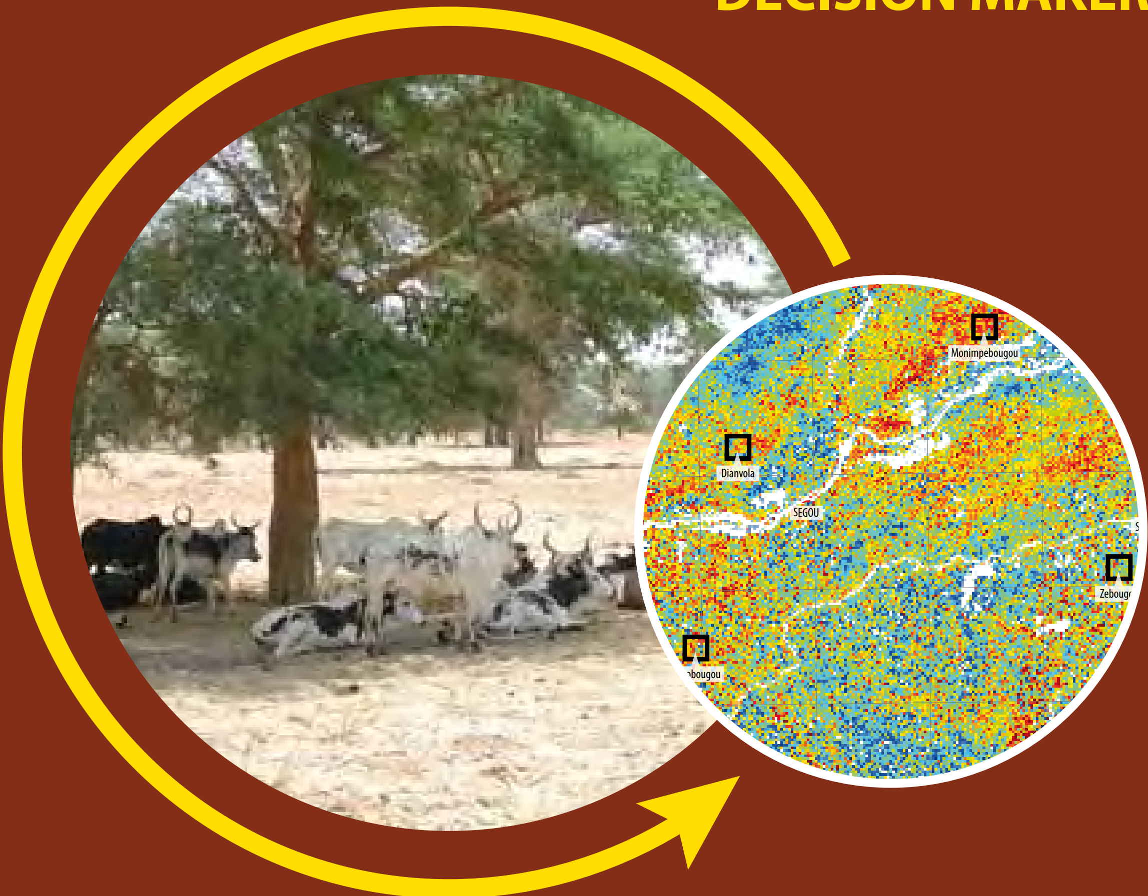
LAND HEALTH SURVEILLANCE

an Evidence-based Approach to Land Ecosystem Management

Illustrated with a Case Study in the West Africa Sahel

SUMMARY FOR DECISION MAKERS



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World Agroforestry Centre
TRANSFORMING LIVES AND LANDSCAPES

This Summary for Decision Makers synthesizes the findings of the main report: *Land Health Surveillance: An Evidence-Based Approach to Land Ecosystem Management. Illustrated with a Case Study in the West Africa Sahel*. United Nations Environment Programme, Nairobi.

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Authors

Gemma Shepherd, United Nations Environment Programme (UNEP).

With contributions from Thomas Gumbricht, Keith D. Shepherd, Tor-Gunnar Vågen, and Markus G. Walsh of the World Agroforestry Centre. Markus Walsh is currently with the Columbia Earth Institute.

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Project manager:

Gemma Shepherd/UNEP.
Email: gemma.shepherd@unep.org

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Contents

Abbreviations and acronyms

AVHRR	Advanced Very High Resolution Radiometer
DNCN	"Directorate for Nature Conservation, Mali"
IER	"Institut d'Economie Rural, Mali"
LAI	leaf area index
LDSF	Land Degradation Surveillance Framework
MDGs	Millennium Development Goals
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
*NDVI	Scaled NDVI
$NDVI_0$	bare soil value of NDVI
QB	Quickbird
RNNDVI	Rain Normalized NDVI
RUE	Rain Use Efficiency
SC	soil condition
SIMPLS	an algorithm for partial least squares regression
SOC	soil organic carbon
UN	United Nations
UNCBD	United Nations Convention on Biological Diversity
UNCCD	United Nations Convention to Combat Desertification
UNEP	United Nations Environment Program

Main messages

Livelihoods and economies in most developing countries depend critically on the ecosystem services that land provides. 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. This report describes and exemplifies Land Health Surveillance – a science-based approach to land health assessment and monitoring designed to address this need.

LAND HEALTH SURVEILLANCE

- Land health surveillance 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.
- Land health surveillance aims to answer many critical questions related to sustainable land management – where land problems exist; whom they affect; where programmatic and prevention activities should be directed; and how well they are working.
- This scientific and evidence-based approach sets out to (i) acquire statistically valid estimates of land health problems, (ii) quantify key risk factors associated with land degradation, and (iii) target cost-effective interventions to reduce or reverse these risks.
- The scientific principles of health surveillance emphasize:
  - Taking random samples from populations (units of land) so that unbiased prevalence estimates of health problems and their associated risk factors can be obtained.
  - Using standardized protocols and procedures for assessing health problems and for measuring associated risks so that results can be aggregated at different scales (e.g. district or watershed, national, regional).
  - Strategies for active dissemination of surveillance findings to different decision makers to ensure findings are used and to assess their impact.
- 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.
- Sentinel site surveillance is designed to provide accurate baseline data and monitoring of land health and factors affecting it. A Land Degradation Surveillance Framework is described, based on sentinel sites consisting of 10 x 10 km blocks (or samples of the landscape), within which randomized sample plots are used for field characterization of vegetation and soil characteristics. The spatial sampling deign is also used for collecting socioeconomic data on people and livestock. Land health indicators and risk factors derived from the ground survey results are linked to fine resolution satellite imagery using statistical models, so that the indicators can be inferred for the whole area and mapped. These results are then used to spatially target and prioritize land management interventions.
- Enormous resource savings are possible from use of land health surveillance to spatially target and prioritize interventions. Knowing not only the size of the areas to be targeted with specific interventions but also their exact location enables the design of cost-effective development programmes with well-defined and quantified targets.
- Land health surveillance provides a scientific approach for evidence-based decision-making on land management and should be an integral part of development policy and practice in tropical developing countries.
- There is a new and revitalized role for land resource departments and a need for capacity building in the new surveillance scientific concepts, technologies and tools.

REGIONAL LAND HEALTH SURVEILLANCE IN THE WEST AFRICA SAHEL

- 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.

- Current understanding of vegetation-climate relationships recognizes that long-term climate fluctuations are inevitable, but 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. Therefore maintaining good vegetation cover is important to avoid undesirable flips to a drier climate and to buffer against climate change.
- New analysis of vegetation growth from remote-sensing and rainfall data for 1982–2006 suggests that land over 50% of the area of the West Africa Sahel with annual rainfall less than 900 mm has degraded (95% certainty). The vegetation recovery since the droughts in the early 1980s has not matched the increase in annual rainfall.
- The Parklands (integrated tree-crop-livestock) ecosystem, located between 11° N and 15° N of the equator, has not degraded as much as surrounding areas. Maintenance of the Parklands is critical for stabilizing regional climate and provisioning of ecosystem services for livelihoods and economies.
- There is insufficient evidence to claim widespread positive impacts on vegetation recovery due to agricultural innovation. Further studies are needed to investigate positive trends in some agricultural areas but not others.
- Follow-up studies using finer-resolution satellite imagery and systematic ground sampling are needed to establish proper baselines and confirm and monitor trends. Large uncertainties will remain until this is done.

SENTINEL SITE SURVEILLANCE IN SEGOU REGION, MALI

- Segou Region includes predominantly pastoralist systems in the drier north, with 27% of the land area under cultivation, to agro-ecosystems in the south, where 73% of the land area is cultivated. These are predominantly Parkland systems. 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.
- Semi-natural areas (not cultivated or managed) were identified as being prone to water run-off and soil erosion. Restoring woody cover in these areas is important to maintain overall ecosystem health. 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 surveillance results provide quantified targets for how many trees to plant where.
- The regional surveillance study pointed to the critical importance of maintaining vegetation cover in the Parklands ecosystem. The sentinel site surveillance provided accurate information on how many trees need to be planted where for enrichment planting to maintain optimal tree densities in the Parklands. 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.
- Contingent valuation surveys identified the cost of tree seedlings as the key constraint on farmers planting more trees. Policies are needed to support cheaper production methods and extension of farmer tree nurseries.
- There is evidence for critically low soil fertility levels and widespread soil health degradation associated with current cultivation practices, threatening food security and soil-related ecosystem services. Low soil available phosphorus is a key fundamental constraint, but exchangeable bases and soil organic matter levels are also critically low for sustainable production.There is limited scope for increasing area under cultivation without further damaging ecosystems, due to the high soil degradation risk associated with inherent soil physical constraints in semi-natural areas. Thus it is imperative that soil health is improved in existing cultivated areas.
- Cultivated areas with no inherent soil physical constraints should be targeted for soil fertility replenishment programmes, centred on phosphorus applications. These areas comprise 31% of the total area and 50% of the currently cultivated area. Lower input conservation agriculture and agroforestry systems can be targeted to currently cultivated areas with high

inherent risk of soil degradation, comprising 7–21% of the area.

