is pronounced. Further into the drier pastoral regions, no vegetation recovery has taken place. The coastal region is influenced by a maritime climate, and the rainfall estimates are more likely to be erroneous. Milich and Weiss (2000) found erratic behaviour in vegetation response to rainfall for Mauritanian rangelands (16.3° N–17.3° N), and suggested that failure of the seed pool to develop after dry years prevents vegetation from making use of good rains in the following years. They also suggested that animal die-off during the drought of the early 1980s caused a large increase in vegetation growth in the years following the drought. Milich and Weiss (2000) also emphasize that small-scale variations in topography and geology largely influence the hydrology and hence the vegetation. Thus large uncertainties surround the Mauritanian responses.

## **SENEGAL**

The vegetation recovery is stronger in the northern half of the country and culminates around the Senegal River. The northern drylands are dominated by pastoralists with limited agriculture and grasses make up most of the primary production (Diallo et al, 1991). It is likely that the same processes discussed for Mauritania also relate to the Senegal grasslands. The more maritime rainfall along the coast makes the estimate less certain, and the timing of those maritime rains is such that they can also be less

biologically available. The wetter south is dominated by millet and groundnut agriculture, with annual productions being discernible in NDVI data (Fuller, 1998; Knudby, 2004). Browning trends are evident along the coast in these agricultural areas. Further inland, vegetation recovery closely follows the rainfall increase. The anomalous stronger vegetation recovery along the Senegal River in both Mauritania and Senegal may indicate changes in managerial regimes, including irrigation. From analysis of 1.1 km AVHRR data, Fuller (1998) found increases in NDVI related to irrigation expansion in the Senegal River Valley. Diouf and Lambin (2001) made a detailed study in the Ferlo region in Senegal using better datasets on rainfall and on both remotely-sensed and ground-based vegetation data than used in this and most other studies. Their results indicated that land degradation had taken place in the period 1987–1997, but also that remotely-sensed vegetation studies (1.1 km NOAA-AVHRR) were still too coarse to capture the ground variation. From a paired field experiment in the Ferlo region with different grazing pressure, Hein (2006) concluded that high grazing pressure could lead to a vulnerable situation during drought. Using the same dataset Retzer (2006), however, concluded that even under high grazing pressure the system could recover resiliently after a drought.

## **MALI**

Most of the Sahelian region in Mali has experienced a pronounced decrease in RNNDVI, except for some areas around the Niger River, and in the south where there is little change in RNNDVI. Herrmann and others (2005a) found a stronger greening than suggested by rainfall alone in the Niger inland delta, and speculated that this is due to irrigation expansion, but only smaller patches of increase in RNNDVI were found in the Niger inland delta in this study. Mali, together with Burkina Faso, is reported to have had increases in agricultural output over the last few decades (Olsson et al, 2005). The relative increase in RNNDVI in southern Mali might hence be a reflection of better production methods. Also Milich and Weiss (2000) found a correlation between NDVI and rainfall for an agroecological transect in Mali. They hypothesized that discrepancy in the NDVI-rainfall relation depended on seed pool germination failures following dry years, and biologically ineffective rainfall (e.g. strong storms that generate run-off and soil erosion). For example, the so-called “Mango” rains fall during the dry season in February and March, causing premature germination of the seed pool before the arrival

of the monsoon rains. Figure 6.5 and the panels representing 1994 in Figure 6.6 show the Mango rains of 1994, which resulted in its being the wettest year in the time series (especially in Mali – Figures 6.8b, 6.11b and 6.14b). Comparing the temporal NDVI variation with field data, Milich and Weiss (2000) found higher variation close to villages and more stable conditions in less inhabited areas. Further north into the pastoral regions, they found a one-year lag between growing season rainfall and growing season NDVI (supported by the relation between very low rainfall and RNNDVI the following year at rainfall levels below 300 mm per year in Figures 7.5–7.8). They attributed the behaviour to failures of the seed pool to germinate both due to thresholds in rainfall and grazing pressure. This study shows that despite the increase in rainfall over central Mali, the vegetation increase has been negligible, indicating pronounced land degradation. The regional ranking analysis of RNNDVI indicates that the region north of the bend in the Niger River in Mali has had the poorest development in terms of RNNDVI in the five included countries.

## **BURKINA FASO**

The central plateau of Burkina Faso has been previously identified as one of the areas hit hardest by desertification during the Sahel droughts in the 1970s and 1980s. The severe situation provoked many studies and attempts for improving soil and water conservation (summarized in Reij et al, 2005). Reij and others (2005) describe the major innovations as traditional pit planting with organic fertilization, contoured stone lines, and damming of gullies. They report significant increases in production in villages that have adopted these methods. Mazzucato and Niemijer (2000) and Niemijer and Mazzucato (2002) also studied local sites and concluded that agroecological adaption had assisted in keeping up, and even increasing agroecological production. They contributed most of the improvements to local forms of agricultural intensification, e.g. networking and sharing of more traditional information and knowledge. Only for maize and rice did they suggest that technologically more advanced methods like irrigation, mechanization and fertilizer use had had any contribution to the increases in yield.

Rasmussen and others (2001) report that recovery of vegetation cover in northern Burkina Faso rangelands started immediately after the drought year of 1984. Herrmann and others (2005a) analyzed

the residual vegetation change after statistical elimination of rainfed-driven changes and identified a stronger than average vegetation recovery over the last 20 years over the central plateau. However, studying the change in RUE using the same datasets, but focusing only on local conditions around rainfall stations, Hountondji and others (2006) found no or little support for the local success stories. They concluded that 40% of the stations in their analysis had experienced ongoing desertification during the 1982–1999 period. They found no pronounced spatial patterns in the trends of RUE over this period for Burkina Faso. In this study the more peripheral parts of northern Burkina Faso and areas around the capital Ouagadougou were found to have increases in RNNDVI, while most of the central plateau shows no increase in RNNDVI.

## **NIGER**

Southern Niger (south of 16° N) has experienced a strong increase in rainfall over the last two decades (averaging almost 10 mm per year). Increases in RNNDVI in this study are restricted to southern Niger, which is dominated by rainfed agriculture on sandy soils and along seasonal watercourses (locally known as *fadama*), and protected grazing zones (Milich and Weiss, 2000). In these ecological environments it seems that management has been able to capitalize on the increase in rainfall over the study period. The regions with the highest increase in vegetation and RNNDVI are in the western part of Niger (around Tahoua and Maradi cities), the same regions that were identified by Herrmann and others (2005a) as strongly greening, and where they suggested that large natural resource-management projects could have influenced this positive development. In the pastorally dominated northern parts, the increases in rainfall are not reflected in vegetation growth, and hence the RNNDVI has dropped markedly, indicating land degradation.

## **OVERALL CONCLUSION**

Overall the results indicate that in most areas over the Sahel there has been extensive incipient desertification, masked by the general greening trend in response to increased rainfall since the early 1980s. Our results do not support reports of large-area impacts of agricultural innovation, for example in the central plateau of Burkina Faso. However increases in RNNDVI, indicating land restoration, were observed along the Senegal River in both Mauritania and Senegal, probably reflecting irrigated agriculture; and in agriculturally-dominated areas in southern parts of Mali, Burkina Faso and Niger, which could be related to improved agricultural management.

The critical need now is for more detailed follow-up studies using time-series satellite data of finer spatial resolution, coupled with systematic field survey, using scientifically sound sampling frames and consistent methods. The rain-normalized NDVI trends reported here can be used to guide sampling frames for such studies.

Priority should also be given to establishment of regional early warning systems so that preventive early actions can be directed to areas with symptoms of developing land degradation problems. This may be most efficiently done at regional (Africa) than national scale so that consistent methods are applied. These should include analysis of covariates as risk factors for land degradation. The availability of MODIS data since 2000, at a spatial resolution of 250 m, provides new opportunities for future monitoring at a scale that is more compatible with landscape features than AVHRR data. There needs to be constant iteration with systematic ground-based measurements continually to improve synoptic indicators of land degradation. An improved network of weather stations in Africa is also an imperative for development of synoptic screening of land degradation.

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# Appendix 2.1

## Web links

### DATA AND RESOURCES USED IN THIS STUDY

Africa Data Dissemination Service (USAID-FEWS) (NDVI and rainfall estimates over Africa for download): <http://earlywarning.usgs.gov/adds/index.php>

GLASOD – National Soil Degradation Maps (FAO) (interactive maps): <http://www.fao.org/landandwater/agll/glasod/glasodmaps.jsp>

Globalis (UNDP) (interactive world map based on statistics from the annual series of human development report): <http://globalis.gvu.unu.edu/>

Human Development Reports (UNDP) (reports and statistics for download): <http://hdr.undp.org/reports/>

Environmental Sustainability Index: <http://sedac.ciesin.columbia.edu/es/es/>

Land Resources Management: Desertification (The World Bank Group): <http://lnweb18.worldbank.org/ESSD/ardext.nsf/17ByDocName/KeyIssuesDesertification>

### OTHER DATA AND RESOURCES

African Monsoon Multidisciplinary Analysis (AMMA): <http://amma.mediasfrance.org>

Global Historical Climatology Network (GHCN): <http://www.ncdc.noaa.gov/oa/climate/research/ghcn/ghcngrid.html>

Global Precipitation Climatology Centre (GPCC): <http://www.dwd.de/en/FundE/Klima/KLIS/int/GPCC/GPCC.htm>

Global Precipitation Climatology Project (GPCP): <http://cics.umd.edu/~yin/GPCP/main.html>

Global Telecommunication System (GTS): <http://www.wmo.ch/web/www/TEM/gts.html>

National Climatic Data Center: <http://www.ncdc.noaa.gov/oa/ncdc.html>

Tropical Rainfall Measuring Mission: <http://trmm.gsfc.nasa.gov/>

Variability Analysis of Surface Climate Observations (VASCLimO) (Germany): <http://www.dwd.de/en/FundE/Klima/KLIS/int/GPCC/Projects/VASCLimO/VASCLimO.htm>

### MILLENNIUM ECOSYSTEM ASSESSMENT

Millennium Ecosystem Assessment (home page): <http://www.maweb.org/en/index.aspx>

Chapter on Dryland systems (download): <http://www.maweb.org/documents/document.291.aspx.pdf>

Desertification Synthesis (download): <http://www.maweb.org/documents/document.355.aspx.pdf>

### OTHER LINKS

United Nations Convention of Combat Desertification: <http://www.unccd.int/>

United Nations Environment Programme: <http://www.unep.org>

# **PART 3**

## **SENTINEL SITE SURVEILLANCE IN SEGOU REGION, MALI:**

**An evidence-based approach to assessing  
land degradation and targeting  
sustainable land management  
interventions**

*Tor-Gunnar Vågen and Markus G. Walsh*

# Summary

## BACKGROUND

Land degradation is a serious hidden threat to sustainable development in developing countries which depend strongly on their natural resource base for their food security and economic development. This work addresses the need to generate relevant and specific information on land condition and land degradation as an integral part of national planning processes. Currently governments and development organizations do not have access to specific data on land condition to be able to identify measurable land management objectives, efficiently target interventions, and monitor progress towards their achievement. Lack of scientifically rigorous monitoring of intervention impacts currently prevents effective feedback into policy improvement. Operational frameworks for systematic collection of data on land condition that are specific enough to guide management interventions do not currently exist. However, recent advances in remote sensing, rapid and cheap methods for soil analysis and new hierarchical statistical analytical techniques provide unprecedented opportunities for establishing operational land degradation surveillance systems (see Part 1).

Part 3 describes the Land Degradation Surveillance Framework (LDSF), a scheme for land degradation surveillance at the local scale, and provides a case study of its application in Segou Region in Mali. The LDSF, based on characterization of 100 km<sup>2</sup> sentinel sites, is designed for sampling entire landscapes in order to provide project-level baselines of land resources (e.g. soil and vegetation) and socio-economic profiles (e.g. household indicators), as well as a framework for monitoring and evaluating project interventions and their impacts on land and people. Moreover, the framework is standardized, and can therefore be used to compare project baselines and monitoring results over a wide range of ecosystems. Also, the framework is relatively simple in that exactly the same procedures are followed both in baseline measurements and in monitoring and evaluation. This application of the LDSF constitutes a sentinel surveillance scheme (see Part 1).

## LAND DEGRADATION SURVEILLANCE FRAMEWORK (LDSF)

The LDSF is built around the use of “Sentinel Sites” or “Blocks” of 10 x 10 km in size. The field sampling scheme is hierarchical or nested: within blocks, clusters of one sq km are located, and within each cluster ten 1,000 m<sup>2</sup> “Plots” (i.e. about 35 m diameter) are sampled. Plots within clusters, and clusters within blocks, are randomly placed so that unbiased estimates of problem prevalence are obtained. On each plot, detailed observations and measurements describing land and vegetation cover and soil condition are recorded, following a standardized protocol. Vegetation cover and abundance and soil characteristics are measured on four 100 m<sup>2</sup> “Sub-Plots” (about 5 m diameter) located at fixed positions within the plots. Soil samples are also taken from each sub-plot. The details of the design can be adjusted according to project objectives.

Vegetation and soil measurements are included in the assessment. Vegetation measurements include land cover, woody vegetation cover and abundance, perennial grass cover, and vegetation life-form diversity. Soil-related measurements include physiography, soil texture, the prevalence of soil depth restrictions and inherent degradation risk, soil infiltration capacity, soil spectral characteristics (based on near-infrared diffuse reflectance measurements), and soil degradation prevalence.

The protocol includes socioeconomic data collected for households located nearest the sampling points. These include a wide range of indicators related to people, households, poverty, agriculture, and the environment. This assessment included data on the number of months of food deficits, annual household expenditure profiles, and household demand for trees using a simple contingent valuation procedure. The collection of socioeconomic data as an integral part of the LDSF allows linkage of land degradation risk factors to key socioeconomic indicators.

In this application of the LDSF, we employ statistical analytical methods called “mixed effects models”, which permit errors to be structured according to the spatial hierarchical structure of the sampling

scheme. These models not only provide ability to make generalizations about the data at the population level at each level of scale (plot, cluster, and block), but also improve estimates of effects and provide richer insights into the data compared with conventional methods.

Some of the field-measured indicators (e.g. woody vegetation cover and soil spectral characteristics) are linked to fine resolution satellite imagery (Quickbird, at approximately 2 m resolution), and moderate resolution imagery (Landsat, Aster at approximately 30 m resolution) so that detailed block-level maps can be provided. The satellite data is also analysed, using a variety of “hard” and “soft” classification modelling methods, to map areas under (i) cultivation or management, (ii) natural or semi-natural vegetation, (iii) woody vegetation cover (trees and shrubs), and (iv) bare soil background and hard-set (compacted) areas. These classes form the basis for a rule-based decision framework for targeting land management intervention strategies, also including such information as tree densities and root depth restrictions. Examples of statistical analysis routines used in the LDSF, written in the ‘R freeware package, as well as a field guide, are given in appendices.

## CASE STUDY

In this case study, the Land Degradation Surveillance Framework (LDSF) was implemented in Segou Region, Mali. This region was selected as it represents a Parkland area where land degradation is perceived to be a serious problem and was a pilot site for the UNEP West Africa Drylands project<sup>1</sup>. Five sentinel sites (blocks) were established in Segou Region during 2005–6. Long-term annual rainfall for the five sites ranges from 450–780 mm. The proportion of the area of the blocks under cultivation ranges from 27–73%, reflecting the transition from predominantly cultivated agro-ecosystems in the south of Segou Region to predominantly pastoralist systems in the drier north.

## VEGETATION CONDITION

Average woody cover (trees and shrubs) ranges from less than 4% in blocks with least cover, to

15–40% in the block with most cover, tending to increase with increasing rainfall. However, there is substantial cluster- and plot-level variability, indicating significant potential benefits from targeting of tree planting efforts at this scale. The potential for tree planting is also evident from the overall low average tree density for all blocks, at about six trees per hectare compared with 15 trees per hectare in the block with the highest tree densities. Average shrub densities at the block level ranged from 416–2,900 shrubs per hectare and were lower in cultivated than in semi-natural areas. Shrub biovolume estimates provided by this study can be converted to estimates of above-ground biomass carbon with development of allometric equations. There was good agreement between woody cover ratings from LDSF field surveys and woody cover abundance analyzed from Quickbird imagery.

## SOIL PHYSICAL CONSTRAINTS

Two of the blocks had a high prevalence (up to 24% of the area) of severe root depth restrictions (hard layers within the top 20 cm of soil). One block had 90% prevalence of root depth restriction within the top 50 cm of soil in semi-natural areas and about 16% in cultivated areas. Cultivation or low woody cover on such soils poses a high degradation risk. We developed an indicator of inherent soil degradation risk based on areas having root-depth restrictions within the top 50 cm of soil and having abrupt textural gradients within this layer (e.g. sandy loam over clay). The prevalence of inherent degradation risk was high in three of the blocks, ranging from about 51–71%. Visual symptoms of erosion were also more prevalent in semi-natural areas and areas with high inherent degradation risk than in cultivated areas that were free of physical constraints. Average saturated infiltration capacity was also lower in areas with severe root depth restrictions than those without.

## SOIL FERTILITY CONSTRAINTS

Soil condition in the five blocks was assessed in the laboratory using near infrared spectroscopy. This is a rapid, low-cost method of soil analysis that involves only shining light on a soil sample and collecting the amount of reflected light back off the sample at different wavelengths in the near infrared range (see Part 1). A number of soil chemical and physical properties can then be calibrated to the spectral signatures obtained. The method is ideally suited to this type of assessment, as large number

<sup>1</sup> An Ecosystem Approach to Restoring West African Drylands and Improving Rural Livelihoods through Agroforestry-based Land Management Interventions.

of georeferenced soil samples can be rapidly and cheaply characterized. Only a subset of the samples needs to be analysed by conventional analytical methods to provide calibrations.

The results show that soils in the study area have mean pH-values in the weakly acid range, generally high sand content and low levels of soil organic carbon. About 80% of the individual samples have SOC contents that are critically low, at less than 5 g kg<sup>-1</sup> (0.5%). About 98% of the soils in the data-set are deficient in phosphorus and about 50% are deficient in potassium. Cultivated areas have on average 0.2 g kg<sup>-1</sup> lower absolute SOC contents than semi-natural areas after controlling for the presence of trees and shrubs.

### **SOIL CONDITION INDICATOR**

We developed a soil condition index based on infrared spectral data. Such indices integrate information on various physicochemical properties of the soil and are useful for identifying land degradation hotspots in the landscape and pinpointing priority intervention areas, as well as monitoring change in soil condition over time. We developed a two-class model to distinguish soils with high risk of having “poor” soil condition (i.e. low soil organic carbon, available P and exchangeable bases, and high sand content) from soil with “good” soil condition. On average, 52% of topsoils in the study area are classified as having “poor” soil condition. Two blocks in particular had a high prevalence (>85%) of poor soil condition. The risk of poor soil condition increases with increasing sand content. When variation in sand content was statistically controlled for (i.e. sand is added to the model as a fixed effect), we found an increased likelihood of poor soil condition when sites are cultivated.

### **MAPPING SOIL CONDITION**

We were successful in calibrating the soil condition index to Quickbird satellite imagery and were able to produce fine resolution “risk maps” for individual blocks. These maps confirmed the findings from the ground-based observations that prevalence of poor soil condition is higher in cultivated or managed areas. In one block, for instance, we see a high risk of poor soil condition associated with areas converted to agriculture during the period from 1986–2001. The ability to statistically calibrate such indices to satellite remote-sensing data constitutes a powerful tool for regional level mapping of land degradation hot spots.

### **FERTILIZER RESPONSE TRIALS**

We conducted fertilizer response trials in three blocks to confirm the soil nutrient deficiencies identified by soil analysis. Two farmers were selected for the trials within each of the 16 sampling clusters per block. Millet was grown under farmer conditions with applied fertilizer treatments of moderate dressings of nitrogen, phosphorus and potassium. Growth and yield of the plots was monitored using a simple protocol. Mixed effects statistical modelling was used to analyse the trial data taking into account the nested sampling structure in the blocks. On average across the blocks, the best treatment was application of both nitrogen and phosphorus, which increased grain yield by 60%, but absolute yield increases were small, and organic amelioration will most likely be needed for profitable fertilizer use.

These trials also served to demonstrate how the hierarchical structure of the sentinel sites provides a powerful and efficient framework for conducting intervention trials. The framework ensures that trials are randomly located and thus sample the diversity in the landscape. The hierarchical statistical approach provides powerful inference at different levels of scale and gives information on uncertainty (risk) associated with responses. Furthermore, the trial response data can be related to the biophysical and socioeconomic baseline indicators and test them as response covariates.

### **TARGETING INTERVENTIONS**

The aim of this rule-based approach is to base basic intervention recommendations on readily observable indicators of the state of the land. Soil management recommendations are linked to our assessments of soil condition to identify cultivated areas having a high likelihood of poor soil fertility. Priority intervention areas for reforestation, based on our field survey data, are linked to fine-resolution remote-sensing data so that we can also spatially target interventions. Such maps also provide a good basis for rigorous assessments of intervention impacts in the future, as woody cover density can be relatively accurately assessed from satellite imagery.

In semi-natural areas (i.e. sites that are not currently cultivated or managed), we target locations having sparse woody cover for reforestation interventions. The estimated priority area for reforestation (i.e. semi-natural areas with sparse woody cover) varies from about 1,900 ha–4,200 ha per 10,000 ha block. Clusters with occurrence of both sparse woody



cover and high inherent risk of soil degradation were identified, which should be prioritized for intervention to improve surface cover and prevent severe soil degradation. Some blocks had few such areas, while two of the blocks had 190 ha and 440 ha of land at high risk.

Cultivated or managed areas having a high inherent risk of soil degradation may be targeted for conservation agriculture, agroforestry, reduced tillage or other practices that increase soil cover and improve soil carbon status. Block-level estimates with areas of high priority for conservation agriculture range from 700–2,100 ha (i.e. 7–21% of the block area). A targeted soil fertility programme to provide phosphorus dressings, to overcome this basic limiting constraint to agriculture, is a high priority for food security in the region. Priority for these higher-level investment programmes should be given to currently cultivated areas with no soil physical constraints. These make up about 50% of the currently cultivated area and 31% of the total area, varying from 9–63% of the area of the blocks.

### **SOCIOECONOMIC CONDITIONS AND TREE PLANTING PREFERENCES**

Two households per sampling cluster in each block were selected at random for collection of socioeconomic data. Not all clusters had households, and 84 households representing 1,272 individuals were surveyed. The results portray a picture of extreme vulnerability. Population in Segou Region has more than doubled between 1960 and 2000. Average prevalence of illiteracy in the 15–65 years age group is 80%, with the majority of the literate part of the population having only primary education. As is customary, none of the households has title deeds to their land. The number of tropical livestock units owned per person, averaged at the block level, ranged from 0.5 to 0.9. Two of the blocks had as many as 70% of households dependent on purchasing of food grains, on average for about two months per year. However, access to drinking water is generally good with all households reporting access to wells within their villages.

A contingent valuation survey indicated that nearly all households are interested in planting trees. Alternative scenarios that households would be either paid to plant seedlings or provided with free seedlings did not affect the average number of trees households were willing to plant: on average 195 trees. However, if farmers were to pay

for seedlings, the number they would be prepared to plant dropped by half. This pattern was quite consistent among the blocks. Thus to increase tree planting priority should be given to low-cost seedling production methods and encouraging farmers to raise their own seedlings. The most popular tree species for additional planting are *Mangifera indica*, for its fruits and as an important source of revenue, and *Eucalyptus camaldulensis* for wood production. *Adansonia digitata* and *Parkia biglobosa* are in demand as sources of food, while *Vitellaria paradoxa* is in demand for fruits and oil and *Gliricidia sepium* as a source of fodder. There was no difference in demand for different tree species between incentive structures.

### **PROSPECTS**

The LDSF provides an operational framework for obtaining project-level baselines of land resources and socioeconomic profiles. Within the project context, the baseline provides a basis for assessing current land condition and constraints, and flexible targeting of priority intervention areas and households at the landscape level. The baseline provides a starting point for reliable detection of change in land condition, for assessing the impact of agroforestry-based interventions to restore degraded areas, and for project impact attribution. For example, the question “to what degree have project-initiated reforestation activities increased carbon storage in the landscape?” can be answered. We have also demonstrated how the LDSF provides an efficient platform for systematic testing of interventions in the landscape, providing much more powerful inference and generalisation capabilities than conventional agronomic testing approaches. The overall approach is evidenced-based and permits representation of uncertainties in measurements at different spatial scales. The framework has potential to transform the way in which agronomic and land management testing is done, greatly increasing our ability to make inferences and evidence-based recommendations.

The baseline data can contribute to basic ecological research by providing a rich body of information on coupled biophysical and socioeconomic variables and their variability at different scales. For example, systematic data collection across different ecosystems can assist with validation and refinement of models and provide empirical data for the development of new concepts and theories. In addition, the sentinel site data also provides valuable data for calibration, classification and interpretation

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of satellite images beyond the scale of the sentinel sites and hopefully lead to the development of new, more generalizable remote-sensing algorithms.

The cost for surveying and documenting each sentinel site, including labour and supervision, vehicle running costs, and analyses of remote sensing and laboratory data is estimated at US\$ 25,000 per sentinel site. These costs are modest when one considers the long-term value of the information generated by the sentinel site surveys and the multiple utilities of the sites. This is especially so when one considers the current lack of science-based learning in multi-million dollar

development projects and the scientific and policy effort spent on studies and inconclusive debates on the degree and extent of land degradation.

The most important potential outcome of this work is for scientific assessment data to become closely integrated into national development and policy decision-making processes. This assessment, with modest resources, has characterized land condition in the agro-ecological zone of Segou Region to a high degree of specificity. It is certainly feasible with modest additional resources to establish a national land degradation surveillance system as an integral part of land management policy.

# The Land Degradation Surveillance Framework

## BACKGROUND

The Land Degradation Surveillance Framework (LDSF) is designed for sampling entire landscapes in order to provide project-level baselines of land resources (e.g. soil and vegetation) and socioeconomic profiles (e.g. household indicators), as well as a framework for monitoring and evaluating project interventions and their impacts on land and people. The framework is flexible and may be adapted to projects of varying size (spatial coverage) and with different objectives, such as measuring land cover change, assessing soil carbon sequestration potentials and biodiversity assessments, to mention some examples. The framework is standardized, and therefore the LDSF can be used to compare project baselines and monitoring results over a wide range of ecosystems, something that is currently not possible in most studies and projects due to inconsistencies in measurement procedures. Also, the framework is relatively simple in that exactly the same procedures are followed both in baseline measurements and in monitoring and evaluation.

Sentinel site baselines are designed to be of help in project implementation by quantifying and locating priority areas; for example, areas for reforestation or enrichment planting, or areas with specific biophysical constraints (e.g. soil fertility decline, soil physical degradation, etc). The baselines can also be used to assess whether project interventions are socially and economically acceptable or viable. There are numerous other examples, as priorities will depend on individual project objectives.

In the context of this project, for example, one of the major questions is related to degradation of West African Parklands, including severity and extents of land degradation, and potential agroforestry-based interventions to restore degraded areas. The other important purpose of a baseline is to provide a starting point for reliable change detection and project impact attribution. For example, the question to what degree have project-initiated reforestation activities increased carbon storage in the landscape, can only be answered reliably by measuring carbon stocks on at least two occasions, and on both non-intervention and intervention project sites. An assessment of the spatial variability of existing carbon stocks is essential in this regard, as this will determine to what degree of precision subsequent changes can be detected and attributed to project activities over time. Again, similar issues will arise in the context of other project objectives

that require monitoring and impact attribution. Thirdly, the baselines should synthesize a quantitative description of the baseline 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.

### FIELD SAMPLING PROCEDURES

The LDSF is built around the use of sentinel sites or blocks, 10 x 10 km in size. The basic sampling unit used in the LDSF is called a cluster. A cluster consists of 10 plots (Part 1, Figure 2.2). The centre-point of each cluster in LDSF is randomly placed within a tile in each sentinel site and sampling plots are randomized around each cluster centre-point, resulting in a spatially stratified, randomized sampling design. Both the number of plots per cluster and the cluster size may be adjusted depending on the specific purpose of the survey being conducted. For example, 1 km<sup>2</sup> clusters are useful for large-area reconnaissance surveys; whereas, 10 ha clusters may be more appropriate

for more detailed project-level surveys. There is in other words a high degree of flexibility as long as randomization is maintained and samples are collected using a nested design (i.e. plot within cluster within block). The randomization procedures are done using customized programs or scripts, but may also be done in any common spreadsheet program.

On each plot, detailed observations and measurements describing land and vegetation cover and soil condition are recorded, following the guidelines provided in the guide to field sampling and measurement procedures (Appendix 3.1). Vegetation cover and abundance, and soil characteristics are measured on four (100 m<sup>2</sup>) subplots per plot (Figure 10.1). Soil samples are pooled by depth increment such that each plot generally contains one composite topsoil (0–20 cm) and one composite subsoil (20–50 cm) sample. These are standardized depth increments maintained in all LDSF studies, but additional samples may be collected at varying depths for special studies.

### LAND RESOURCE INDICATORS

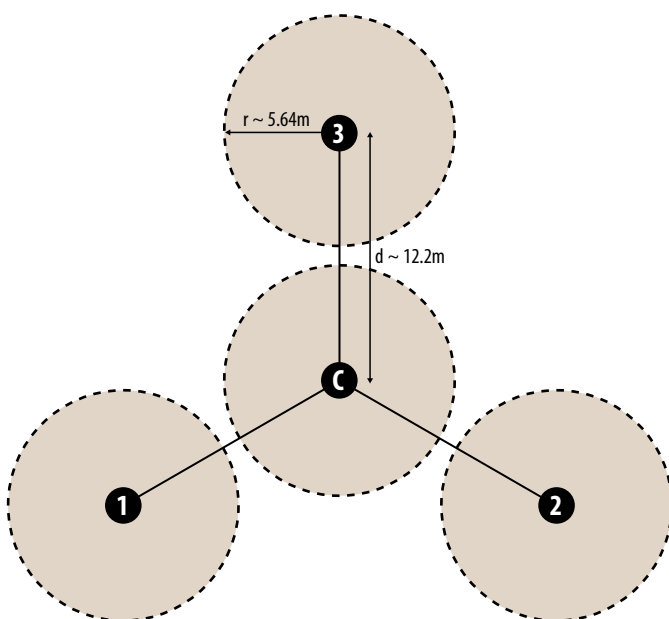
The central role of land resource indicators is to measure changes in the condition or state of the land, and in particular to monitor land degradation, or conversely, land improvement or reclamation. Additionally, combinations of land resource indicators may be used to target specific project activities and interventions on the ground.

Included in the current assessment are measurements of land cover, woody vegetation cover and abundance (plant density and biovolume), perennial grass cover, vegetation life form diversity, physiography, soil texture, the prevalence of soil depth restrictions, soil infiltration capacity, visual signs of erosion, and soil spectral characteristics based on near-infrared diffuse reflectance spectroscopy (NIR).

For some of these indicators (e.g. woody vegetation cover and soil spectral characteristics), it is usually possible to link ground surveys to remote-sensing data, and correspondingly block-level maps of these indicators are provided. Again, specific indicators actually used and reported may vary between studies or projects, depending on their individual objectives. However, the underlying database is the same for all studies making meta-analysis possible across projects, studies and regions.

**FIGURE 10.1**

Illustration of Land Degradation Surveillance Framework (LDSF) sampling plot layout. Sub-plots (dotted circles) have a radius of 5.64 m (area 100 m<sup>2</sup>), and the distance along the radial arms between subplot centres is 12.2 m. The whole plot has a radius of 17.84 m (area 1000 m<sup>2</sup>).



## HOUSEHOLD INDICATORS

The main role of household indicators is to measure changes in the composition and socioeconomic status of the human population in the block or sentinel site. The information collected includes household details (number of people, female-headed, widow-headed, etc), availability of land and land tenure, agricultural practices, off-farm income, livestock, availability of water and so forth. Additionally, combinations of indicators may be used to identify particularly vulnerable segments of the population that should receive special attention from the project. For example, households with a large proportion of children and seniors might constitute such a group. Included in the current assessment are number of months of food deficits and annual household expenditure profiles (i.e., farm improvement, veterinary care, food purchases, water, home improvement, education and other expenditures). Finally, household demand for trees using a simple contingent valuation procedure is assessed.

## ANALYTICAL METHODS

### Land resource surveys

Multiple levels of variance often occur in ecological data, and the LDSF sampling protocol is specifically designed with this in mind. Linear and non-linear mixed-effects models are able to handle a wide range of complications in regression-type analyses and can be used to account for within-subject or within-group correlation. The key is that the random part of the model, or what is often referred to as the error, is allowed to have structure. In the analyses presented here the structure arises from the spatially nested design in which subplots are nested within plots, plots are nested within clusters, and clusters are nested within blocks. Each level represents a different spatial scale at which a given land resource indicator may be observed (or measured).

The levels (of scale) do not represent fixed, repeatable factors like an experimental treatment; they are a sample drawn from a larger population of similar levels. Ideally, we would like to generalize our limited observations and measurements to, for example, the population of clusters in the block, and

ultimately to the population of blocks in the project area. Models are needed to achieve this because of the random variability that occurs at each level, and correlation of observations within the same groups, as well as spatial correlation structures. A common and convenient way of handling nested or hierarchical data is the use of random effects, which as their name implies are random and it therefore does not make sense to estimate them. We therefore try to explain or estimate parameters that describe the distribution of random effects. The unknown constant that we try to estimate from the data is referred to as the fixed effect, hence the term mixed-effects models for the statistical methods we apply in the LDSF.

### Household surveys

Unlike in the land resource surveys, households are usually not selected randomly prior to conducting the survey. Instead, the survey team selects a central survey location on a given day, and then randomly selects 5–10 households in proximity to that point. In the future this procedure may be improved, by selecting a sample of households from Quickbird or other high-resolution satellite images. The advantage of this would be that households could be sampled in proportion to their occurrence in the landscape, and that the total number of households and their locations could be established to a high level of accuracy within the block. For the time being the main dwelling of the household was georeferenced by averaging GPS position estimates for several minutes.

### Selection of priority intervention areas

Selection of priority intervention sites should be based on a readily observable description of the state of the land. For example, sites which are currently not cultivated, and that have sparse woody vegetation cover and high inherent soil degradation risk, should be targeted for reforestation interventions. Alternatively, cultivated sites with high soil degradation risk might be targeted for soil conservation, agroforestry or other practices that minimize tillage and increase soil cover during the onset of the rainy season.

# Case study background

## **BACKGROUND**

In this case study, the Land Degradation Surveillance Framework (LSDF) was implemented in Segou Region, Mali. This region was selected as it represents a Parkland area where land degradation is perceived to be a serious problem and was a pilot site for this project. Five sentinel sites (blocks) were established in the region.

Mali is a continental country, covering an area of 1,241,138 km<sup>2</sup> and lying between 10° N and 25° N, and 4° E and 12° E (Figure 11.1). The total population was estimated at almost 12,000,000 in July 2007, with a growth rate of almost 2.7%, and is composed of 5 main ethnic groups, the Mande (Bambara, Malinke, Soninke) being the dominant group with about 50% of the population (CIA 2007). Mali has 8 administrative regions: Gao, Kayes, Kidal, Koulikoro, Mopti, Segou, Sikasso, and Timbouctou. Approximately 16% of the country is arable land. The Segou Region covers an area of about 56,623 km<sup>2</sup>, and has an estimated population of almost 1.9 million.

The sentinel sites were established in early 2006 following training of national partners (IER) and field teams in October 2005. The sites form a set of pilot sites for the project in the region, and were located near the villages of Konobougou, Zebougou, Sokoura, Monimpebougou and Dianvola. Site selection was conducted in collaboration with national partners to coincide with agroforestry intervention areas. The only exception was the selection of Dianvola block, which was based on a time-series of satellite imagery between 1984 and 2001 and subsequent detection of major land use conversions in the area.