- Fertilizer response trials suggest soil fertility management will need to combine 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.
- Maps at fine spatial resolution (2 m) are provided showing land health constraints and priority intervention areas for sentinel blocks. Key indicators are also mapped for Segou Region at medium spatial resolution (30 m).
- If the trends found in Segou Region are found to be representative of those across the Sahel, then there is a looming regional food security and environmental crisis, unless well-targeted land management programmes are put in place. Land health surveillance can speed reliable learning and increase efficiencies by targeting cost-effective interventions and assessing outcomes with scientific rigour.

Policy recommendations

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 policy 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 to:

- Revitalizate 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:

- Developing 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 pose 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 farmers' 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.

Land health surveillance

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

BOX 1

Examples of critical questions related to land management.

- Where is degraded land located and what are the specific degradation processes to be overcome?
- What are the national trends in land degradation and which areas should receive priority for land rehabilitation in relation to ecosystem vulnerability?
- 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 land health risks threaten food security?
- What is the cost-effectiveness of alternative intervention strategies to reduce and reverse land health risks?
- Where are there opportunities for avoiding land degradation as a climate change mitigation strategy?
- How much carbon could be sequestered through improved land use and where in the landscape can the biggest gains be made?
- What impacts are intervention programmes having on land health and human well-being and are they cost-effective?

BOX 2

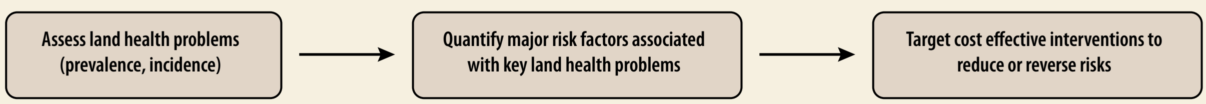
Land health surveillance defined.

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.

This scientific and evidence-based approach sets out to acquire statistically valid estimates of land health problems, quantify key risk factors associated with land degradation, and a target of cost-effective interventions to reduce or reverse these risks (Figure 1). Land degradation problems share many similarities with chronic disease problems (Box 3) and are of sufficient importance to development to merit the same degree of scientific rigour. For example, public health surveillance conducted by the World Health Organization has established that 75% of deaths from cardiovascular disease (the world's leading cause of death) are attributable to only three key risk factors – tobacco use, high cholesterol, and high blood pressure. The main emphasis of intervention is now on population-wide programmes to reduce the average levels of these risk factors in the general population, with less emphasis than in the past on rehabilitation of chronic cases. We do not yet have surveillance systems that are able to provide this type of evidence to guide land health interventions. This work aimed to lay down principles and procedures towards operational land health surveillance systems for developing countries.

FIGURE 1

Key steps in land health surveillance.



associated risk factors to justify, target and prioritise investments (Box 1).

Land health surveillance is a science-based approach to land health assessment and monitoring designed to address this need (Box 2). 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. 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. It provides a scientific conceptual framework and set of multiscale assessment tools aimed at enhancing land management.

BOX 3

Similarities between land degradation problems and chronic (non-communicable) disease problems in human health, meriting similar scientific surveillance approaches to guide policy and practice.

- 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.
- Lack of data to evaluate cost-effectiveness of alternative preventive and rehabilitation interventions.

The scientific principles of health surveillance (Box 4) emphasize taking random samples from populations (whether people or units of land) so that unbiased prevalence estimates of health problems and their associated risk factors can be obtained, and use of standardized protocols and procedures for assigning samples to specific health problems and for measuring risks so that results can be aggregated at different scales (e.g. district or watershed, national, regional). Surveillance includes strategies for active dissemination of surveillance findings to different decision makers (Table 1) to ensure findings are used and to assess their impact.

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.

BOX 4

Principles of health surveillance.

- Emphasis on the health of populations of sample units rather than on individual units.
- Random sampling designs to enable inferences to be made about populations.
- Standardized protocols for data collection to enable statistical analysis of patterns, trends, and associations; including aggregation of data at different scales.
- 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 for design of public policy and health programmes.
- Statistically rigorous evaluation of intervention impacts.
- Integration of these principles into operational systems as part of regular policy and practice.

TABLE 1

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	• Prevalence data and maps of land health constraints in a locality • Proximal, behavioural risk factors for land degradation • Evidence-based evaluation of performance and risks for specific land management interventions	• Develop individual and community knowledge of predominant land health constraints and hazards in the locality to help mobilise action • Guide screening of appropriate management interventions for testing by individual land users or communities • Guide good preventive practice by individuals and communities • Develop individual and community knowledge on trade-offs and risks associated with different management interventions

TABLE 1 *continued*

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

Scale	Audience	Information products	Uses
District	Agricultural extension providers	• Prevalence and incidence data and maps of land health constraints in a district • Information on proximal, behavioural risk factors for land degradation • Maps targeting intervention strategies and priorities in relation to constraints • Early warning of land degradation outbreaks • Evidence-based evaluation of performance and risks for specific land management interventions • Standardized operational norms or case definitions and screening tests for assessing good/poor land health	• Develop extension knowledge of predominant land health constraints and hazards in the district to mobilize appropriate action • Guide preparation of extension materials on best preventive practice for prevalent hazards • Guide preparation of extension messages and materials on rehabilitation of degraded land for prevalent land health constraints • Guide preparation of extension materials on performance and risk of specific management interventions • Use of standardized screening tests to identify land health constraints in the field
	Local government planners; development assistance organizations	• As above	• Plan public information and awareness campaigns on prevalent land health problems, best preventive practice and rehabilitation interventions • Knowledge of land health status in district; assess needs of different groups and areas • Plan land health intervention programmes; target priority areas; define and monitor measurable objectives and targets • Take early action in relation to new land degradation outbreaks • Prepare funding proposals to central government and donors based on evidence of problems • Adjust surveillance programmes in light of user feedback, evaluation of interventions and new emerging threats
	Local stockists	• Prevalence of major constraints by land use type and matching recommendations on input-based management recommendations	• Project input requirements (type, amounts, packaging) and potential market • Develop knowledge of prevalent constraints and management recommendations to be able to advise customers
National	National research organizations (agriculture, livestock, forestry, environment, etc)	• Prevalence and incidence data and maps of land health constraints in country • Information on proximal, behavioural risk factors for land degradation • Maps targeting intervention strategies and priorities in relation to constraints • Early warning of land degradation outbreaks • Evidence-based evaluation of performance and risks for specific land management interventions • Standardized operational norms or case definitions and screening tests for assessing good/poor land health • Standardized protocols for monitoring land health nationwide	• Priority setting for agricultural, forestry and environmental research programmes (constraints, spatial targeting) • Systematic evaluation of impact of land management interventions • Target land management strategies for climate change adaptation and mitigation • Identify opportunities for schemes for payments for ecosystem services • Operational systems for land health surveillance • Evaluation and modification of national land health surveillance system • Frameworks for systematic design of national crop, tree and livestock trials linked to surveillance data.

TABLE 1 *continued*

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

Scale	Audience	Information products	Uses
	Ministries of agriculture, livestock, forestry, environment, etc	• As above	• Develop extension knowledge of predominant land health constraints and hazards in different districts to mobilize appropriate action • Guide preparation of extension materials on best preventive practice for prevalent hazards • Guide preparation of extension messages and materials on rehabilitation of degraded land for prevalent land health constraints • Guide preparation of extension materials on performance and risk of specific management interventions • Use of standardized screening tests to identify land health constraints in the field
	Planning and finance ministries	• Identification of priority risk factors for prevention of land degradation at national level • Information on time trends in land health and associated risk factors • Reliable and comparable estimates of the burden of land degradation in relation to factors such as poverty, region • Cost-effectiveness analysis to identify high, medium and low priority interventions to prevent or reduce land health risks • Evaluation of targeting strategies: population-wide versus high-risk individuals; distal versus proximal risks; primary versus secondary prevention; prevention vs rehabilitation	• Formulate risk prevention and rehabilitation policies for land health management and set priorities and targets • Formulate concrete and specific action plans and monitor impacts • 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) • Improve public awareness and understanding of risks to land health • Identify opportunities for combining risk reduction strategies, including those with other sectors (e.g. human health) • Identify priorities for investments in land health surveillance systems to strengthen the scientific evidence base
	Development assistance and conservation organizations; bilateral donors	• As above	• Formulate development assistance strategies and priorities for land health management and in relation to other sectors, poverty reduction strategies, environmental management plans • Identify and spatially target interventions • Assess impacts of interventions on land health and human welfare
	Universities and colleges	• Training and educational materials on land health surveillance approaches and methods • Identification of research needs and priorities • Information on risks to land health and cost-effectiveness of alternative intervention strategies	• Curriculum development • Identification of research priorities and topics for MSc and PhD programmes and research departments
	Private sector input suppliers	• Information on priority intervention strategies, technology, inputs, and information products for land health care (e.g. fertilizers, germplasm, implements, extension products) • Information on land health surveillance research priorities	• Projection of potential markets for technology, inputs and information products • Planning for manufacture or importation of appropriate products, product formulations (e.g. fertilizer types) and quantities • Identification of future technology needs for research and development • Formulation of reliable information products for private sector extension services