## **POPULATION DENSITY**

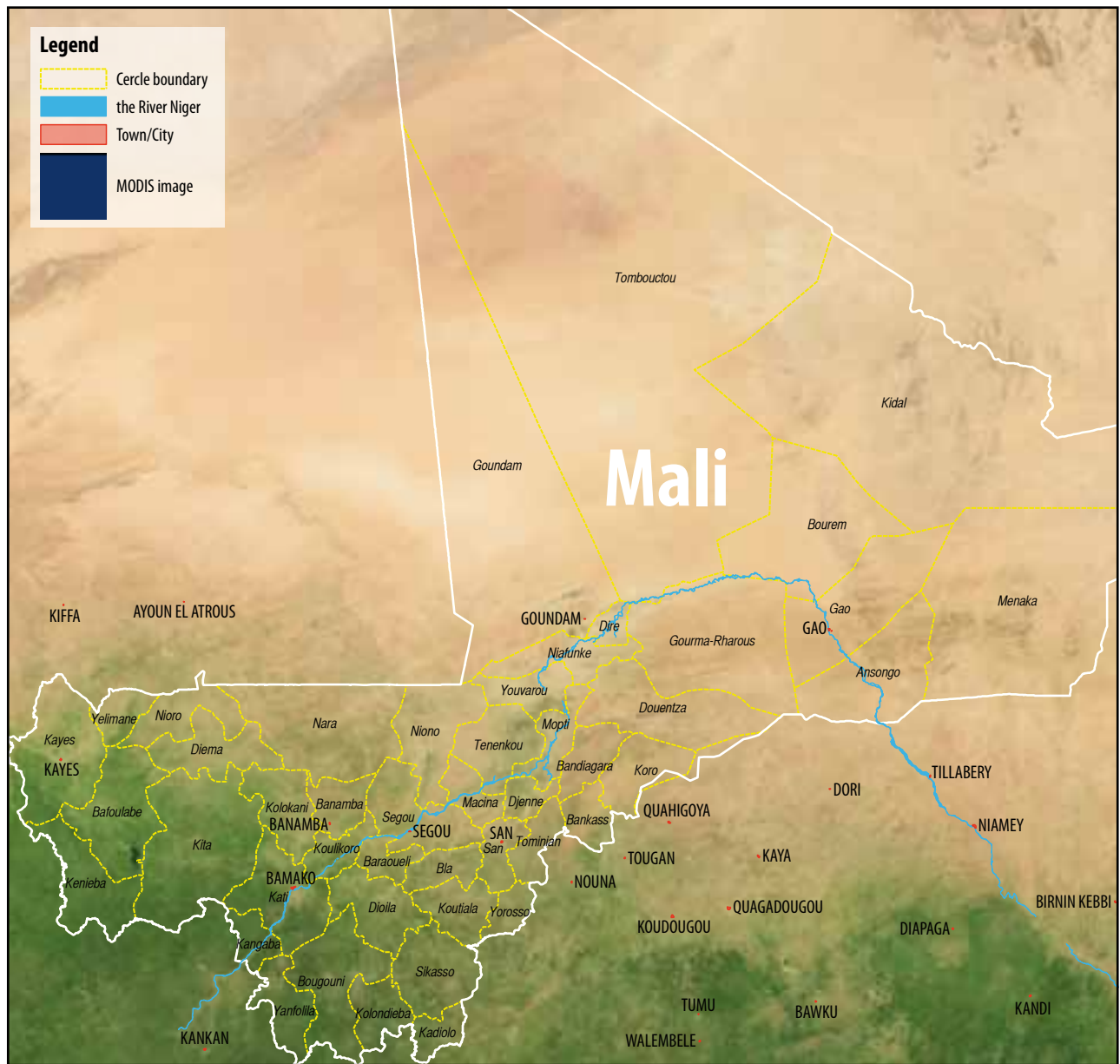
Mali in general and the Segou Region in particular has seen significant population increases during the past four to five decades (Figure 11.2). In 1960, none of the Segou Region had population densities exceeding 100 persons per km<sup>2</sup>, while significant parts had high population densities in 2000. Population in the study area is highest east of the Niger, and around the towns of Segou and San, with all sites having more than a doubling in population density between 1960 and 2000.

## **CLIMATE AND TOPOGRAPHY**

Climate zones in the Sahel run more or less parallel to the equator (Figure 11.3), with rainfall increasing southwards from the Sahara. The Segou Region falls

**FIGURE 11.1**

Map of Mali showing regions.



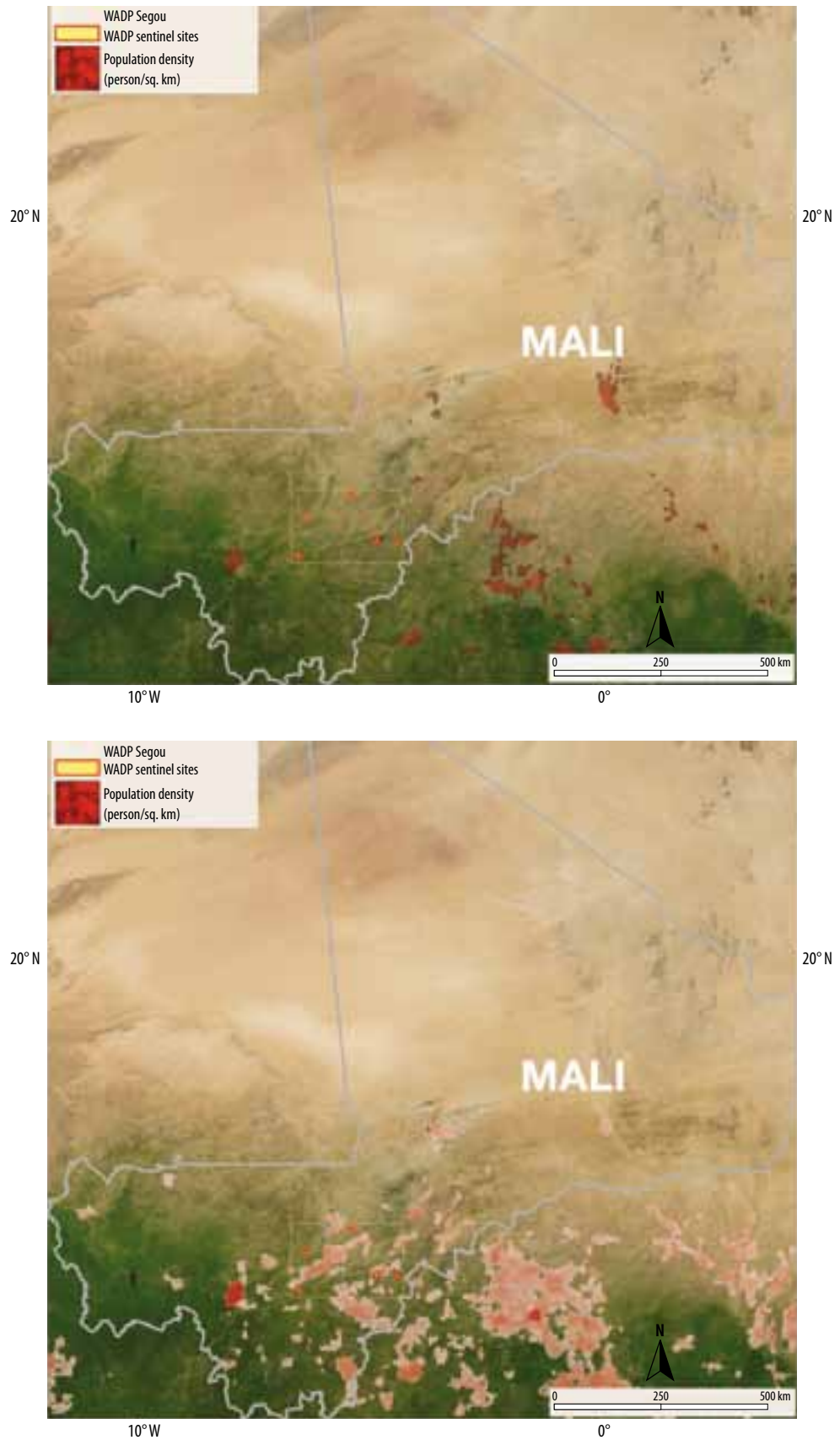
within a precipitation range of about 450–900 mm (Figure 11.4), with mean annual rainfall of 850 mm (average for region between 1950 and 2000), with one rainy season, normally starting in May and ending in October (Figure 11.4). The highest rainfall amounts normally occur in August with 203 mm on average, and the highest recorded monthly rainfall exceeding 400 mm in 1961 and 1962. As is evident from Figure 11.4, rainfall is extremely variable, particularly in April, May, September, and October. Extended dry periods occurred in 1972 and from 1982–1985 (Figure 11.5). The 1950s and 1960s were generally wetter than the 1970s and 1980s, and

there appears to be an upward trend in rainfall following the 1984 drought (see Part 2).

The five blocks included in the study span a range of isohyets in Figure 11.3, with Konobougou having the highest rainfall on average (783 mm yr<sup>-1</sup>) and Monimpebougou the lowest (450 mm yr<sup>-1</sup>) (Table 11.1 and Figure 11.5). Konobougou, Sokoura and Zebougou have the largest variability in rainfall. The topography of the Segou Region is generally flat, with a median altitude of 292 m (range; 262–500 m).

**FIGURE 11.2**

Areas with  $>100$  persons  $\text{km}^{-1}$  in 1960 (upper) and 2000 (lower).





**FIGURE 11.3**

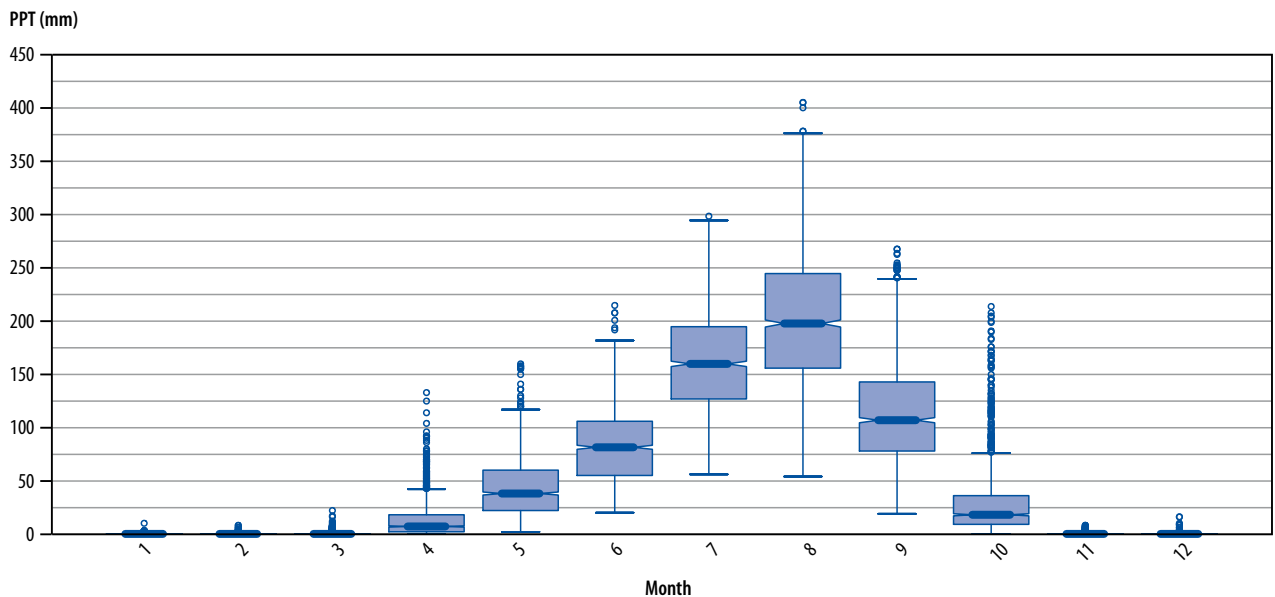
Rainfall isohyets (average between 1951 and 2000) for Mali, showing locations of sentinel sites in the Segou Region (based on VasClimo data; Beck et al, 2005).



**FIGURE 11.4**

Distribution of 50-year (1951–2000) monthly rainfall estimates (PPT) for the Segou Region (based on VasClimo data; Beck et al, 2005). Notches are 95% CI of the median monthly rainfall.

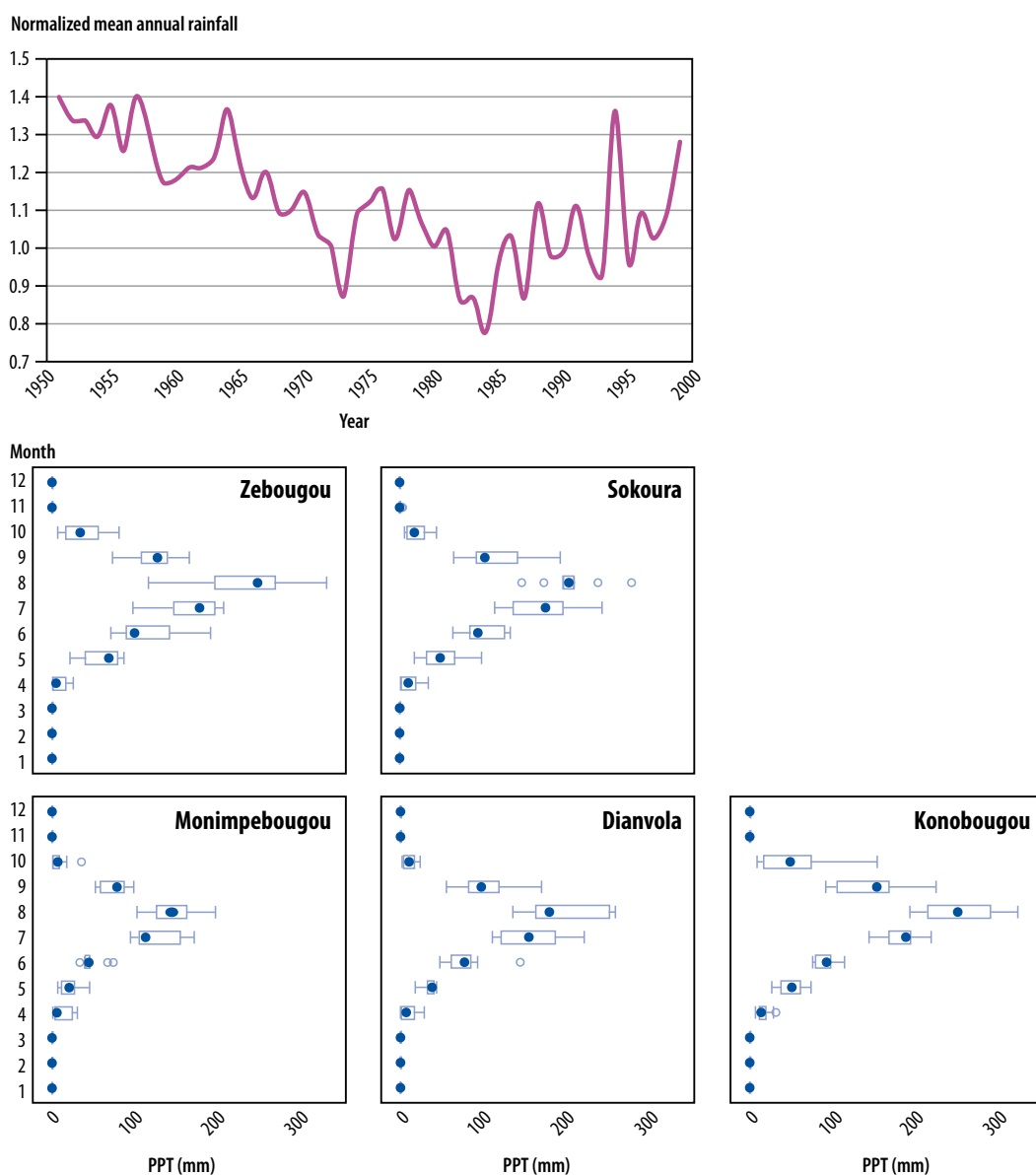
Boxes are the upper and lower quartiles. Points indicate extreme rainfall events.



**FIGURE 11.5**

Upper: Mean annual rainfall in the Segou Region, normalized based on the average for the period 1951–1991. Lower: Distribution of 50-year (1951–2000)

monthly rainfall estimates for individual blocks. Notches are 95% CI of the median monthly rainfall. Month of year is on the y-axis.



**TABLE 11.1**

Summary of mean annual rainfall estimates by Sentinel Site.

Block	Mean	SD	Min	Max
	mm			
Dianvola	610	92	427	805
Konobougou	783	104	560	999
Monimpebougou	450	69	304	588
Sokoura	724	105	471	910
Zebougou	758	108	503	954

# Vegetation health

## LAND USE AND VEGETATION COVER

Forest species richness and tree density have been reported to have declined in West Africa during the second half of the 20th century. Gonzalez (2001) reported decreases in forest species richness in NW Senegal by 33% between 1945 and 1993, and falls in tree densities of 23% from 1954–1989. Studies conducted in the 1980s (e.g. Ringrose and Matheson, 1992) showed decreases in rangelands and increases in millet and sorghum cultivation accompanied by increases in windblown sand. However, several recent studies using data from the NOAA AVHRR remote-sensing system suggest a consistent “greening trend” over large parts of the Sahel during the past 20–25 years, partly attributed to increases in rainfall over the region (Olsson et al, 2005; see Part 2).

Other studies have found evidence of sudden climatic and ecological regime shifts in the Sahara and Sahel – including sudden transitions from vegetated to desert conditions approximately 5,500 years ago (Foley et al, 2003), and the onset of major droughts towards the end of the 1960s, culminating in the 1984 drought in the Sahel (Figure 12.1). These rainfall trends are evident in Figure 11.5, and recent trends (greening) in the Sahel may simply reflect a recovery of vegetation cover after these droughts (see Part 2). Taken in a longer perspective current conditions in the Sahel are well below the wetter conditions that characterized the region between the 1930s and mid-1960s, suggesting only a partial recovery in vegetation cover (Anyamba and Tucker, 2005; see also Part 2). There are therefore many unresolved questions concerning current trends in vegetation cover in the Sahel, particularly with regard to human influence versus natural change (i.e. due to climate variability).

Land use and land cover in the sentinel sites was assessed using a combination of historical data where available, field survey observations and measurements, and moderate to high resolution satellite imagery. We applied a range of remote-sensing techniques from hard-classifiers (e.g. Maximum Likelihood classification) to soft classifiers (e.g. spectral angle mapping, linear unmixing and matched filtering techniques) to analyze vegetation cover, woody cover densities and soil background from satellite data. Broadly, we are interested in estimating and locating:

- Area under cultivation or management.
- Area under natural or semi-natural vegetation.

- Woody vegetation cover (trees and shrubs).
- Bare soil background and hard-set areas.
- Areas under cultivation or management.

Regional level change in vegetation cover was assessed using rainfall-normalized NDVI (RNNDVI) estimates based on a NOAA NDVI time-series from 1982–2004 (Figure 12.2). The time-series plots of NDVI in Figure 12.2 also show the 1984 drought, as well as relative differences in overall vegetation response between blocks. The use of RNNDVI rather than NDVI removes the effects of variations in rainfall from our data and thus provides a proxy for screening large areas for potential land degradation or other change. The RNNDVI was calculated as the ratio of NPP over rainfall, and was based on rainfall station data for the period 1900–1996, and a combination of rainfall station data and satellite image derived Cold Cloud Durations for the period 1996–2004 (see Part 2). Trends in annual RNNDVI for our pilot study area are shown in Figure 12.3.

Table 12.1 summarizes the area estimates of cultivated or managed land in the 5 blocks, based on

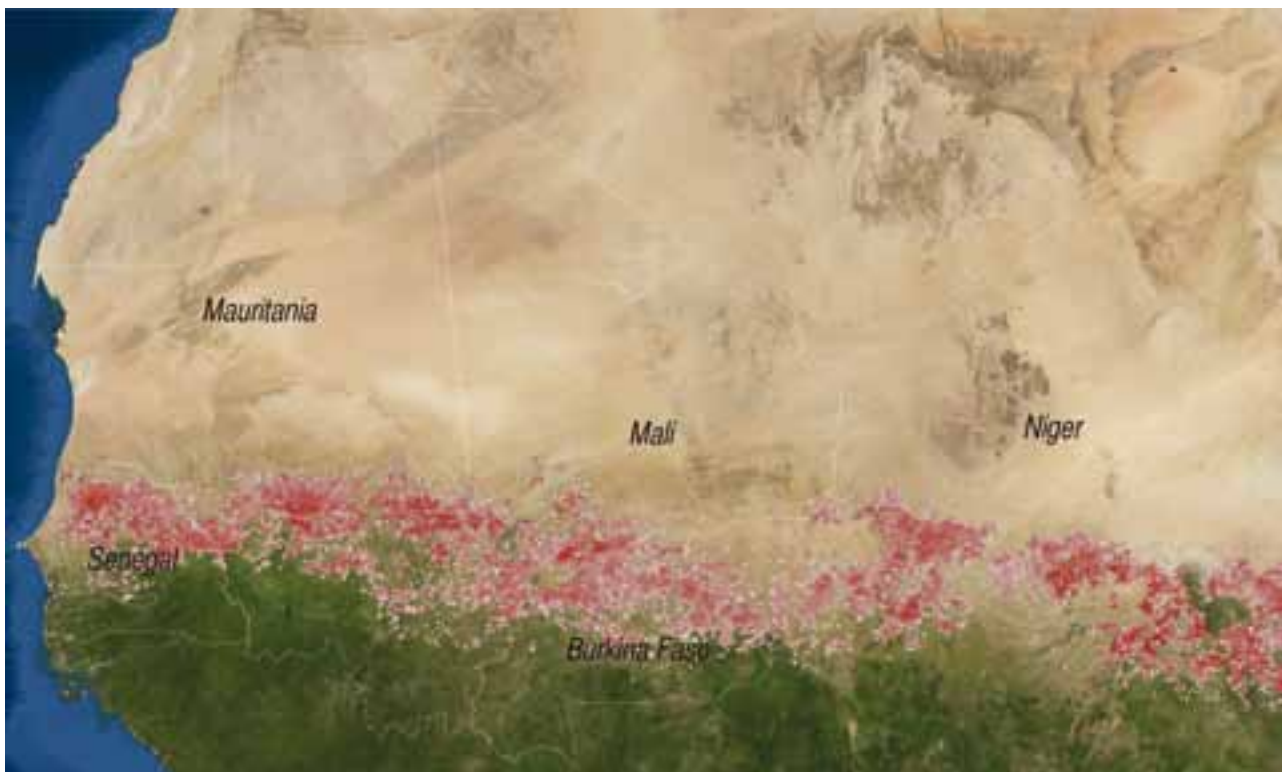
field survey observations (i.e. cultivated or managed versus semi-natural). Observations on land use are conducted at plot level, and we therefore have random effects for block, and cluster within block, levels in this model. Probabilities are converted into percentage cover for each 10 ha cluster in the blocks. Monimpebougou has an estimated total (based on cluster averages) of 7,300 ha (73%) under cultivation or management, and conversely 2,700 ha under semi-natural vegetation cover (Table 12.1), while Konobougou has the lowest estimated area under cultivation or management with 2,700 ha on average.

### VEGETATION COVER AND STRUCTURE

Vegetation structure has a major influence on carbon assimilation, storage and transport in ecosystems, and therefore also on cycling of water and other nutrients. At the landscape scale (which is the focus in the LDSF), vegetation density, height and architecture modify the availability of light and moisture, and stand structure is of fundamental importance for wildlife biology and numerous other disciplines. A range of techniques has been developed for field-based assessments of canopy

**FIGURE 12.1**

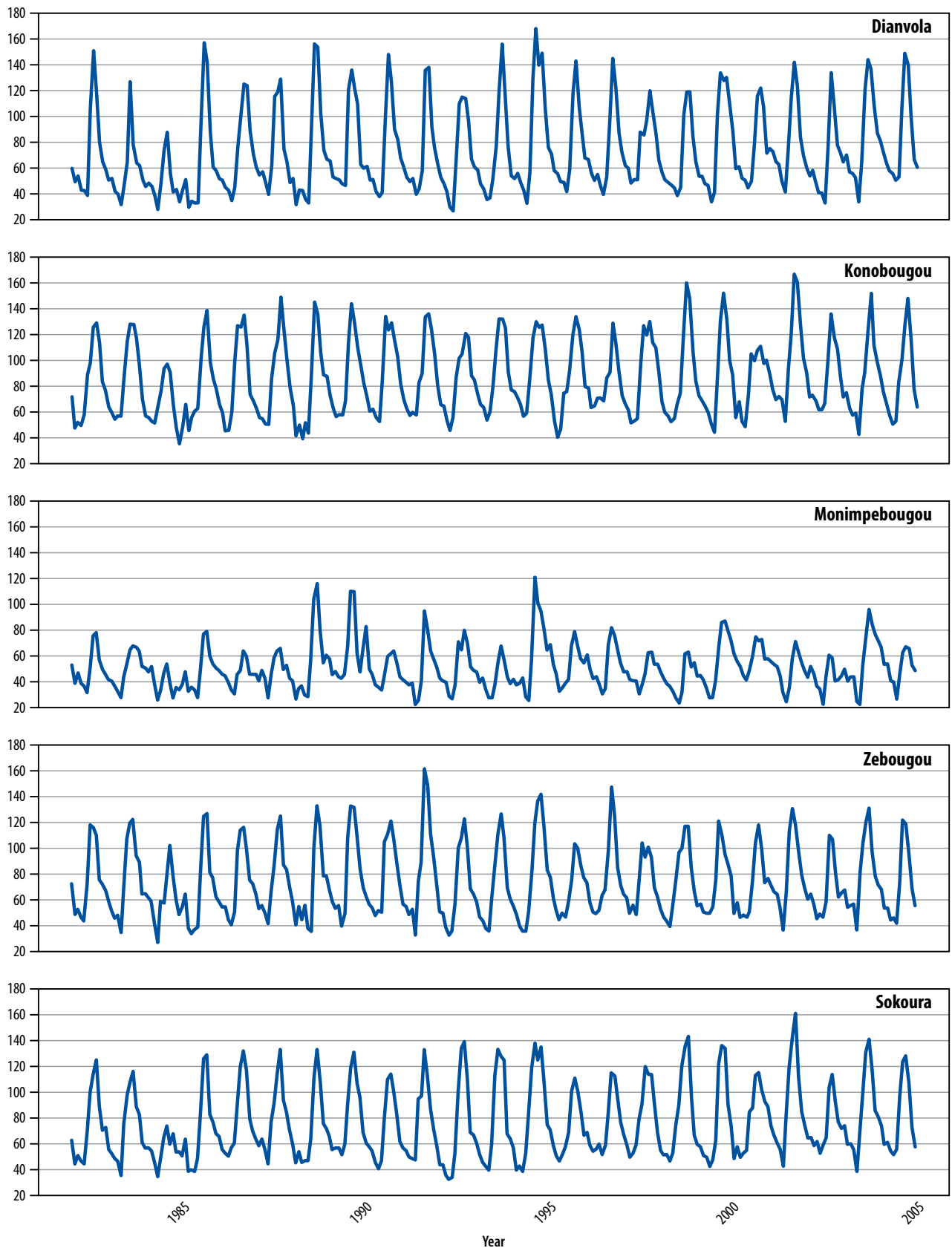
Areas having less than 75% NDVI in 1984 (annual integral), relative to median annually integrated NDVI for the period 1982–2004.



**FIGURE 12.2**

Vegetation dynamics for the five blocks, showing monthly maximum normalized difference vegetation index (NDVI) values for the period January 1982–December 2004.

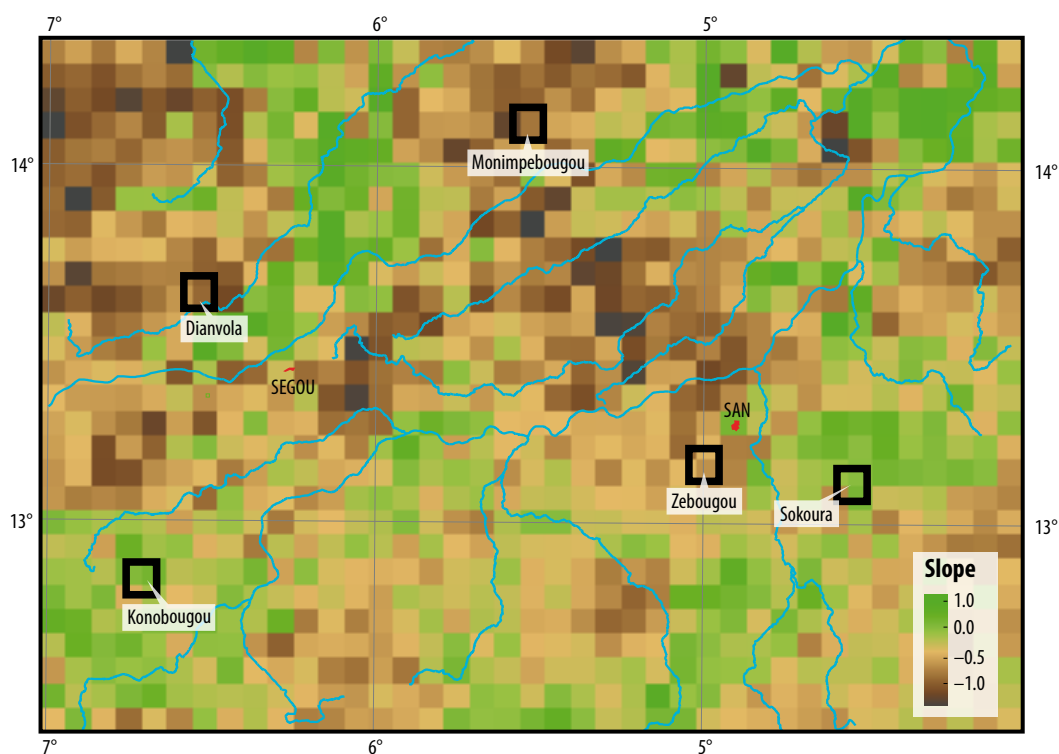
NDVI timeseries (monthly maximum)



**FIGURE 12.3**

Trend surface for annual rainfall-normalized NDVI (RNNDVI) between 1982 and 2004, showing sentinel

site boundaries and flowpaths. Brown indicates areas that are "browning" (i.e. may be degrading).



**TABLE 12.1.**

Estimated area under cultivation or management in each cluster for each of the five blocks (names are abbreviated).

Cluster	Dian	Kono	Moni	Soko	Zebo
	% area				
1	60	5	77	59	14
2	34	77	87	39	6
3	6	6	95	30	7
4	6	86	61	13	76
5	6	40	57	39	71
6	83	40	95	30	7
7	15	5	79	5	76
8	44	88	86	57	24
9	58	5	70	33	92
10	24	5	25	66	81
11	40	22	77	6	48
12	40	14	87	7	83
13	92	13	28	21	31
14	31	6	70	61	40
15	67	7	79	39	49
16	49	5	95	14	6
Average <sup>1</sup>	41	27	73	32	44

<sup>1</sup> Estimated block average

architecture and stand structures, and numerous remote sensing methods are also available (aerial and satellite based). In the LDSF we use a combination of satellite sensors, but for the block baselines we principally use Landsat (MSS, TM and ETM), ASTER and Quickbird imagery.

Shrubs and trees are counted within each sub-plot (0.01 ha) in LDSF blocks, and distance based estimates of woody cover distribution are made using the T-square method (Figure 12.4). For trees, their height and Diameter at Breast Height (DBH) are measured (Figure 12.5), while height, width and length of shrubs is measured. Woody cover densities and distributions are therefore modelled statistically using 4 levels of nesting; sub-plot within plot within cluster within block.

Woody cover is also analyzed from Quickbird (plot-level), and Landsat and ASTER (cluster-, block- and regional-level) imagery, resulting in a combination of field survey data and remotely-sensed data at varying scale. This information is then used in conjunction with analyses of, for example, soil physical degradation, visible erosion, land use, and soil condition to assess where in the landscape problems occur or conversely where in the landscape interventions are needed.

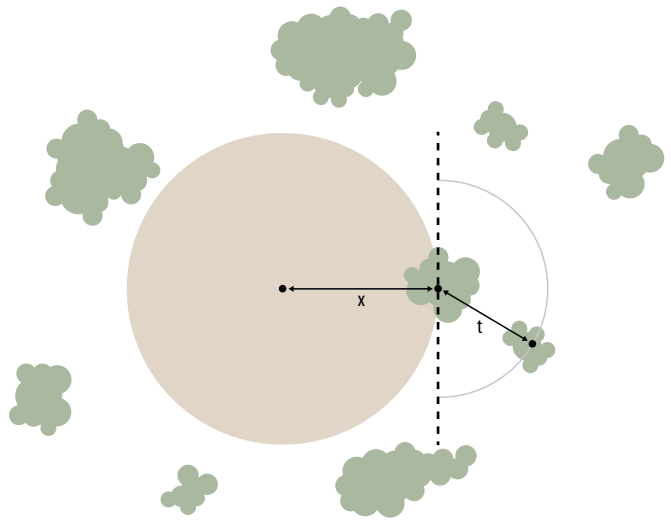
## WOODY COVER

Woody cover types in the five blocks are predominantly *Adansonia digitata*, *Guiera senegalensis*, *Acacia spp.*, *Pterocarpus lucens*, *Combretum spp.*, *Prosopis africana*, *Sclerocarea birrea*, and *Piliostigma reticulatum*. Dianvola is characterized by a natural vegetation pattern of banded thickets (Tiger Bush; Figure 12.6), with *Combretum micranthomas* the dominant species in the thickets. We report shrubs (<3 m height) and trees (>3 m height) separately (Table 12.2 and Table 12.3) and together as woody cover (Table 12.4), and assess block and cluster level variability. The results presented here are averages at cluster and block levels (random effects).

Average woody-cover (trees and shrubs) ratings are highest in Konobougou (15–40%) and lowest in Monimpebougou (<4%), with the other blocks having ratings between 4 and 15%. Tree density is relatively low when we look at the average for all blocks, with about 5.8 trees ha<sup>-1</sup>. The highest tree densities are found in Zebougou (Table 12.2), with just over 11 trees ha<sup>-1</sup> on average, or a

**FIGURE 12.4**

The T-square sampling procedure.  $x$  is the point-to-nearest-plant distance,  $t$  is the plant-to-nearest-plant distance constrained to lie in the hemisphere of the dashed line perpendicular to  $x$  (after Krebs, 1989).



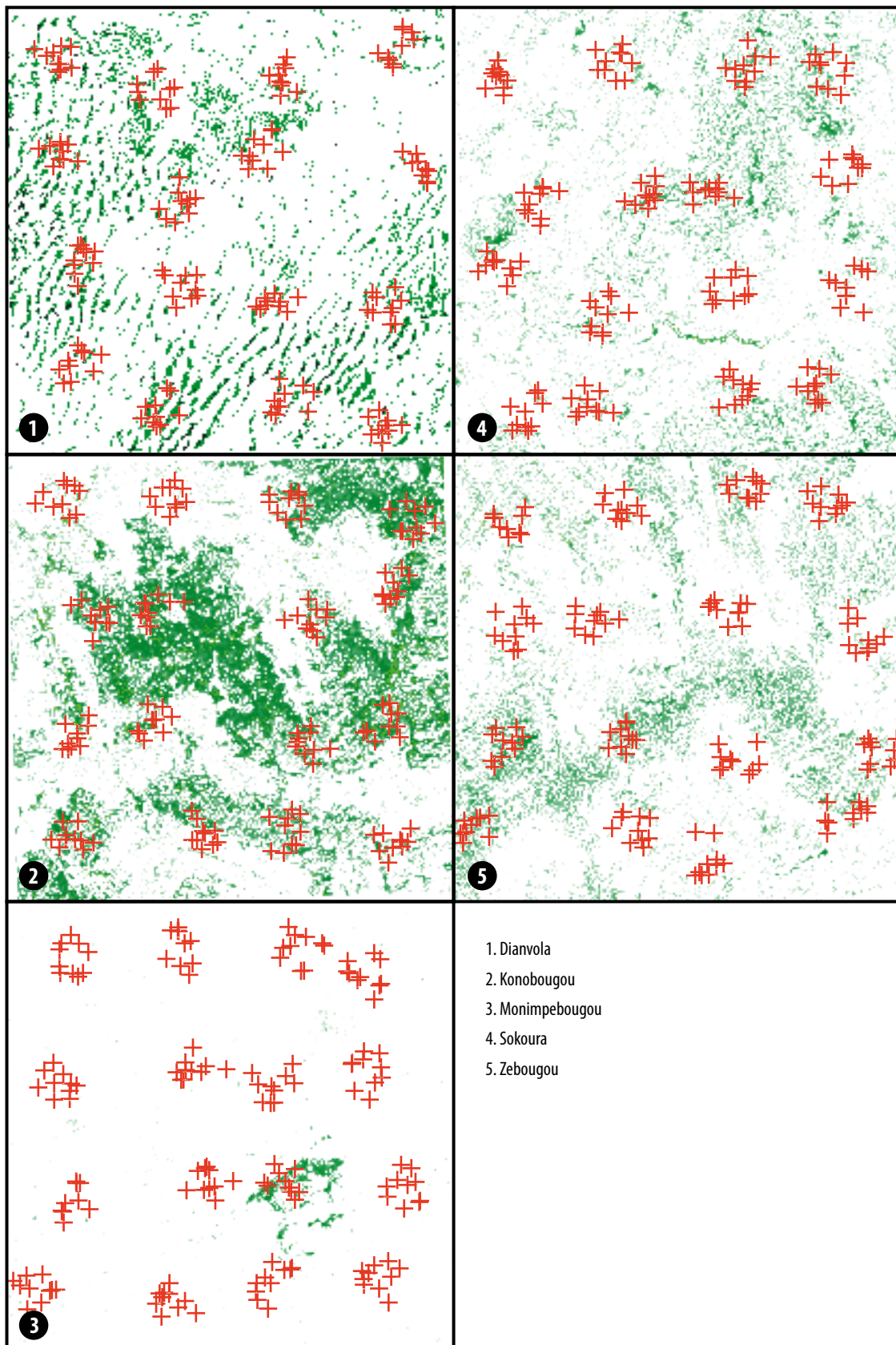
**FIGURE 12.5**

Measurement of tree height, DBH and density in Zebougou using the T-square method.



**FIGURE 12.6**

Spatial distribution of woody vegetation (green) in the five blocks. Images are based on tree and shrub spectral endmembers from Quickbird reflectance.





total of about 110,000 trees. There is, however, significant cluster level variability, as is evident from the cluster-level estimates in Table 12.2 and the GLMM variance components (not presented here). Monimpebougou has the lowest number of trees of the five blocks, with about 15,000 trees in the entire block. Tree densities are similar in cultivated and semi-natural areas ( $p=0.52$ ). There is an increase in shrub and tree densities with increasing mean annual precipitation (MAP), explaining some of the differences observed in Table 12.2 and Table 12.3 between blocks.

Shrub densities are highest in Konobougou with an average of about 2,200 shrubs  $ha^{-1}$  (Table 12.3), and lowest in Monimpebougou with 398 shrubs  $ha^{-1}$  on average. Shrub densities are lower in cultivated areas ( $p=0$ ) than in semi-natural areas, as may be expected (Figure 12.7). In fact, when introducing cultivation as an independent variable in our model, the effect of mean annual precipitation falls out. In Konobougou, the highest shrub densities are found in hard-set areas on laterite outcrops.

Shrub biovolume estimates (biovolume x shrub density) can be converted to estimates of above-ground biomass carbon (C) if and when suitable allometric equations become available. Some authors have applied conversion values, but these estimates remain very uncertain. In Figure 12.8, cluster-level estimates of shrub biovolume are presented, illustrating the level of variability in some of the blocks. Konobougou has an average shrub biovolume of 707  $m^3 ha^{-1}$  with high variance, while Monimpebougou has about 24  $m^3 ha^{-1}$  and very little variance. In Dianvola, shrubs occur mainly in "tiger-bush" vegetation stripes (see Figure 12.6).