TABLE 1 *continued*

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

Scale	Audience	Information products	Uses
Regional	Regional scientific bodies	• Regional level information on land health status and risks and their spatial distribution and time trends • Information on cost-effectiveness of alternative land health intervention strategies • Information on land health surveillance approaches and methods • Priority research needs in land health management and surveillance	• Identification of common land health problems and solutions, including trans-boundary issues, where regional coordination on policy or research may be beneficial • Early identification of emerging land health issues that may have regional impacts • Development of harmonized land health surveillance and intervention testing approaches so that results can be compiled at regional level
	Regional economic development bodies	• As above	• Development of harmonized regional policies and intervention strategies for land health management based on scientific evidence • Coordinated efforts to improve public awareness and understanding of risks to land health
International	Development assistance organizations	• Multiscale (continental to sub-national) data on land health status and risks • Information on priority intervention strategies and their cost-effectiveness for different countries and regions • Information on priority research and training needs in land health care and surveillance	• Priority setting and targeting of support programmes based on scientific evidence on land health status and cost-effectiveness of alternative intervention strategies • Assessment of impacts of intervention strategies on land health based on scientifically sound information • Formulation of capacity building programmes based on systematic appraisal of needs and bottlenecks
	Scientific community	• Scientifically sound multiscale data and information on land health status and risks over time • Priority research and training needs in land health care and surveillance	• Scientifically credible and systematic assessments of land health status and risks at different scales • 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) • Development of new scientific methods and technology for land health assessment and management (e.g. remote-sensing algorithms, diagnostic tools, statistical methods)
	UN bodies, Conventions	• Scientifically sound multiscale data and information on land health status and risks over time • Priority research and training needs in land health care and surveillance • Information on priority intervention strategies and their cost-effectiveness	• Scientifically credible and systematic assessments of land health status and risks at different scales, including early warning • Evidence-based information on land health intervention priorities as a basis for policy development, advocacy, science coordination, and capacity building • Scientifically credible monitoring and impact assessment with respect to achieving goals of international conventions related to land management
	International donors	• 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) • Information on research and training needs in land health management and surveillance	• Formulation of development assistance plans and priorities related to land management based on scientifically sound data and information • Formulation of well-targeted capacity building assistance programmes for land health care
	International private sector	• As above	• Assess markets for technology, inputs, information products related to land management and surveillance • Identify technological opportunities for research and development • Development of land health surveillance strategies within agricultural industries (e.g. for auditing of environmentally sound practices, monitoring impacts on land quality)

Implementing land health surveillance

In this case study, land health surveillance was implemented at two main levels of scale: regional surveillance, employing long-term satellite data at coarse spatial resolution (8 km) in conjunction with rainfall data over a regional extent (West Africa Sahel); and sentinel site surveillance, which employs ground sampling in conjunction with remote-sensing imagery at fine spatial resolution (1–30 m) for Segou Region in Mali.

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. Due to variations limitations of this 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, a Land Degradation Surveillance Framework was used, which is based on sentinel sites consisting of 10 x 10 km blocks (or samples of the landscape), within which randomized sample plots are used for field characterization of vegetation and soil characteristics. The spatial sampling deign is also used for collecting socioeconomic data on people and livestock. Land health indicators and risk factors derived from the ground survey results are linked to fine resolution satellite imagery using statistical models so that the indicators can be inferred for the whole area and mapped. These results are then used to spatially target and prioritize land management interventions.

Regional surveillance of land health

The objectives of the study were to (i) synthesize existing knowledge from satellite-derived studies on land degradation in the West Africa 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, with the aim of providing a sampling frame for more detailed studies.

The Sahel is a semi-arid region, predominantly grassland and shrubland, located approximately between 11° N–18° N, with a steep north-south gradient in annual rainfall (Figure 2). 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. The focus of this study was on the West Africa Sahel, centring on the project countries: Burkina Faso, Mauritania, Mali, Niger, and Senegal. The Parklands mixed tree-crop-livestock system, which predominates the region from 11° N–18° N of the equator, is of special interest because of its critical importance for livelihoods and the economy of the region (Figure 3).

FIGURE 2

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).

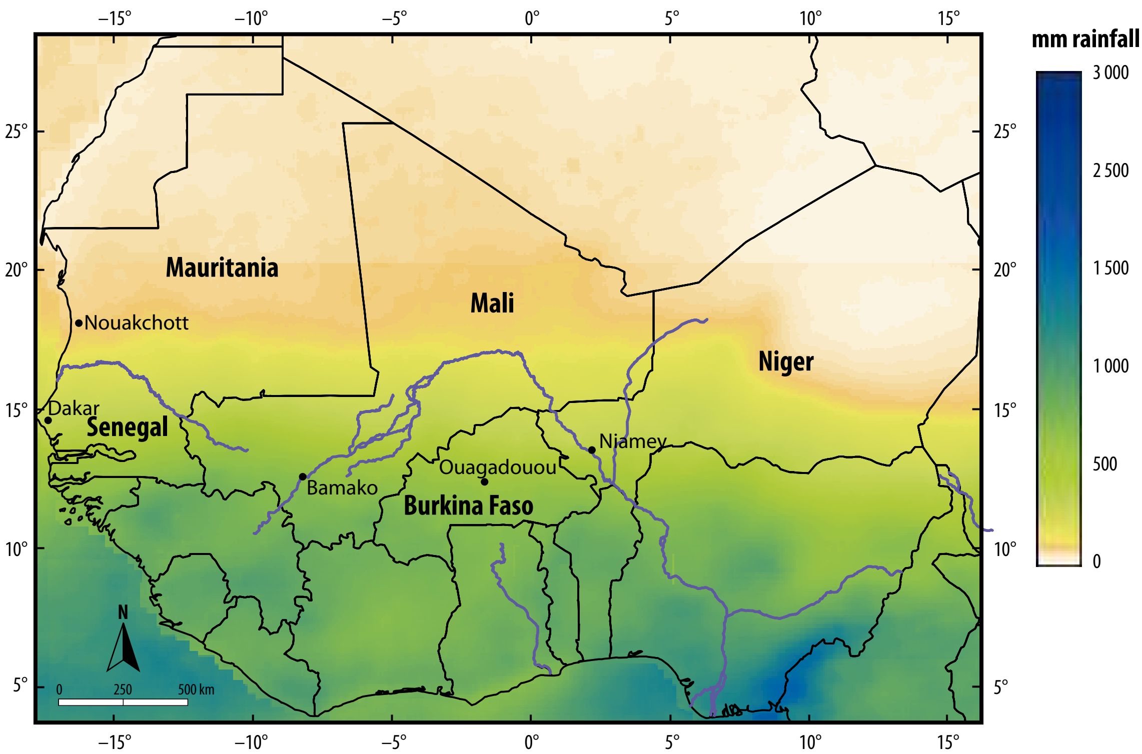


FIGURE 3

Photo of the Parkland system during the dry season. In the rainy season crops such as millet are grown among the trees.

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 developed, 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.

Previous remote-sensing studies on vegetation changes in the Sahel over the past 25 years provide conflicting results. The vast majority of studies find no evidence for land degradation in the West Africa Sahel and some studies even report a greening trend that is stronger than expected from rainfall increases alone, which has been attributed to improvements in land management. However, other recent reports using more detailed datasets indicate that there has been a degradation trend that is actually reflected in lower biomass than might be expected from the rainfall increase.

ANALYSIS OF VEGETATION TRENDS 1982–2006

We analysed time trends in long-term (1982–2006) satellite-derived (Advanced Very High Resolution Radiometer) data on vegetation productivity (ten-day intervals) in combination with rainfall data combined from ground recording stations and satellite-derived rainfall estimates (Figure 2). 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.

However there were important differences with previous studies in the way we calculated our NDVI index. First, we adjusted the index to correct for interference from soil background signal at low vegetation cover, to help prevent over-estimation of vegetation cover in dry conditions. Secondly, we summed increments of NDVI increase over the growing season to minimize non-growth related differences between land use systems, such as amounts of standing biomass. This new index proved to be much more stable and suitable for assessing vegetation growth in the Sahel, where there are large spatial and temporal changes in land-use systems. For example, the boundary between pastoral and agricultural systems tends to track the 300 mm rainfall isohyet (Figure 4). Thirdly, we used newer versions of the AVHRR NDVI data, which has higher quality than previous versions, and a more comprehensive compilation of rainfall data.

Our analysis confirmed the greening trend in response to the increased rainfall since the droughts in the early 1980s, although the trend was weaker than found in previous studies (Figure 5 upper). However, when normalizing the data for rainfall differences (Figure 5 lower), we found that recovery in vegetation growth did not match the increase in rainfall, giving a net decreasing trend in the rain adjusted increment NDVI indicator. In regions with average rainfall below 900 mm per year, where the indicator is most reliable, rainfall adjusted vegetation growth decreased in over 90% of the area (3.3 million km^2), and in 50% of the total area (2.0 million km^2) at a statistical confidence of 95% certainty (Table 2). The corresponding area over which the index increased was only 10% (0.4 million km^2) and almost none of this area showed a statistically significant increase at a 95% certainty level. 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 West Africa Sahel there has been extensive incipient desertification. Some other recent studies using fine resolution NDVI imagery and rainfall data support our conclusions.

The degradation trends were less pronounced in the Parklands region than surrounding areas to the north and south, indicating the importance of maintaining the health of the Parkland ecosystem for regional climatic and ecological stability. 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

TABLE 2

Changes in rain-normalized scaled 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%.

		Increment RNNDVI	
		Increase	Decrease
Country	Area km^2	%	
Mali	1,124,224	13 (0)	87 (54)
Mauritania	1,039,808	4 (0)	96 (78)
Niger	1,182,784	7 (0)	91 (40)
Senegal	176,064	36 (0)	64 (29)
Burkina Faso	205,760	27 (0)	73 (16)

FIGURE 4

Variation in latitudinal position of the 300 mm isohyet in the Sahel for 1930–2006. 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).

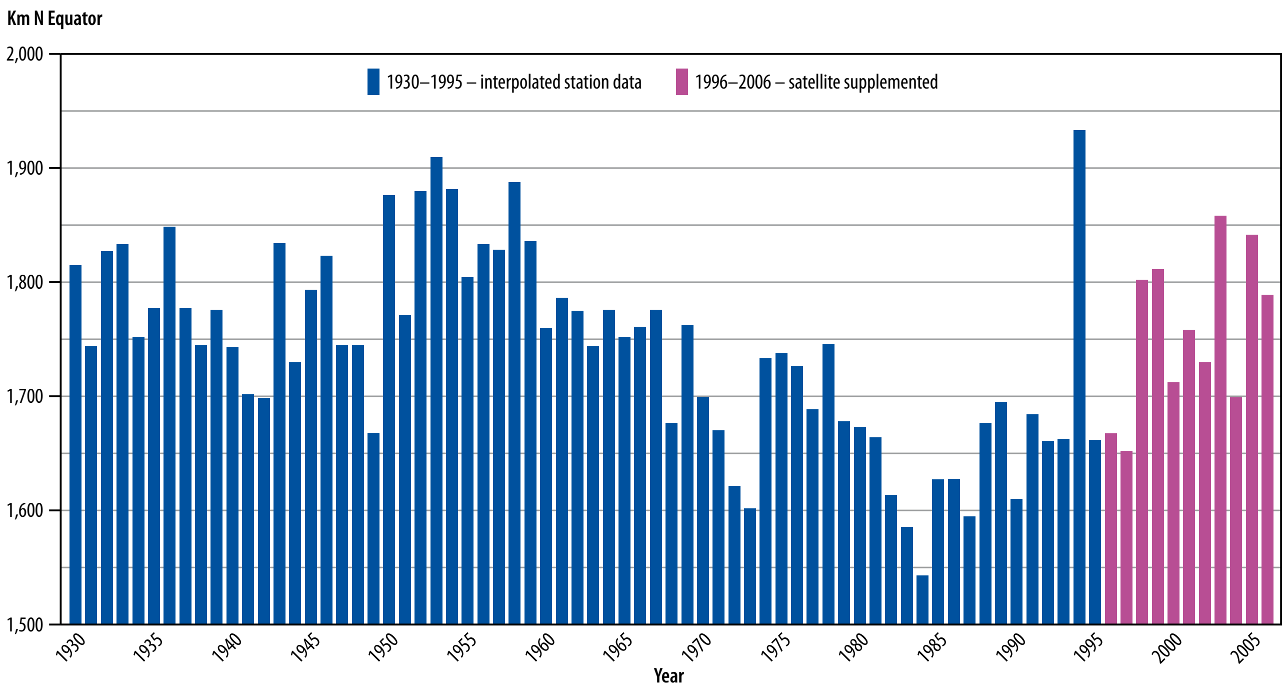
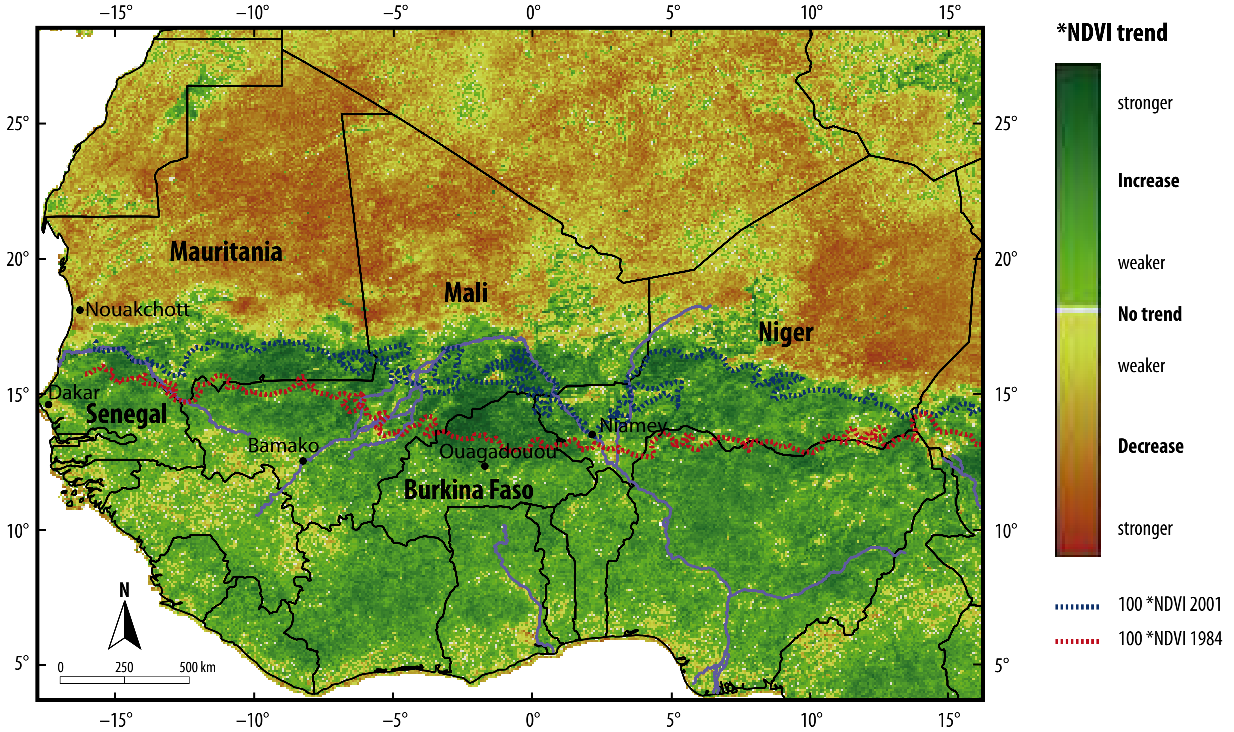


FIGURE 5

Normalized trend in annual increment-scaled NDVI for the period 1982–2006 (top) and after normalization for rainfall differences (bottom).