Block-level estimates of area under dense woody vegetation (trees and shrubs) based on woody cover (WC) scores  $>3$  (i.e.  $\geq 40\%$  WC) are shown in Table 12.4. Most of the blocks have sparse woody vegetation cover, except Konobougou, where there are quite significant areas with dense woody cover (mainly shrubs) (Table 12.4). Monimpebougou has particularly sparse woody cover, based on the ground surveys, with about 411 ha (~4%) dense woody cover. These differences are also clearly visible in the woody cover map shown in Figure 12.6, and there is generally a good correspondence between estimates from Quickbird imagery (see next section) and the statistically derived estimates from the field surveys.

**TABLE 12.2**

Estimated tree density in each cluster for the five blocks.

Cluster	Dian	Kono	Moni	Soko	Zebo
	Trees $ha^{-1}$				
1	2	3	1	3	31
2	2	2	1	6	25
3	4	2	1	2	5
4	18	10	1	2	12
5	2	3	2	3	16
6	3	10	2	2	10
7	5	8	1	4	20
8	4	2	2	4	3
9	3	6	2	2	10
10	2	5	1	7	13
11	3	5	2	2	3
12	2	8	2	13	31
13	2	2	1	2	10
14	2	14	1	4	8
15	2	2	3	3	16
16	3	6	1	7	6
Average <sup>1</sup>	3.3 <sub>2,7</sub> <sup>4,0</sup>	5.7 <sub>5,1</sub> <sup>6,2</sup>	1.5 <sub>1,4</sub> <sup>1,5</sup>	4.2 <sub>3,7</sub> <sup>4,7</sup>	13.8 <sub>12,4</sub> <sup>15,2</sup>
<b>Estimated total number of trees</b>					
	33,400	56,600	14,700	42,000	138,000

<sup>1</sup> Estimated block averages with 25% (lower) and 75% (upper) Markov chain Monte Carlo simulated quantiles

**TABLE 12.3**

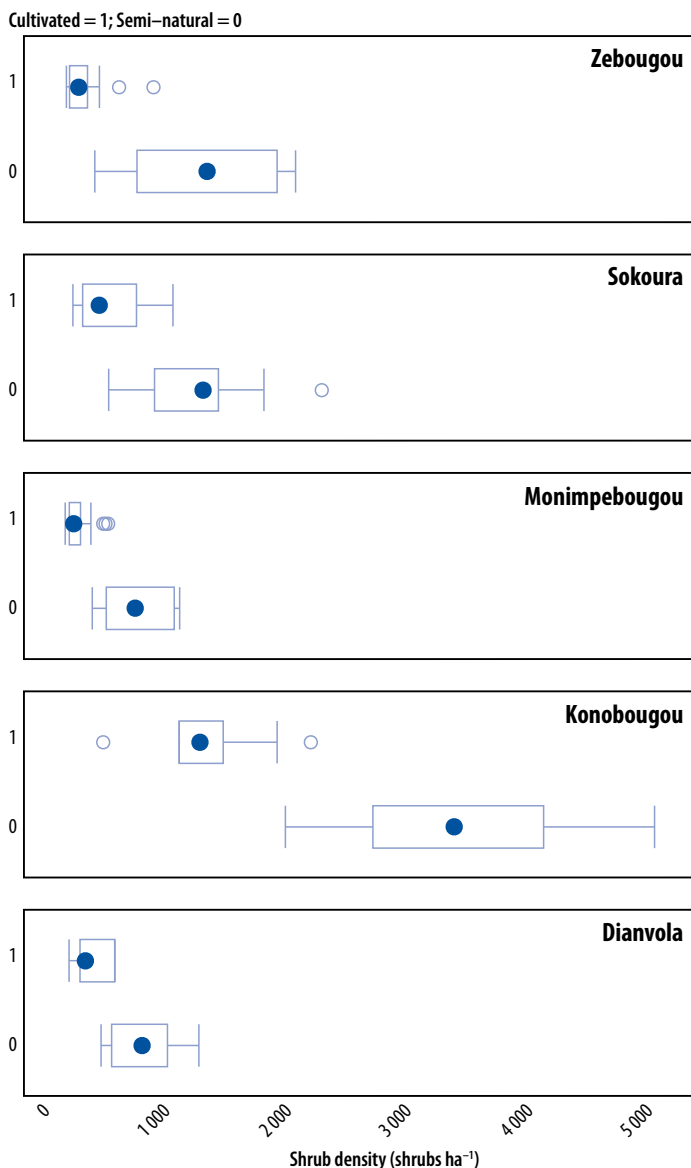
Estimated shrub density in each cluster for the five blocks.

Cluster	Dian	Kono	Moni	Soko	Zebo
	Shrubs $ha^{-1}$				
1	700	1,920	655	197	2,098
2	709	1,314	224	1,508	2,170
3	841	4,208	194	482	751
4	1,405	1,042	576	648	329
5	426	2,354	954	1,309	324
6	814	3,461	153	825	2,345
7	1,093	5,179	194	1,381	93
8	463	188	99	232	274
9	501	2,032	449	1,664	351
10	310	2,459	1,181	447	15
11	548	2,766	119	1,373	277
12	260	3,975	263	1,189	193
13	742	2,789	395	2,277	895
14	934	2,537	631	589	1,197
15	317	3,201	340	1,049	274
16	458	4,740	231	1,456	1,903
Average <sup>1</sup>	658 <sub>610</sub> <sup>710</sup>	2,760 <sub>2,560</sub> <sup>2,960</sup>	416 <sub>370</sub> <sup>460</sup>	1,035 <sub>950</sub> <sup>11,120</sup>	850 <sub>72</sub> <sup>0970</sup>

<sup>1</sup> Estimated block averages with 25% (lower) and 75% (upper) Markov chain Monte Carlo simulated quantiles.

**FIGURE 12.7**

Estimates of shrub density (shrubs ha<sup>-1</sup>) in cultivated (1) and semi-natural (0) areas based on estimates for each cluster.



### REMOTE SENSING OF WOODY COVER

Land cover can also be assessed from satellite imagery (e.g. Quickbird and/or Landsat or ASTER) since woody cover and various background materials generally have distinct reflectance signatures. There are several methods available for analyzing woody cover, usually broadly classified into hard and soft classifiers.

Hard classifiers include supervised and unsupervised classification techniques, including Maximum Likelihood (ML), Mahalanobis Distance (MD), and Nearest Neighbour analysis, to mention some. The output of a classification is usually a class image and

**TABLE 12.4**

Block-level average estimated area under dense woody cover.

Block	Area (ha)
Dianvola	841
Konobougou	1,931
Monimpebougou	411
Sokoura	817
Zebougou	982

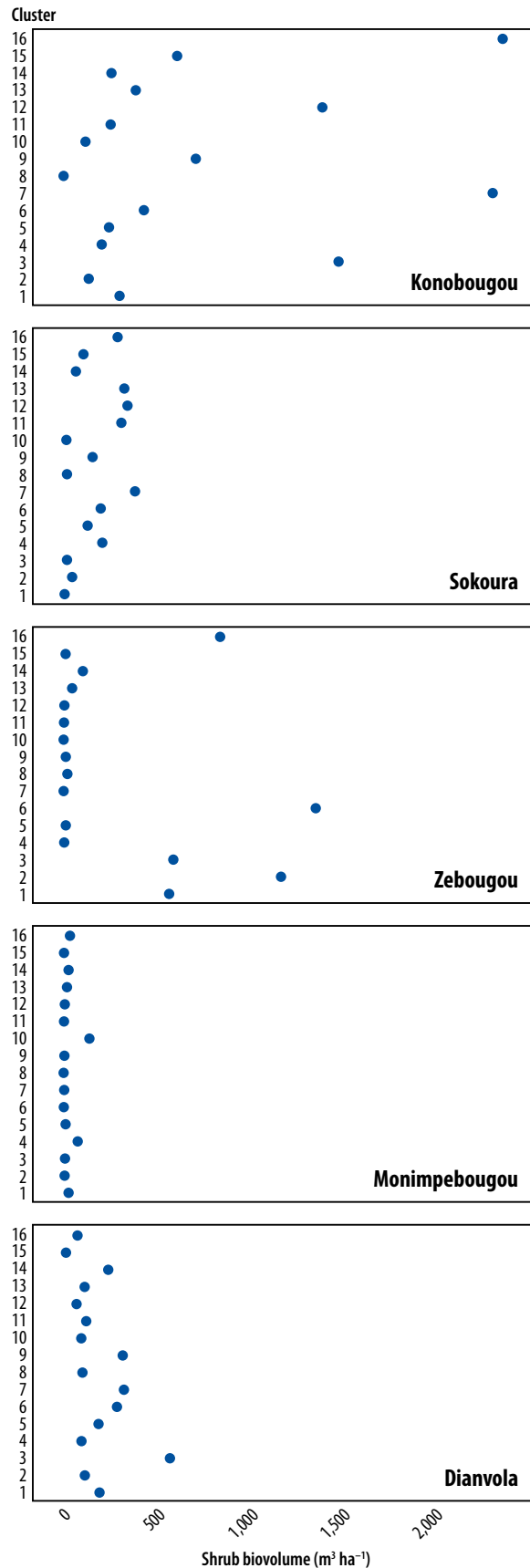
an image showing probabilities or distances of/from belonging to specific land cover classes, as well as an error image (residuals) in some cases. Soft classifiers are often also referred to as hyperspectral image analysis techniques, and are based on analyzing individual image pixels relative to target spectra (endmembers). The result is one or more images showing spectral abundance (e.g. in linear spectral unmixing) or spectral angles (e.g. in spectral angle mapping). These techniques may be very useful for assessing, for instance, woody cover density, and may be used as classifiers by applying thresholds to the output.

In this section we analyze Quickbird multispectral (MS) images for woody vegetation cover using soft classification. The Quickbird sensor orbits at an altitude of 450 km and records data in 4 spectral wavebands (450–520, 520–600, 630–690 and 760–900 nm) at a resolution of 2.4 m in its MS wavebands. In the analysis of woody cover types and densities, as well as abundance and types of background materials (dead plant materials, soil, gravel, rock) we apply a spectral feature fitting (SFF) technique based on least squares, where reference spectra are scaled to image spectra after continuum removal. Continuum removal is a decorrelation method that lets us analyze the effects of spectral absorption features in the imagery.

Woody cover area estimates were calculated by thresholding the scale images for shrubs and trees. In the assessment of SFF spectral scales in each plot (Figure 12.9), SFF image values were extracted for an area buffered by a radius of 17.84 m around the centroid of each sampling plot, and the mean relative spectral abundance of woody vegetation was computed and compared to field observations. As is evident in Figure 12.9, there is greater variance in Konobougou than in the other blocks. There is also much higher variance in semi-natural areas than in cultivated areas, and the latter generally has the lowest

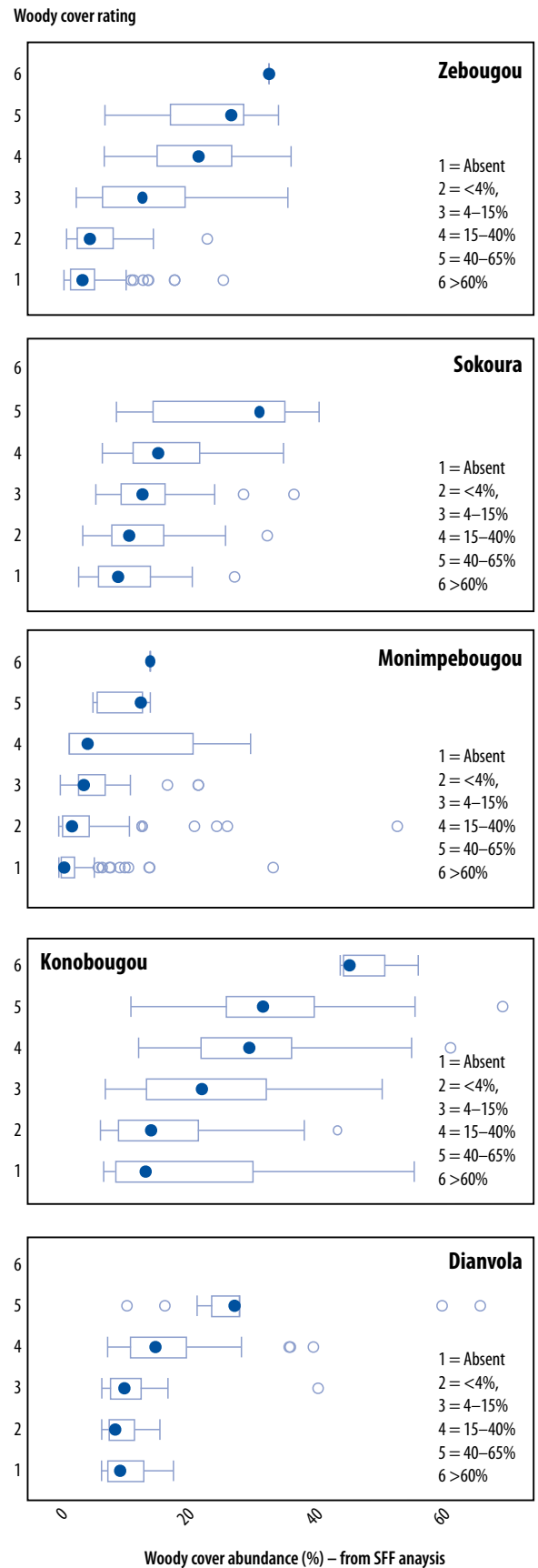
**FIGURE 12.8**

Cluster-level estimates of shrub biovolumes ( $\text{m}^3 \text{ha}^{-1}$ ) in the five blocks (dots are medians).



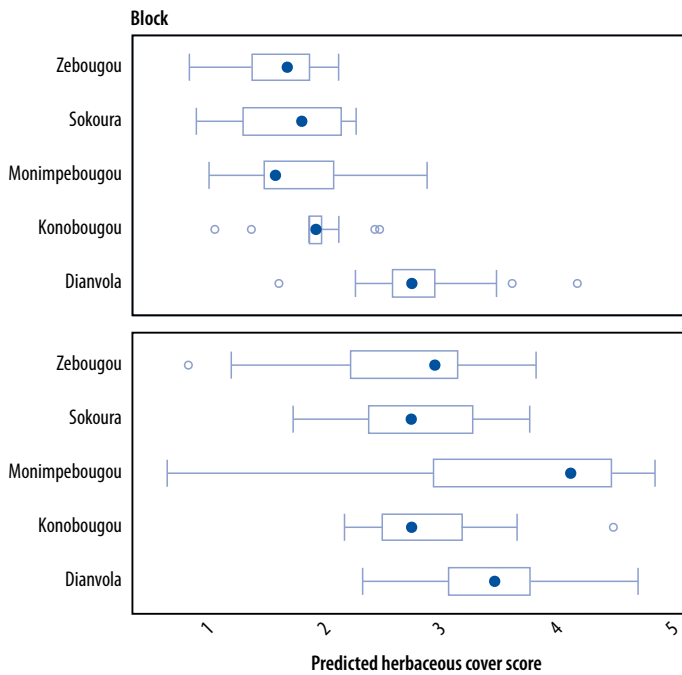
**FIGURE 12.9**

Woody cover ratings from LDSF field surveys and estimated relative woody cover abundance (SFF) from Quickbird images.



**FIGURE 12.10**

Block-level predicted herbaceous cover scores in semi-natural (0) and cultivated or managed (1) areas.



woody cover abundance, as expected given our earlier findings based on shrub and tree counts. There is good agreement between woody cover ratings from LDSF field surveys and woody cover abundance analyzed from Quickbird imagery (Figure 12.9): the woody cover ratings (scores) largely reflect increased woody cover abundance as estimated using Spectral Feature Fitting.

Spatial distributions of woody cover in the five blocks is shown in Figure 12.6, with a summary of block-level area coverage in Table 12.5. Comparing Table 12.5 to our earlier assessment of dense woody cover

**TABLE 12.5**

Block-level woody cover estimates based on Quickbird image classification.

Block	Woody cover (ha)
Dianvola	1,860
Konobougou	3,130
Monimpebougou	160
Sokoura	1,400
Zebougou	1,520

(Table 12.4), we seem to be overestimating dense woody cover in Monimpebougou from field ratings of dense woody cover, while we are underestimating slightly in the other blocks. It is important, though, to keep in mind the field survey rating of woody cover is based on a visual assessment by the field teams and is thus only indicative. The estimates from high-resolution satellite imagery will therefore be more accurate. As we have discussed briefly earlier, these differences are partly due to effects of lower MAP in Monimpebougou and Dianvola. Other studies have also shown similar relationships between MAP and woody cover (Sankaran et al, 2005), with significant increases up to a MAP of about 650 mm yr<sup>-1</sup>. However, after controlling for the effects of rainfall, cultivation or management reduced woody cover abundance.

### HERBACEOUS COVER

Herbaceous cover in the blocks is predominantly annual, with some perennial grasses in Konobougou. Average herbaceous cover ratings are similar for all blocks (between 4 and 15%). As expected, there is less herbaceous vegetation in cultivated fields than in semi-natural areas (Figure 12.10). Dianvola has higher herbaceous cover in cultivated or managed plots than the other blocks (Figure 12.11).

**FIGURE 12.11**

Panorama (view = 360°) from Dianvola (Cluster 9), October 2007.



# Soil health

## SOIL PHYSICAL CONSTRAINTS

### Root depth restrictions

The root restricting depth is the depth at which root penetration is strongly inhibited by physical and/or chemical characteristics of the soil. In the LDSF sampling framework, we record physical root depth restriction (RDR) in the field as areas where soil augering is restricted. In each sampling sub-plot, the depth at which augering is restricted is noted down. In this section we assess the distribution of areas with RDR occurring in the upper 0–20 cm of the profile, and RDR occurring in the upper 0–50 cm, versus areas without RDR. Physical restrictions of root development have major implications for water transport and storage in soils and therefore also management options, including choice of tree species for agroforestry-based interventions. Alternatives for management are generally much more restricted in such areas. Areas with severe root depth restrictions are also more prone to erosion by water, particularly if vegetation cover is decimated, and are often more prone to drought due to limited water storage capacity.

Konobougou and Zebougou have root depth restrictions in significant areas of the blocks. For example, for Konobougou an estimated 24% of the area has severe RDR (upper 0–20 cm) (Table 13.1) and 56% of the area has RDR in the upper 0–50 cm of the soil profile (Table 13.2). Dianvola and Monimpebougou blocks have virtually no recorded severe RDR.

Earlier, we showed that shrub densities are higher in semi-natural than in cultivated areas. An analysis of the effect of shrub density on RDR shows that increasing shrub density reduces the likelihood of RDR 0–20 ( $p=0$ ) and has no influence on RDR 0–50. When testing for the differences in RDR 0–20 and RDR 0–50 between cultivated or managed and semi-natural areas in our data we control for shrub density. Generally, the frequency of severe RDR (RDR 0–20) is highest in semi-natural areas ( $p=0$ ; Figure 13.1), indicating that either (i) farmers deliberately do not cultivate these areas, or (ii) that they are degraded to a state making them unsuitable for cultivation (i.e. hard-set) or (iii) that they are located on naturally rocky or hard-set areas.

In Zebougou, RDR in the upper 50 cm of the soil profile is predicted to occur in 53% of the block on average, or almost 90% of semi-natural areas and about 16% of cultivated or

**TABLE 13.1**

Estimated cluster-level frequency of root depth restriction within 0–20 cm soil depth (RDR20) for the five blocks.

Cluster	Block				
	Dian	Kono	Moni	Soko	Zebo
	%				
1	0	36	0	2	50
2	0	1	0	1	36
3	0	32	0	1	73
4	0	1	0	17	4
5	0	14	0	0	8
6	0	0	0	0	64
7	0	5	0	39	0
8	0	0	0	0	12
9	0	35	0	3	0
10	0	74	0	0	1
11	0	23	0	7	33
12	0	4	0	29	0
13	0	18	0	21	6
14	0	60	0	1	2
15	0	31	0	0	2
16	0	48	0	3	71
Average <sup>1</sup>	0	24	0	8	23

<sup>1</sup> Estimated block average.

**TABLE 13.2**

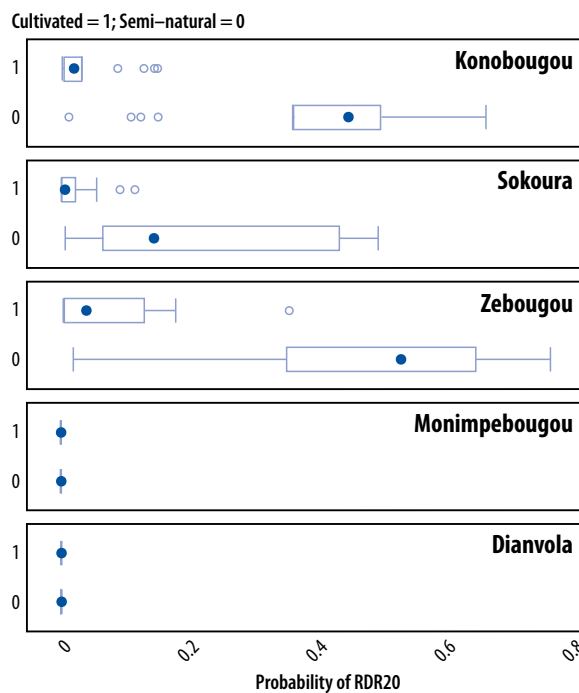
Estimated cluster-level frequency of root depth restriction within 0–50 cm soil depth (RDR50) for the five blocks.

Cluster	Block				
	Dian	Kono	Moni	Soko	Zebo
	%				
1	0	92	0	3	100
2	0	1	0	8	99
3	0	92	0	1	100
4	0	1	0	96	7
5	0	27	0	0	13
6	0	0	0	0	100
7	0	38	0	99	1
8	0	0	0	1	97
9	0	84	0	11	1
10	0	95	0	0	2
11	0	39	0	90	98
12	0	71	0	99	1
13	0	87	0	89	93
14	0	92	0	1	44
15	0	81	0	1	1
16	0	98	0	83	100
Average <sup>1</sup>	0	56	0	36	53

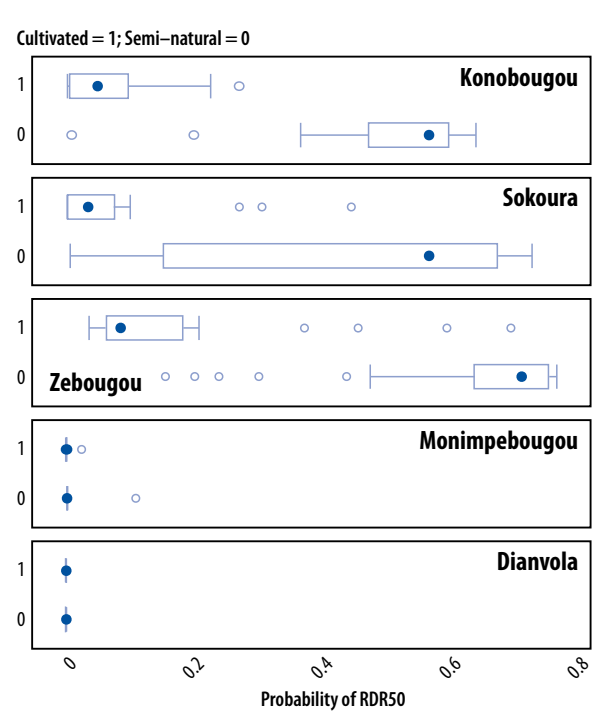
<sup>1</sup> Estimated block average.

**FIGURE 13.1**

Predicted probability of root depth restriction within 0–20 cm soil depth (RDR20) in semi-natural (0) and cultivated (1) areas, by block.

**FIGURE 13.2**

Predicted probability of root depth restriction within 0–50 cm soil depth (RDR50) in semi-natural (0) and cultivated (1) areas, by block.



managed fields (Figure 13.2). In Sokoura and Zebougou, shrub densities are higher in areas with severe RDR (~45 shrubs ha<sup>-1</sup>) than in areas without root depth restrictions (~5 and 25 shrubs ha<sup>-1</sup>, respectively), which corresponds well with earlier estimates of shrub densities in cultivated and semi-natural areas.

### Inherent soil degradation risk

We define high inherent soil degradation risk (HIDR) as areas having physical degradation (i.e. root-depth restrictions at 0–50 cm depth) or abrupt textural gradients (e.g. sandy loam over clay), or areas with slope  $\geq 30^\circ$ . The last does not occur in the data reported here. The highest average block-level HIDR is found in Zebougou, with about 71%, while Konobougou and Sokoura have 68 and 51%, respectively (Table 13.3). Monimpebougou has the lowest HIDR on average (29%) due to an almost complete absence of root-depth restrictions (Table 13.2). Prevalence of abrupt textural changes between top- and subsoil layers is relatively low, and ranges between 6% (Sokoura) and 15% (Dianvola), while prevalence of visible signs of erosion (mainly sheet erosion) is highest in Zebougou (72%) and Sokoura (65%) and lowest in Monimpebougou (1%). Although observations of visible signs of erosion are somewhat uncertain given that they are subjective observations made by the field teams, they may provide useful indications of land degradation hot spots in the landscape. On average for all blocks, we observe about 30% higher erosion risk ( $p < 0.001$ ) in semi-natural areas than in cultivated areas.

### Soil infiltration capacity

Infiltration capacity was measured using single infiltration rings (Figure 13.3) on two to three plots per cluster (Appendix 3.1). In semi-arid areas, runoff from hillslopes occurs as Hortonian overland flow, as the rate of rainfall often exceeds the infiltration capacity of the soil (Dunne 1978). Infiltration capacity is influenced by surface conditions such as soil crusts or physical root depth restrictions, vegetation cover and geomorphological situation, in addition to rainfall characteristics. It is given by:

$$i(t) = i_c + (i_0 - i_c)e^{-kt}$$

(Eq. 13.1)

where  $i$  is observed infiltration rate (mm hr<sup>-1</sup>),  $t$  is time,  $i_0$  is initial infiltration rate (mm hr<sup>-1</sup>),  $i_c$  is infiltration rate at saturation (mm hr<sup>-1</sup>), and  $k$  is a rate parameter.

**TABLE 13.3**

Estimated cluster- and block-level proportion of areas predicted to have high inherent soil degradation risk. The 25% (lower) and 75% (upper) Markov chain Monte Carlo simulated quantiles are shown for block averages.

Cluster	Dian	Kono	Moni	Soko	Zebo
	%				
1	50	85	19	22	96
2	34	53	45	31	93
3	19	85	46	37	95
4	32	62	20	88	63
5	57	58	33	18	61
6	8	57	49	34	98
7	15	77	25	95	50
8	13	49	14	63	91
9	30	72	39	32	38
10	22	90	38	24	36
11	24	78	23	84	89
12	7	84	28	93	78
13	64	90	44	77	90
14	3	81	28	39	82
15	21	74	34	14	57
16	20	93	58	87	98
Average	29 <sub>23</sub> <sup>34</sup>	68 <sub>61</sub> <sup>73</sup>	35 <sub>29</sub> <sup>41</sup>	51 <sub>44</sub> <sup>57</sup>	71 <sub>65</sub> <sup>76</sup>

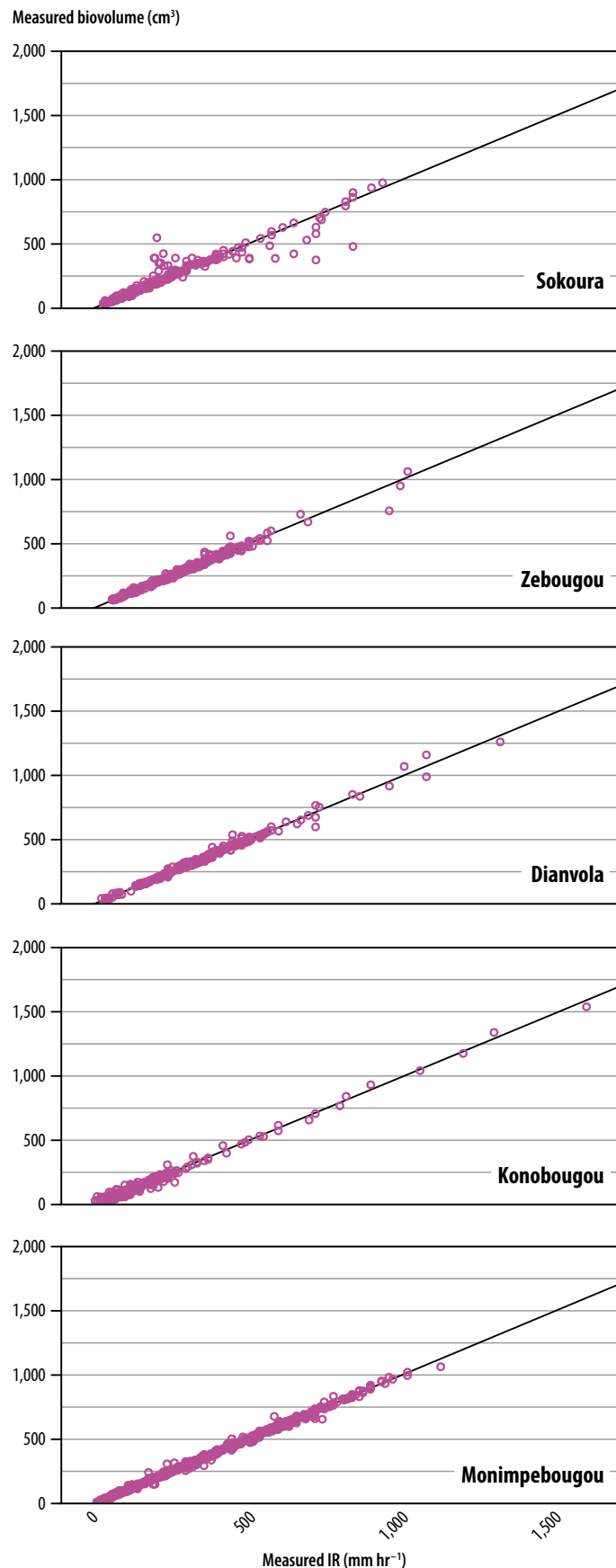
**FIGURE 13.3**

Infiltration testing using single rings.



**FIGURE 13.4**

Predicted versus measured infiltration rates (mm hr<sup>-1</sup>) for each block.



Saturated infiltration capacity was estimated using a non-linear mixed-effects (NLME) model based on single-ring infiltration tests in 202 plots. Figure 13.4 shows predicted infiltration rates (IR) in the NLME model and measured IR. As is evident in Figure 13.4, some of the plots from Sokoura show relatively large deviations from the model estimates. Fitting the above model letting  $i_0$  and  $i_c$  vary between blocks and in clusters within blocks (i.e. using a multilevel NLME), the average saturated infiltration capacity for all blocks was estimated at 204 mm hr<sup>-1</sup> (95% CI = 166–242 mm hr<sup>-1</sup>).

Block-level average estimated infiltration curves are shown in Figure 13.5, together with the average for all sites (mean). Monimpebougou has the highest average  $i_c$  at about 300 mm hr<sup>-1</sup>, and Sokoura the lowest at about 100 mm hr<sup>-1</sup> (Figure 13.5). Infiltration capacity is highest in cultivated areas in Monimpebougou ( $i_c = 376$  mm hr<sup>-1</sup>) and Zebougou ( $i_c = 250$  mm hr<sup>-1</sup>), while in Sokoura and Dianvola,  $i_c$  is highest in semi-natural areas (179 and 306 mm hr<sup>-1</sup>, respectively). Konobougou has similar infiltration capacities in cultivated and semi-natural areas. The higher infiltration capacities in Dianvola and Monimpebougou may in part be explained by lack of physical root depth restrictions in these blocks (Table 13.2).

We further examined the relationships between RDR and the parameters of our NLME infiltration model. Saturated infiltration capacity is lower when there are root-depth restrictions in the upper 50 cm ( $p=0.03$ ), while the presence of RDR in the upper 20 cm does not lead to significant reductions in  $i_c$  ( $p=0.7$ ) (Figure 13.6).

### Soil condition

Soil condition in the five blocks was assessed using near-infrared (NIR) spectroscopy (Shepherd and Walsh, 2007), in combination with analytical data on a selection of the samples, as well as the field measurements and observations reported earlier. NIR spectral signatures were obtained using a Fourier-transform near infrared spectrometer (Bruker Multipurpose Analyser) using air-dried 2-mm sieved samples. NIR spectral signatures were subset for the spectral region between 4,000–8,000 cm<sup>-1</sup> and pre-treated by calculating first derivatives using a polynomial smoothing function over 21 wavebands (Figure 13.7) prior to analysis. This minimizes potential errors resulting from high-frequency noise due to variations



in grinding and optical setup. In the results we present here, wavelengths have been converted to nanometers (nm). Average raw and first derivative spectral signatures for soil samples (n=1389) from the five blocks, +/- their standard deviations, are shown in Figure 13.7.

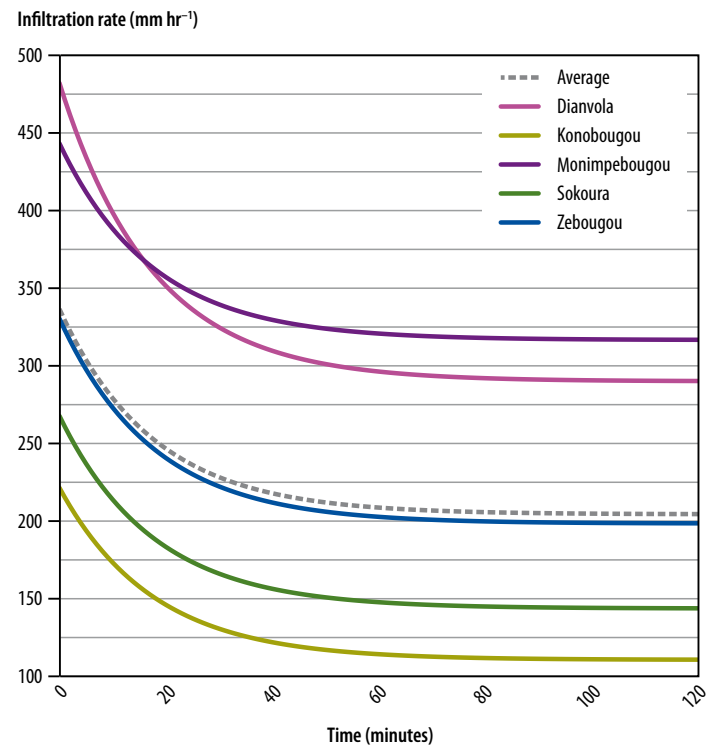
Near-infrared reflectance spectra integrate a number of soil properties, including soil organic carbon (SOC) content, texture and mineralogy to mention but a few (Shepherd and Walsh, 2007). They have therefore been successfully applied in predicting various soil physicochemical properties, including SOC content, and in developing indices of soil condition or fertility (Vågen et al, 2006), as well as erosion risk indices (Cohen et al, 2004). There has also been some success in linking such indices to satellite imagery allowing mapping of the indices over larger areas (Vågen et al, 2006).

Conventional analysis of soil physicochemical properties was done using methods described by Shepherd and Walsh (2002), except SOC was analysed by combustion using a carbon analyser on acidified samples to remove carbonates. The results showed that soils in the study area are moderately acid with mean pH values between 5 and 6, and generally high sand content, with Dianvola and Monimpebougou having very high sand contents (Table 13.4), relative to the other blocks. Soil organic carbon contents are low (range 0.87–18.79 g kg<sup>-1</sup>). About 80% of the samples have SOC contents that are lower than 5 g kg<sup>-1</sup> (0.5%). About 98% of the soils in the data set are P-deficient, with extractable phosphorus (P) lower than 7 mg kg<sup>-1</sup>, while about 50% are potassium (K) deficient with exchangeable K lower than 0.2 cmolc kg<sup>-1</sup>.

The correlation matrix (Table 13.5), after transforming soil variables to normal distributions, showed strong correlation between SOC and total N and between exchangeable Ca and exchangeable Mg, as expected. These properties were also moderately strongly correlated with silt plus clay content, reflecting the fact that cation exchange surfaces and organic matter protection are associated with content of soil colloids in these predominantly sandy soils. The moderately strong correlation of extractable P with SOC points to the importance of organic matter as the main source of available phosphorus in these soils.

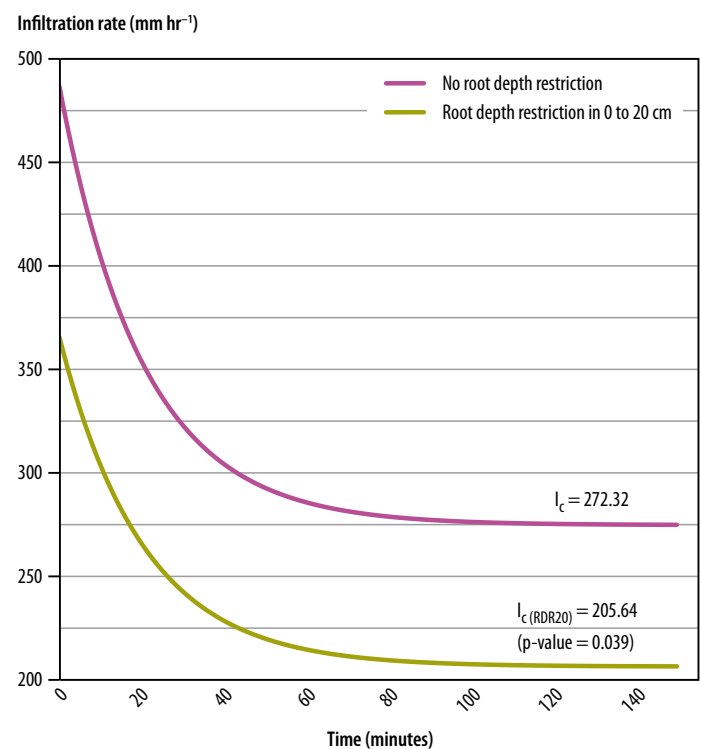
**FIGURE 13.5**

Infiltration curves showing average for all blocks and individual block averages.