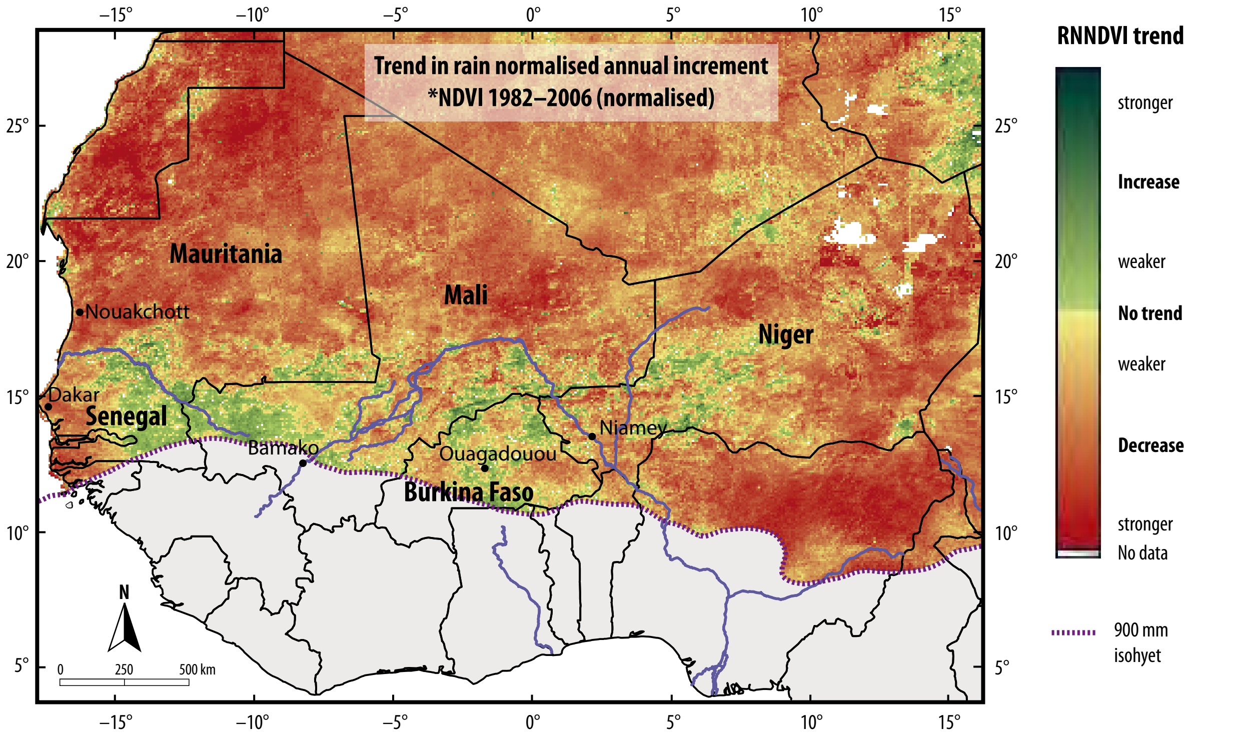
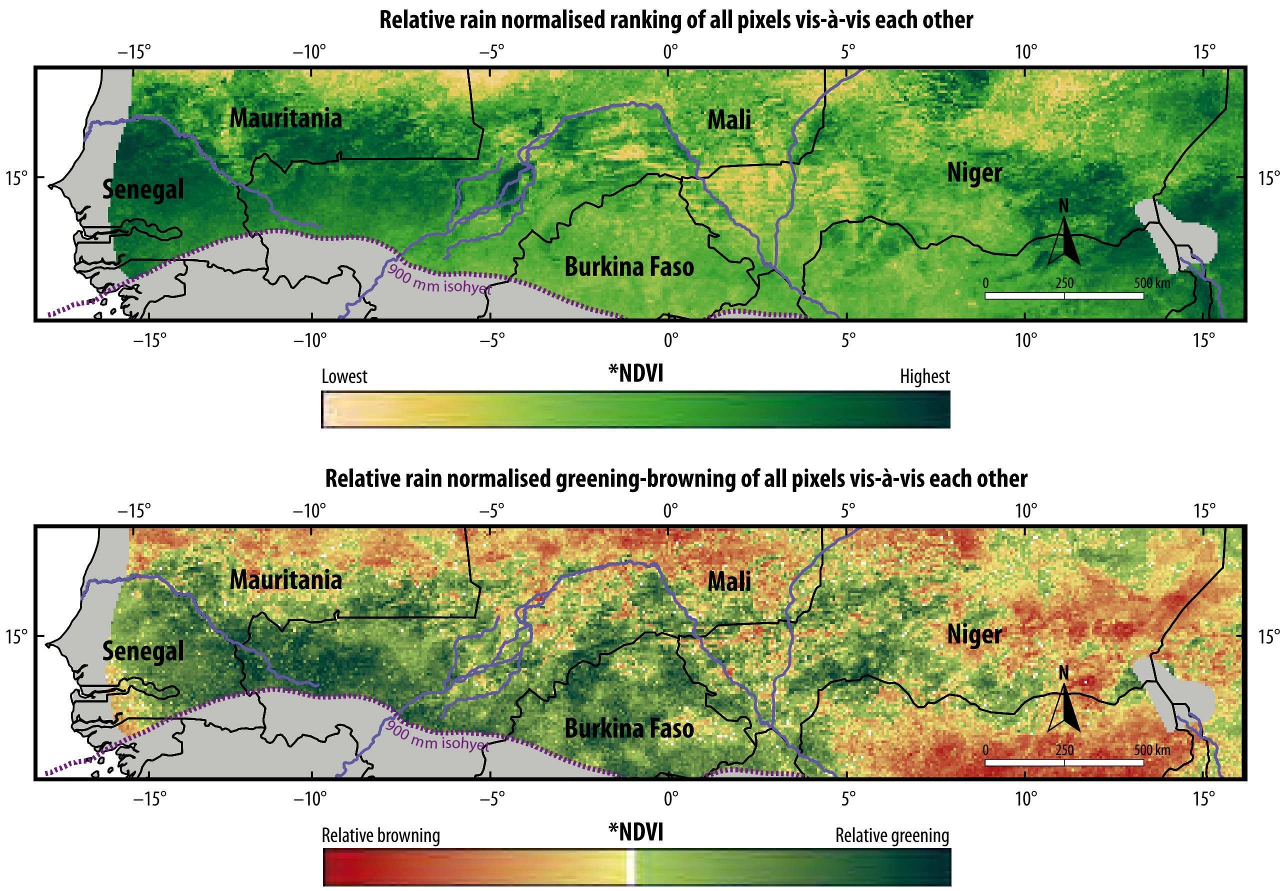


FIGURE 6

Relative regional ranking of rain-normalized increment *NDVI (RNDVI) 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.



large area impacts of agricultural innovation in the central plateaux of Burkina Faso. Other areas showing improvement in rain-normalized vegetation index are restricted to areas along the Senegal River in both Mauritania and Senegal, probably reflecting an increase in irrigated agriculture.

We also conducted a relative ranking of rain-normalized NDVI for the Parklands region, which compares all pixels *vis-à-vis* all others, and establishes an ordinal relation showing pixels from the highest RNNDVI to the lowest RNNDVI (Figure 6). 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. This analysis confirmed the worst affected regions identified from the trend rain-normalized NDVI index.

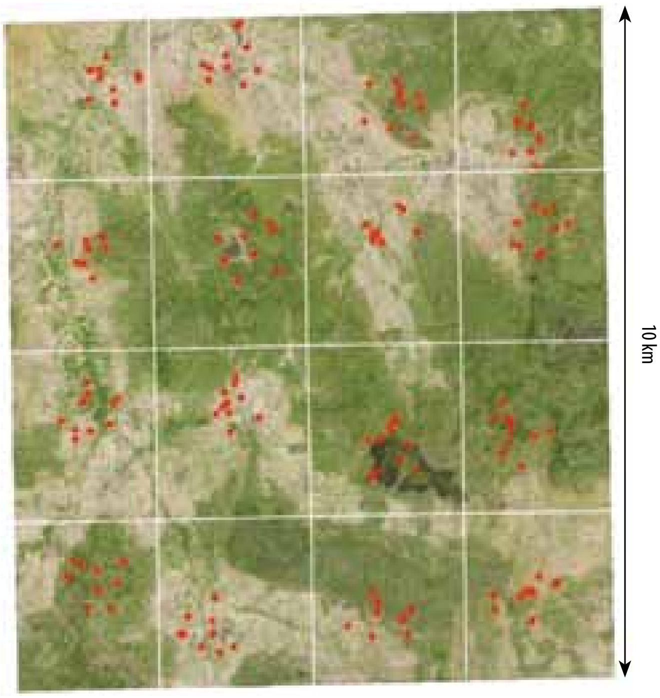
The indication of widespread land degradation in the Sahel raises a critical need for more detailed and systematic follow-up studies to validate and interpret the trends and establish casual factors, using higher resolution time-series satellite data and field survey. It is doubtful whether much further progress can be made towards informing policy on the extent of land degradation, and strategies for sustainable land management, until such follow-up studies are conducted and proper baselines established. Regional application of the sentinel site surveillance framework described below could meet this need.

Sentinel site surveillance of land health

The Land Degradation Surveillance Framework is a standardized surveillance protocol for measuring vegetation, soil and socioeconomic conditions in landscapes. This field-based framework is built around the use of "Sentinel Sites" or "Blocks" of 10 x 10 km in size (Figure 7). The sampling scheme is hierarchical or nested: within blocks, 1 sq km clusters are located, and within each cluster ten 1,000 m^2 "Plots" (i.e. about 35 m diameter) are sampled. Plots within clusters, and clusters within block tiles, are randomly placed so that unbiased estimates of problem prevalence are obtained. The details of the sampling design can be adjusted according to project objectives.

FIGURE 7

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.



At each plot a standardized measurement protocol is applied (Figures 8 and 9) based on rapid, quantitative, repeatable, and interpretable measurements of indicators of land health. Vegetation cover and abundance and soil characteristics are measured on four 100 m^2 "Sub-Plots" (about 5 m diameter) located at fixed positions within the plots. Soil samples are also taken from each sub-plot and analysed in the laboratory using a new low-cost, high-throughput technique: infrared spectroscopy (Figure 10). With this technology, spectral signatures of light reflected off air-dried soil samples are used to provide estimates of soil fertility indicators and soil organic carbon.

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.

Hierarchical statistical analytical methods are used to analyse patterns, associations and risk factors at different levels of scale and to generalize findings for the population of sentinel sites. In this application, we employ "mixed effects models", which permit errors to be structured according to the spatial hierarchical structure of the sampling scheme. These models not only provide the ability to make generalizations about the data at the population

FIGURE 8

Summary of types of variables measured in the Land Degradation Surveillance Framework.