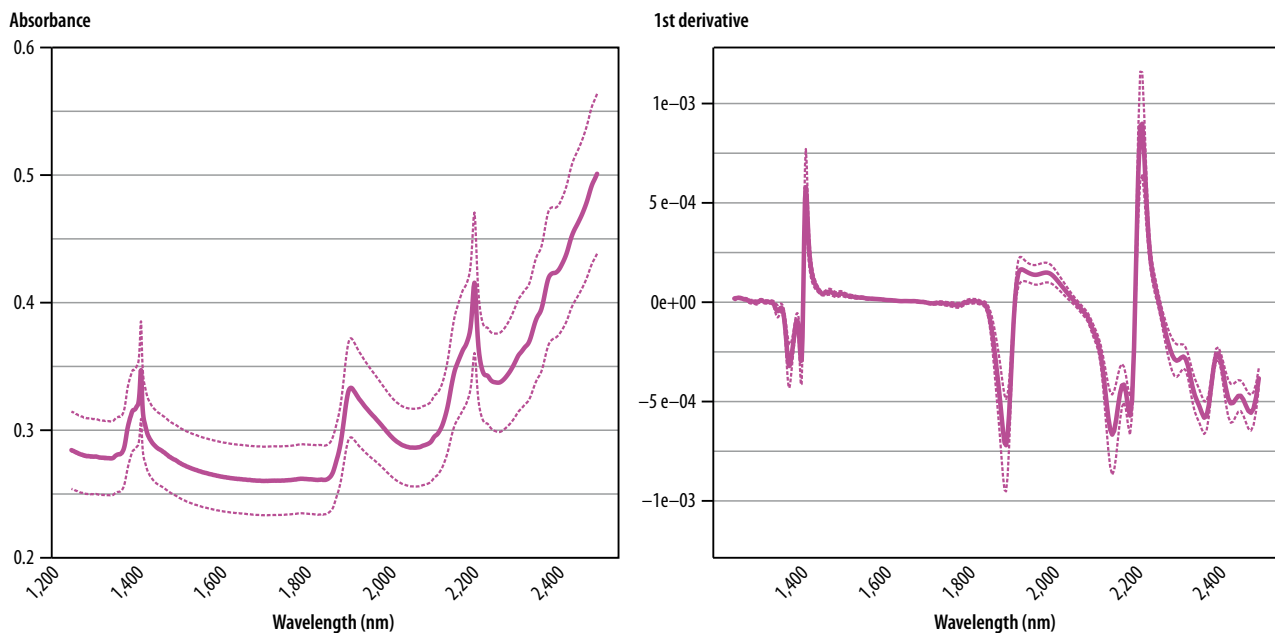
**FIGURE 13.6**

Infiltration curves showing average for plots with and without root depth restriction within 0–20 cm soil depth (RDR 0–20).



**FIGURE 13.7**

Raw (upper) and 1st derivative (lower) plots of near infrared soil spectra, showing means for library (red) +/- standard deviations (dashed).



### Soil organic carbon

Measured SOC contents are low in all blocks, but with significant between block variation (Table 13.4). Konobougou, Zebougou and Sokoura have the highest average SOC contents, and SOC is generally higher in semi-natural areas than in cultivated or managed areas ( $p=0.003$ ) (Figure 13.8). In Monimpebougou and Dianvola, SOC contents are very low, and there is no significant difference between cultivated and semi-natural areas in Dianvola (Figure 13.8). Plots with shrub-densities lower than 2,000 shrubs  $ha^{-1}$  have lower SOC concentrations than

plots with higher shrub-densities, while increasing shrub-densities beyond 4,000 shrubs  $ha^{-1}$  does not seem to have much impact on SOC concentrations.

One of the advantages of using NIR spectral libraries for predicting SOC and other soil physicochemical properties is in the double-sampling procedure applied here. This lets us conduct ordinary (and costly) laboratory analysis procedures on a subset or holdout of samples (normally 15–20% of the dataset), and predict these properties for the remaining samples. A partial least squares (PLS) calibration

**TABLE 13.4**

Summary of soil physicochemical properties by block (n=238).

	Dian		Kono		Moni		Soko		Zebo	
	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.	Mean	Std.dev.
pHwater	5.5	0.29	5.8	0.46	5.9	0.59	5.2	0.86	5.2	0.33
Exch. K ( $cmol_c kg^{-1}$ )	0.2	0.2	0.3	0.2	0.3	0.2	0.3	0.3	0.2	0.5
Exch. Ca ( $cmol_c kg^{-1}$ )	0.5	0.28	1.1	0.72	1.5	1.38	2.6	2.06	1.3	0.88
Exch. Mg ( $cmol_c kg^{-1}$ )	0.3	0.12	0.6	0.26	0.5	0.27	0.8	0.27	0.7	0.30
Extr. P ( $mg kg^{-1}$ )	0.8	0.66	0.6	1.15	0.8	0.75	1.8	2.3	0.8	0.51
SOC ( $g kg^{-1}$ )	1.8	0.46	6.0	3.74	1.7	0.75	4.5	0.75	4.3	2.47
TN ( $g kg^{-1}$ )	0.11	0.04	0.48	0.34	0.11	0.05	0.26	0.15	0.27	0.20
Sand (%)	81	3	57	13	76	12	52	15	62	12

**TABLE 13.5**

Correlation (upper triangle) and partial correlations (lower triangle) for topsoil (0–20 cm) samples (n=104).

	pH	TN**	SOC**	K**	Ca**	Mg**	P**	S+C*
pH		-0.1	-0.19	0.49	0.15	0.01	0.21	-0.23
TN**	0.15		0.93	0.23	0.27	0.39	0.61	0.57
SOC**	-0.26	0.85		0.19	0.35	0.45	0.57	0.66
K**	0.38	0.03	-0.02		0.32	0.29	0.45	0.11
Ca**	0.26	-0.19	0.17	0.1		0.76	0.17	0.56
Mg**	-0.08	0.09	-0.04	0.14	0.58		0.21	0.64
P**	0.2	0.15	0.15	0.31	-0.09	-0.06		0.29
S+C*	-0.18	-0.04	0.26	-0.07	0.21	0.29	0.01	

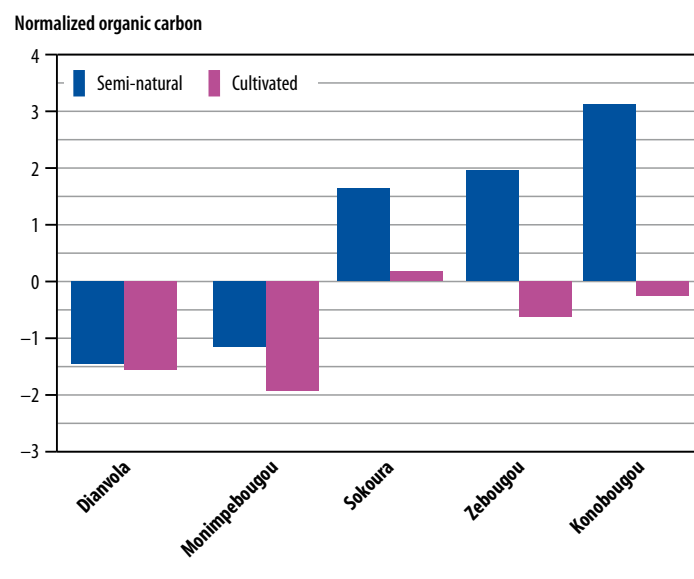
S+C = Silt + Clay; \* square-root transform; \*\* log transform

model for predicting SOC content was developed on a subset of 238 soil samples ( $\approx 15\%$ ), spanning a range (in principal components space) of spectral conditions in the full data-set. Soil organic carbon (SOC) values were transformed by taking their natural logarithm to obtain approximately normal distribution, and the smoothed first derivative NIR spectra were mean centered, scaled and pretreated using Multiplicative Scatter Correction (MSC) as described by Martens and Naes (1985). Model fitting was conducted in R-statistics (R Development Core Team 2007) using the PLS package of Mevik (2006).

Diagnostic plots for the prediction model are shown in Figure 13.9. Based on the model diagnostics, a model containing nine latent variables was used for predicting SOC contents in the remaining soil samples (n=1181). This is a relatively conservative number of latent variables, but explains almost 99% and 93% of the variance in the spectral properties and  $\ln(\text{SOC})$ , respectively. The root mean squared error of prediction (RMSEP) is  $1.25 \text{ g C kg}^{-1}$ , and the coefficient of variation ( $r^2$ ) is 0.88, indicating that we have a relatively stable prediction model.

Figure 13.9 presents measured versus predicted SOC ( $\text{g kg}^{-1}$ ) in the training data set. The regression lines shown in the plot represent the 1:1 line, an Ordinary Least Squares line and a robust regression estimate, which, as is obvious from the plot, is more resistant to outliers. We have two outliers (extreme predictions) from Konobougou, both of which are topsoil samples (Figure 13.9). Predicted SOC contents for the entire spectral library (n=1,389) fall in the same range as the measured subset of samples, and they generally confirm the block-level differences discussed earlier (Figure 13.8).

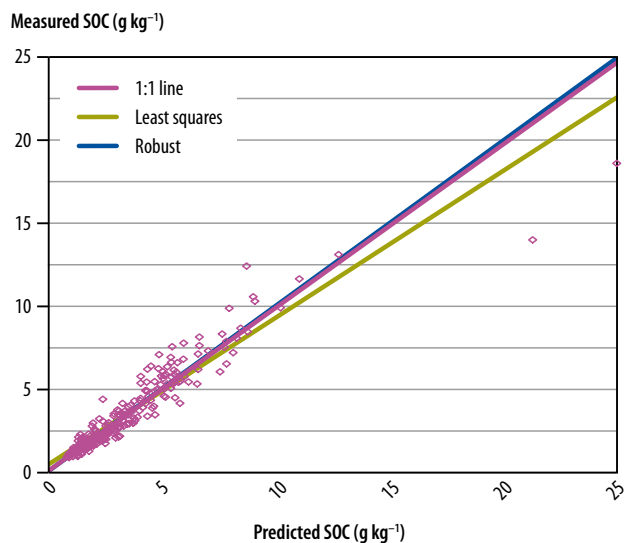
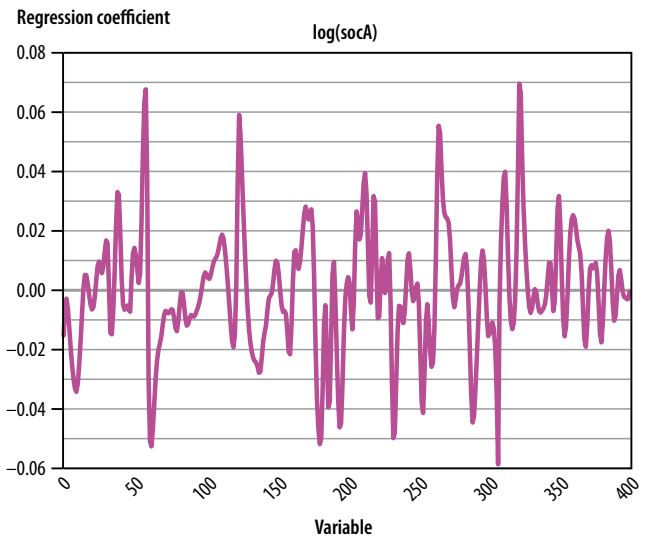
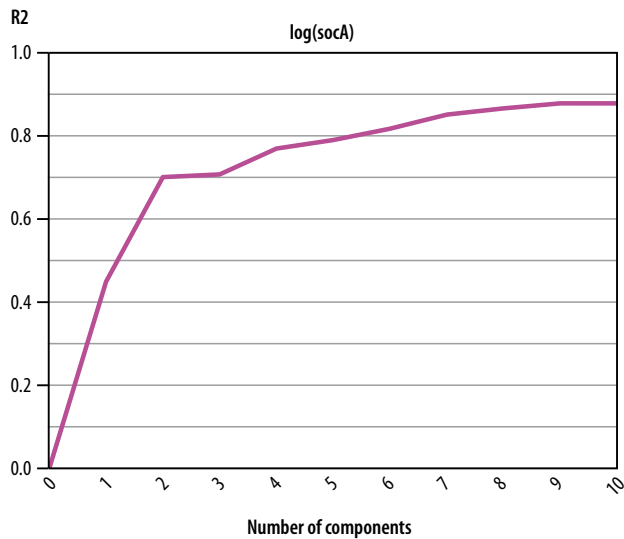
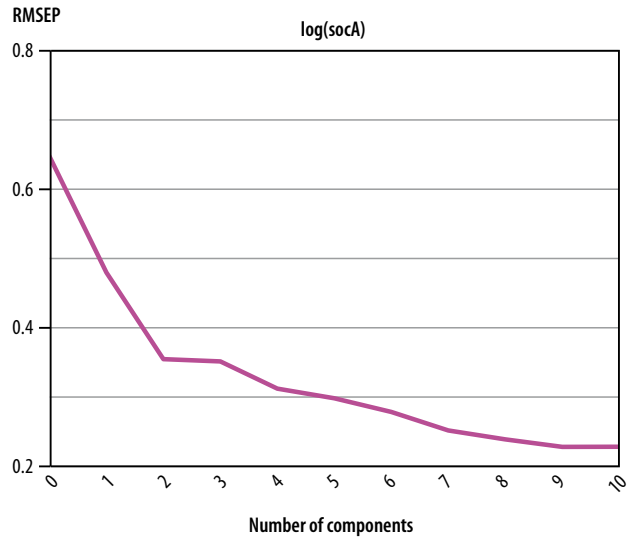
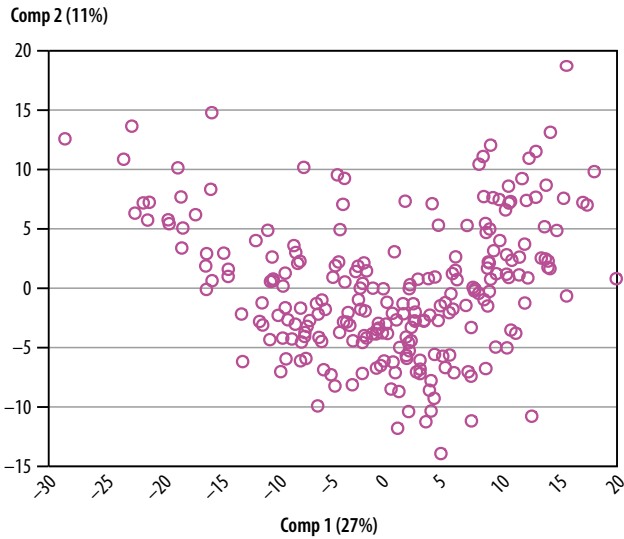
Figure 13.10 shows median SOC contents (dots) for each cluster, together with their upper and lower quartiles (boxes). All sampling clusters in Dianvola and Monimpebougou are extremely low in SOC, with contents lower than  $5 \text{ g kg}^{-1}$ , and very little variance. Konobougou has the highest SOC content on average, and the highest within-cluster variability. Cluster 10 has an average SOC content of about  $15 \text{ g kg}^{-1}$ , and is located in a semi-natural part of the block (i.e. not cultivated or managed). Both herbaceous and woody cover ratings are high, but the cluster has severe root depth restrictions in most plots and high gravel content in the soil.

**FIGURE 13.8**Measured soil organic carbon ( $\text{g kg}^{-1}$ ) contents in semi-natural and cultivated areas, split by block. Bars are means, relative to overall mean.

**FIGURE 13.9**

Upper: Diagnostic plots for the soil organic carbon (ln(SOC)) SIMPLS model. From upper left, clockwise; (1) first two principal components (% variance explained in brackets), (2) RMSEP plot, (3) R<sup>2</sup> with increasing number of components in model, and (4)

variable number (wavelength) vs. regression coefficient. Lower: Measured vs. predicted SOC content (g kg<sup>-1</sup>) for the model-building data set (n=238).



After controlling for the presence of trees and shrubs, cultivated areas have on average 2.2 g C kg<sup>-1</sup> (q25 = -3.6; q75 = -1.1) lower SOC contents than semi-natural areas (p=0.002). The difference between cultivated and semi-natural areas is particularly large in Konobougou (-5.9 g C kg<sup>-1</sup>) and Zebougou (-3.3 g C kg<sup>-1</sup>) (Figure 13.11), and as expected less pronounced in Dianvola and Monimpebougou where SOC contents are generally low.

### Soil condition index

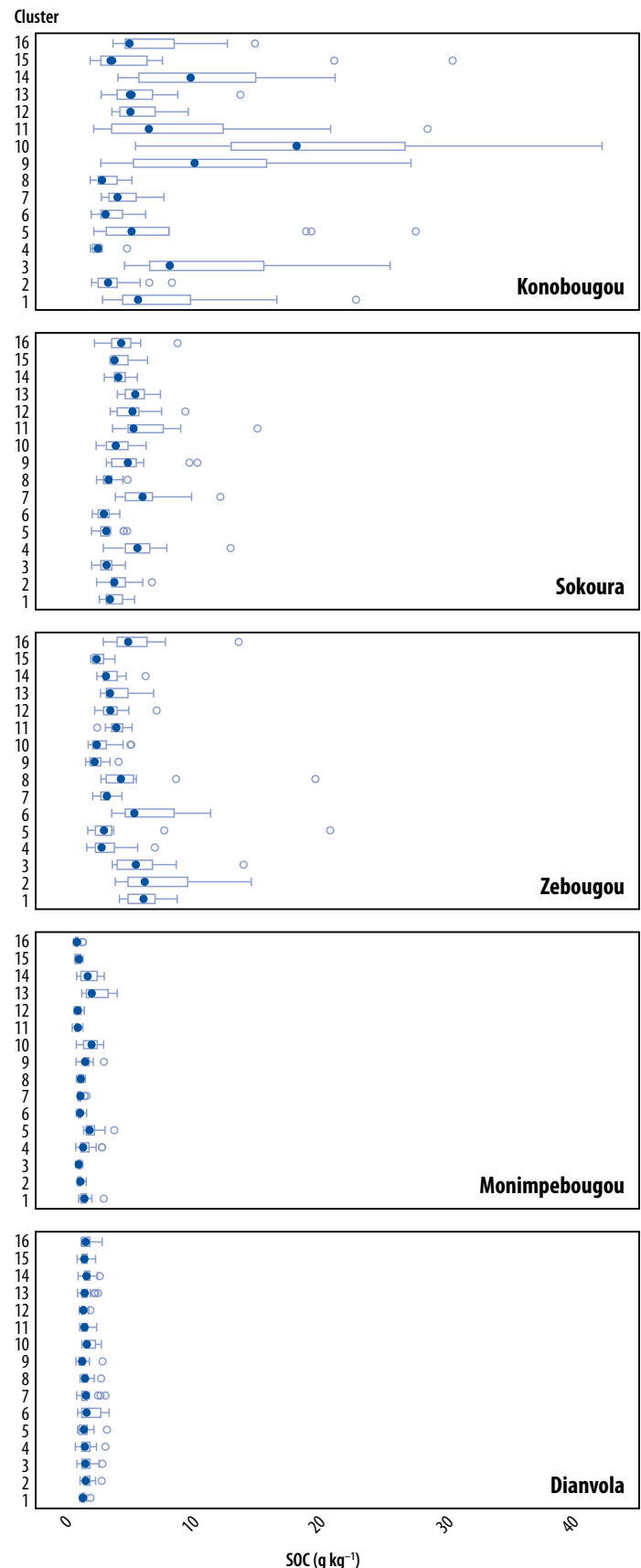
Indices of soil condition that integrate various physicochemical properties of the soil are useful for a wide range of applications, including identification of land degradation hotspots in the landscape and priority intervention areas. In cases where such indices can be calibrated to or predicted from satellite remote-sensing data, they become powerful tools for regional-level mapping of land degradation hot spots.

We developed a soil condition index for topsoils in the study area, based on NIR spectral data. The first derivative NIR spectra were first analyzed using principal components (PC) analysis, and the first 10 principal components (PCs) were used in discriminating between soil condition classes. In short, PC analysis (PCA) is a technique that was developed by Karl Pearson in 1901 (Pearson, 1901) where a data-matrix is reduced to a small number of variables (principal components). Classification of subsoils was conducted separately.

Soil condition classes were developed using clustering techniques based on normal mixture models (Fraley and Raftery, 2006) implemented using the mclust package for R. The mixture parameters are estimated via the EM algorithm (Dempster et al, 1977), initialized by model-based hierarchical clustering (Banfield and Raftery, 1993; Fraley, 1998). Data generated by mixtures of multivariate normal densities are characterized by groups or clusters centred on the means, with increased density for points nearer the mean. Two spectrally derived soil condition (SC) classes were identified for the study area, and validated using analytical data from a subset of 238 soil samples. The two SC classes are generally widely different in terms of soil physicochemical properties, including SOC, TN, available P, Ca and sand content, but not pH and exchangeable K. A summary of the variation between SC classes for selected soil properties is shown in Figure 13.12.

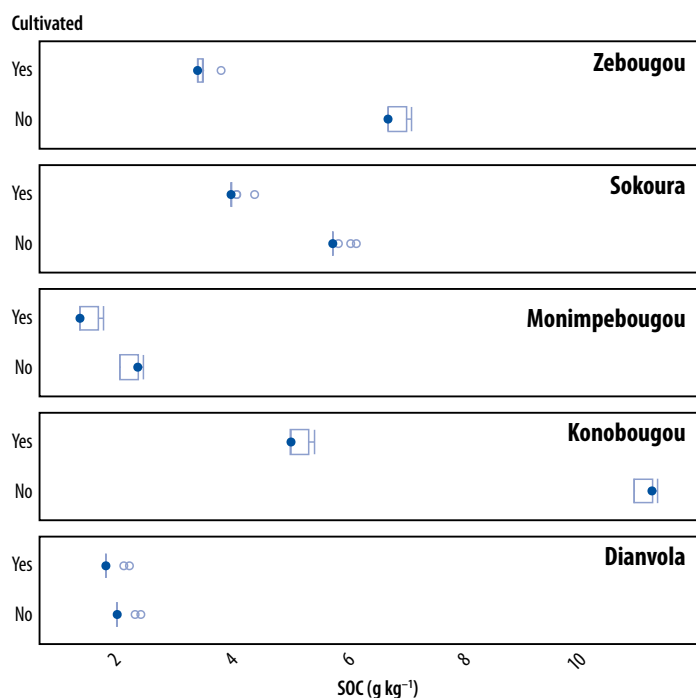
**FIGURE 13.10**

Cluster level median soil organic carbon contents (g kg<sup>-1</sup>) (dots) and upper and lower quartiles (boxes). Points are extreme values.



**FIGURE 13.11**

Estimated soil organic carbon contents (g C kg<sup>-1</sup>) in semi-natural and cultivated or managed areas, by block.



We label the soil condition class with high SOC content and low sand content as good, and conversely the other class as poor. Note that the classes are developed for the sentinel sites included in the current study. However, given the relatively homogeneous soils in the region, generalizations for the Segou Region and possible larger parts of the Sahel may be possible.

Having identified the SC classes, we can calculate the risk of having poor soil condition (i.e. low SOC, P, base cations and high sand content) at block and cluster within block levels (Table 13.6), as well as in cultivated vs semi-natural areas. A combination of the above and other covariates lets us identify areas that are at risk of having severe land degradation. On average, approximately 52% of topsoils in the study area are classified as having poor soil condition. As shown in Table 13.6, Dianvola and Monimpebougou have a higher prevalence of poor soil condition (>85%) than the other blocks, with limited variation (variance) between clusters in the blocks. The other blocks show much more variability between clusters (Table 13.6), and on average 16–22% of the area of these blocks have poor topsoil condition. The risk of poor soil condition increases with increasing sand content ( $p \approx 0$ ) and is related (but not significantly) to decreasing SOC content. When controlling for sand content, there is a relatively strong cultivation effect ( $p=0.02$ ), with an increase in the risk of having poor soil condition when sites are cultivated (Figure 13.13), also reflecting our earlier findings of lower SOC content in cultivated relative to semi-natural areas.

**TABLE 13.6**

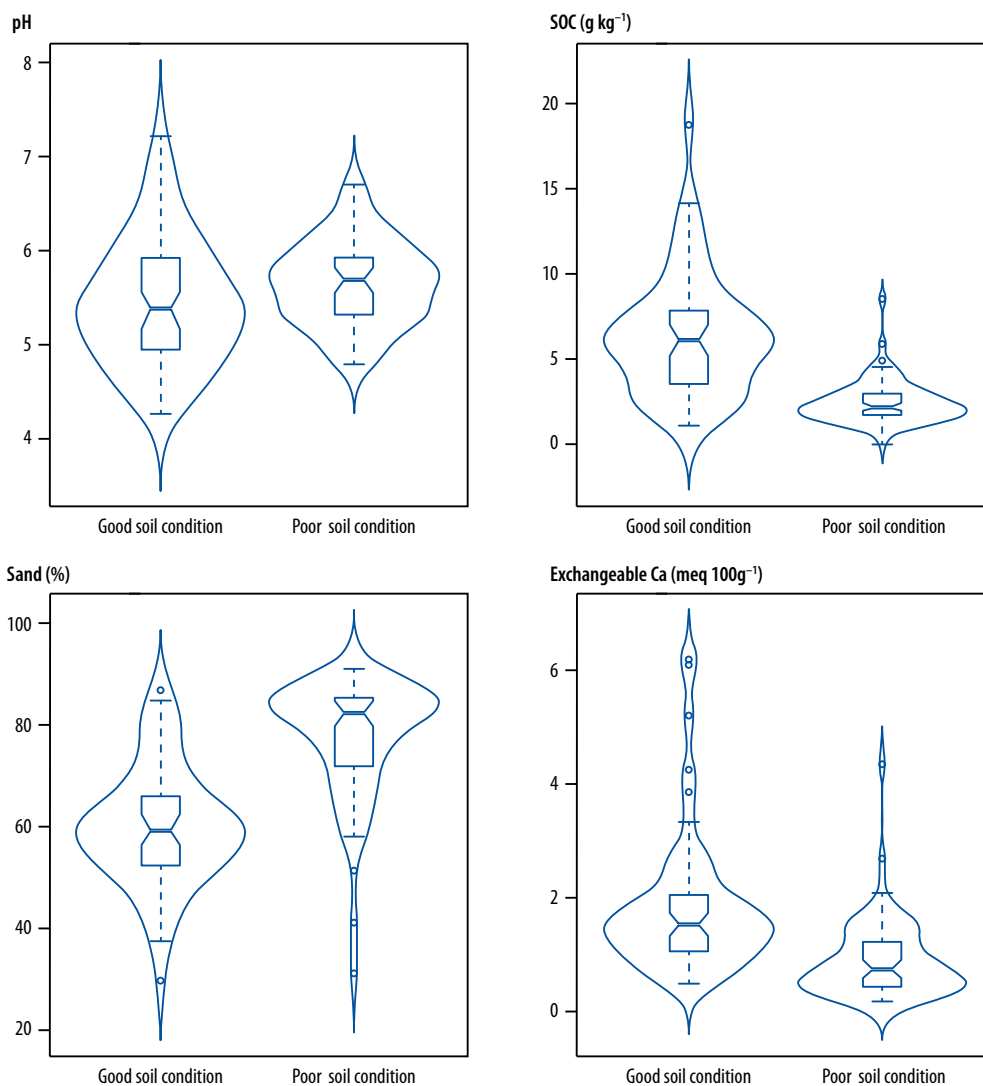
Estimated cluster- and block-level proportion of areas predicted to be in poor soil condition class, based on NIR data. 25% (lower) and 75% (upper) Markov chain Monte Carlo simulated quantiles are shown for block averages.

Cluster	Dian	Kono	Moni	Soko	Zebo
	%				
1	90	5	96	48	5
2	98	65	97	40	5
3	98	6	97	49	6
4	68	60	90	5	49
5	84	16	53	75	26
6	91	76	90	58	6
7	98	5	97	5	58
8	91	65	96	31	6
9	98	5	83	14	83
10	98	5	48	22	48
11	92	23	96	6	45
12	84	25	97	7	54
13	98	13	53	5	5
14	98	6	66	33	13
15	98	7	90	40	70
16	98	5	90	14	5
Average	94 <sup>95</sup> <sub>84</sub>	16 <sup>31</sup> <sub>12</sub>	88 <sup>89</sup> <sub>69</sub>	22 <sup>38</sup> <sub>15</sub>	21 <sup>38</sup> <sub>15</sub>

We extracted Quickbird (calibrated) reflectance values for each plot by buffering plot centroids by 17.84 m (i.e. the plot radius). A Generalized Linear Mixed-effects Modeling (GLMM) approach was then applied to assess whether we could predict soil condition (SC) from Quickbird reflectance. We have interactions between bands 2 and 3 ( $p=0$ ), and 2 and 4 ( $p=0$ ), respectively, that contribute significantly to describing differences in topsoil condition. There is also a weak influence of band 4 (near infrared) ( $p=0.09$ ). Although bands 2 (green) and 3 (red) do not explain the variations in soil condition in the data we retain them in our model due to the mentioned interactions. As shown in Figure 13.4, the GLMM model developed based on Quickbird reflectance is able to predict prevalence of poor soil condition relatively well.

**FIGURE 13.12**

Summary of selected soil properties by NIR spectral-based soil condition class. Lines are density distributions (mirrored).



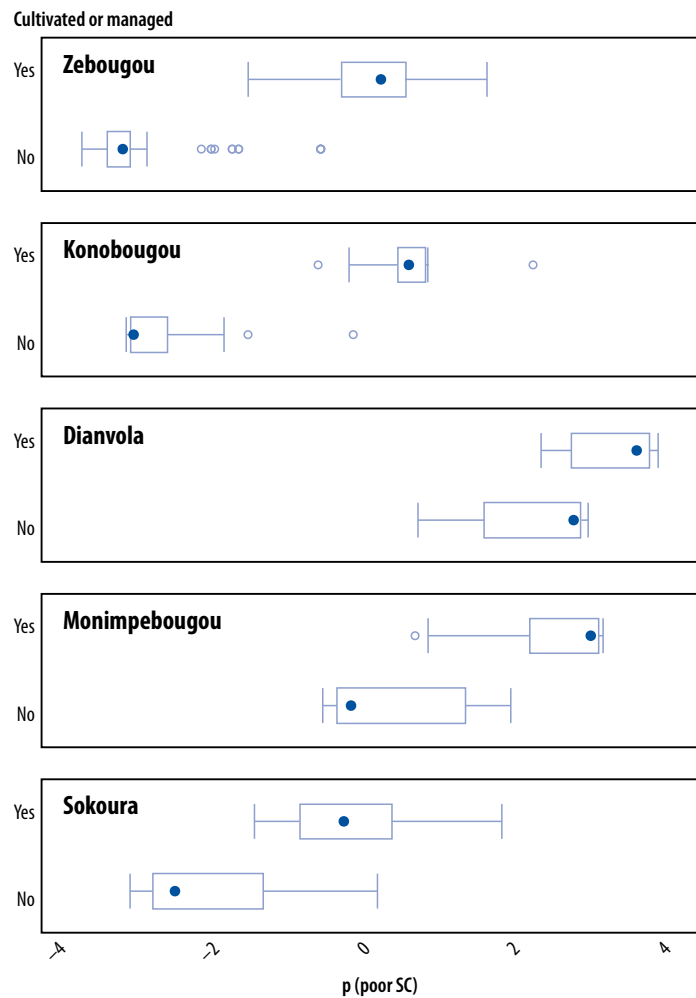
This is due to the fact that QuickBird reflectance bands detect differences in vegetation and soil reflectance that relate to soil condition. In Dianvola and Monimpebougou we generally have a high prevalence of poor/degraded soils, as reported earlier (Table 13.6). Using the developed model, we can predict the prevalence of poor soil condition using the Quickbird images, thus getting a fine resolution risk map, as shown in Figure 13.15. The maps for individual blocks (Figure 13.15) confirm our earlier findings that prevalence of poor soil condition is higher in cultivated or managed areas. In Dianvola, we see a high risk of poor soil condition associated with areas converted to agriculture during the period from 1986–2001.

### Mapping regional level risk of soil degradation

Mapping of topsoil condition or risk of soil degradation (or poor soil fertility status) was demonstrated by Vågen and others (2006), who fitted a proportional-odds logistic regression model to soil condition classes using Landsat reflectance as independent variables in a study in the highlands of Madagascar. We take a similar approach, by predicting a Landsat reflectance-based soil condition index from the NIR-based soil condition (SC) classes developed above, using a generalized linear mixed-effects model (GLMM) (Equation 13.2).

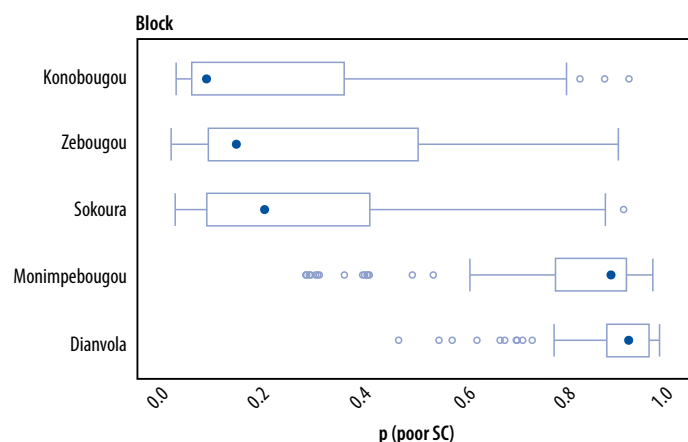
**FIGURE 13.13**

Probability (logit) of having poor soil condition (SC) in cultivated versus semi-natural areas.



**FIGURE 13.14**

Estimated probability of being in poor soil condition class based on Quickbird (QB) reflectance for individual plots.



The five sentinel sites span three Landsat scenes (path/row 197/51, 198/50 and 198/51) (Figure 13.16). Ground reflectance values were extracted from the images for each sampling plot, and the modes of reflectance values in each band were used as independent variables in the model. A model was first fit using all Landsat bands, and the significance of the various bands in determining soil condition (SC) was assessed. Bands 2 (green), 3 (red) and 4 (near-infrared) were retained in the final model (Equation 13.2):

$$Prob\{SoilCondition = Poor\} = \frac{1}{1 + \exp(-X\beta)}$$

(Eq. 13.2)

where  $X\beta = -2.8503553 + 0.0011185etmG - 0.0013773etmR + 0.0023999etmNA$ .

The final model was used to estimate the risk of poor soil condition from Landsat reflectance values (Figure 13.17), covering an area of approximately 69,000 km<sup>2</sup> of the Segou Region. The NIR-based SC index (SCI) shows a high degree of correlation with the ETM-based SCI (Figure 13.18), and a comparison of the soil degradation risk maps generated from Landsat data (Figure 13.17) and those based on Quickbird reflectance (Figure 13.15) at sentinel site (block) level shows relatively good correspondence for most of the sites (Figure 13.19). Given the differences in spatial resolution (i.e. 2.4 vs 28.5 m) between these sensors, the level of correspondence between the estimates is quite good, permitting the development of a regional-level SCI for mapping (or identifying) hot-spot areas in the region with a high likelihood of having poor topsoil condition (Figure 13.17).

## FERTILIZER RESPONSE TRIALS

### Trial design

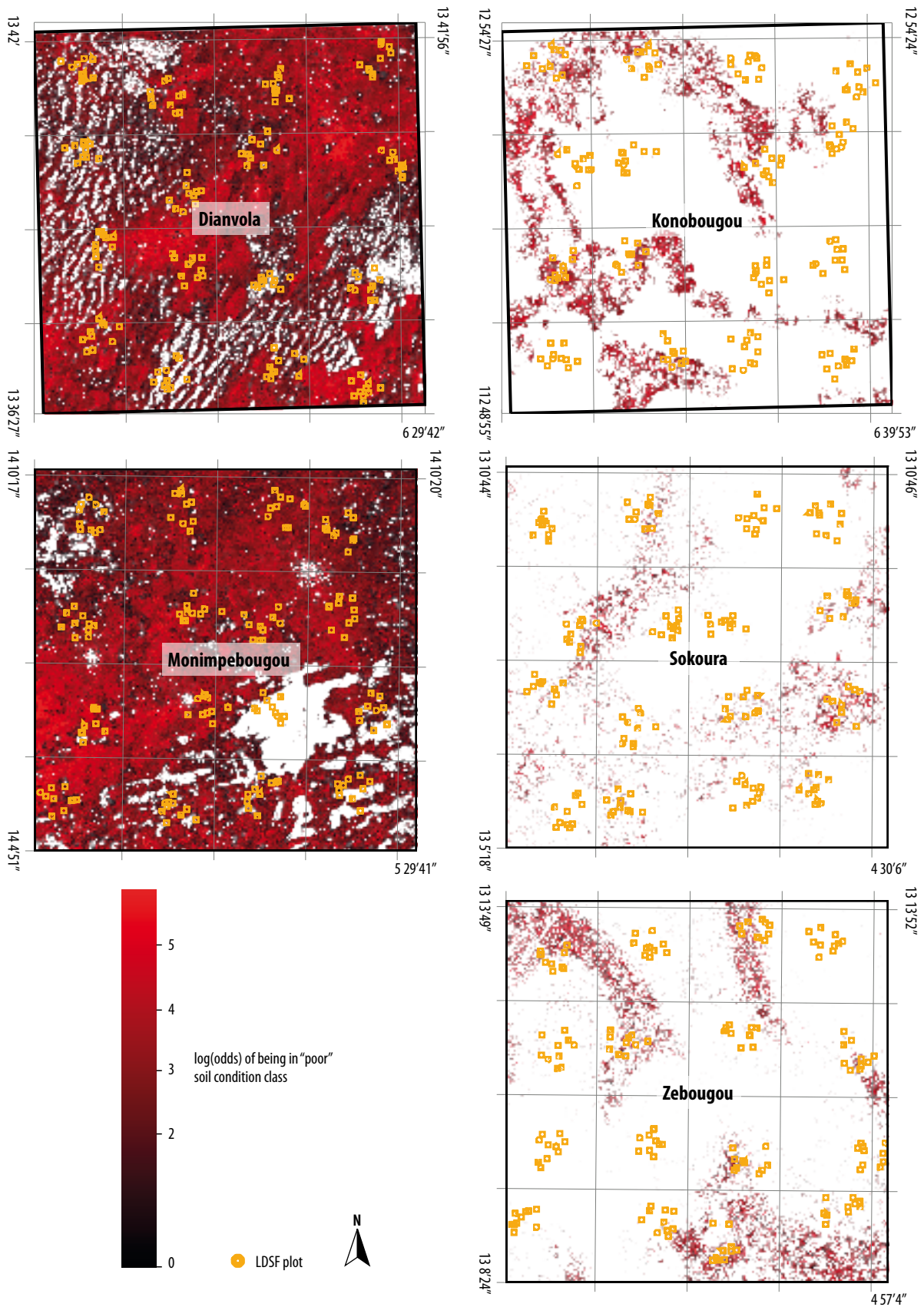
Fertilizer response trials were conducted in three sentinel blocks (Konobougou, Zebougou and Monimpebougou) to confirm soil nutrient deficiencies identified by soil testing and to demonstrate how the sentinel blocks can provide a powerful framework for intervention testing and modelling of responses in landscapes. Distributing intervention trials across clusters and blocks ensures that a wide range of conditions are sampled and allows responses to be modelled in relation to other baseline data, thereby enhancing knowledge on factors influencing intervention performance, and increasing ability to generalize results to other areas. A similar approach was used to establish agroforestry trials, although not reported here.



**FIGURE 13.15**

Estimated risk of being in poor soil condition class based on Quickbird (QB) reflectance. Red represents areas with >50% probability of having "poor" topsoil condition. The probability

increases with increasing intensity in the red colour (logit scale with white areas <0). Spatial resolution  $\approx$  2.4 m.



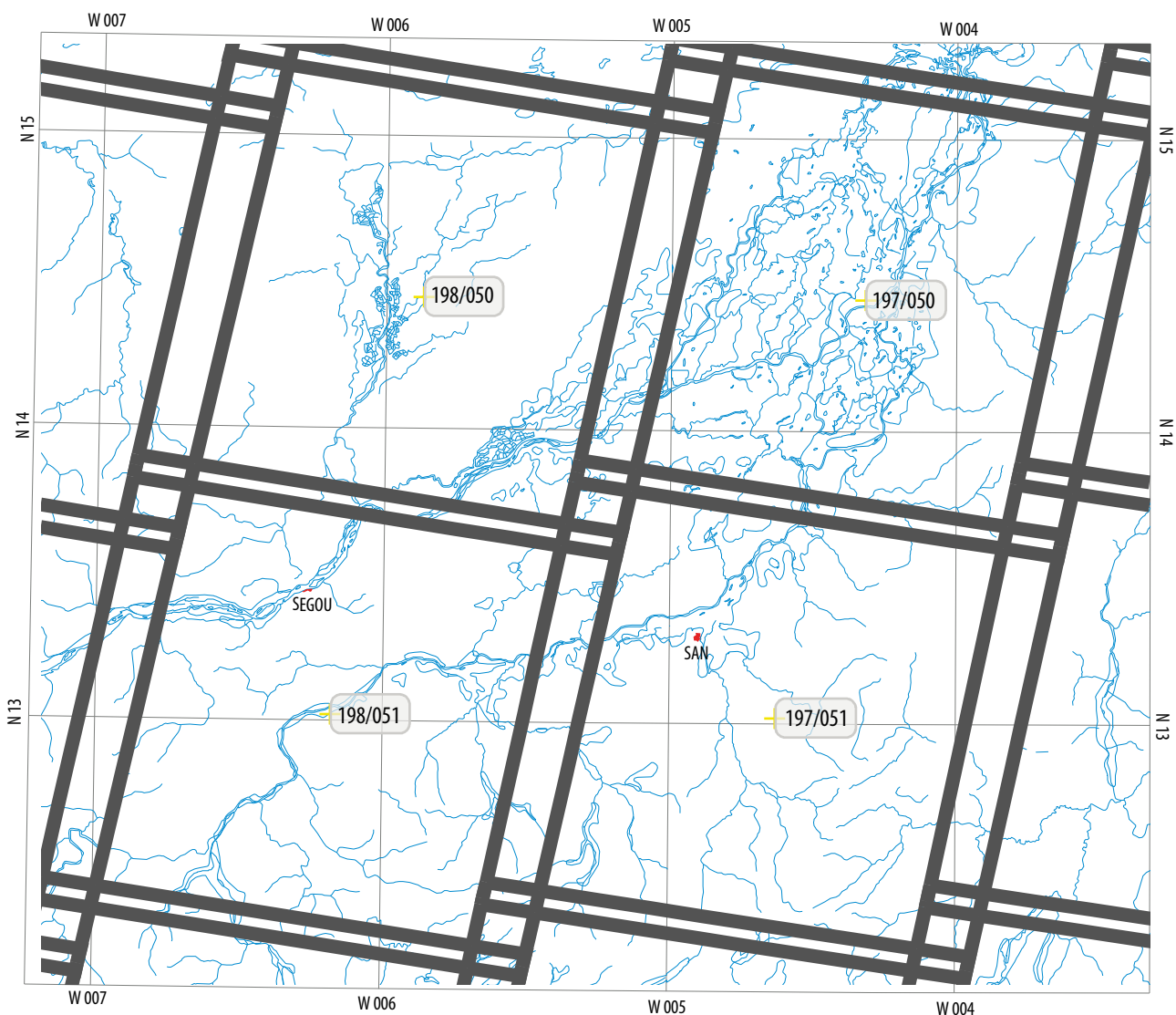
These trials were designed to model the effects of various fertilizer applications on millet growth performance and yield in farmer fields (Figure 13.20). Two farmers were randomly selected within each sampling cluster. Millet was planted at a population of 2.44 hills per m<sup>2</sup> in 36 m<sup>2</sup> plots. Management was not altered other than applying various fertilizer combinations (Table 13.7). The land was tilled following normal practices in the region. Fertilizers were applied as Urea, PNT (a natural phosphate rock) and potassium sulphate (K<sub>2</sub>SO<sub>4</sub>) (Table 13.7). Potassium sulphate and PNT were applied prior to sowing, while Urea was applied at tasseling, based on recommendations from researchers at the Cinzana Agronomic Research Station (CRRA). All fertilizer trials were georeferenced.

Millet (*Pennisetum glaucum* L. – Figure 13.20) variety Toroniou C1 was used in the trials, based on recommendations from local research. This variety is early maturing. Seeds were purchased from the CRRA to ensure proper (and as uniform as possible) seed quality. Four to five seeds were sown in each planting hole, and the millet was thinned a few days after germination. Weeding was also conducted a few days after germination and as needed through the rest of the growing season.

Plant counts were monitored through the season, while 9 plants were monitored for their growth performance through measurements of height and basal stem circumference every 3 weeks. Finally,

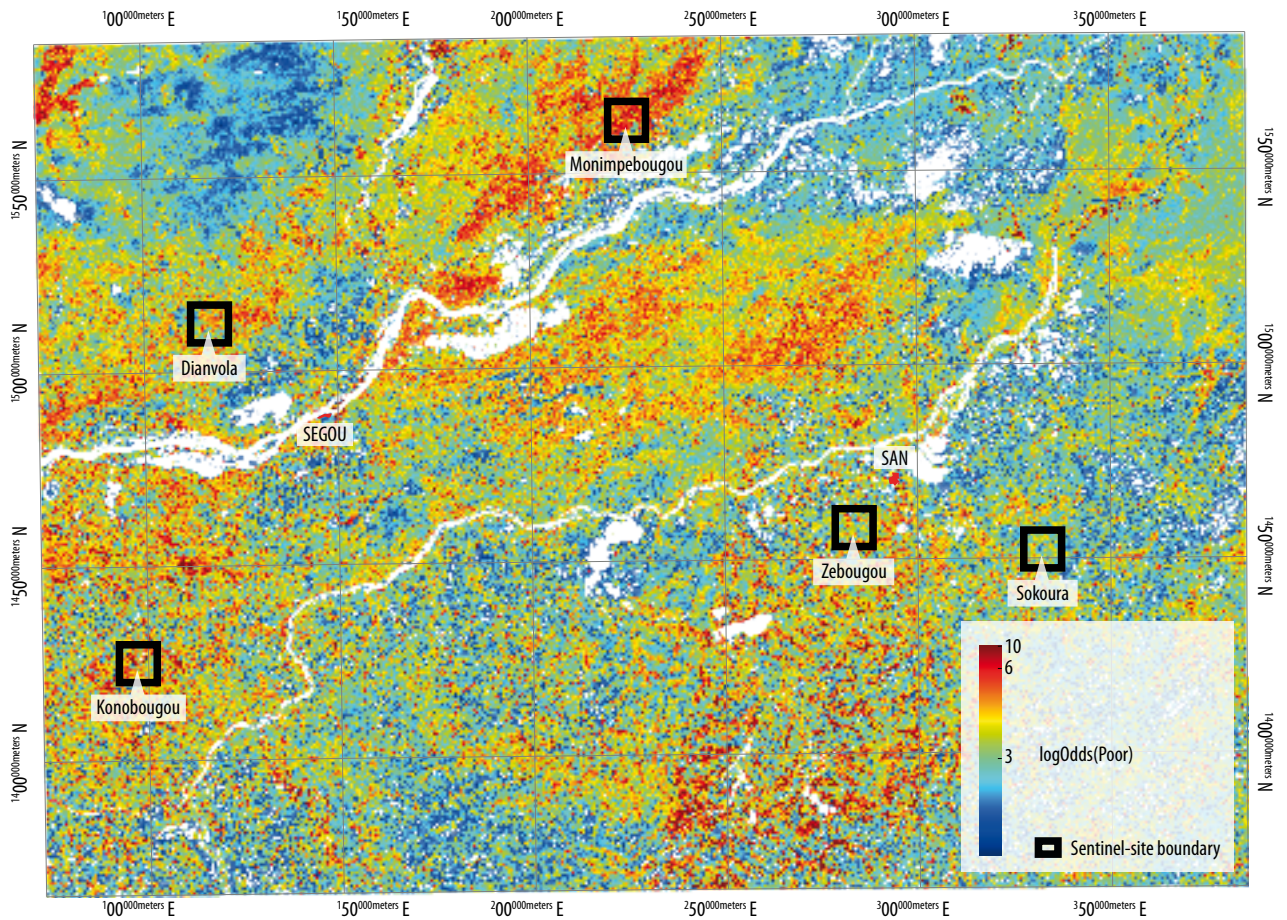
**FIGURE 13.16**

Map showing Landsat ETM+ (WRS 2) scenes (October–November 2001) used in development of regional soil degradation hot-spot map.



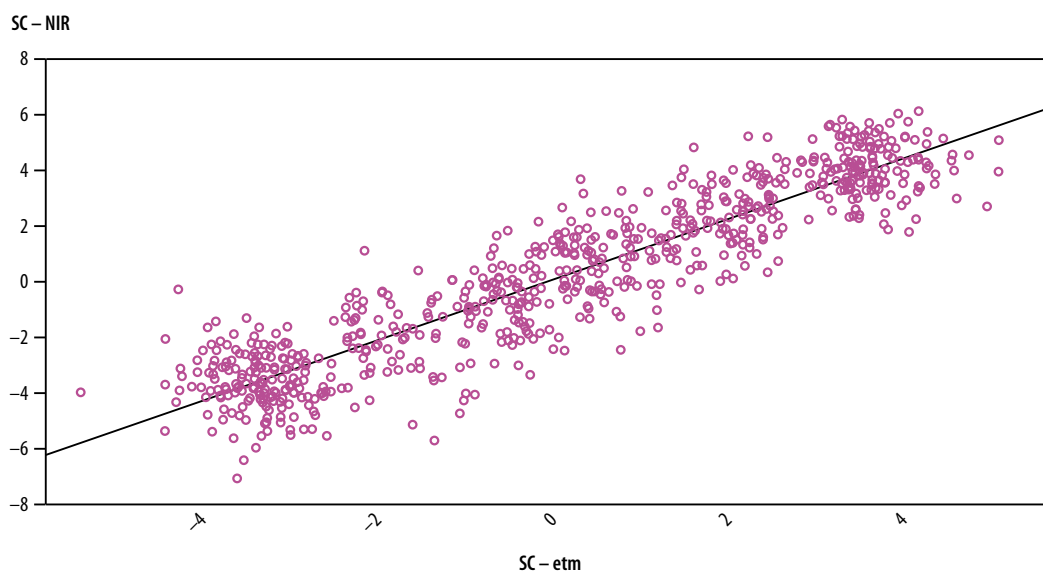
**FIGURE 13.17**

Map of Segou Region showing areas with >75% probability of being in poor soil condition class. Red areas are predicted to have a very high risk of soil degradation.



**FIGURE 13.18**

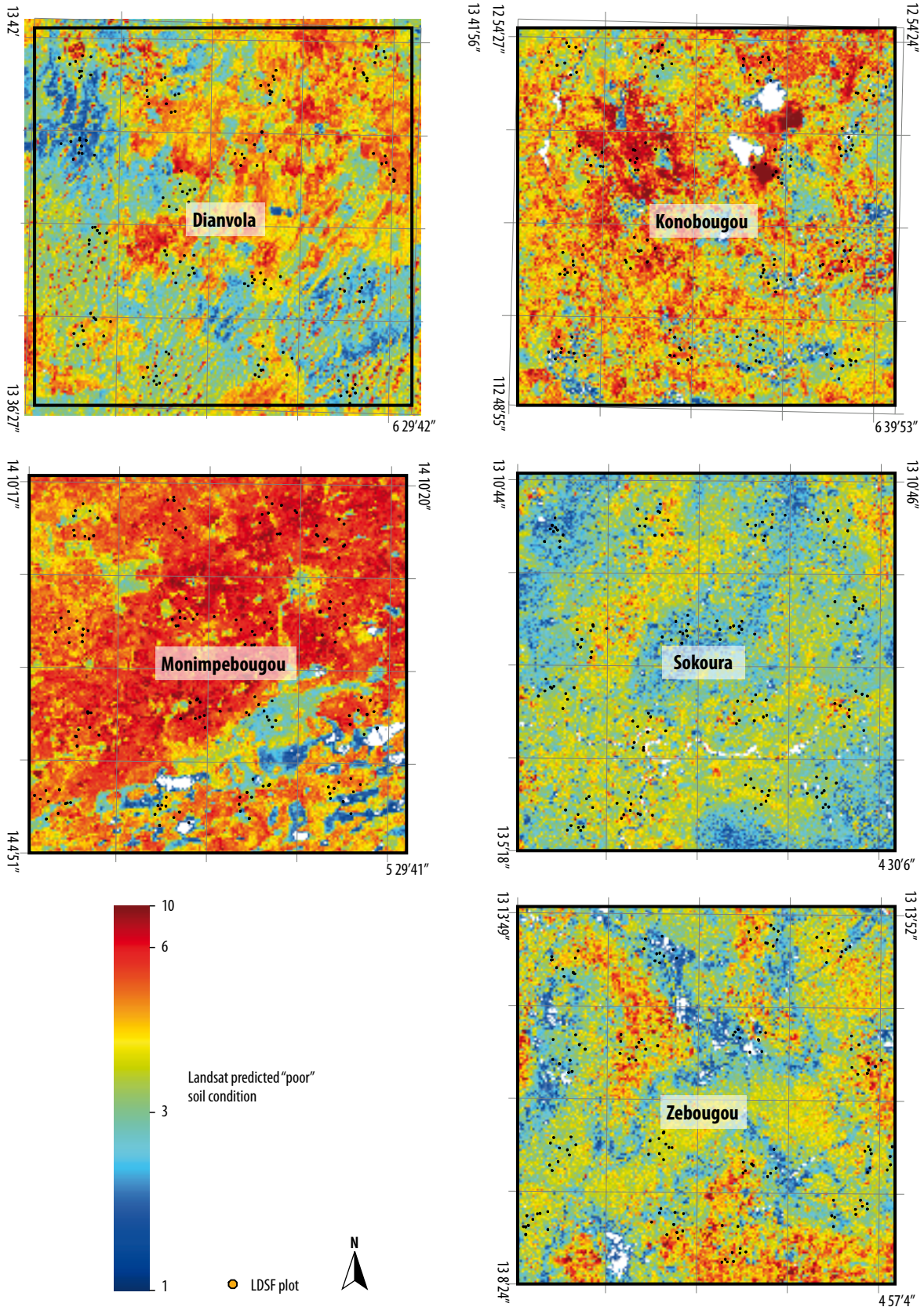
NIR-based vs. ETM-based soil condition (SC) indices ( $r^2 \sim 0.85$ ).



**FIGURE 13.19**

Estimated risk of being in poor soil condition class based on Landsat (ETM+) reflectance, coloured areas represent areas with high probability (logit scale) of having "poor" topsoil condition (see

Legend and Figure 13.17). Spatial resolution  $\approx$  28.5 m. See also Figure 13.15 for a comparison with results based on Quickbird reflectance.



straw and grain yields were measured at harvest. Altogether eight fertilizer treatments were included in the trials (Table 13.7). Occurrences and severity of pests, diseases and damage were scored at the same time as the growth measurements. Topsoil (0–20 cm) and subsoil (20–50 cm) samples were collected from each plot by compositing samples from 5 auger holes in each plot.

Growth performance was assessed by fitting non-linear models to calculated biovolumes for individual plants in the trials, much like dose-response curves in medical trials, while grain and straw yields were measured at harvest and after drying (i.e. dry-weight). We also assess the relationships between yields and maximum biomass production.

### Crop growth

A major benefit of using non-linear models is that the parameters of the models have physical meaning (i.e. are mechanistic), as they describe both the rate of growth and maximum biomass production at the end of the season. Growth response also provides a robust estimate of fertilizer response in such trials. We model plant response using a non-linear mixed-effects (NLME) model (Pinheiro and Bates, 2000) with random intercepts for block and treatment within block levels (Equation 13.3):

$$y_{ij} = \frac{\theta_1}{1 + \exp[-(t_{ij} - \theta_2)/\theta_3]} + \epsilon_{ij},$$

$$b_{1i} = \begin{bmatrix} b_{10} \\ b_{11} \\ b_{21} \end{bmatrix} \sim \mathcal{R}(0, \Psi_1), b_{1j} = \begin{bmatrix} b_{10,j} \\ b_{11,j} \\ b_{21,j} \end{bmatrix} \sim \mathcal{R}(0, \Psi_2),$$

$$\epsilon_{i,j,k} \sim \mathcal{R}(0, \sigma^2)$$

(Eq. 13.3)

**FIGURE 13.20**

Millet variety used in fertilizer response trials.



**TABLE 13.7**

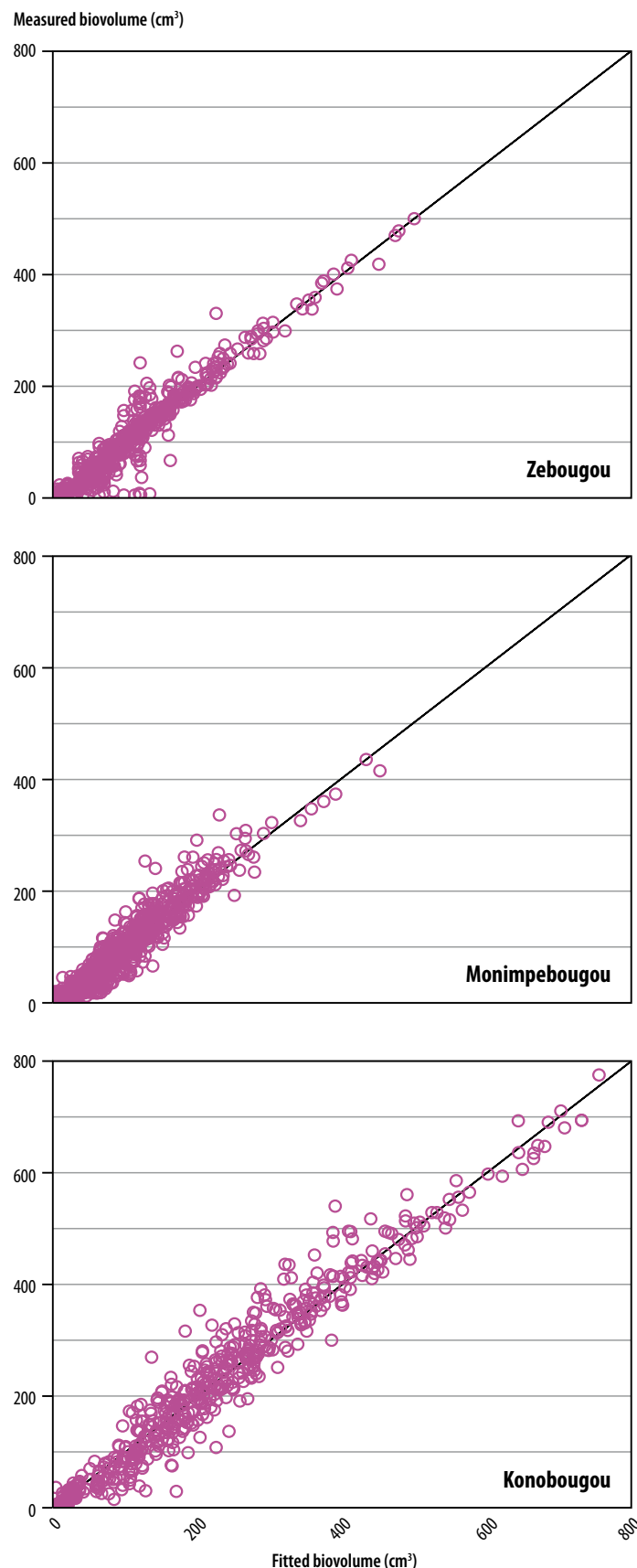
Overview of fertilizer response trial treatments.

Treatment number	Treatment code	Treatment	Fertilizer application
T.1	000	Control	
T.2	111	NPK	Urea* + PNT† + K <sub>2</sub> SO <sub>4</sub> ‡
T.3	100	N	Urea
T.4	010	P	PNT†
T.5	001	K	K <sub>2</sub> SO <sub>4</sub> ‡
T.6	011	PK	PNT† + K <sub>2</sub> SO <sub>4</sub> ‡
T.7	110	NP	Urea + PNT†
T.8	101	NK	Urea + K <sub>2</sub> SO <sub>4</sub> ‡

N = Nitrogen; P = Phosphorus; K = Potassium \*50 kg ha<sup>-1</sup>; †100 kg ha<sup>-1</sup>

**FIGURE 13.21**

Fitted (using Equation 13.3) versus measured biovolume production per plant for the three blocks included in the fertilizer response trials.



where  $y_{ij}$  is the average crop biovolume for each plot at each of four occasions (recordings) during the growing season,  $t$  is day number,  $\theta_1$  is the asymptotic crop biovolume,  $\theta_2$  is the day on which each crop attains half its biovolume (inflection point), and  $\theta_3$  is the crop growth scale (shape parameter).

As shown in Figure 13.21, the logistic model in Equation 13.3 describes the millet growth pattern reasonably well. The estimated maximum biomass production ( $\theta_1$ ) for the eight fertilizer treatments shown in Table 13.7 are presented in Table 13.8, together with estimates of standard errors and significance tests. Average growth curves for each treatment are shown in Figure 13.22. The application of N and P together (NP) yielded the highest growth rates, while NPK has less effect though it is significantly higher than the control treatment. The lowest growth rates are in treatments receiving K alone and in the control treatment. The point of inflection on the growth curves is generally at between 48 and 50 days (Figure 13.22), and does not vary much between treatments. There is, however, some difference in maximum biomass production at the end of the growing season between the three sampling blocks, with Konobougou generally having higher average biomass production for all treatments than Zebougou and Monimpebougou (Figure 13.22 sub-figure).

### Crop yields

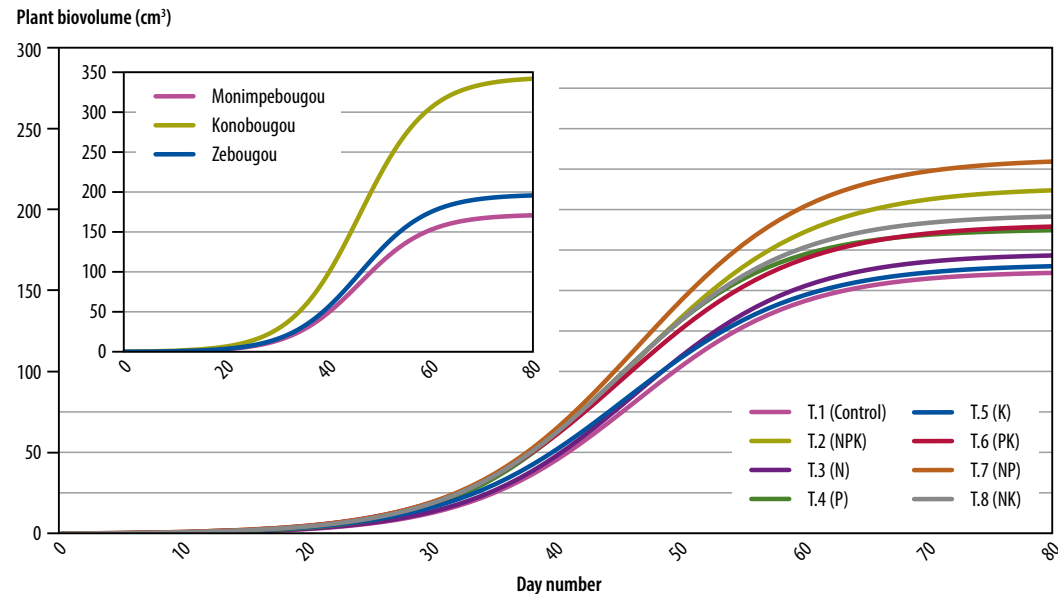
We assess grain and straw yield responses to fertilizer treatments using linear mixed-effects (LME) models, with random effects at block, cluster and farmer levels. The grain and straw yield data sets were log-transformed to obtain approximately normal distributions (i.e. to remove a right-tail skew in the data).

Monimpebougou has the lowest average grain yield, with 218 kg ha<sup>-1</sup>, and generally lower grain yields for all treatments, relative to Zebougou and Konobougou (Figure 13.23). Part of the explanation for the lower grain yields in Monimpebougou is that a number of plots were affected by downy mildew (*Peronosporaceae* spp.) due to late planting after the onset of rains. We therefore cannot put too much confidence in the grain yield data. On average, grain yields are highest in treatments receiving N and P (T.7) and N, P and K (T.2) (Table 13.9). Plots receiving N or K alone have similar yields as the control treatment while plots receiving P alone have higher grain yields than the control ( $p=0.03$ ). Straw yields are less variable between blocks than grain yields,

**FIGURE 13.22**

Average growth response curves expressed as estimated plant biovolume (cm<sup>3</sup> per plant) for the

eight fertilizer treatments (see also Table 11.8), and averages for each block (sub-figure).

**TABLE 13.8**

Estimated average maximum biovolume (cm<sup>3</sup>) production per plant ( $\theta_1$ ) for the various fertilizer treatments, together with standard error (SE) and p-value estimates.

Treatment	$\theta_1$	SE	p
Control	162	45.9	
N	173	17.0	0.524
P	188	17.0	0.126
K	166	17.0	0.800
NP	231	17.0	0.000
NK	197	17.0	0.041
PK	191	17.0	0.090
NPK	214	17.0	0.002

but Konobougou generally has the highest straw yields (Figure 13.24), and the highest within-block variability, largely reflecting biovolume estimates. As for grain yield, NP and NPK treatments (T.2 and T.7) give the highest straw yields (Table 13.9). However, in absolute terms yield responses were small and would not justify the cost of fertilizer use.

The growth and yield responses generally correspond with the soil analyses, with available phosphorus being an over-riding constraint, and nitrogen (due to the low organic matter contents) being the next limiting factor. The soil analyses suggested that available K was

not as strong a constraint as N and P deficiency and this is also reflected in the yield responses. Clearly low-availability of soil P is a fundamental constraint on food crop production in the region and little progress will be made towards increasing food production until this problem is ameliorated. However, the damped yield responses suggest that soil organic matter may be limiting in these soils and organic amelioration may be required for profitable fertiliser use. Future work should focus on field trials combining organic and inorganic inputs, together with the development of spectral screening tests to diagnose sites in need of organic amelioration for profitable fertilizer use.

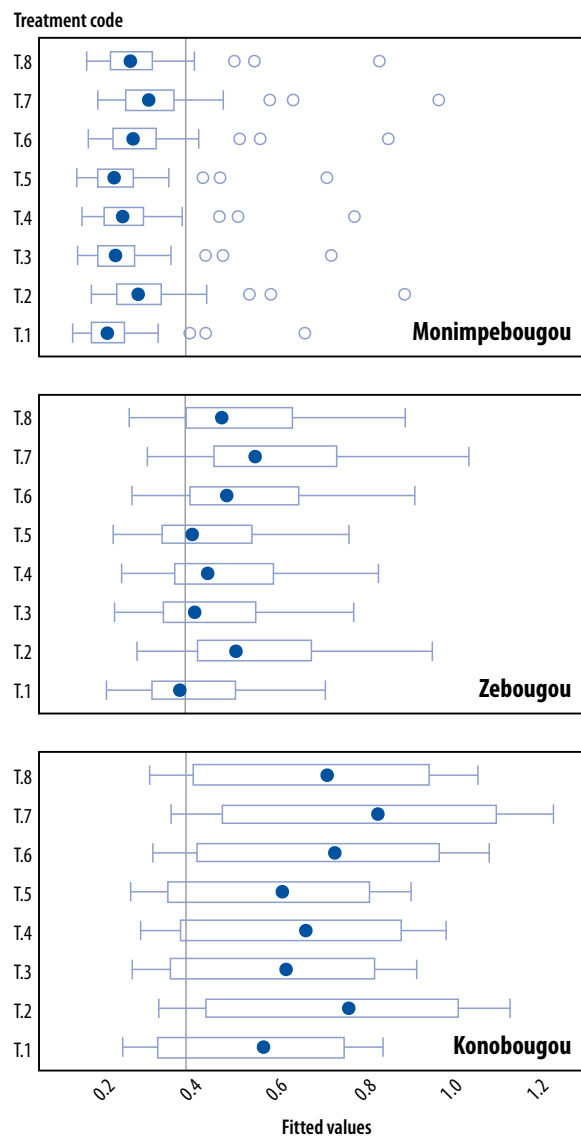
**TABLE 13.9**

Average grain and straw yields across blocks (Mg ha<sup>-1</sup>), including 95% Confidence Intervals.

Treatment	Grain yield			Straw yield		
	L	Mean	U	L	Mean	U
Control	0.08	0.32	0.55	0.40	0.65	0.91
NPK	0.16	0.46	0.76	0.49	0.87	1.25
N	0.08	0.38	0.68	0.41	0.79	1.17
P	0.08	0.39	0.69	0.38	0.76	1.14
K	0.05	0.35	0.66	0.27	0.65	1.03
PK	0.13	0.43	0.73	0.42	0.80	1.18
NP	0.22	0.52	0.82	0.62	1.00	1.38
NK	0.13	0.43	0.73	0.47	0.85	1.23

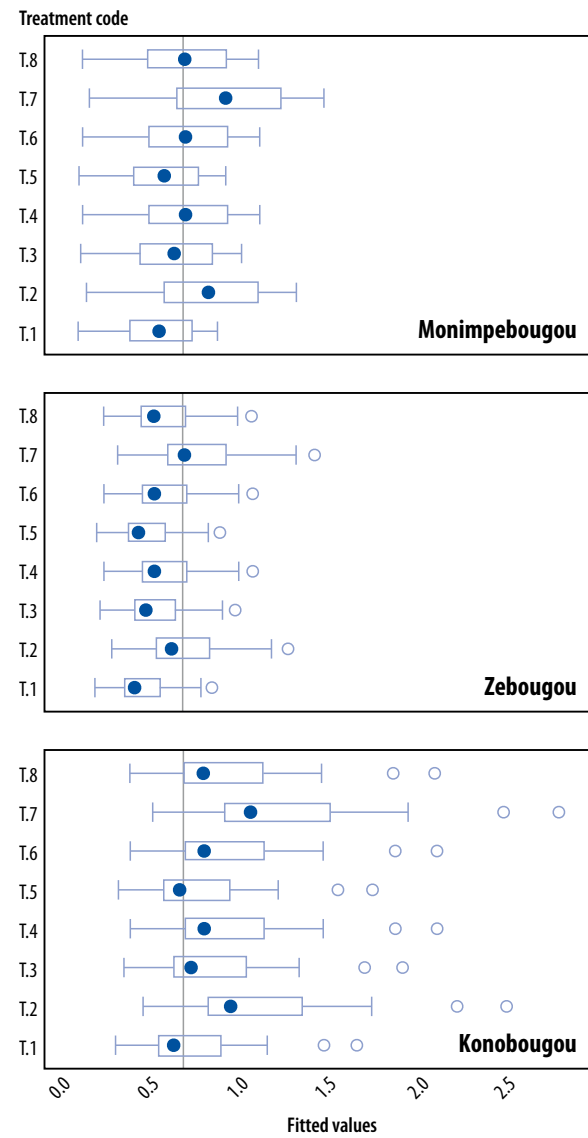
**FIGURE 13.23**

Estimated grain yields for the various fertilizer treatments, split by block. Vertical lines are population medians.



**FIGURE 13.24**

Estimated straw yields for the various fertilizer treatments, split by block. Vertical lines are population medians.





# Identification of priority intervention areas

## INTRODUCTION

One of the functions of the sentinel block baselines is to help target priority areas and type of interventions in relation to the types of land degradation problems and soil constraints that exist. This information can then be fed into policy formulation and local extension programmes as part of a negotiation-support process combining information on socioeconomic factors and land user preferences (Chapter 15). Here we propose a rule-based approach to determining priority intervention areas based on the ground survey data. The aim of the basic intervention recommendations is that they are based on readily observable indicators of the state of the land. Since management options will vary depending on whether interventions are made in, for instance, cultivated or managed areas or in semi-natural and natural areas (e.g. forest or bush-land), as well as on MAP and other climate variables, we treat cultivated and semi-natural and natural land separately and consider environmental covariates. We finally link the management recommendations to our assessments of soil condition, based on NIR spectra, to identify cultivated areas having a high likelihood of poor soil fertility. By linking the analysis of priority intervention areas for reforestation, based on our field survey data, to high-resolution remote-sensing data we can also spatially target interventions. Such maps provide a good basis for setting quantitative targets for intervention programmes and rigorous assessments of intervention impacts in the future, as woody cover density can be relatively accurately assessed from satellite imagery. The LDSF, in combination with ancillary information, thus provides a monitoring and evaluation framework, starting with the baselines reported here.

## INTERVENTIONS IN SEMI-NATURAL AREAS

In semi-natural areas (i.e. sites that are not currently cultivated or managed), we target locations having a sparse woody cover for reforestation interventions. We also identify areas having a high inherent soil degradation risk (HIDR), combined with sparse woody cover. In some of our blocks, root depth restrictions occur very frequently in semi-natural areas, since they are located mainly on laterite outcrops. Areas having both sparse woody cover and root depth restrictions or abrupt textural changes (e.g. sandy loam overlaying clay loam) will generally be in urgent need of intervention to improve surface cover and prevent severe soil degradation. In defining priority areas for intervention we use a

**TABLE 14.1**

Estimated priority reforestation intervention area (ha) based on woody cover ratings for each cluster (100 ha).

Cluster	Dian	Kono	Moni	Soko	Zebo
	Area (ha)				
1	30	20	20	50	0
2	50*	10	10	40	0
3	60*	10	0	70	78
4	30	0	20	88	20
5	50	40	20	40	30
6	10	0	0	70	20
7	70	8	10	70	20
8	50*	0	0	33*	70
9	40	50	30	28	0
10	70*	28	60	20*	10
11	45*	30	20	60	18
12	60	10	10	60	0
13	0	40*	70*	50	40
14	60	35	30	10	20
15	10*	40	10	38	50*
16	40*	15	0	80*	60

\* Sparse woody cover and high inherent soil degradation risk.

cut-off probability estimate of 0.75 of having sparse woody cover and/or HIDR.

The estimated priority area for reforestation (i.e. semi-natural areas with sparse woody cover) is highest in Sokoura with about 5,000 ha, followed by Dianvola ( $\approx 4,200$  ha), Zebougou  $\approx 2,700$  ha), Konobougou ( $\approx 2,100$  ha), and Monimpebougou ( $\approx 1,900$  ha). The cluster-level distribution of priority areas is shown in Table 14.1.

As shown earlier, Monimpebougou has predominantly cultivated or managed sampling plots, limiting the area under semi-natural vegetation and thus also the intervention area for reforestation. There are, however, areas with semi-natural vegetation having both sparse woody cover and high inherent risk of soil degradation (Table 14.1). In Konobougou, most clusters in semi-natural areas have a high woody cover rating ( $>40\%$ ), limiting the number of priority intervention areas in semi-natural parts of the block. In Dianvola, about 440 ha have both sparse woody cover and HIDR, while the estimate for Sokoura is about 190 ha. Clusters with occurrence of both sparse woody cover and HIDR should be prioritized for intervention given their higher susceptibility to rapid degradation. Figure 14.1 shows a selection of priority intervention clusters, together with woody vegetation cover estimates based on Quickbird imagery and colour composites of Quickbird images. The randomized plot locations on which the estimates in Table 14.1 are based are also shown.