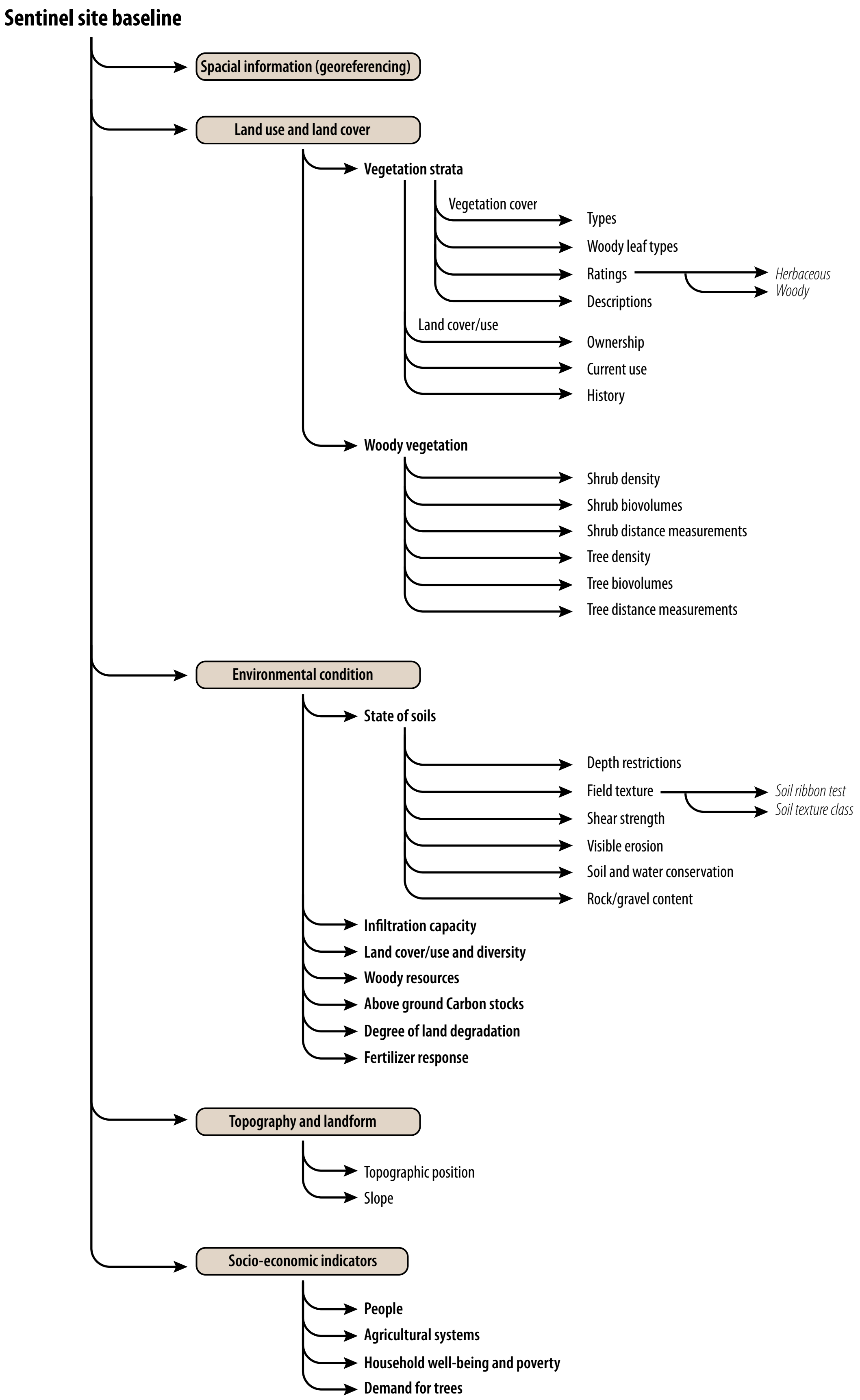


FIGURE 9

Photos of field measurements in progress. Measuring tree heights (left) and infiltration rates (right).

FIGURE 10

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.

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

FIGURE 11

Locations of sentinel sites in the Segou Region of Mali. Rainfall isohyets are also shown.

restrictions. These methods also allow wider area (e.g. 100 km) mapping in conjunction with satellite imagery at medium spatial resolution (30 m).

SEGOU REGION CASE STUDY

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 the UNEP West Africa Drylands project[1]. Five sentinel sites (blocks) were established in Segou region during 2005–6 (Figure 11). Long term annual rainfall for the fives 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. Population density in this area has more than doubled over the past 40 years, but 80% of the population between 15–65 years old are still illiterate and primarily depend on agriculture for their livelihoods.

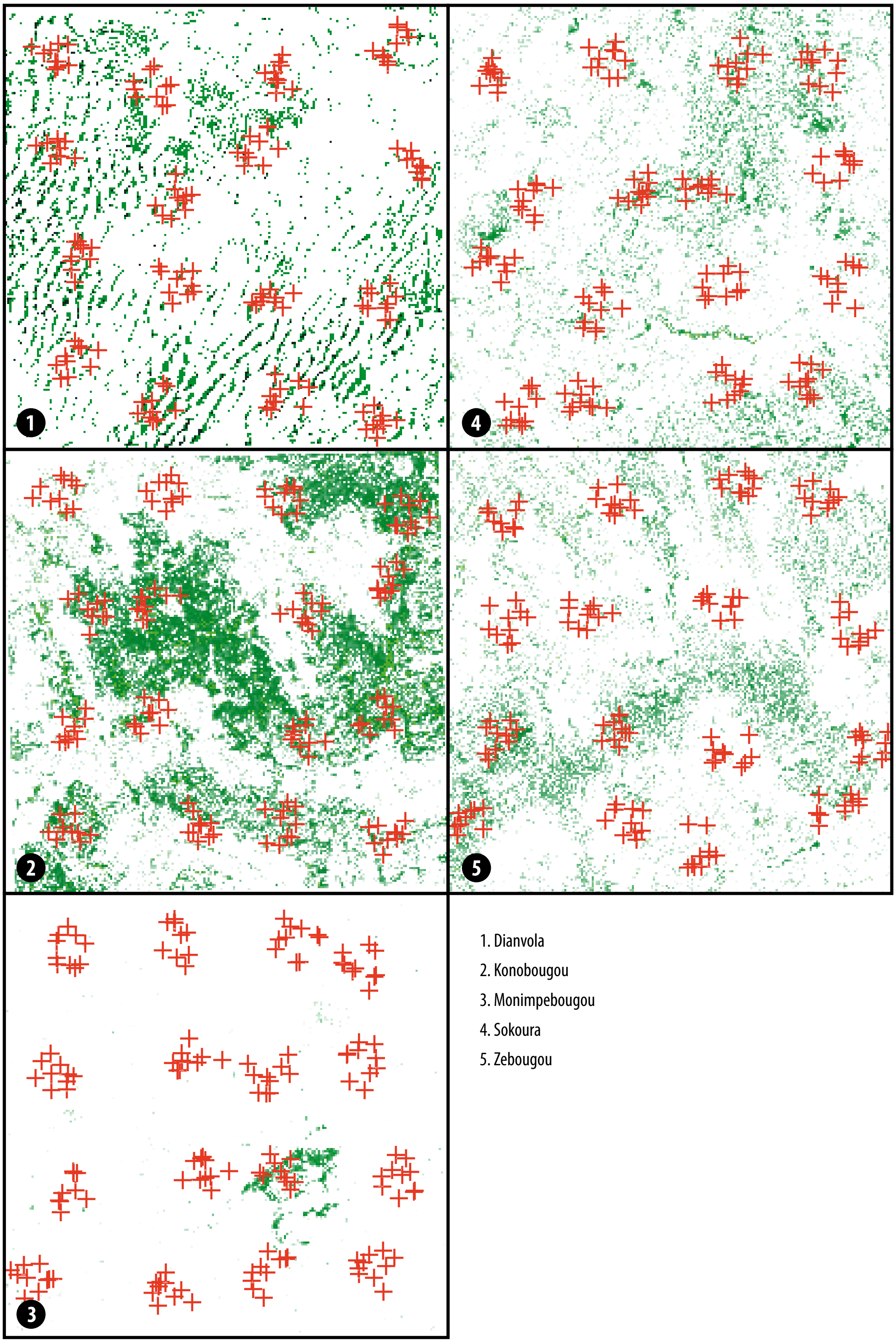
VEGETATION CONDITION

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

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

FIGURE 12

Spatial distribution of woody vegetation (green) in the 5 blocks. Images are based on tree and shrub spectral endmembers from Quickbird reflectance. Blocks are (from top to bottom): Dianvola, Konobougou, Monimpebougou, Sokoura and Zebougou.



increasing rainfall. However, there was substantial cluster- and plot-level variability (Figure 12), 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.

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, than without, severe root depth restrictions (Figure 13).

SOIL FERTILITY

The 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^{-1} (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^{-1} lower absolute SOC contents than semi-natural areas after controlling for the presence of trees and shrubs.

We developed a soil condition index based on infrared spectral data. Such indices integrate information on various physicochemical properties

TABLE 3

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

	Dian	Kono	Moni	Soko	Zebo
Cluster			%		
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_{23}^{34}	68_{61}^{73}	35_{29}^{41}	51_{44}^{57}	71_{65}^{76}

FIGURE 13

Infiltration curves averaged for plots with and without root depth restriction within 0–20 cm soil depth.