**TABLE 14.2**

Priority conservation agriculture intervention area (ha) for each cluster (100 ha).

Cluster	Dian	Kono	Moni	Soko	Zebo
	Area (ha)				
1	40	0	30	10	8
2	0	50	30	10	0
3	0	0	48	0	0
4	0	30	10	10	20
5	0	0	0	0	30
6	0	8	40	10	0
7	0	0	10	0	20
8	0	30	10	30	10
9	20	0	30	0	10
10	0	0	10	20	0
11	0	20	10	0	30
12	0	10	10	0	70
13	60	10	10	0	28
14	0	0	20	10	40
15	0	10	20	0	20
16	0	0	50	10	0

## INTERVENTIONS IN CULTIVATED AREAS

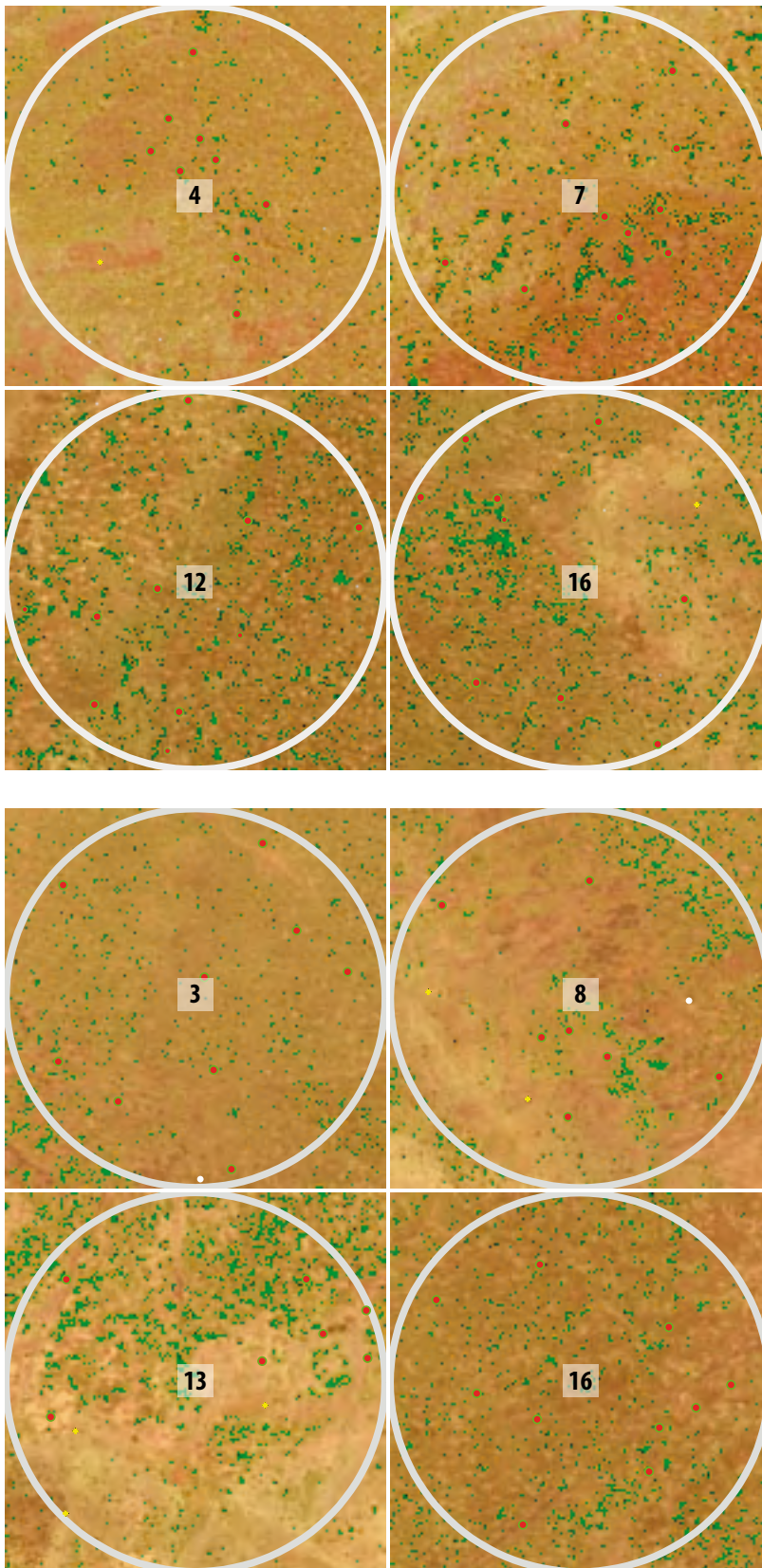
Cultivated or managed areas having a high inherent risk of soil degradation may be targeted for conservation agriculture, agroforestry, reduced tillage or other practices that increase soil cover and improve soil carbon status. An estimated 2,100 ha in Monimpebougou should be targeted for conservation agriculture practices, while the estimates are about 1,800, 1,000, 750 and 700 ha for Zebougou, Konobougou, Dianvola and Sokoura respectively.

The clusters having the highest frequency of HIDR are highlighted in Table 14.2, and shown for Monimpebougou in Figure 14.2, and for Dianvola and Zebougou in Figure 14.3. Boundaries between semi-natural and cultivated areas are very clear in Zebougou, while recently cultivated areas (red) contrast fallow-land in Dianvola (green to blue).

## FIGURE 14.1

Maps of selected identified priority reforestation clusters in Sokoura (top) and Zebougou (bottom) (see also Table 14.1). Green is dense woody cover and orange is sparse or absent woody cover. Points are

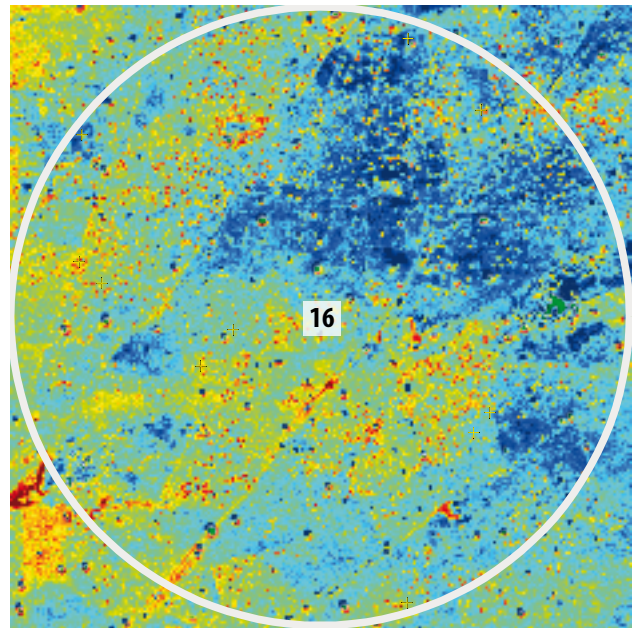
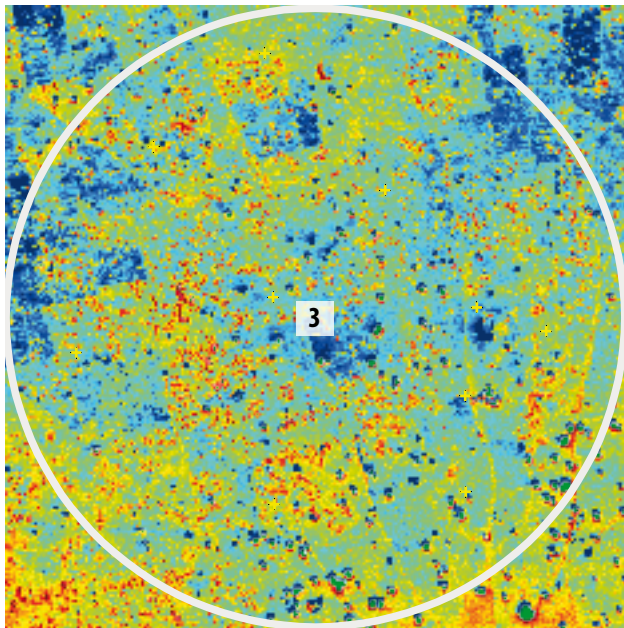
LDSF sampling plot centroids: crosses are cultivated or managed, and circles are semi-natural. Quickbird image (true-colour composite) is shown in the background.



**FIGURE 14.2**

Priority intervention areas in cultivated or managed clusters in Monimpebougou (see also Table 14.2). Background shows

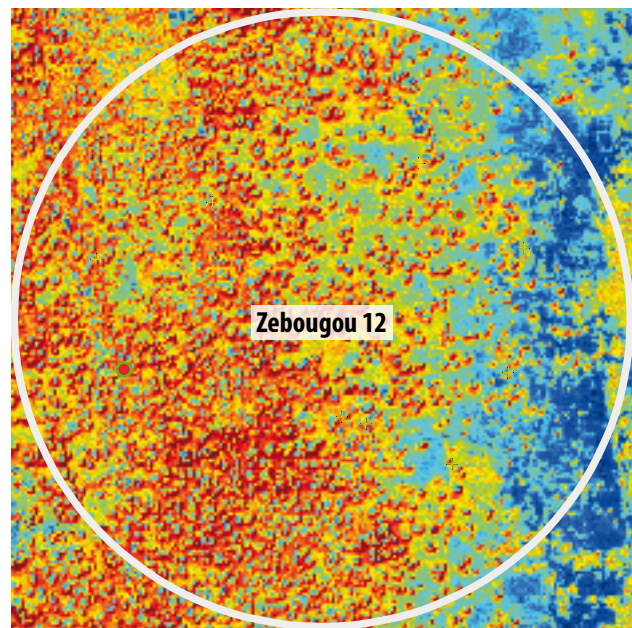
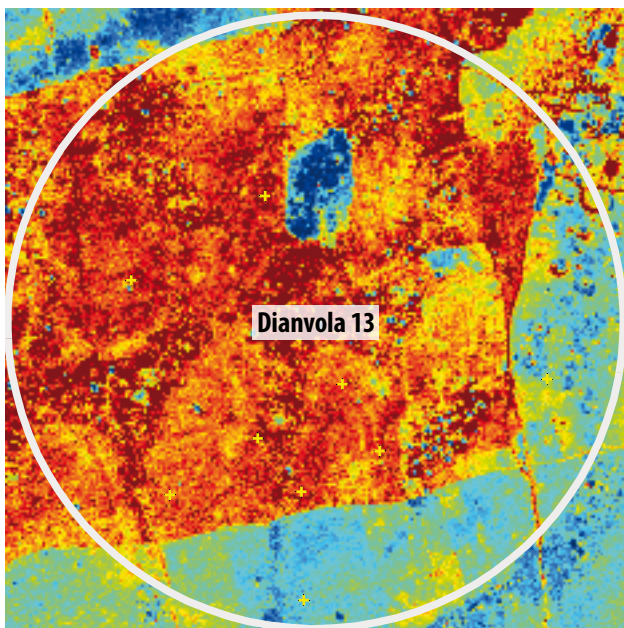
predicted soil condition from near infrared spectra, calibrated to Quickbird reflectance (Figure 13.15).



**FIGURE 14.3**

Priority intervention areas in cultivated or managed clusters in Dianvola (left) and Zebougou (right) (see also Table 14.2).

Background shows predicted soil condition from near-infrared spectra, calibrated to Quickbird reflectance.



A targeted soil-fertility programme to provide phosphorus dressings, to overcome this basic limiting constraint to agriculture, is a high priority for food security in the region. These high-level investments should be targeted to currently cultivated areas where there is low inherent risk of soil degradation. These areas comprise only 9–63% of the total area of the sampled blocks (average area 31%), and only half of the total currently cultivated area.

In parkland systems, cultivated areas may also be targeted for enrichment planting of trees. We set a target of 15 trees ha<sup>-1</sup>, which is the random intercept at block-level for Zebougou when fitting a Poisson model to tree counts in cultivated areas only. The target was based on this block as it had the highest proportion under fairly intact Parkland. Using the random effects coefficients from this model at cluster level, we can calculate an estimated number of trees that need to be planted per hectare to meet this target (Table 14.3). Wall maps showing the intervention priority areas and tree planting targets, overlaid on the Quickbird images for each block, were supplied to the Segou forest extension services (Directorate for Nature Conservation, DNCN) and extension officers were shown how to navigate to positions on the map using a Global Positioning System.

In this case study, the emphasis of the rule-based approach to intervention targeting was on agroforestry-based interventions for rehabilitation of degraded areas. The decision

**TABLE 14.3**

Estimated number of trees ha<sup>-1</sup> to be planted as enrichment planting in cultivated areas within each cluster to reach a target density of 15 trees ha<sup>-1</sup>.

Cluster	Dian	Kono	Moni	Soko	Zebo
	Trees ha <sup>-1</sup>				
1	13		13	12	0
2	13	10	13	12	
3			13	12	
4		5	13	12	0
5		9	13	12	0
6	13	4	13	12	
7	13		13		0
8	13	10	13	11	3
9	13		13	12	3
10	13		13	12	0
11	13	8	13		4
12	13	9	13		0
13	13	9	13	12	0
14	13		13	11	3
15	13	9	13	12	0
16	13		13	12	7
<b>Estimated total number of trees to be planted in each block</b>					
	130,830	79,130	132,870	117,590	0

rules have been kept relatively simple and limited to indicators that are readily observed. There is, however, scope for expanding this approach in future studies, combining biophysical and socioeconomic variables.

# Human well-being and tree planting preferences

## **SOCIOECONOMIC PROFILES**

Socioeconomic profiling of the Land Degradation Surveillance Framework (LDSF) sentinel blocks is conducted using a wide range of indicators related to people, households, poverty, agriculture and the environment (Figure 15.1). Indicators used may vary from region to region, depending on the relevance of questions to specific locations or settings. The collection of socioeconomic data is designed to complement LDSF biophysical baselines by applying indicators that enable us to link land degradation risk factors to key socioeconomic indicators such as land tenure, farm size, livestock, household demography, education, water access, food security, and demand for trees. Another objective with socioeconomic surveys may be to identify particularly vulnerable segments of the population. The sentinel blocks also provide a spatial framework and rich baseline data set on which more detailed socioeconomic studies and historical reconstructions can be superimposed.

In this chapter we provide basic socioeconomic profiles for the five sentinel sites studied, as well as analytical results on key indicators for the Sahel, such as water, soil fertility, trees, and agricultural constraints. In theory, the surveys would have covered 2 households in each cluster (total of 160 households), but some clusters did not have any villages or settlements in them and farmers in some areas are semi-nomadic, and so the number of households surveyed is lower. The households were randomly selected within the clusters in the five sentinel sites.

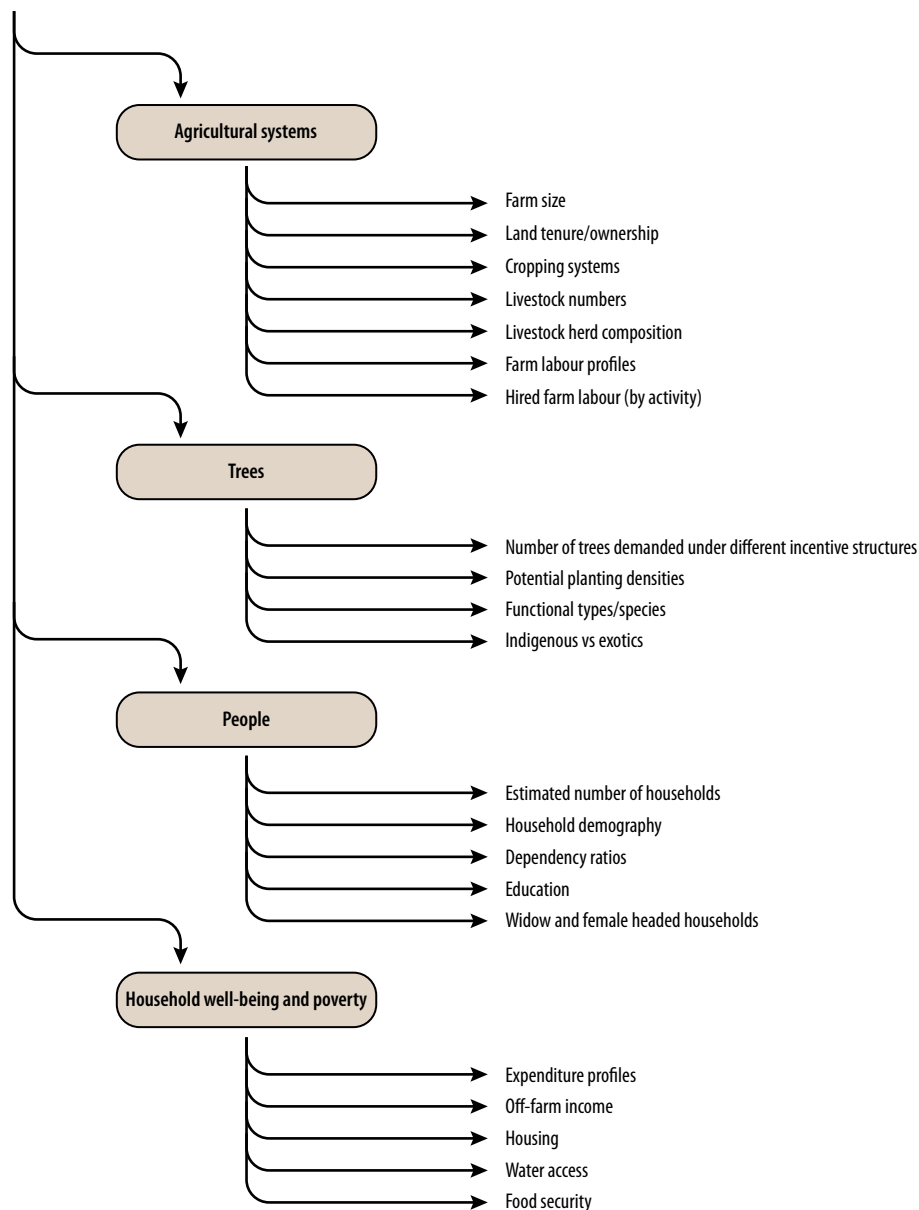
## **HOUSEHOLD CHARACTERISTICS**

A total of 84 households with 1,272 household members were surveyed in the five blocks (Table 15.1) during March and April 2007. Few households were available for interview during the survey period in Dianvola since people in this area are semi-nomadic and the majority of the area was abandoned, resulting in only 6 households being interviewed for the survey. The average number of members in each household varies from 11 (Dianvola) to 21 (Konobougou) (Table 15.1), all surveyed households being male-headed. Basic statistical summaries of average age and sex distributions in each block are presented in Table 15.2. If we exclude Dianvola, the number of males and females in the households is similar. Illiteracy in the age group from 15–65 years is at about 80%, with the majority of the literate part of the population having only primary

**FIGURE 15.1**

Socioeconomic indicators in the Land Degradation Surveillance Framework (LDSF).

**Socio-economic indicators**



education. None of the individuals surveyed had university-level education, while two individuals in Monimpebougou had secondary or equivalent education levels.

**AGRICULTURAL SYSTEMS**

None of the households surveyed reported having title deeds to their land, as is customary in Mali. Food crops in the blocks were mainly millet and sorghum, with some fruit and vegetable production, mainly near the villages, while the major cash crop in the region is cotton.

**TABLE 15.1**

Basic summary of households surveyed in each block.

Block	Households (members)	Average age of respondent	Average number of household members
Dianvola	6 (65)	49	11
Konobougou	17 (364)	57	21
Monimpebougou	25 (325)	44	13
Sokoura	21 (259)	47	12
Zebougou	15 (259)	53	17

**TABLE 15.2**

Age and sex distributions (counts) of household members, summarized for each block.

Block	Age (years)			Sex	
	<15	15–65	>65	Female	Male
Dianvola	14	44	1	18	41
Konobougou	140	185	7	147	185
Monimpebougou	149	140	11	148	152
Sokoura	107	128	5	120	120
Zebougou	115	131	5	131	120
SUM	525	628	29	564	618

Livestock numbers (Table 15.3), reported in tropical livestock units (TLU), vary between blocks. Konobougou has the highest livestock numbers on average, and the highest densities, when calculated in number of TLUs per person in the surveyed households (Table 15.4). The lowest livestock densities are found in Monimpebougou, with about 0.5 TLUs per person, on average. In Konobougou, the ratio of goat and sheep TLUs to human population is about 1.3, while the ratios are 0.9, 0.9, 0.7 and 0.6 in Dianvola, Zebougou, Sokoura and Monimpebougou respectively. Konobougou also has the highest

densities of cattle, with an estimated 0.54 cattle per person on average.

Most of the households surveyed (>80%) reported spending money on their livestock in the previous year, although expenditure prevalence was lower in Monimpebougou at about 68%. About 50% of the respondents had spent money on veterinary services, while 29% had spent money on purchasing animals. The remainder reported not spending money on their livestock in the previous year. The annual amounts spent on livestock

**FIGURE 15.2**

Well in Zebougou.





**TABLE 15.3**

Tropical livestock units (TLU) assigned to different types of livestock.

Livestock type	TLU
Camels	1.10
Cattle – adults	0.80
Cattle – calves	0.25
Donkeys	0.80
Smallstock	0.20
Poultry	0.01

**TABLE 15.4**

Ratio of tropical livestock units (TLU) to human population.

Block	Mean
Dianvola	0.84
Konobougou	0.90
Monimpebougou	0.52
Sokoura	0.70
Zebougou	0.48

vary from about 30,400 fCFA in Sokoura to about 52,000 fCFA in Konobougou, but some households report having spent >200,000 fCFA on the purchase of animals.

### HOUSEHOLD WELL-BEING

Of the five sentinel sites surveyed, Zebougou and Konobougou have the highest proportion of households that are dependent on purchasing food grains: 71% and 69%, respectively. Based on the available data from the survey reported here, households purchase food grains for about two months of the year, although there is significant variability within blocks (Table 15.5). The amounts spent on food grains vary between blocks from about 25,000 fCFA on average for all households in Sokoura to almost 80,000 fCFA in Konobougou.

An estimated 19% of the households in Sokoura hire external labour, while the estimate is less than 5% of the households in the other blocks. In Sokoura, an estimated average annual amount of 14,600 fCFA is spent on external labour.

Access to drinking water is generally good in the households surveyed, with all households

**TABLE 15.5**

Food grain purchase in each of the surveyed clusters.

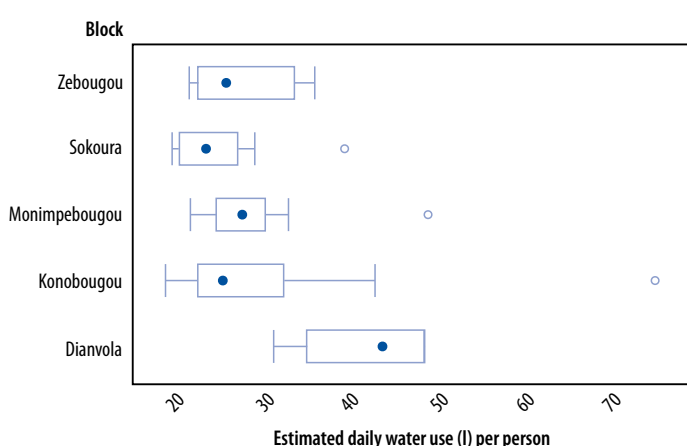
Cluster	Dian	Kono	Moni	Soko	Zebo
	Number of months per year				
1	-	-	1.6	0.5	2.6
2	0.8	0.6	0.2	0.5	-
3	-	4.9	1.9	0.3	-
4	-	3.8	-	4.1	2
5	-	6.5	2.3	1.1	-
6	0.2	4.7	0.8	0.5	-
7	-	-	0.8	-	1.3
8	-	0.8	0.9	1.9	0.3
9	-	-	2.7	1.3	1.3
10	-	-	1.2	0.7	-
11	-	1.6	2.3	-	1.6
12	-	1	2.4	-	4.1
13	-	1	3.6	2.3	2.5
14	-	-	0.6	0.5	2
15	-	1.1	0.4	1.7	3.4
16	1.9	-	2.6	2.6	-
Average <sup>1</sup>	1.7	2.1	1.7	1.6	1.9

<sup>1</sup> Estimated block average.

reporting access to wells within their villages (Figure 15.2). Block averages for daily consumption of water for domestic use (i.e. washing and drinking) are between 28 and 30 litres per person per day. However, there is significant variation between households within blocks (Figure 15.3).

**FIGURE 15.3**

Estimated daily water use (litres) per person in the five blocks. Note that the estimate for Dianvola is based on data from only three clusters.



**FIGURE 15.4**

*Vitellaria paradoxa* leaves, flowers and fruit.



Source: Flora of Tropical East Africa (Hemsley, 1968).

### TREE PLANTING PREFERENCES

The respondents from the households were initially asked to identify important agroforestry tree species that they protect, and rank each species according to importance. *Vitellaria paradoxa*, or karite-nut or shea, is the tree species ranked as most important by farmers (Table 15.6; Figure 15.4) as a source of oil or fat, and for economic use. Other important species that farmers protect include *Adansonia digitata*, *Faidherbia albida* and *Sclerocarea birrea*.

Farmers were then asked whether they had any plans for or interest in planting more trees in their farms. Those who responded that they would like to plant more trees were then asked how many and what type of tree(s) they would plant if they were:

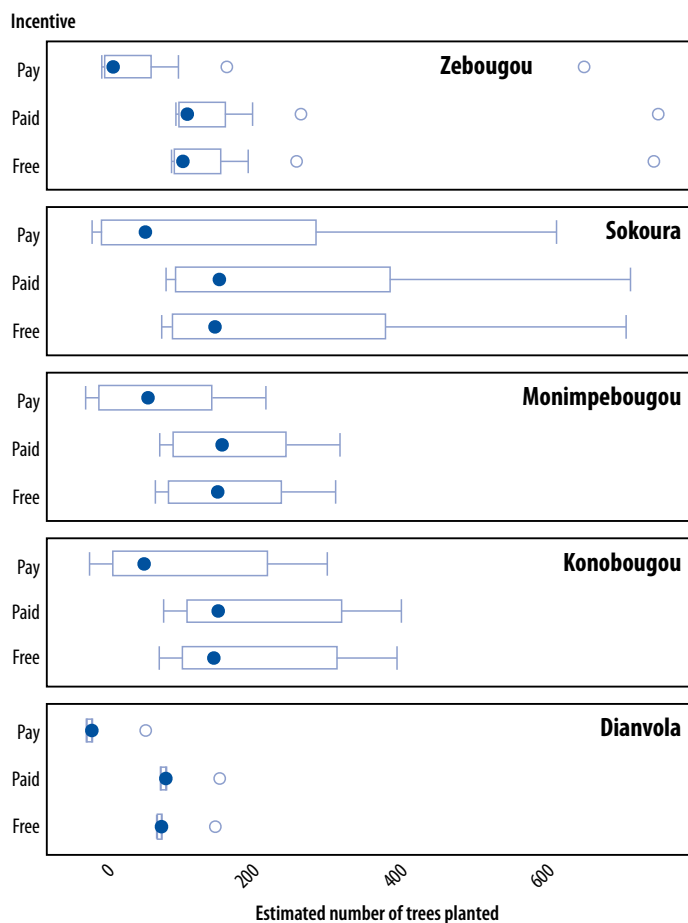
1. Given no incentive (pay),
2. Paid for each seedling planted,
3. Asked to pay for the seedlings themselves.

Among the households interviewed, 82 (of 84) responded that they were interested in planting more trees. On average, each household was willing to plant 162 trees. It made no difference whether no incentive was given (alternative 1) or they were paid to plant seedlings (alternative 2): respondents would on average plant approximately 195 trees under either scenario. If, however, farmers were to pay for seedlings (alternative 3), they would plant about half of the above number of trees ( $p < 0.01$ ), or an estimated 100 seedlings per household. These differences in response to the proposed incentives are fairly consistent between blocks, as shown in Figure 15.5. The results indicate that farmers are willing to invest labour to plant trees but the capital cost of seedlings poses a disincentive. Therefore policies should be directed towards reducing seedling costs and promoting farmer tree nurseries.

The most popular tree species for additional planting (Table 15.6) are *Mangifera indica*, for its fruits and as an important source of revenue, followed by *Eucalyptus camaldulensis* for wood production. *Adansonia digitata* and *Parkia biglobosa* are in demand as sources of food, while *Vitellaria paradoxa* and *Gliricidia sepium* are in demand as sources of fruits or oil and fodder, respectively. There is no difference in demand for different tree species among incentive structures. Tree germplasm improvement and supply programmes should thus prioritize on the high-ranking species.

**FIGURE 15.5**

Estimated number of trees planted under the three incentive structures.



**TABLE 15.6**

Tree species ranked by farmers as important in the five blocks. The species are sorted in descending order based on ranking (i.e. 1 is most important), while the numbers are counts of respondents.

Species	Ranking			
	1	2	3	4
<i>Vitellaria paradoxa</i>	42	17	7	
<i>Adansonia digitata</i>	8	5	10	
<i>Faidherbia albida</i>	7	5	4	
<i>Sclerocarea birrea</i>	3	9	11	1
<i>Borassus aethiopum</i>	3	2	1	
<i>Mangifera indica</i>	3	1		
<i>Lannea microcarpa</i>	2	12	9	
<i>Prosopis africana</i>	2	4	3	1
<i>Pterocarpus erinaceus</i>	2	2	1	
<i>Acacia senegal</i>	2			
<i>Parkia biglobosa</i>	1	8	6	
<i>Diospyros melpiliformis</i>	1	2		
<i>Ziziphus mauritiana</i>	1	1	2	
<i>Anogeissus leiocarpus</i>	1	1	1	
<i>Azadirachta indica</i>	1			
<i>Gliricidia sepium</i>	1			
<i>Mangifera indica</i>	1			
<i>Prosopis juliflora</i>	1			
<i>Tamarindus indica</i>		4	8	
<i>Khaya senegalensis</i>		2	1	
<i>Cordyla pinnata</i>		2		
<i>Lannea acida</i>		2		
<i>Acacia seyal</i>		1		
<i>Combretum ghasalense</i>		1		
<i>Balamites aegyptiaca</i>			4	2
<i>Annona squamosa</i>			1	
<i>Combretum glutinosum</i>			1	
<i>Detarium microcarpum</i>			1	
<i>Saba senegalensis</i>			1	1

## COSTS

There has been emphasis by many agencies on rapid and low-cost land degradation assessment methods. Our emphasis has been on the design of measurement systems that are (i) scientifically sound, especially with respect to the unbiased sampling frame and use of consistent plot sizes, (ii) robust in being practical and widely applicable under diverse and harsh African conditions, (iii) highly repeatable, and (iv) interpretable with an emphasis on slowly changing variables that genuinely reflect ecosystem health rather than short-term noise. This type of protocol has not

**TABLE 15.7**

Estimated costs (US\$) for sentinel site characterization.

Cost unit	Total
Senior field technician (2 months)	5,200
2 Field staff (2 months)	5,200
2 Casual staff (2 months)	2,600
<b>Subtotal</b>	<b>13,000</b>
Vehicle running costs	2,400
Food & field accommodation	3,000
Laboratory analyses	1,875
Satellite imagery	2,200
<b>Subtotal</b>	<b>9,475</b>
<b>Overhead (@10%)</b>	<b>2,247</b>
<b>Total</b>	<b>24,722</b>

often been implemented in the past at wide scale, partly because of a perception of high cost. The sentinel site characterization protocol demands dedicated field crews but is not technically demanding. A field team of one senior technician and two assistants can be trained in two days, and labour can be readily recruited from local communities. A field team can under average conditions complete one cluster per day and one sentinel block in 16 days of fieldwork.

The basic field operational cost for surveying and documenting each sentinel site, including labour, vehicle running costs, and analyses of remote-sensing and laboratory data is estimated at about US\$ 25,000 per sentinel site (Table 15.7). Time for preparation and data entry is included, however this estimate does not include scientists' time for data analysis and supervision, fixed costs for field office installations, or equipment costs, including vehicles, computers, and spectrometers. Costs associated with remote-sensing and data analysis will come down with further development of standardized software, such as 'R' scripts (Appendix 3.2).

These costs are modest when one considers the long-term value of the information generated by the sentinel site surveys and the multiple utilities of the sites. This is especially so when one considers the current lack of science-based learning in multi-million dollar development projects and the scientific and policy effort spent on studies and

inconclusive debates on the degree and extent of land degradation.

### **PROSPECTS**

We have demonstrated that the LDSF provides an operational framework for obtaining project-level baselines of land resources and socio-economic profiles, and for monitoring and evaluating project interventions and their impacts on land and people. Within the project context, the baseline provides a basis for assessing current land condition and constraints, and flexible targeting of priority intervention areas and households at the level of landscapes and human populations. The baseline provides a starting point for reliable detection of change in land condition, for assessing the impact of agroforestry-based interventions to restore degraded areas, and for project impact attribution. For example, the question “to what degree have project initiated reforestation activities increased carbon storage in the landscape?” can be answered. We have also demonstrated how the LDSF provides an efficient platform for systematic testing of interventions in the landscape, providing much more powerful inference and generalisation capabilities than conventional agronomic testing approaches. The overall approach is evidenced-

based and permits representation of uncertainties in measurements at different spatial scales.

The baseline data can contribute to basic ecological research by providing a rich body of information on coupled biophysical and socioeconomic variables and their variability at different scales. For example, systematic data collection across different ecosystems can assist with validation and refinement of models and provide empirical data for the development of new concepts and theories. In addition, the sentinel site data also provides valuable data for calibration, classification and interpretation of satellite images beyond the scale of the sentinel sites and hopefully lead to the development of new, more generalizable remote-sensing algorithms.

The most important potential outcome of this work, though, is for scientific assessment data to become closely integrated into national development and policy decision-making processes. This assessment, with modest resources, has characterized land condition in Segou Region to a high degree of specificity. It is certainly feasible with modest additional resources to establish a national land degradation surveillance system as an integral part of land management policy.

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# Appendix 3.1

The Land Degradation Surveillance Framework

# LDSF



*Guide to Field Sampling and Measurement Procedures*

Markus G. Walsh and Tor-G. Vågen

October 2006

# Table of Contents

**Before you go into the field.....3**

**Cluster-level sampling plan.....4**

**Plot layout..... 5**

**Measuring soil infiltration capacity..... 6**

**Land form and land cover classification.....6**

**Soil surface characterization.....6**

**Appendices.....8**

## The Land Degradation Surveillance Framework

### Before you go into the field

There are five main things you should do or consider before going into field:

- I. Assemble pre-existing information about the area, where this is available. Particularly important are items like topographical, geological, soils and/or vegetation maps, satellite images and/or historical aerial photographs, long-term weather station data, government statistics, census data etc. This help will help you conduct the field survey, for example you can use topographical maps for orienteering and navigation, but also later in interpreting the data.
- II. Make sure that everyone in the field team knows what they are doing, this includes navigation and orienteering (you don't want anyone getting lost in a remote area), as well as knowing all the relevant field procedures. Some initial practice runs with a team may be needed to accomplish this.
- III. Obtain a set of random coordinates for laying out sampling locations on the ground and record these in the GPS units. The randomization procedures are described in Section 2.
- IV. Do a thorough equipment check against the table in Appendix II. Ideally, each 5 person field team should have this equipment. In cases where 2 or more field teams are working in close proximity to one another, it may be possible to share things like GPS units and soil augers.
- V. Obtain permission from the land owner(s) to sample a given area, and make sure that he/she understands what you are doing. Informing local government officers and community leaders about your activities is also a good idea. In remote areas without cellular phone access make sure that someone knows where you are going to be on any given day.



#### Note!

1. Definitely avoid any areas where you might be placing your field team at any risk of harm or injury.
2. Always carry an emergency first aid kit.
3. Make sure you have the necessary equipment listed in Appendix II.

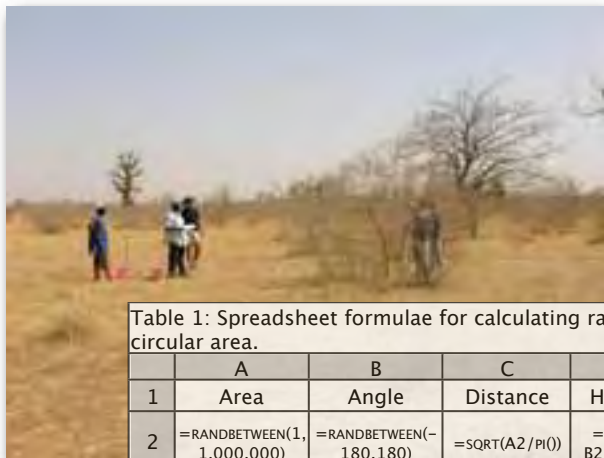


Table 1: Spreadsheet formulae for calculating random coordinates located in a 1 km<sup>2</sup> circular area.

	A	B	C	D	E	F
1	Area	Angle	Distance	Heading	+X	+Y
2	=RANDBETWEEN(1, 1,000,000)	=RANDBETWEEN(-180,180)	=SQRT(A2/PI())	=If(B2<0, B2+360,B2)	=C2*COS(RADIANS(B2))	=C2*SIN(RADIANS(B2))



## Cluster-level sampling plan

Abandoning and replacing plots:

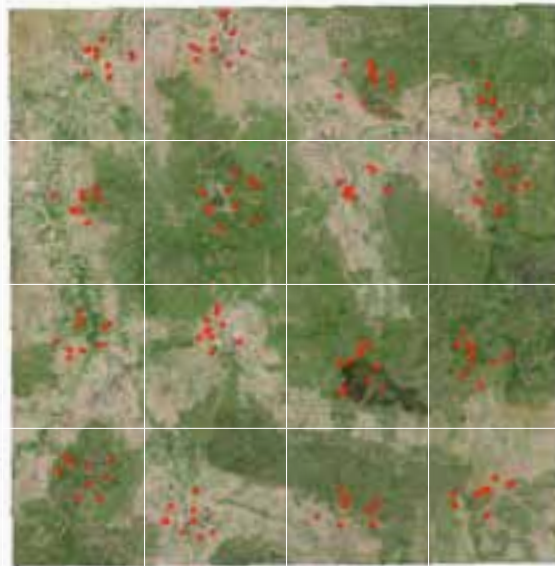
The LDSF is built around the use of "Sentinel Sites" or "Blocks", 10 x 10 km in size. The basic sampling unit used in the LDSF is called a "Cluster". A Cluster consists of 10 "Plots" (described on page 3). The centre-point of each cluster in LDSF is randomly placed within a "tile" in each Sentinel Site (see figure on the right). The sampling plots are then randomized around each cluster centre-point, resulting in a spatially stratified, randomized sampling design

Both the number of plots per cluster and the cluster size may be adjusted depending on the specific purpose of the survey being conducted. For example, 1 km<sup>2</sup> clusters are useful for large-area reconnaissance surveys; whereas, 10 ha clusters may be more appropriate for more detailed project-level surveys.