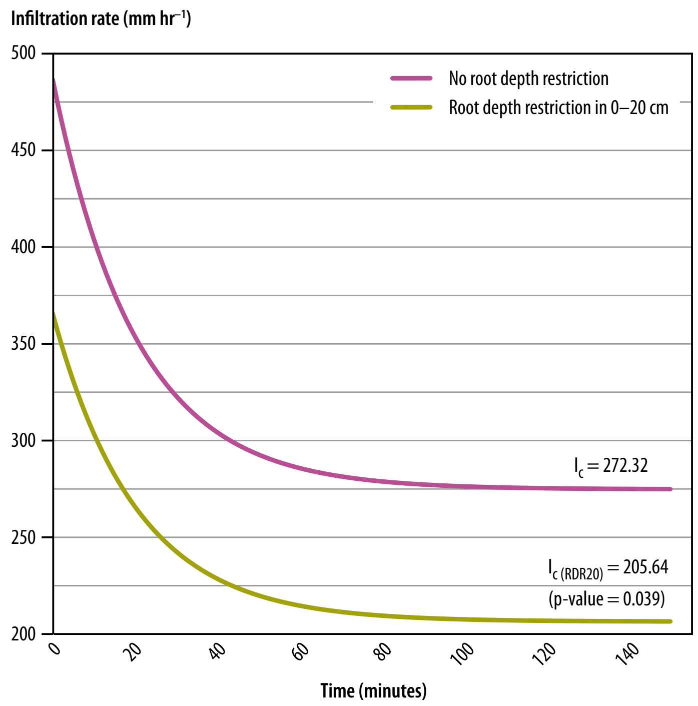
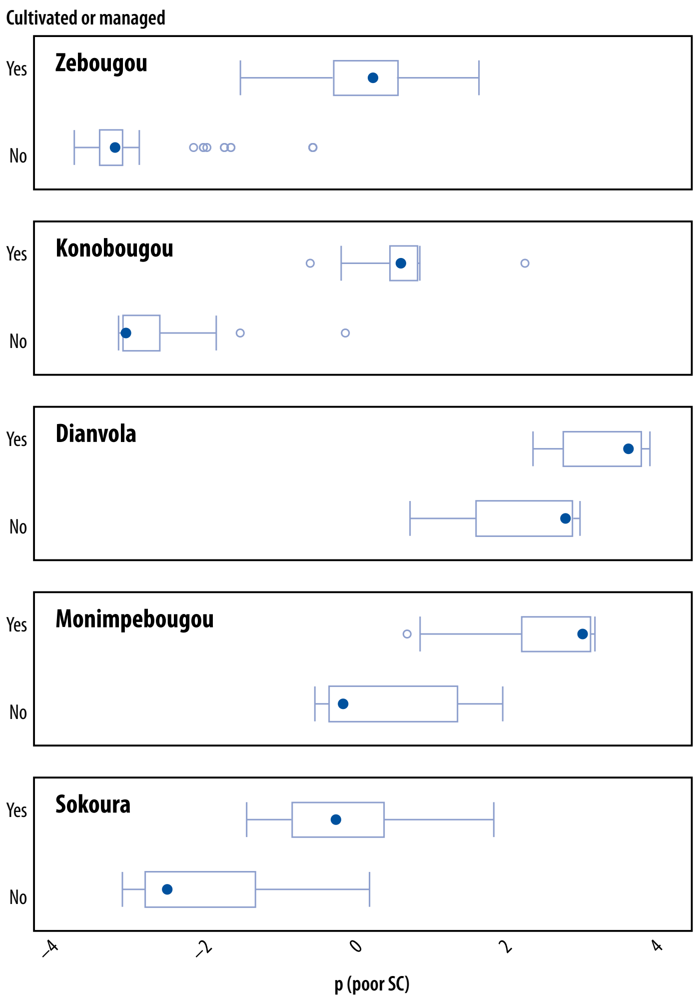


FIGURE 14

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



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 based on the soil spectra, which effectively distinguished 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 increased with increasing sand content. When variation in sand content was statistically controlled for, 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 (Figure 17) was grown under framed 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 grain yield increases were small (200 kg per hectare), and organic amelioration will most likely be needed for profitable fertilizer use.

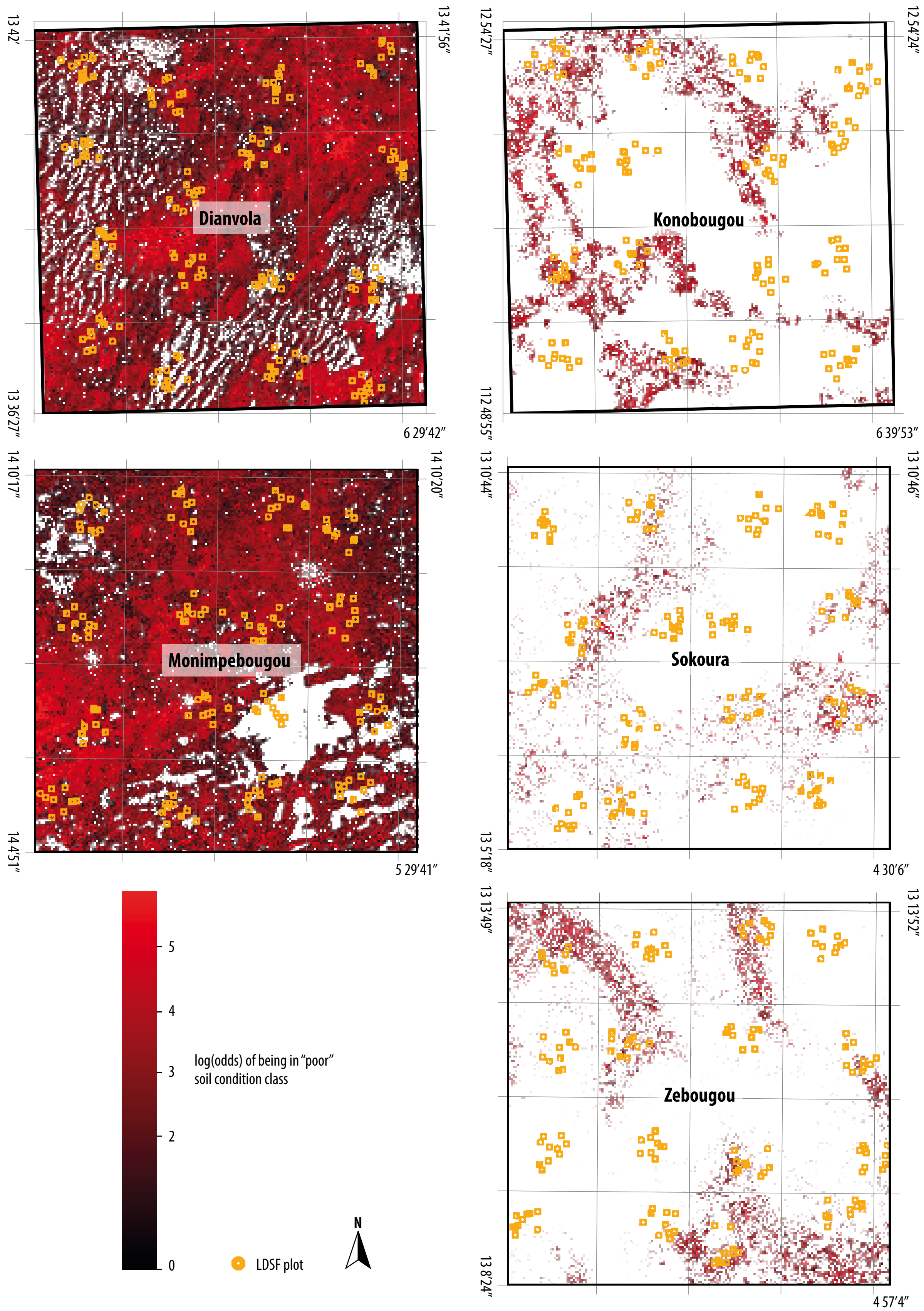
These trials also served to demonstrate how the hierarchical structure of the sentinel sites provides a powerful and efficient framework for conducting intervention trials. The framework ensures that trials are randomly located and thus sample the diversity in the landscape. The hierarchical statistical 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 the rule-based approach is to establish 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

FIGURE 15

Estimated risk of being in poor soil condition class for each sentinel block 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. Spatial resolution ≈ 2.4 m.



areas having a high likelihood of poor soil fertility. Priority intervention areas for afforestation, 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 targeted locations having sparse woody cover for afforestation interventions. The estimated priority area for afforestation (i.e. semi-natural areas with sparse woody cover) varies from about 1,900–4,200 ha per 10,000 ha block (i.e. 19–42% of the area). 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 (Table 4).

The high priority areas make up less than 5% of the region. Thus reforestation efforts can be accurately targeted to these 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 (Figure 19). 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).

In particular, a targeted soil fertility programme to provide phosphorus dressings, to overcome this basic limiting constraint to agriculture, is 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 were accurately located

FIGURE 16

Map of Segou region showing areas with >75% probability of being in poor soil condition class based on calibration to Landsat imagery. Red areas are predicted to have a very high risk of soil degradation. Spatial resolution ≈ 28.5 m.

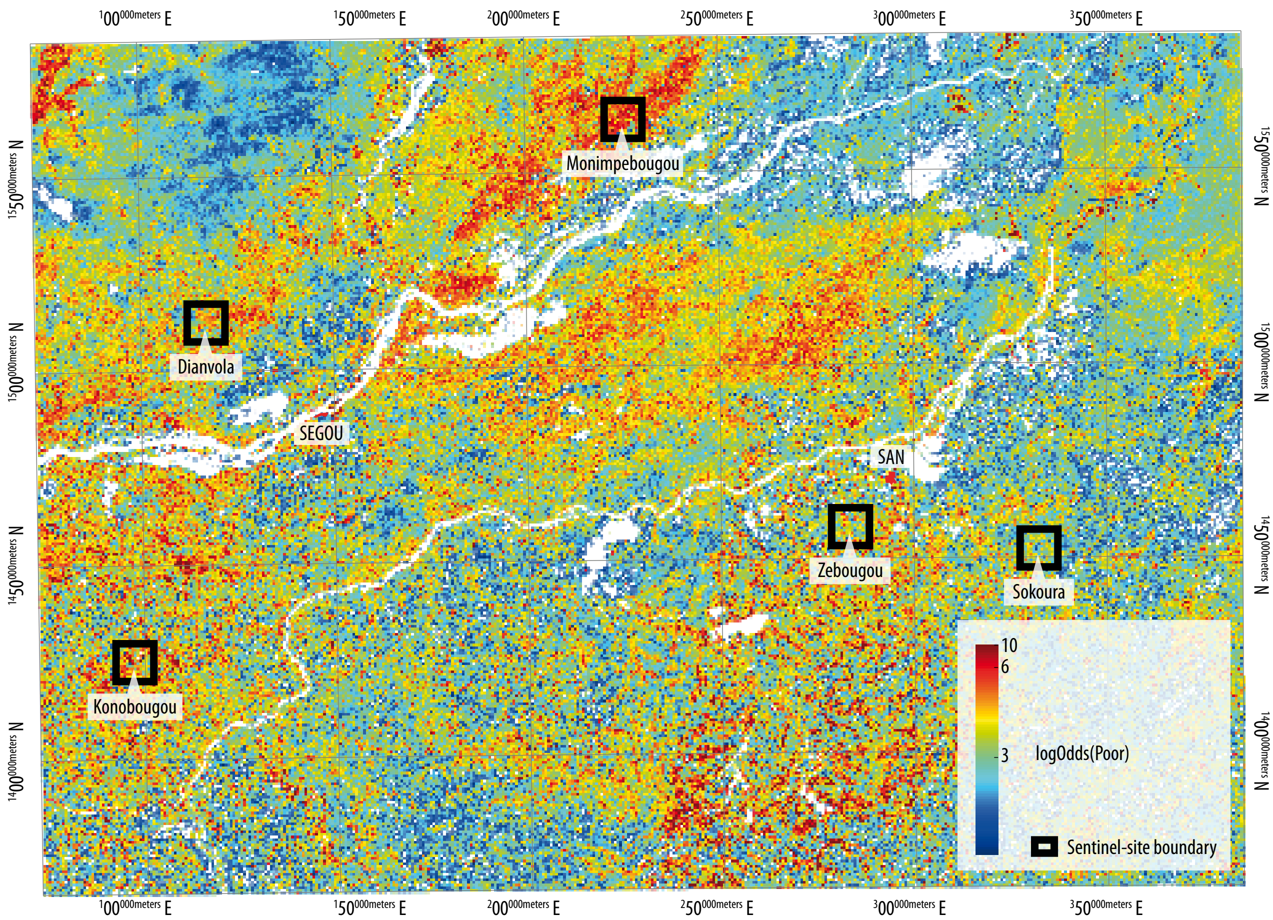


TABLE 4

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

	Dian	Kono	Moni	Soko	Zebo
Cluster	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.

FIGURE 17

Millet variety used in fertilizer response trials.

FIGURE 18

Average growth response curves expressed as estimated plant biovolume (cm³ per plant) for eight fertilizer treatments, and averages for each block (sub-figure).

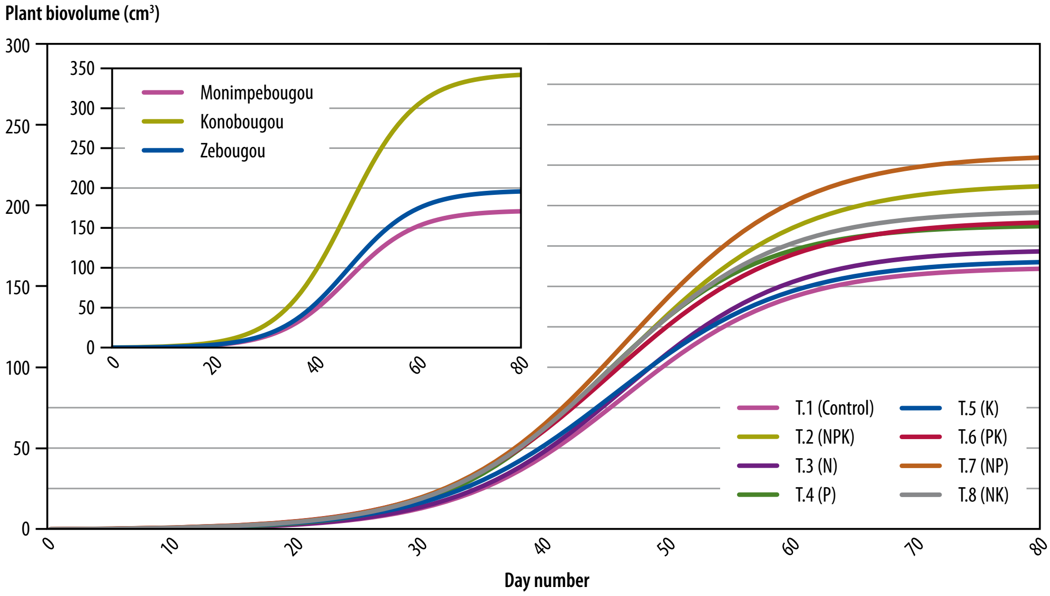
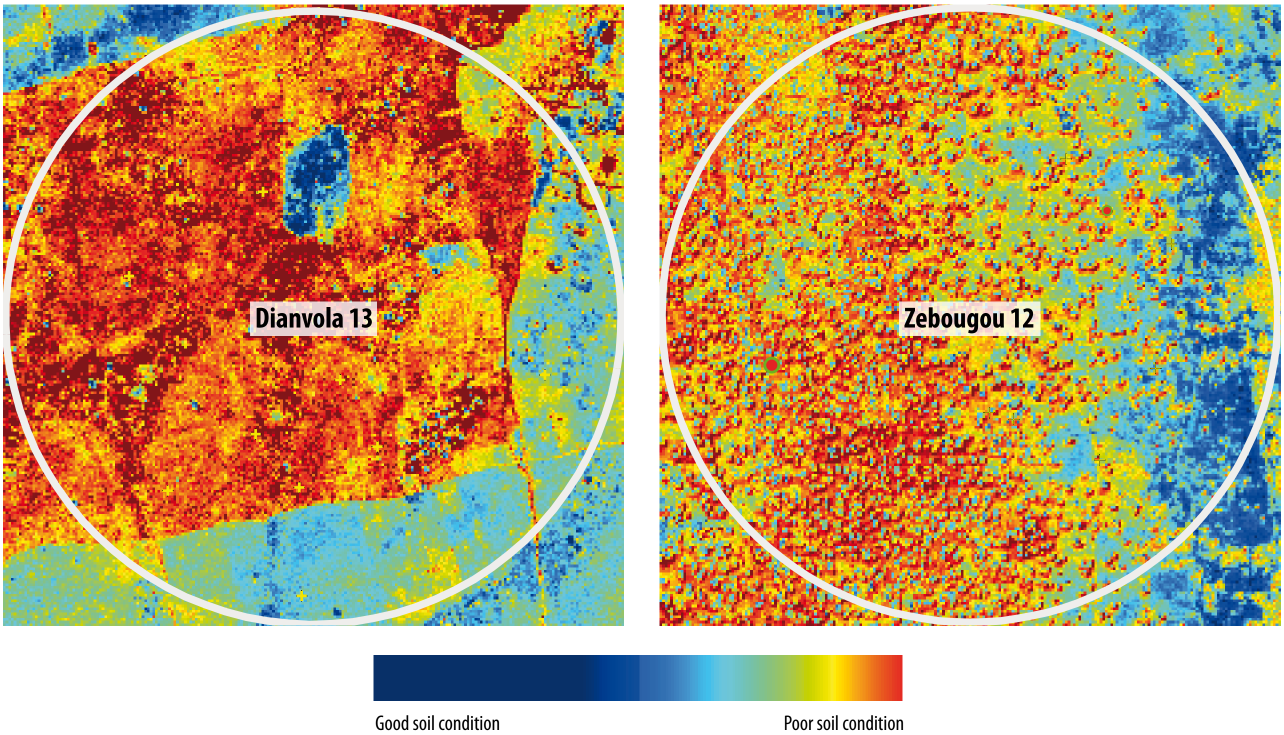


FIGURE 19

Priority intervention areas in cultivated or managed clusters in Dianvola (top) and Zebougou (bottom) sentinel blocks.

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



and comprise 9–63% of the area of the sampled blocks (average area 31%), and only half of the currently cultivated area.

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 only having primary education. As is customary, none of the households have title deeds to their land. The number of tropical livestock units per person, averaged at the block level, ranged from 0.5–0.9. 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 Land Degradation Surveillance Framework provides an operational framework for obtaining

TABLE 5

Estimated number of trees ha^{-1} to be planted as enrichment planting in cultivated areas within each cluster to reach a target density of 15 trees ha^{-1}.

	Dian	Kono	Moni	Soko	Zebo
Cluster			Trees ha^{-1}		
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
	Estimated total number of trees to be planted in each block				
	130,830	79,130	132,870	117,590	0

project-level baselines of land resources and socio-economic 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. Through repeat surveys this provides a scientific basis for assessing the impact of agroforestry and other interventions to restore degraded areas, and for project impact attribution.

The sentinel site framework 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. This evidence-based and spatially explicit framework has potential to transform the way in which agronomic and land management testing is done, greatly increasing our ability to make sound inferences and recommendations. The sentinel site surveillance protocol can be used for assessing baselines and monitoring land health at regional, national, or sub-national levels.

Conclusions and recommendations

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. Further expansion of cultivated areas poses a high risk of ecosystem degradation, due to inherent soil physical constraints, and it is imperative that soil health is improved in existing cultivated areas. 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 conditions in Segou Region are 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 land capacity to provide essential services, such as water and climate regulation. The regional analysis indicated that this could well be the case. 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.

Land health surveillance provides a scientific approach for evidence-based decision-making on land management and should be an integral part of development policy and practice in tropical developing countries. Regional synoptic screening 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 at national level using the sentinel site ground-sampling scheme demonstrated here, to quantify the burden of land degradation attributable to major modifiable risk factors. This data will provide a sound basis for the design of population-wide preventive interventions targeted at reducing and reversing these risks. 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.

At the same time there is 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.

The Sentinel Site Surveillance protocols advanced in this project have since been taken up by the Africa Soil Information Service (www.africasoils.net/) and the Ethiopian Soil Information System (EthioSIS), as well as in a number of other projects.

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 heath 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.

www.unep.org

United Nations Environment Programme
P.O. Box 30552 - 00100 Nairobi, Kenya
Tel.: +254 20 762 1234
Fax: +254 20 762 3927
e-mail: uneppub@unep.org
www.unep.org

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