**Whatever the cluster size and sampling intensity, randomizing the plots in the cluster is extremely important as you will want to minimize any local biases that might arise from convenience sampling.**

The randomization procedures are done using customized programs or scripts. Send an e-mail to [t.vagen@cgiar.org](mailto:t.vagen@cgiar.org) giving either the center or the four corners of your sampling block (in Lat/Lon or UTM coordinates). A file is generated containing the plot location coordinates and labels (based on a name that you give). This file can then be loaded to your GPS unit and you can navigate to the various plots in your Sentinel Site, completing the sampling procedures and field observations described in the next sections of this guide. Alternatively you may do the randomization for each cluster in an Excel spreadsheet using the formulas in Table 1 (previous page).

A team of five people should generally be able to complete all the field measurements in a "standard" 1 km<sup>2</sup> cluster on one day.



10x10 km sentinel site (block) with sampling clusters

To achieve a sample that is representative of the cluster area and statistically valid, every plot identified for measurement within the cluster should be measured at its mapped location. For example, if a plot point falls in a part of the cluster containing a school yard, a house or a road, the plot should still form part of the sample and should not be abandoned or moved to a new location. While you will not take any measurements in these situations, the presence of these types of areas should be noted and GPS coordinates should be recorded.

There are some limited circumstances in which a plot can be abandoned. These are unlikely and include situations where:

1. The plot coordinates overlap in part with another plot. You can evaluate this possibility in the office.
2. The plot point falls in a stream, lake, cliff or other completely inaccessible place.
3. There are safety concerns in completing the plot.

Where a plot cannot be completed for one of the above reasons, an alternate plot should be selected instead. Randomly choose the alternate plot using the procedures outlined above. Note the alternate plot used and the reason for abandoning the original plot on the field recording sheet.

## Plot layout

The figure on the right shows the radial arm plots used in the LDSF. The plots are designed to sample a 1000 m<sup>2</sup> area, but you may have to apply slope corrections to the center point distances and sub-plot radii to achieve this.

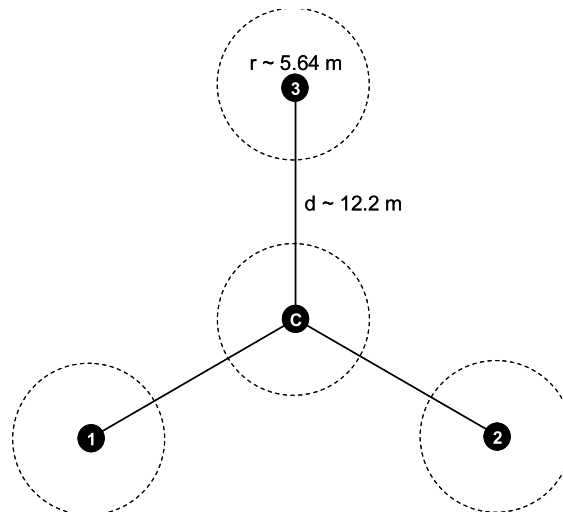
1. To lay out the plots you will need: a Field recording sheet (Annex III), a slope correction table (Annex), a GPS, a 30 meter tape measure, or for dense vegetation, a pre-marked chain, a clinometer, a compass and two, 2 meter range poles.
2. Initially GPS the point by averaging position fixes for at least 5 minutes. Store this as a waypoint on your GPS, and record the Easting, Northing, Elevation and Position error on the field recording sheet Annex III).
3. While the GPS is averaging, complete the slope measurements. To measure the slope, stand in the centre of the plot. Take a sighting along the steepest part to a point on the up-slope plot boundary using the clinometer. Ensure that you sight to a location that is at the same height as the observer's eye-level. A marked range pole is useful for this, or alternatively a point on another person may be used. Also remember to look at the scale in degrees, rather than in percent.
4. Rotate 180 degrees and repeat the process in the down-slope direction. Record both the up-slope and down-slope measurements on the field recording sheet. Then average the two figures, and use the slope correction table to determine the correct center-point distances

$$\text{Slope distance} = \frac{\text{Horizontal distance}}{\cos(\text{Slope})}$$

and subplot radii. Alternatively use the following slope correction formula:

Note: that the Slope must be measured in degrees

5. Using a measuring tape or a pre-marked chain, measure out the center-point distance from the plot center to the center of the up-slope sub-plot. Mark this point for soil sampling. The second and third soil sampling points should be offset 120 and 240 degrees (use the compass to determine this) from the up-slope point, respectively, on the plot boundary.



0.1 ha radial-arm plot layout and sampling locations. The black dots indicate soil (0-20 and 20-50 cm) sampling locations. Georeferencing and infiltration measurements should be completed in the center of the plot. The larger (dashed) circles represent 0.01 ha sub-plots in which soil surface and vegetation observations should be carried out.  $r$  is the subplot radius,  $d$  is the center-point distance. Note that the distances are for a flat plot. In instances where slope is >10 deg, the radii and center-point distances of the subplots should be slope corrected





## Measuring soil infiltration capacity

The soil infiltration measurements will be the most time consuming aspect of the field measurements, so these should be set as soon as possible. The easiest way to do this is to use the first three plots in the cluster sequence (see Fig. 1). However time allowing, it is generally desirable to obtain more than three (as many as possible) infiltration measurements, particularly in large clusters. So, should you be able complete more than three infiltration measurements per day, allocate these randomly to the different plots in the cluster.

1. To complete the infiltration measurements you will need: three, 12 inch diameter infiltration rings per cluster, a sledge hammer, approximately 25 liters of water per ring, and an infiltration field recording sheet (Annex).
2. The infiltration ring should be placed at the center of the plot (see Fig. 2). To ensure that the ring does not leak, drive it at least 2 cm into the soil with a sledge hammer. Under some circumstances it may be necessary to seal the ring with clay on its inside edge.
3. Remove any vegetation, litter and large stones from inside the ring, but make sure not to disturb the soil surface by digging out large stones or uprooting vegetation. If the soil surface is accidentally disturbed, reset the ring at another location.
4. Pre-wet the soil with 2-3 liters of water. Let this soak in for at least 15-20 minutes. Then slowly pour water into ring to a level of 20 cm, again making sure not to disturb the soil surface.
5. The infiltration rates at the beginning of the test will be quite variable. So for the first half-hour of the test record at 1-5 minute intervals. Note that it will be easier to process the data if you record time in minutes since initiation of the test rather than as clock time.
6. After each recording top up the water level to 20 cm. After the first half hour record at 10-20 minute intervals for an additional 2.5 hours, or until the infiltration rates have stabilized. Top-up the water level to 20 cm after each reading.



## Land form and land cover classification

The land cover of all plots should be recorded using the FAO Land Cover Classification System (LCCS), which has been developed in the context of the FAO-AFRICOVER project (also see [www.africover.org](http://www.africover.org)).

The "binary phase" of LCCS recognizes 8 primary land cover types, only 5 of which should be sampled including:

- cultivated and managed terrestrial areas,
- natural and semi-natural vegetation,
- cultivated aquatic or regularly flooded areas,
- natural or semi-natural aquatic or regularly flooded vegetation, and
- bare areas.

Artificial surfaces and associated areas, natural and artificial waterbodies, and surfaces covered by snow, or ice should not be formally surveyed under the LDSF, though their presence within a cluster should be noted and georeferenced.

The "modular-hierarchical phase" of LCSS further differentiates primary land cover systems on the basis of dominant vegetation life form (tree, shrub, herbaceous), cover, leaf phenology and morphology, and spatial and floristic aspect. All the associated features are assessed visually and are generally coded on either categorical or ordinal rating scales. The ratings can subsequently be converted to unique hierarchical identifiers representing different land cover types. The questions in the field recording sheet are designed to guide you through the classification process.

Initially complete the section describing landform and topographic position. To do this, visually inspect the area surrounding the plot and select the appropriate categories provided on the field recording sheet and the major landform designation table (Annex). Skip the section on topographic position if the Major Landform is "Level Land".

Continue through the form completing the "plot-level" information before moving to sub-plots.

## Soil surface characterization

To sample soils, you will need 2 buckets, an appropriate (hard soil, sand or general purpose) soil auger marked at 20 and 50 cm, 2 buckets, sturdy plastic bags, a mixing trowel, a permanent marker, labels, a torvane, and the provided soil texture table (Annex).

### Soil sampling:

1. Top-soil (0-20 cm) and sub-soil (20-50 cm) samples should be collected from the four soil sampling positions (Fig. 2) and pooled into separate plastic buckets, one for topsoil, one for subsoil. Record the depth (to the nearest 5 cm) to any restriction at any one of the four sampling locations on the field sheet.
2. When augering, make sure that you avoid overfilling the auger or collapsing the hole. So, take small, steady bites, empty the auger frequently, and do not lever the auger against the side of the hole when removing it. Should the hole collapse, reset the auger at another location within 50 cm of the original position.
3. Mix the samples thoroughly in the buckets using the mixing trowel. Then, take a ~250 g sub-sample and place it in a plastic bag. Note that there should be one bag of topsoil and one bag of subsoil for each plot.
4. **Labeling is critical.** The cluster and plot ID's should be legibly recorded with a permanent marker on the outside of the plastic bag. Additionally, a paper label containing the same information should be placed inside the bag.

After getting back from the field the samples should be air-dried for at least 3 days.

### Visual soil surface characterization

Examine the plot and note down visible erosion and/or soil conservation measured in the field recording sheet.

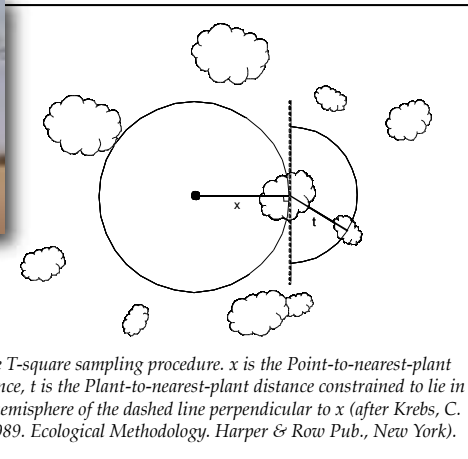
### Soil texture determination

Follow the procedure outlined in Annex IV for determining field texture, and note down the results on the field recording sheet.





## Measuring woody vegetation



*The T-square sampling procedure.  $x$  is the Point-to-nearest-plant distance,  $t$  is the Plant-to-nearest-plant distance constrained to lie in the hemisphere of the dashed line perpendicular to  $x$  (after Krebs, C. J. 1989. *Ecological Methodology*. Harper & Row Pub., New York).*



The "T-square" method is one of the most robust distance methods for sampling woody plant communities, particularly in forests, but also in rangelands. It can be used to estimate stand parameters such as density, basal area, bio-volume, and depending on the availability of suitable allometric equations, also biomass. The advantage of this method, over other commonly used distance methods such as the point-centered quarter (PCQ) method, is that it is less prone to bias where plants are not randomly distributed.

Under the LDSF protocol shrubs and trees are sampled separately.

To complete the T-square measurements for trees and shrubs you will need, the field recording sheet (Annex), a 15+ meter measuring tape, a diameter tape, a height pole and/or a clinometer and a calculator.

1. Standing at the center of each subplot record the distance from the subplot center point to the nearest tree and shrub ( $x$ ) (see figure). Measure this either to the center of the tree trunk, or to the central portion of the shrub. Record this figure in the appropriate space on the field recording sheet.
2. Next measure the distance to the nearest neighboring plant ( $t$ ). Note, however that the angle of the measurement must be constrained to lie in the hemisphere of a line that lies perpendicular to  $x$ . This is the T-square distance. Also record this measurement.
3. For both trees and shrubs measure and record the height using either the height pole or clinometer methods described further below. Measure only the 2<sup>nd</sup> plant identified (i.e. the tree and/or shrub identified by the plant-to-nearest-plant measurement).
4. For trees measure the diameter at breast height (DBH) of the 2<sup>nd</sup> tree. The DBH should be measured 1.3 meters above ground level. In instances where a tree branches below this level, measure the diameters of all of the branches at 1.3 meters above ground level and sum these. For trees that are tilted determine the 1.3 meter level from the down-slope direction.
5. For shrubs, measure their width, length and height (at centre).

Fill the above recordings into the field recording sheet in Annex III.

# Appendices

## I

### Landform designations

Level land	Sloping land	Steep land	Land with composite forms
Plain	Medium gradient mountain	High gradient mountain	Valley
Plateau	Medium gradient hill	High gradient hill	Narrow plateau
Major depression	Med. gradient escarpment	High gradient escarpment	Major depression
Low gradient footslope	Ridges	High gradient valley	
Valley floor	Mountainous highland		
	Dissected plain		



**LDSF - equipment required for land cover classification, soil and vegetation inventory.**

Activity	Equipment required	People required
Cluster and Plot layout	Cluster cover sheet	1 Person
	Field recording sheets	
	Random coordinates	
	Digital camera	
	GPS	
	Calculator	
	Clinometer	
	Compass	
Landcover classification & vegetation inventory	Field recording sheet	2 People
	15+ meter measuring tape	
	Diameter tape	
	Height pole	
Soil inventory	Field recording sheet	1 Person for infiltration measurement
	Infiltration recording sheet	1 Person for soil collection
	Soil texture table	
	Watch or stop watch	
	3 × 12" inside diameter infiltration rings	
	4 × 20 liter jerry cans	
	Sledge hammer	
	Hard soil auger	
	Sand auger	
	General purpose auger	
	Electrical tape	
	Torvane	
	2 × 20 liter buckets	
	Mixing trowel	
	Sturdy plastic bags	
Permanent marker		
Paper or cardboard labels		
	Electrical tape	
Other	First aid kit	

III

Country:

Name of data recorder:

**LDSF Data-Entry Form**

<b>Block Name</b>		<b>UTM zone</b>	
<b>Cluster No</b>		<b>Northing</b>	
<b>Plot No</b>		<b>Easting</b>	
<b>Date (dd/mm/yyyy)</b>		<b>Elevation</b>	
<b>Photo ID</b>		<b>Pos. Error (m)</b>	

<b>PLOT</b>	<b>Slope (degrees)</b>	Up:		Down:		
	<b>Major landform</b>	Level	Sloping	Steep	Composite	
	<b>Landform designation (see table)</b>					
	<b>Position in topographic sequence</b>	Upland	Ridge/Crest	Midslope	Footslope	Bottomland
	<b>Artificial surface?</b>	Yes	No			
	<b>Vegetation cover &lt; 4% for 10 mo yr<sup>-1</sup></b>	Yes	No	Don't know		
	<b>Plot regularly flooded</b>	Yes	No	Don't know		
	<b>Plot cultivated or managed</b>	Yes	No	Don't know		
	<b>Vegetation types present</b>	Trees	Shrubs	Graminoids	Forbs	Other
	<b>Woody leaf type</b>	Broadleaf	Needleleaf	Allophytic	Evergreen	Deciduous
	<b>Herbaceous height (m)</b>	0.8 – 3	0.3 – 3	0.3 – 0.8	0.03 – 0.3	
	<b>Herbaceous annual</b>	Yes	No	Mixed	Don't know	
	<b>Vegetation strata description</b> (include dominant species where known) - use keywords where possible					
	<b>Same land cover / use since 1990</b>	Yes	No	Don't know		
	<b>Land ownership</b>	Private	Communal	Government	Don't know	
	<b>Primary current use</b>	Food / Beverage	Forage	Timber / Fuelwood	Other	
	<b>Describe land cover / use history</b> (where known – use back of sheet if necessary)					
	<b>Rock / stone / gravel cover</b>	< 5%	5 – 40%	> 40%		
<b>Visible erosion</b>	None	Sheet	Rill	Gully / Mass		
<b>Conservation structures</b>	None	Vegetative	Structural	Description:		
<b>Number of structures</b>						

Woody & Herbaceous cover ratings: 0 = absent, 1 = < 4%, 2 = 4 – 15%, 3 = 15 – 40%, 4 = 40 – 65%, 5 = >65%

<b>SUBPLOT</b>		1		2		3		4	
	<b>Woody cover rating</b>								
	<b>Herbaceous cover rating</b>								
	<b>Auger depth restriction (cm)</b>								
	<b>Topsoil ribbon (mm) / Texture grade</b>								
	<b>Subsoil ribbon (mm) / Texture grade</b>								
	<b>Shear strength (2 per subplot)</b>								
		<b>Shrubs</b>				<b>Trees</b>			
		1	2	3	4	1	2	3	4
	<b>Subplot plant density (count)</b>								
	<b>Point – plant distance (m)</b>								
	<b>Plant – plant distance (m)</b>								
<b>Height (m)</b>									
<b>Length (m, Shrubs) / Circumference (cm, Trees)</b>									
<b>Width (m)</b>									

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Notes:

## IV

Soil texture table.

Soil texture grade	Soil texture class	Behavior of moist bolus	Approximate clay content
K	Coarse sand	Obviously coarse to touch, cannot be molded. Sand grains are readily seen with the naked eye.	< 5 %
S	Sand	Coherence nil to very slight, cannot be molded; sand grains of medium size. Commonly single sand grains adhere to fingers.	< 5 %
F	Fine sand	Fine sand can be felt and often heard when manipulated, cannot be molded.	< 5 %
LS	Loamy sand	Slight coherence; sand grains of medium size; can be sheared between thumb and forefinger to form <b>minimal ribbon of about 5 mm.</b>	~5 %
CS	Clayey sand	Slight coherence, sand grains of medium size, sticky when wet. Sand grains stick to fingers. Will form <b>minimal ribbon of 5–15 mm.</b> Discolours fingers with clay stain.	5-10 %
SL	Sandy loam	Bolus coherent but very sandy to touch. Will form <b>ribbon of 15–25m.</b> Sand grains are of medium size and are readily visible.	10-20 %
L	Loam	Bolus coherent and rather spongy. Smooth feel when manipulated but with no obvious sandiness or silkiness. May be somewhat greasy to the touch if much organic matter present. Will form <b>ribbon of about 25 mm.</b>	~25 %
ZL	Silty loam	Coherent bolus; very smooth, often silky when manipulated. Will form <b>ribbon of about 25 mm.</b>	~25%, 25%+ silt
SCL	Sandy clay loam	Strongly coherent bolus, sandy to touch; medium size sand grains visible in clay loam finer matrix. Will form <b>ribbon of 25–40 mm.</b>	20 – 30 %
CL	Clay loam	Coherent plastic bolus, smooth to manipulate. Will form <b>ribbon 40–50 mm.</b>	30 – 35 %
CLS	Sandy clay loam	Coherent plastic bolus; medium size sand grains visible in finer matrix. Will form <b>ribbon of 40–50 mm.</b>	30 – 35 %
ZCL	Silty clay loam	Coherent smooth bolus, plastic and often silky to the touch. Will form <b>ribbon of 40–50mm.</b>	30 – 35 %, 25%+ silt
LC	Light clay	Plastic bolus; smooth to touch; slight resistance to shearing between thumb and forefinger; will form <b>ribbon of 50–75 mm.</b>	35 – 45%
LMC	Light medium clay	Plastic bolus; smooth to touch; slight to moderate resistance to ribboning shear; will form <b>ribbon about 75 mm.</b>	40 – 45 %
MC	Medium clay	Smooth plastic bolus; handles like plasticine and can be molded into rods without fracture; has moderate resistance to ribboning shear; will form <b>ribbon of 75 mm or more.</b>	45 – 55 %
MHC	Medium heavy clay	Smooth plastic bolus; handles like stiff plasticine; can be moulded into rods without fracture; has moderate to firm resistance to ribboning shear; will form <b>ribbon of 75 mm or more.</b>	> 50 %
HC	Heavy clay	Smooth plastic bolus; handles like stiff plasticine; can be moulded into rods without fracture; has firm resistance to ribboning shear; will form <b>ribbon of 75 mm or more.</b>	> 50 %





# Appendix 3.2

## Examples of LDSF statistical models and database

The statistical analytical procedures used in the Land Degradation Surveillance Framework (LDSF) centre around the use of R-statistics, which may be freely downloaded from [www.r-project.org](http://www.r-project.org). In this section we demonstrate some worked examples, including basic R-statistics sample code, for a few of the main models applied in this study. The examples are deliberately chosen to be relatively simple, and are designed to provide a brief introduction. Sample data can be obtained by contacting [t.vagen@cgiar.org](mailto:t.vagen@cgiar.org), but readers are encouraged to try the examples below with their own data.

### GENERALIZED LINEAR MODELS AND GENERALIZED LINEAR MIXED-EFFECTS MODELS

Some of the more commonly used classes of linear models in this study are Generalized Linear Models (GLMs), due to the complexity of our field survey data. While classical linear models assume that the outcome variable is defined on a continuous scale, as well as normality of errors and constant variance, GLMs are based on the likelihood function. When the likelihood is maximized, the coefficients and variances of independent variables are achieved. GLMs can therefore handle outcomes that are expressed as proportions, Poisson distributed (counts) and other distributions such as gamma and negative binomial distributions. These outcomes are often referred to as the “family” of the model. Independent variables may be both continuous and categorical.

Our first example comes from Chapter 10, where we estimated the proportion of the cultivated area in each cluster. In this particular example the outcome

is binary (or dichotomous). Model outcomes are on a log (odds) or *logit* scale, which is more appropriate for a binary outcome than probability. However, computing the probability from the *logit* is straightforward as:

$$Pr(Y|X) = \frac{\exp(\beta X)}{1 + \exp(\beta X)}$$

which is what we have reported in Table 10.1. Note that in this model we don't have any independent variables, but random effects at block and cluster within block levels. The coefficients are also commonly referred to as “Best Linear Unbiased Predictors” or BLUPs. We are therefore fitting a generalized linear mixed-effects model (GLMM), which incorporates the nested structure of our data in its variance components:

```
require(MASS)
cultMod <- glmmPQL(Cultivated
~1, random = ~1|Block/Cluster,
family = binomial, data = veg)
summary(cultMod) #Shows a
summary of model parameters
coef(cultMod) #Prints the coefficients
(BLUPs) of the model
```

Another example of a GLMM model, but using counts data:

```
shrubMod <- glmmPQL(ShrubCount
~1, random = ~1|Block/Cluster,
family = poisson, data = veg)
```

The library lme4 has a function called lmer, which will also let you fit the GLMM models above, as well as ordinary linear mixed-effects models (depending on what family argument you specify) (Bates, 2007).

### LINEAR MIXED-EFFECTS MODELS

Linear mixed-effects models (LME) may be fitted in R using the nlme (Pinheiro and Bates, 2000) or lme4 (Bates, 2007) libraries.

```
require(nlme)
# A look at the grain yields using
density plots (e.g. plot(density(...)))
shows a right-tail skewness in the data
and we therefore take the natural log
(ln) of the yields before fitting our LME
models;
gY.mod <- lme(lnG ~Treatment,
random = ~1|Block/Cluster/
FarmerNo, data = mYield);
summary(gY.mod)
#To show a summary of model
parameters and significance tests, etc.
for the fixed effects;
plot(gY.mod); qqnorm(gY.mod);
#Fitted values vs residuals and QQ-
normal plot - show nothing amiss
# Same model using lme4:
gY.lmer <- lmer(lnG ~Treatment
+(1|Block)+(1|Block:Cluster)+(1
Block:Custer:FarmerNo), data =
mYield);
The summary function now shows
the variance at the different levels
of nesting - in addition to standard
deviation. Otherwise, it is similar to the
summary for the lme model above.
Interestingly, the variance at individual
farmer level is quite high (~0.09),
indicating a high level of variability in
yields at the local scale.
```

## NON-LINEAR MIXED-EFFECTS MODELS (NLME)

In Chapter 11 we fitted non-linear mixed-effects models (NLMEs) to our infiltration measurements. These are fairly advanced classes of models, and reference is made to Pinheiro and Bates (2000) for an excellent introduction to, and detailed description of, NLME models.

```
require(nlme)
# Create grouped dataset with
infiltration rate (IR) as a function of
time and grouped by plot:
infDat <- groupedData(IR ~Time |
Plot, data = infDat)
infDat.lis <- nlsList(SSasym, infDat)
# Create a list object using the self-
starting function SSasym
summary(infDat.lis); plot(infDat.lis) #
Various diagnostics... study carefully!
infDat.nlme <- nlme(indDat.lis) # Fits
model to each individual measurement
- initial model
summary(infDat.nlme);
plot(infDat.nlme, IR ~fitted(.) | Block)
# Figure 11.4.
# We may now proceed to include
other levels of nesting in this model, as
well as fixed effects such as root-depth
restrictions, cultivation, etc. As an
example we fit a nested version of the
above model;
infDat.nlme2 <- nlme(IR
~SSasym(Time,Asym,R0,Irc), data =
infDat, fixed = list(Asym+R0+Irc~1),
random = list(Block =
pdDiag(Asym+R0+Irc~1), Plot =
pdDiag(Asym+R0~1), start =
fixef(infDat.nlme), method = "REML")
```

## PLOTTING AND VISUALIZING DATA IN R

R-statistics has a wide range of plotting and visualization routines for creating high-quality graphical outputs. Some of the key commands are plot, histogram, plot(density(...)), qqnorm, boxplot, etc. Most of the libraries used in this study have specific plotting functions for the various model types fitted, as demonstrated above. Reference is made to the documentation for each library for specific plotting functions.

The lattice package (library(lattice)) implements Trellis Graphics in R (based on Cleveland, W.S. (1993) Visualizing Data). The package includes functions for univariate (e.g. barchart, bwplot, etc.), bivariate (e.g. qq, xyplot), trivariate (e.g. levelplot, contourplot, wireframe), and hypervariate (e.g. splom, parallel) graphics.

A good place to start looking for examples of R graphics is; <http://addictedtor.free.fr/graphiques/>, while the book "Data Analysis and Graphics Using R" by John Maindonald and John Braun (Cambridge Series in Statistical and Probabilistic Mathematics) provides a good introduction.

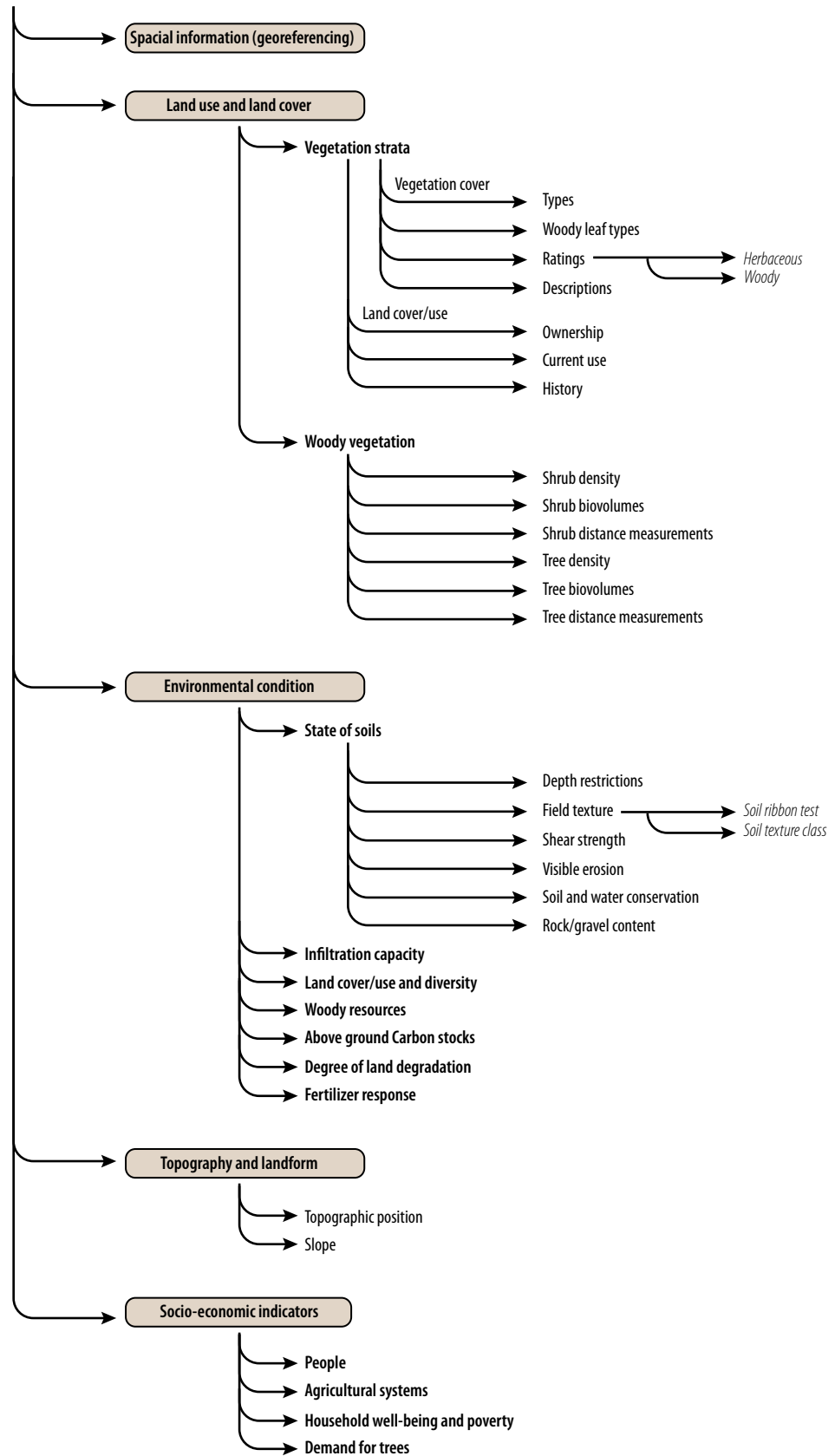
## THE LDSF DATABASE

The LDSF database system exists in several formats, including MySQL and FileMaker, the latter system providing "mobile" databases, and being used as an interface for data-entry and web-integration for the former system. The general structure of the LDSF database system used in the baseline study presented here is shown in Figure A3.2.1. In addition, a script for assigning randomized sample clusters and plots around a given location and exporting these directly to Global Positioning System units is available.

**FIGURE A3.2.1**

Summary of content and structure of the LDSF database.

**Sentinel site baseline**



**PART 4**

**SYNTHESIS AND  
IMPLICATIONS FOR POLICY,  
RESEARCH AND APPLICATION**

*Gemma Shepherd*

# Condition and trend in land health

**Implications for Sahelian food security, climate change mitigation and adaptation strategies, and ecosystem management**

## INTRODUCTION

Drylands have traditionally tended to be marginalized in development planning for a number of reasons, not least because of their remoteness and poor infrastructure. However, it is difficult to mobilize political will and commitment at both international and national levels to tackle dryland environment-development problems while large uncertainties remain over the degree and extent of the problems, and there is a lack of specific information on what interventions make sense where, and what are the impacts of investments. The land health surveillance approach described in this report is designed to make progress towards providing this type of information. Two scales of land health assessment have been presented: a regional scale analysis of vegetation trends, and a more detailed land degradation assessment for Segou Region in Mali. This chapter draws out the implications of the findings for Sahelian food security, and climate change and ecosystems management strategies.

## REGIONAL LAND HEALTH TRENDS

The regional surveillance study (Part 2) was based on vegetation indices derived from remote-sensing data over the period 1982–2006 coupled with data on rainfall trends over the same period. Most recent previous studies using this type of data have concluded that vegetation cover has improved in the Sahel (a greening trend) in response to increased rainfall since the severe droughts that occurred in the early 1980s. Further studies have attributed greening in part to improvements in agricultural practice. Taken together, those studies have introduced doubt on the picture painted by the World Atlas of Desertification (UNEP, 1997) of serious and widespread human-induced soil degradation across the Sahel.

Our study employed new data-analytical approaches and came to different conclusions compared with most previous remote-sensing studies of the Sahel for this period. Most importantly, we used a vegetation index derivation that is more robust across land use types and transitions than those used in previous studies and more suitable for examining trends in vegetation productivity. Our results indicate a weaker greening trend than found in most previous studies, with the strongest greening trends restricted to the Parklands area, located between 11° N and 18° N. The rainfall-normalized vegetation index showed a predominantly negative trend over the region, indicating that incipient desertification has occurred, masked by the increase in rainfall. For

areas with average rainfall below 900 mm per year, for which the index is most robust, and using a 95% certainty level, almost none of the area showed an increase in rainfall-normalized vegetation index, whereas 50% of the total area (2.0 million km<sup>2</sup>) showed a decrease in the index, indicating widespread degradation.

Areas with a tendency for a positive trend in rainfall-normalized vegetation index were restricted to the Parklands area, pointing to the importance of maintaining the integrity of the Parkland agroecosystem for the ecological and climatic stability and economic development of the region. More specific recommendations on how to maintain the Parkland system and how these recommendations may be accurately targeted are given below, based on the Segou Region case study.

Our analysis provided little evidence to support large area impacts of agricultural innovation in the central plateaux of Burkina Faso, but there were indications of improved land health in agriculturally dominated areas in southern parts of Mali, Burkina Faso and Niger. More detailed analysis to investigate these possible differences in impacts should be given high priority. Other areas showing improvement in rainfall-normalized vegetation index are restricted to areas along the Senegal River in both Mauritania and Senegal, probably reflecting increase in irrigated agriculture.

The regional land health assessment based on indices of vegetation growth puts up a warning signal that the West Africa Sahel may have undergone subtle but widespread land degradation over the past 25 years. Especially considering that this region contains one of the most vulnerable populations in the world in terms of poverty and climatic risk, there is an urgent need for more detailed and systematic follow-up assessment studies to validate trends, establish baselines and quantify risk factors. Further analysis of the vegetation index trends using moderate resolution imagery (see Part 1) is presented in an atlas of climate and vegetation change in the Sahel (UNEP, 2012).

### **LAND HEALTH STATUS AND TRENDS IN SEGOU REGION, MALI**

More detailed land health surveillance was conducted in Segou Region, Mali (Part 3). The assessment was based on ground survey and soil sampling in five 100 km<sup>2</sup> sentinel blocks, sited to

span the ecological variation in the region. Sampling within blocks was based on randomized sampling to provide unbiased data on land health and human welfare. The ground survey data was statistically linked to fine and moderate resolution satellite imagery to map out selected indicators of land health. This evidence-based approach differs markedly from conventional soil survey approaches.

The range in ecological and socioeconomic conditions in Segou Region is probably fairly typical of much of the semi-arid regions of the Sahel. This assessment showed that average annual rainfall in Segou Region varies from 450–780 mm, with the proportion of land under cultivation ranging from 27% in the drier north to 73% in the wetter south, and woody cover following the same pattern ranging from less than 4% in the north to 15–40% in the south. These trends reflect the transition from predominantly pastoral systems in the north to cultivated agro-ecosystems in the south. Populations in Segou Region are particularly vulnerable: population density has more than doubled over the past 40 years, with significant increases in areas with more than 100 people per km<sup>2</sup>, but illiteracy is high at 80% among 15- to 65-year-olds. No one has secure land ownership and most households strongly depend on purchased food grains for at least two months of the year. The average number of tropical livestock units per person in sentinel blocks is low, ranging from 0.48 to 0.90, providing households with little buffering. Household access to freshwater is generally good at present due to access to groundwater through wells, but the sustainability of this supply will likely depend on upholding the overall integrity of the Parkland ecosystem. Agriculture is expected to be the main source of livelihoods and food security for people over the next several decades, but the Sahel has been flagged as vulnerable to climate change impacts over this period due to decreased precipitation and increased surface temperatures (Lobell et al, 2008). Thus maintenance of land health will be vital to sustainable development and adaptive capacity in the face of climate change.

### **Woody vegetation management**

Restoring woody cover in semi-natural areas is important to maintain overall ecosystem health and buffer against climate change. The sentinel site surveillance results showed that these are the areas of the landscape most prone to surface run-off and soil erosion. The semi-natural areas requiring increased woody vegetation cover make up between 19–42% of

the whole landscape, but the areas with high inherent degradation risk, which should be accorded highest priority, make up less than 5% of the total area. Thus reforestation efforts can be accurately targeted to these areas. The regional surveillance results indicated the importance of maintaining the Parkland system for the overall stability of the region.

The sentinel site surveillance results showed the need for enrichment planting to maintain optimal tree densities in the Parklands and provided accurate information on how many trees need to be planted, and where, to meet biophysical potentials. These interventions will improve the resilience and adaptive capacity of the ecosystems and at the same time contribute to increased carbon sequestration for climate change management. The contingency valuation survey also indicated farmer demand for tree products and interest by farmers in tree planting, and pinpointed the need for policies aimed at providing cheaper tree seedlings, through cheaper production methods and extension of farmer tree nurseries.

### **Soil health and food security**

The sentinel site surveillance study provided evidence for low and declining soil health in Segou Region, posing a major threat to food security and other key ecosystem services essential for human well-being. Declining soil health in turn translates into reduced adaptive capacity to climate and global change. Soil physical conditions constrain options for food production in the region. More than 50% of the area in three out of the five blocks surveyed has high inherent soil degradation risk, due to root depth restrictions and soil textural discontinuities in the surface 50 cm. High inherent degradation risk is also associated with lower water infiltration rates and higher prevalence of visible soil erosion. Farmers have apparently selectively cultivated areas with low inherent degradation risk but options for increasing cultivated areas are running out, and further expansion of cropping will dramatically increase the risk of soil degradation and disruption of water regulation. To reduce this risk in the face of increasing food demands from a rapidly growing population, priority must be given to increasing soil fertility in cultivated areas that have low inherent soil degradation risk (i.e. good agricultural potential). These areas were accurately located and comprise only 9–63% of the area of the sampled blocks (average area 31%), and only half of the currently cultivated area. Conservation agriculture and

agroforestry systems should be targeted to cultivated areas with high inherent soil degradation risk, and these comprise 7–21% of the areas of the blocks. It is clear that targeting soil management interventions in these areas will be much more cost-effective than strategies based on blanket recommendations.

Although soil acidity or soil alkalinity does not currently pose a constraint for food production in the region, soil fertility is critically low in terms of available phosphorus and potassium, exchangeable bases, and soil organic carbon. Soil organic matter in these predominantly sandy soils provides the main source of nitrogen and nutrient retention capacity, as well as soil structural integrity. Low available phosphorus, which is a fundamental constraint for crop production, has a prevalence of 98%. After correcting for variation in sand content, we found higher likelihood of poor soil fertility where sites were cultivated, indicating that current cultivation practices are depleting rather than building soil fertility. Soil fertility was also found to be lower in areas that had been converted to agriculture during 1986–2001 than in unconverted areas. The combination of high prevalence of inherent soil degradation risk in uncultivated areas, and low and declining soil fertility in cultivated areas, poses a dire threat to food security and agriculture-based livelihoods in the region. Attempts to increase the area under cultivation will pose a severe threat to soil degradation and associated ecosystem services. Interventions to improve soil phosphorus status and soil fertility in cultivated areas are therefore vital for sustainable food production.

The fertilizer response trials conducted, although limited to one season, indicate that improving soil fertility may not be as simple as applying correct doses of fertilizer, and integrated soil fertility management practices that rebuild soil organic matter may be simultaneously required. Poor crop responses to fertilizers may lose the confidence of both farmers and policy makers. It is therefore imperative that further response trials are conducted to establish risks associated with different practices.

### **Application of land health surveillance**

Countries that depend heavily on their land resource base for development stand to gain most from application of land health surveillance. Application of this science-based approach to land management can accelerate learning on what problems exist and what interventions work where. We have demonstrated the capability of land health



surveillance to provide synoptic screening of land degradation at regional scale and accurate spatial information on land health constraints leading to specific targeting of land management interventions in landscapes at local level. This information provides a sound basis for efficient design of development projects involving improved land management and an operational framework for measuring their impacts with scientific rigour.

Land health surveillance information must also be fed into climate change adaptation and mitigation strategies. For example, there is the opportunity to explore adaptation options by examining avoidable vulnerability through land use and land management practices (modifiable behaviour) at the household level. The surveillance approach could also help to demonstrate the limits to adaptation by indicating where in the landscape adaptation interventions could have the highest returns on investment. In the study area, there is relatively limited land area available for afforestation, mainly restricted to semi-natural parts of the landscape. There is, however, a large scope for enrichment planting in Parklands, and some potential for conservation agriculture in degraded agricultural areas, which could help to increase carbon sequestration.

Land health surveillance provides a basis for setting measurable targets (e.g. which areas to be afforested by when) as well as measuring impacts through repeat surveys. For example, in the Segou study, increases in woody cover can now be assessed from a QuickBird image obtained for the same sentinel blocks in five years' time, using calibrations developed in the baseline survey. Similarly, repeat soil analysis using infrared spectroscopy can be performed at very low cost on samples taken from the same georeferenced locations, using soil condition indicators developed during the baseline survey.

We have demonstrated how land health surveillance has potential to provide enormous increases in cost-effectiveness from carefully targeted and prioritized interventions as opposed to untargeted blanket recommendations. For example in the Segou Region study, we showed that soil fertility replenishment programmes only need to be implemented in between 7% and 21% of the area of the region, while high priority areas for restoring woody vegetation cover in semi-natural areas make up less than 5% of the region, with medium priority areas covering between 19% and 42% of the area.

## CONCLUSION

Regional analysis of vegetation cover derived from remote-sensing data using new analytical methods indicates widespread incipient land degradation in the West Africa Sahel over the past 25 years, masked by a general trend of increase in rainfall. These trends justify more detailed systematic assessments across the region to establish baseline land health conditions, identify degradation risk factors and target interventions.

More detailed assessments in Segou Region in Mali, using systematic ground survey, provided evidence of widespread soil health degradation in cultivated areas and critically low soil fertility levels, threatening food security and soil-related ecosystem services. The problem is that there is limited prospect for increasing area under cultivation without further damaging ecosystems, due to high soil degradation risk associated with inherent soil physical constraints. Thus it is imperative that soil health is improved in existing cultivated areas. There is evidence that this will require integrated soil fertility management, combining organic and inorganic inputs: strategies based on inorganic fertilizers alone may fail. Systematic testing of soil management options is urgently needed to provide a firm evidence base for intervention programmes.

If the soil health situation found in Segou Region is found to be common across the Sahel, there is an impending threat to food security for a rapidly growing population and loss of adaptive capacity to climate change, through loss of ecosystem capacities to provide essential services. The regional analysis indicated that this could well be the case. High priority should therefore be accorded to establishing evidence-based land health surveillance across the Sahel.

The land health surveillance results illustrate the potential for enormous resource savings from carefully spatially targeted and prioritized interventions, as opposed to generalized blanket recommendations. Knowing not only the size of the areas to be targeted with specific interventions but also their exact location is of great help for designing cost-effective development programmes with well-defined and quantified targets. The surveillance procedures provide a baseline and monitoring framework for measuring intervention impacts with scientific rigour.

# Land health surveillance research and practice

## Opportunities and priorities

### LAND HEALTH SURVEILLANCE CONCEPT

A principal purpose of this initiative is to develop land health surveillance as an approach for improving scientific rigour in land health management, and further develop and test methods and tools for making the approach operational under developing country conditions. This work has attempted to lay out principles and concepts for land health surveillance (Part 1) and to illustrate them with a case study for West Africa drylands (Parts 2 and 3). In this chapter we provide an overview of progress with the methods and point to needs for further research and development.

Land health surveillance is modelled on scientific approaches used in the public health sector, where surveillance forms a basis for the design and evaluation of public policy and practice. Although we do not equate land health directly with human health, many of the types of problems and approaches required to deal with them are similar. More specifically, many of the problems associated with addressing land degradation are similar to those encountered when dealing with non-communicable diseases in the public health sector, including:

- A rapidly increasing burden in developing countries; chronic if not treated.
- Caused by a complex web of proximal and distal risk factors, with long-time lags between cause and effect.
- Risk factors include biophysical and socioeconomic factors, and behavioural as well as inherent characteristics.
- Difficulty of defining a normal case and diagnosing poor health, requiring decision guides to be based on observed or expected patterns.
- Problem of how to evaluate cost-effectiveness of alternative preventive and rehabilitation interventions.
- How to mainstream health surveillance into development decision-making at all levels.

The major gap, however, is that public health surveillance systems are operational and actively informing global and national actions to improve health, at a global level coordinated by the World Health Organization, and at national level in most countries, whereas this is far from being the case for land health surveillance.

In approaches to dealing with land management problems, there has perhaps been too much focus on the individual land user and units of

land as opposed to populations of land users and land units. The parallel is the difference between medicine and public health (Merson et al, 2006). Medicine focuses on diagnosis and treatment for the well-being of the individual patient and provision of personal services. For example, the thinking in much agricultural research is orientated towards improving diagnosis, and recommendations for individual farmers or farm fields. Public health, on the other hand, focuses on health promotion and disease prevention in populations, with reliance on inputs from many sectors. The parallel in land health management is a focus on understanding the main causes of land health problems in relation to variation in natural conditions and human actions, the impacts of poor land health on human well-being and the environment, and roles of various agencies in preventive and land care services. Land health surveillance is orientated towards addressing this public service role.

As a result of a 'medical' versus 'public health' bias in land-management research, there has tended to be more focus on land rehabilitation than on strategies for preventing land degradation. Thus much effort is directed at identification of land degradation hot spots and direction of rehabilitation projects to these areas, despite the fact that efforts to rehabilitate ecosystems are usually only partially successful and incur very high costs. In contrast, recent efforts in public health are moving towards an emphasis on population-wide prevention strategies as a key to risk reduction (WHO, 2002). The health sector now recognizes that strategies directed towards the minority of people at high risk, above commonly used thresholds (severe underweight or obesity), would provide only a fraction of the benefits of strategies aimed at changing population-wide risk levels. For example, high blood pressure causes seven million premature deaths a year: a small change in population average blood pressure would have a dramatic effect on reducing this disease burden. The WHO concludes that actions to bring about modest changes in a few key risk factors could have major impacts on the global disease burden within the next decade. We suspect that the situation is the same for land health. Therefore there is an absolute priority for land health surveillance now to play a vital role systematically to quantify land health risks in developing countries.

Risk prevention strategies also require a change in ownership of responsibility for tackling health risks, away from individuals at the extremes towards governments and ministries tackling population-wide risk levels (WHO, 2002). Therefore it is recommended that governments establish national land health surveillance systems as an integral part of development policy and planning. There is clearly a new role for soil and land survey institutes in developing countries to take up this challenge: they have tended to be in decline over the last several decades since having completed basic natural resource surveys (Young, 2000).

Deficiencies in three related areas have presented over-riding stumbling blocks to the application of surveillance approaches in land health. These are a lack of: (i) case definitions (ii) standardized measurement protocols and (iii) random-sampling schemes. None of these deficiencies are insurmountable. The development of case definitions for land health has the challenge of wide variation in natural land conditions, complexity of ecosystems, and strong trade-offs among ecosystem services. However, concepts of ecosystem health are now well established and it is widely accepted that systematic diagnosis of ecosystem condition is possible at an operational level based on objective criteria (e.g. Rapport, 1998). Operational case definitions are a prerequisite for science-based land management. It is time to start specifying.

While there is much continued investment in defining indicators of land degradation and desertification, there is lack of investment on the development of population-level reference values at different scales (local, regional and global) in relation to covariates. This in turn requires unbiased samples of populations at different scales and use of standardized measurement protocols. Once these requirements are satisfied, progress can be made towards establishing norms and reference values and establishing case definitions as a basis for aiding management decisions. Examples of this are given in Part 2, where multivariate spectral data on soils was subjected to a cluster analysis to arrive at a soil condition index, or case definition, expressed as poor or good condition classes. The soil condition index was then used as a basis for evaluating the effects of cultivation on soil health and for targeting soil fertility replenishment recommendations. Expanding these systematic data collection efforts will provide an increasingly sound basis for establishment of case definitions and norms.

Once land health surveillance systems are established, the next most pressing operational need is for behavioural risk-factor surveillance in developing countries. If over the next decade the key modifiable risks to land health can be established, and cost-effectiveness of alternative intervention options for reducing risks conducted, then there will be a sound scientific basis for public policy and governmental intervention. Application of the Land Degradation Surveillance Framework protocol to a randomized sample of sentinel sites across developing regions could also form a basis for risk factor surveillance.

Risk-factor surveillance will quantify the burden of land degradation attributable to major risk factors, and show the size of the potentially avoidable burden if the population distribution of risk is reduced across the board. The second step will be to assess what interventions are available to reduce risks or their impacts with available resources. There tends to be limited evidence on the costs and effectiveness of population-based interventions. Therefore there is a need for the development of standardized methods and tools to analyze the costs and population health impact of current and new interventions. For example, WHO has done this for public health interventions and provides regularly updated databases on the costs and effects of promotive, preventive, curative, and rehabilitative health interventions. There is a need to start this now for land health interventions, so these data can be coupled with the results of risk-factor surveillance.

Land health surveillance has important implications for the development of university curricula and capacity strengthening in developing countries. Surveillance concepts and principles, and their application through new and advanced geoinformatic, laboratory and statistical tools, requires a new or rejuvenated generation of educators and scientists. The new "generation" of land resource scientists will not only have good skills in fields such as remote sensing and multivariate statistics, but also have capacity for consistent and dedicated fieldwork, and the ability to interact with other disciplines and communication specialists. Agronomists and soil scientists will be dealing with much larger numbers of trials and soil samples than now, associated with national-level sampling schemes. Social scientists engaged in land health surveillance will need to work with statistical sampling frames and meta-analysis, as well as areas such as risk perception. A basic knowledge of

cyberinfrastructural developments in data capture, transmission, organization, and long-term storage will be increasingly needed by all scientists. Above all there will be the need for dedication and discipline, for upholding scientific rigour, and the consistent application of standardized measurement protocols across studies and regions, so that data can be coherently analysed at different levels of spatial scale and over time, and enable the use of meta-analysis as the main scientific tool for advising public policy on land health.

## **REGIONAL LAND HEALTH SURVEILLANCE METHODS**

The objective of regional land health surveillance is to assess land health at regional extents, to identify degraded areas and provide early warning of land degradation, so that these sites can be screened for further investigation and preventive or rehabilitation action as necessary. This study, as have a number of previous studies, used vegetation indices derived from NOAA-AVHRR data to assess land degradation. Our study employed improvements in the way that the vegetation index was calculated, adjusting NDVI for soil signal and using increments in NDVI to better reflect vegetation growth across different land use types and over time. These improvements had a significant impact on the results, suggesting an overall declining trend in rainfall-adjusted vegetation index over the Sahel over the past 25 years, in contrast to the conclusion of most other studies based on this type of data. However, there is still a number of limitations with the approach. As a result of the coarse spatial resolution (8 km) of the satellite data, the average trend may simply reflect a mosaic of finer scale patterns in the landscape where there have been simultaneous improvement and degradation processes. Flooding, irrigation or urban area in parts of pixel can have a large effect on the average signal. The trends in the signal are sensitive to the starting point (e.g. a drought year) and there may be complex dynamic patterns within the period considered. Despite being statistically significant, the absolute magnitude of a trend (slope) may be small. There are further problems with changes in sensor and sensor drift during the period of analysis, cloud contamination, and artefacts and outliers due to other factors. Spatial interpolation of rainfall data and the different sources of data (station data and satellite derived estimates) during different parts of the period analyzed add further uncertainties to the rainfall normalization of trends in vegetation index. The approach is also not generalizable to

wetter areas: in addition to the problem of cloud contamination, NDVI signal saturates at high levels of vegetation growth and the relationship between vegetation growth and rainfall breaks down. Areas with strong relief pose additional problems due to shade effects and problems of spatially interpolating rainfall data. However, despite these limitations the approach was shown to be useful as a synoptic screening tool for showing up regional trends in the Sahel and to help direct follow-up studies.

Further remote-sensing studies should focus on use of MODIS data, because of its finer spatial resolution (250 m), richer spectral information, and consistency in sensor characteristics. Even though the data is available only from 2000, this data should form a baseline for future studies. This may be supplemented by use of radar data in humid areas, to overcome problems with cloud cover. There is urgent need for the development of reliable “slow” indicators of land degradation that reveal trends against the background noise of short-term seasonal trends, validated through use of systematically collected ground data over the whole of any target geographic area of interest. There is scope to further investigate soil spectral unmixing techniques to identify and track badly degraded areas. Once reliable indicators are validated, there is the opportunity to investigate the influence of risk factors such as climate, topography, soils, population, infrastructure, and poverty, as far as spatial data is available. Therefore, the real bottleneck is currently the lack of operational ground-sampling schemes for land health assessment that are well designed and use standardized ground survey protocols. Until such baselines are established and monitored, large uncertainties will remain in interpretation of satellite-derived land degradation indicators. The sentinel site surveillance scheme, coupled with the land degradation surveillance field sampling protocol and associated statistical methods described in Part 3, provides a basis for establishing the type of regional baselines and monitoring schemes that are required.

### **SENTINEL SITE SURVEILLANCE**

The sentinel site surveillance scheme was designed to put into field operation the land-health surveillance principles laid out in Part 1, emphasizing use of case definitions, standardized measurement protocols and random sampling schemes. The land-degradation surveillance protocol was shown to be operationally feasible under some of the toughest conditions in Africa. The results illustrate the power

of inference when data are available from simple, repeatable, and interpretable measurements, consistently applied. The Mali case study demonstrated that robust ground measurement schemes need not be prohibitively expensive and the costs are minimal compared with total costs associated with acquiring earth observation products, let alone bringing soil samples back from Mars! We now have the science and technology to make ground sampling efficient and cost-effective.

The increased availability of Global Positioning Systems, providing the ability to collect accurately georeferenced field data, has been a major enabling technology development. Coupled with GIS technology and publically available remote-sensing products, this makes it now easy to generate sampling schemes in advance of going to the field, and to use electronic maps in the field to aid navigation. Further efficiencies could be obtained through development of electronic field books for data capture and wireless data transmission for central storage and processing. Once a first-level sampling of a region has been done, statistical procedures can be used to guide how many more samples are required to achieve a given level of precision and where samples should be taken to maximize information per number of additional samples.

Infrared spectroscopy has been key in enabling soil assessments to be made at the scale required for surveillance systems to become operational. The technology has all the characteristics required for a robust surveillance system: a simple, rapid, repeatable measurement, strongly related to soil functional properties. Restricting reference analytical measurement to a limited number of regional laboratories also generates efficiencies and improves quality. The results presented here provide further proof that the technology can provide a valuable screening tool for assigning soils to quality classes for the purpose of aiding soil-management decisions. Future work should focus on development of spectrally based soil-health reference values and building up linked response data from soil-management experiments, to enable an evidence-based approach to predicting responses to interventions and the risks associated with them. The development of palm-held infrared devices for direct work in the field will further increase efficiencies, subject to achieving good reproducibility both among instruments and over time.

Mixed-effects statistical modelling was shown to be a powerful and efficient tool for dealing with hierarchically structured land-health surveillance data and incorporating control variables at different levels of scale. Research on extension of these types of methods to Bayesian hierarchical modelling is warranted to provide more explicit treatment of uncertainty. Currently efforts are underway to establish a database of sentinel site data in Africa, which will provide a rich testing ground for such approaches.

This case study demonstrated the value of random sampling schemes for land-health management. The ability to make population-level statements, for example about the prevalence of land health constraints, enabled powerful policy messages to be formulated on the importance of soil fertility constraints on cultivated land and on environmental constraints associated with expanding areas under cultivation. Random sampling ensured that the major variation in land conditions was captured, enabling robust relationships to be established, for example between soil condition and effects of cultivation, and between ground data and satellite data.

We have shown the feasibility and efficacy of conducting agronomic and soil management trials spatially distributed within sentinel sites. The power to make statistical inferences and generalizations and generate understanding about management responses is greatly magnified when results can be related to measured indicators of land health and socioeconomic conditions and combined across sentinel blocks. Efforts to coordinate this evidence-based approach to evaluating land management interventions could generate enormous efficiencies in terms of knowledge-to-cost ratio, for better targeted and more effective interventions. Good data on how response risks to management interventions, such as fertilizer use, vary according to environmental and socioeconomic conditions will greatly reduce risks for policy makers and land users alike and allow intervention programmes to be targeted to conditions under which they are most likely to be successful.

Further work should emphasize risk-factor surveillance, to acquire reliable data on what are the key modifiable and behavioural risk factors associated with different types of land degradation, and how these interact with non-modifiable and environmental risk factors. For example, modifiable

risk factors such as land-use type may be an important risk factor for soil erosion only on steep slopes and sensitive soil types. Insecure land tenure may be an important risk factor only in certain settings. Currently evidence on risk factors for land degradation is based largely on case studies and expert opinion (e.g. Geist and Lambin, 2004), and there are bound to be surprises once unbiased data are acquired. Risk-factor surveillance will allow us, for example, to estimate how much land degradation could be avoided through a given reduction in specific risk factors and quantify the impact of poverty as a risk factor. Once data is available on the frequency of key risk factors, the final information required is on the cost-effectiveness of alternative intervention programmes aimed at diminishing threats to land health. Here the needs are to standardize methods and analytical tools and to assemble regional databases on the costs of key interventions and their impact on land health and human well-being. The land-health surveillance framework itself can provide a useful tool for measuring intervention impacts at project and national level, by measuring baselines and changes in land health and human well-being in intervention and control areas.

Demonstrating land-health surveillance systems at national level is of high priority as this is perhaps where the greatest benefits of land-health surveillance will accrue, by providing the evidence base for national planning and priority setting as an integral part of development processes and practice. The potential for land-health surveillance to provide very specific information for targeting and evaluating interventions should provide justification and incentive for mobilizing programmes and actions to improve land health. The functional use of data on land-health problems and risks for planning and evaluating intervention programmes should effectively help to dissolve the often-debated problem of the science-policy gap.

Putting land-health surveillance into operation at national level will require good design and skilled data analysts, and above all dedicated field teams for collecting consistent data in remote rural areas, sometimes under harsh environmental conditions. Land-health surveillance creates an opportunity for a revived, invigorated and dynamic role for national land resource survey teams, and better integration into development processes than in the past.

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## CONCLUSION

The work presented here has illustrated a set of scientific principles, methods and technologies that could enable evidence-based land-health management in developing countries, and shows that the approach can be put into operation with modest resources and consistent dedicated effort. Developing countries stand most to gain from evidence-based land-health surveillance systems because these countries are strongly dependent on the land resource base for food security, economic development, environment, and poverty alleviation, and yet land health appears to be declining at a time when population and economic pressure on the land is increasing. Sustainable development in the region will rely heavily on sustaining the land resource base. More rapid progress could be achieved through developing a sound evidence base on land-health problems and risk factors, providing a scientific basis for targeting interventions, and systematic measurement of costs and effectiveness of interventions. Land-health surveillance systems could be established at a national level to achieve this within a few years with modest resources, based on a randomized set of sentinel sites linked to remote-sensing information, serving both agricultural and environmental needs.

Surveillance systems aggregated to regional scale are needed to provide the evidence on major risks to land health to guide regional and international public policy on issues such as food security, sustainable ecosystems management, and climate-change adaptation and mitigation. A large effort to support the development of land-health surveillance systems in developing countries, especially in Africa, is well justified given the importance of land health for sustainable development and poverty alleviation, and the need for rapid and efficient actions to improve land health. The highest priority for support is for consistent application of basic standardized surveillance protocols at national and regional levels to build the evidence base, supported by capacity strengthening and scientific and technical backstopping in surveillance methods and continued methods development.

The Sentinel Site Surveillance protocols advanced in this project have since been taken up by the Africa Soil Information Service ([www.africasoils.net/](http://www.africasoils.net/)) and the Ethiopian Soil Information System EthioSIS, as well as in a number of other CGIAR projects.

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# Policy recommen- dations

## INTRODUCTION

Maintenance of the integrity of the Sahelian Parkland system is critical for regional food security, sustainable ecosystem management, climate-change adaptation and mitigation, and economic development. Several key recommendations for sustainable management of the West Africa Sahel are synthesized below from this study. Investments in land-health surveillance and management must become an integral part of national and regional strategies for economic development, poverty reduction, environmental management, and climate-change adaptation and mitigation.

## REGIONAL PRIORITIES

Establish and maintain regional and national land-health surveillance systems to provide a scientifically sound and policy-relevant approach to land-health management. Investments are needed to:

- Establish a regional scale, synoptic early warning system based on MODIS satellite data, linked to systematic ground sampling.
- Implement a systematic ground-sampling scheme based on the sentinel site protocols described in this report.
- Quantify behavioural risk factors associated with land degradation and identify population-wide interventions
- Evaluate the cost-effectiveness of alternative population-wide interventions for reducing and reversing land health risks.

Implementing land-health surveillance systems requires investment in infrastructural and human capacity in several areas:

- Revitalize national soil and land survey institutions, equipped with remote-sensing, geographical information systems, soil infrared spectroscopy laboratories, statistical analysis tools, cyberinfrastructure, and vehicles and equipment for field survey.
- Establish teams of land health surveillance and land management scientists supported by dedicated field technical staff.
- Develop new university curricula and provide on-the-job training in land-health surveillance concepts and associated scientific and technical methods, including surveillance and sampling theory, remote sensing, geographical information systems, soil infrared spectroscopy, digital soil mapping, and advanced multivariate and hierarchical statistical analysis.

Specific priority areas for further research include:

- Develop improved remote-sensing indicators of land degradation and their validation through systematic ground observations.
- Further methods for spatial and syndromic land-health surveillance, including incorporating uncertainty through Bayesian hierarchical modelling of land-health surveillance data.

### **PRIORITIES FOR SEGOU REGION AND SIMILAR AREAS**

To secure food production for rapidly growing population of the region, investments must be urgently targeted to improve soil fertility in areas with relatively high agricultural potential. These areas, which can be accurately mapped, make up only one third of the total land area and one half of the presently cultivated area. Investments needed are:

- Apply phosphorous fertilizers to overcome chronically low soil phosphorous levels, which currently poses a basic constraint to crop productivity.
- Promote integrated nutrient management to increase organic matter, nutrient retention, and basic cation levels as a foundation for sustained crop production. This includes improved management of organic resources and strategic application of liming materials, nitrogen and potassium fertilisers, and micronutrient supplements.

- Implement evidence-based soil fertility management through a systematic programme of agronomic testing and soil and plant analysis, linked to the soil-health surveillance system.
- Intensify extension services to improve farmer knowledge and obtain farmer feedback on integrated nutrient management.

Agricultural potential over more than half of the area of the region is limited by soil physical constraints. Protection of these areas is important for maintenance of the overall functioning of the ecosystem. Recommended measures include:

- Promote enrichment planting of Parkland systems to maintain biophysically optimal tree densities.
- Extend agroforestry and conservation agricultural practices in low potential areas that are currently under cultivation (7–21% of area of the region)
- Reforest semi-natural areas (19–42% of the region) giving high priority to the 5% of the area with high soil degradation risk.
- Deploy land health surveillance to geographically pinpoint the above areas, establish targets and monitor progress.
- Implement policies to support cheaper tree seedling production methods and promote farmer tree nurseries.

# Index

Page numbers in *italics* indicate figures or tables

Advanced Very High Resolution Radiometer (AVHRR) 33, 46, 67–9, 68, 194

Africa, climate 58–60, 59

African Data Dissemination Service (ADDS) 61

African Easterly Jet (AEJ) 60

African Monsoon Multidisciplinary Analysis (AMMA) 55

Agenda 21 55

agricultural systems, Segou Region (Mali) 165–7, 166, 167

Burkina Faso

geographical baseline data 58

rain-normalized NDVI 87, 89, 90

vegetation trends 80–1, 81, 82, 108–109

case definitions, land health 28–9, 193

climate, Sahel 58–66

climate change, and land degradation 25, 46, 55

Club of Rome 52

communication, surveillance data 23, 37–8, 38, 42, 43

cultivated areas, interventions 160, 160, 162, 163

desertification

definition 49–51

discourse 46, 52–5, 103

satellite imagery 53, 54

*see also* land degradation

drought, Sahel (1970–1985) 52, 55, 103

Earth Summit (Rio de Janeiro, 1992) 55

ecosystems

and land health 24–5, 25

Sahel 56–8, 57, 58

El Niño 60

equilibrium hypothesis, desertification 46, 52, 55, 103

evidence-based decision making, land health 26–7, 38–42, 39–42

Famine Early Warning System (FEWS) 69

fertilizer response trials 118, 150, 152, 155–7, 155, 156, 157, 158, 192

food security, Segou Region (Mali) 192

future needs 31

generalized linear mixed-effects modeling (GLMM) 148, 186

geoinformatics 32

Global Assessment of Human Induced Soil Degradation (GLASOD) 26, 51, 51

Global Inventory Monitoring and Modeling System (GIMMS) 47, 69–71, 83, 104

ground survey *see* sentinel site surveillance

Hadley cells 59

Harmattan 60

household surveys, Segou Region (Mali) 123, 164–5, 165, 166

human well-being

and land health 24–5

Segou Region (Mali) 167

information technology 23, 42

infrared spectroscopy 29, 30, 35, 35, 195–196

*see also* near-infrared spectroscopy

International Soil Reference and Information Centre (ISRIC) 51, 52, 104

Intertropical Convergence Zone (ITCZ) 58–60, 59

intervention

cultivated areas 160, 160, 162, 163

impact evaluation 31, 36

priority areas 123, 159–161, 160, 161, 162, 163

semi-natural areas 159–160, 160

Lake Chad 89

land degradation

indicators 103–5

Sahel 51–5, 51, 54

*see also* desertification

Land Degradation Surveillance Framework (LDSF)

analytical methods 123

application of 192–3

case study 117, 124–70

costs 169–170, 169

database 185, 186

field guide 172–84

land resource indicators 122

methodology 116–17, 121–3, 122

prospects 170

socioeconomic indicators 119, 123, 164–5, 165

statistical models 184–5

land health

concept 24–5, 25

decision making 26–7

regional trends 188–9

Segou Region (Mali) 189–191

land health surveillance

communication of information 23, 37–38, 38, 42, 43

concept 27, 192–4

evidence-based decision making 26–7, 38–42, 39–42

future of 197, 199–200

- implementation 22–3
- methods 28, 32–6
- principles 22, 27–31
- recommendations 191, 199–200
- regional 194–5, 199–200
- sentinel site surveillance 194–7, 200
- land resource indicators 122
- land resource surveys 123
- Landsat, soil degradation mapping 150, 152, 154
- livestock, Segou Region (Mali) 166–7, 167
- Mali
  - geographical baseline data 58
  - rainfall 72, 74, 75
  - rain-normalized NDVI 87, 89, 90
  - regions 124, 125
  - vegetation trends 72, 74, 75, 80–1, 81, 82, 83, 108
  - see also* Segou Region
- Malthus, Thomas 52
- mapping, soil degradation risk 149–50, 152, 153, 154
- Mauritania
  - geographical baseline data 58
  - rain-normalized NDVI 87, 89, 90
  - vegetation trends 80–1, 81, 82, 107
- meta-analysis 31
- Millennium Ecosystem Assessment (MA) 24, 26, 51–2
- millet, fertilizer trials 152, 155–7, 155, 156, 157, 158
- mixed effects models 36, 116–17, 123, 156, 184–5, 196
- Moderate Resolution Imaging Spectroradiometer (MODIS) 50, 57, 109, 195, 199
- monsoons 60
- National Oceanic Atmospheric Administration (NOAA), satellite imagery *see* Advanced Very High Resolution Radiometer (AVHRR)
- near-infrared spectroscopy (NIR) 142–3, 144
  - see also* infrared spectroscopy
- Niger
  - geographical baseline data 58
  - rain-normalized NDVI 87, 89, 90
  - vegetation trends 80–1, 81, 82, 109
- Niger Inland Delta (Mali) 89
- non-equilibrium hypothesis, desertification 46, 52–3, 55, 103
- Normalized Difference Vegetation Index (NDVI) 33, 46, 67–83, 68, 70, 71
  - annual increment index 75, 78–80, 79, 80, 81, 104
  - discrepancies 105–6
  - land degradation indicator 103–4
  - spatial ranking 99–102, 100, 101, 102
  - trends 71, 72–5, 72, 73, 74, 75, 196–7
  - see also* Rain-Normalized NDVI
- operational surveillance systems 31
- Parklands area
  - rain-normalized NDVI 89, 90, 99–102, 100, 101, 102
  - vegetation trends 47, 80–1, 83, 90, 99–102, 106–9, 188–9
- populations, land health analysis 22, 28
- priority intervention areas *see* intervention
- public health surveillance
  - communicating information 37–8, 42
  - decision making 27
  - strategies 192–3
- QuickBird satellite imagery 35–6, 35, 117, 134, 136–8, 148–9, 150, 151
- rainfall
  - data records 61–2, 62
  - maps 46
  - Sahel 49, 57, 60–6, 62, 63, 64, 65, 72, 73, 75
  - satellite data 61, 62–5
  - Segou Region (Mali) 124–5, 127, 128
  - spatial variations 91, 104–5
  - trends 47–8, 49, 53–5, 65–6, 65, 72, 73, 74, 92–8, 92, 93, 94, 95, 96, 97, 104–5
  - and vegetation 60, 69, 76, 78, 80, 83, 84–98, 105–6
- Rain-Normalized NDVI (RNNDVI)
  - methodology 46, 84–5
  - regional ranking 99–102, 100, 101, 102
  - trends 47–8, 75, 85–98, 86, 87, 88, 89, 92, 93, 94, 95, 96, 97, 106–7
- Rain Use Efficiency (RUE) 84–5, 90–1, 103–4, 105
- reforestation, intervention areas 159–160, 160, 161
- regional surveillance
  - methods 22, 32–4, 46–7, 194–5
  - priorities 199–200
- remote sensing *see* satellite imagery
- risk factors 29–30, 196
- root depth restrictions (RDR) 139–141, 140
- Sahel
  - climate 58–66
  - desertification 46, 49–55, 51, 54, 103
  - drought (1970–1985) 52, 55, 103
  - ecosystems 56–8, 57, 58
  - land health trends 188–9
  - rainfall 49, 57, 60–6, 62, 63, 64, 65, 72–5, 72, 73
  - rain-normalized NDVI 84–98, 99–102
  - vegetation 56–8, 57, 67–83, 68, 70, 71, 72, 73, 75, 76, 77, 78, 79, 80, 81, 82, 106–9, 129, 130
- satellite imagery
  - AVHRR 33, 46, 67–9, 68, 196
  - land degradation 53, 54
  - Landsat 150, 152, 154
  - MODIS 50, 57, 109, 197, 201
  - QuickBird 35–6, 35, 117, 134, 136–8, 148–9, 150, 151
  - rainfall 61, 62–5
  - sentinel site surveillance 35–6
  - vegetation 33–4, 33, 34, 67–9, 68, 194–5
  - woody cover 136–8
- screening tests 29, 30

- Segou Region (Mali)
- agricultural systems 165–7, 166, 167
  - fertilizer response trials 118, 150, 152, 155–7, 155, 156, 157, 158, 192
  - food security 192
  - herbaceous cover 138, 138
  - household surveys 123, 164–5, 165, 166
  - household well-being 167
  - inherent soil degradation risk 141, 141
  - intervention recommendations 118–19, 159–163, 160, 161, 162, 163
  - Land Degradation Surveillance Framework 117–120, 124–5
  - land health trends 189–191
  - land use 129–130
  - population density 124, 126
  - priorities 200
  - prospects 119–120
  - rainfall 124–5, 127, 128
  - root depth restrictions 139–141, 140
  - satellite imagery 34
  - socioeconomic indicators 119, 164–5, 165, 189
  - soil condition 142–3, 144, 145, 151
  - soil condition index 147–9, 148, 149, 153
  - soil degradation mapping 149–150, 152, 153, 154
  - soil health 117–18, 139–150, 190
  - soil infiltration capacity 141–2, 141, 142, 143
  - soil organic carbon 143, 144–7, 145, 146, 147, 148
  - tree planting preferences 119, 168, 168, 169
  - vegetation cover and structure 130–3, 131, 132, 133
  - vegetation health 117, 129–38, 189–90
  - water use 167, 167
  - woody cover 133–8, 134, 135, 136, 137, 138, 189–190
- semi-natural areas, interventions 159–160
- Senegal
- geographical baseline data 58
  - rain-normalized NDVI 87, 89, 90
  - vegetation trends 80–1, 81, 82, 107–8
- sentinel site surveillance 23, 34–6, 35, 122, 195–7
- see also* Land Degradation Surveillance Framework
- socioeconomic indicators 119, 123, 164–5, 165, 189
- soil analysis
- infiltration capacity 141–2, 141, 142, 143
  - inherent soil degradation risk 141, 141
  - methods 35, 35
  - physicochemical properties 143, 144, 147
  - root depth restrictions 139–141, 140
  - Segou Region (Mali) 117–18, 139–50, 190
  - soil condition 142–3, 144, 145, 151
  - soil condition index 147–9, 148, 149, 153
  - soil degradation mapping 149–150, 152, 153, 154
  - soil organic carbon 143, 144–7, 145, 146, 147, 148
- spatial surveillance 30
- statistical analysis, sentinel site surveillance 36
- syndromic surveillance 30–1
- tree planting preferences, Segou Region (Mali) 119, 168, 168, 169
- Tropical Easterly Jet (TEJ) 60
- Tropical Rainfall Measuring Mission (TRMM) 60, 61
- United Nations Conference on Desertification (UNCOD) 52
- United Nations Conference on Environment and Development (UNCED) (Rio de Janeiro, 1992) 55
- United Nations Convention to Combat Desertification (UNCCD) 52, 55
- vegetation
- and rainfall 60, 69, 76, 78, 80, 83, 84–98, 105–6
  - Sahel 56–8, 57, 67–83, 68, 70, 71, 72, 73, 75, 76, 77, 78, 79, 80, 81, 82, 129, 130
  - Segou Region (Mali) 117, 129–38, 189–200
  - trends 47–8, 53, 54, 106–9, 188–9
- vegetation indices
- satellite data 33–4, 33, 34, 46–7
  - spatial ranking 99–102
  - trends 47–8, 71, 72–5, 72, 73, 74, 75, 75, 85–98, 86, 87, 88, 89, 92, 93, 94, 95, 96, 97
- water use, Segou Region (Mali) 167, 167
- Water Use Efficiency (WUE) 84
- Zaire Air Boundary (ZAB) 59













Improving and maintaining land health – the capacity of land to sustain delivery of ecosystem services – is a prerequisite for wise ecosystem management and sustainable development. However there is a lack of objective, quantitative and cost-efficient methods for assessment of land health to justify, target and prioritise investments.

This report presents the concepts of land health surveillance – a science-based approach to land health assessment and monitoring. The approach is 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 approach is operationalized using latest advances in earth observation from space, in the field, and on the laboratory bench, combined with geographic information systems and hierarchical statistical methods.

The report illustrates the land health surveillance concepts with a case study in the West Africa Sahel, presenting results on regional remote sensing studies of historical changes in vegetation growth and rainfall patterns and on field level assessment of land degradation in Mali. Implications of the methods and results for development policy and research are given.

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