Land Use Dynamics and Demographic Change in Southern Burkina Faso

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Cover: wood extraction for fuel, cropland expansion for food and cash money, livestock grazing ... contributed to drastically reduce forest cover in Sissili Province within 30 years.
(photo & design: I. Ouedraogo)

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Abstract

With the increasing world's population, coupled with the technology improvement, man has emerged as the major, most powerful and universal instrument of environmental change in the biosphere today. To understand and predict the impacts of this change in the future, long-term reconstruction of land use and cover changes at global, regional and local scales is a prerequisite. The objective of this study was to assess the impacts of population growth on land cover change and generate knowledge that supports sound and informed decision-making on sustainable resource management. The study was done in Sissili Province, southern Burkina Faso, West Africa, where favorable rainfall and availability of arable land have contributed to attract farmers from the arid, crowded and unproductive zones of the north and centre of the country. The methodologies used were a combination of land cover change detection through time-series image processing (1976 – 2006), assessment of population dynamics, measurement of selected landscape metrics, and detection of systematic and random cover transition underlying the processes of change. The results showed that since the 1970s, cultivated areas have been expanded to the detriment of forest, and the expansion of cropland and the decline in forest cover are associated with population growth. Measurements of landscape metrics (Normalized Landscape Shape Index, Interspersion and Juxtaposition Index, and Area Weighted Fractal Dimension Index) highlighted the prevalence of environmental-unfriendly shifting cultivation practices and continual forest degradation. Land cover transition analyses showed that most changes were driven by systematic processes, such as changes induced by population growth, which underpin random changes that bring rapid and abrupt change temporarily with a potential to recover or not, depending on resilience and feedback mechanisms of the land cover type. To sustain the resource base, appropriate land management policy should be issued. The strategies that aim at minimizing the side-effects of the growing population on the environment in southern Burkina Faso might include population control, application of the national land tenure system, promotion of agricultural intensification related policies, promotion of fast-growing trees in plantations, and diversification of sources of income generation for rural people.

Keywords: Burkina Faso, image processing, population mobility, landscape metrics, systematic transition, forest cover change.

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Dedication

To my parents
To my wife Aguira
To our son Abdoul Razack
… for being so patient and always supporting me.

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Ouedraogo I., Tigabu M., Savadogo P., Compaoré H., Odén PC., Ouadba JM. (2010). Land cover change and its relation with population dynamics in Burkina Faso, West Africa. *Land Degradation & Development,* DOI: 10.1002/ldr.981: p n/a.

II Ouedraogo I., Savadogo P., Tigabu M., Cole R., Odén PC., Ouadba JM. (2009). Is rural migration a threat to environmental sustainability in southern Burkina Faso? *Land Degradation & Development* 20(2), 217-230.

III Ouedraogo I., Savadogo P., Tigabu M., Cole R., Odén PC., Ouadba JM. (2010). Trajectory Analysis of Forest Cover Change in the Tropical Dry Forest of Burkina Faso, West Africa. *Landscape Research* (in press).

IV Ouedraogo I., Savadogo P., Tigabu M., Dayamba SD., Odén PC. (2010). Systematic and Random Transitions of land cover types in Burkina Faso, West Africa. *International Journal of Remote Sensing* (in press).

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The contribution of Issa Ouedraogo to each paper included in this thesis amounted to 85 % of the total work load.

Abbreviations

ASL	Above Sea Level
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer
FAO	United Nations Food and Agricultural Organization
FRAC_AM	Area Weighted Fractal Dimension Index
GDP	Gross Domestic Products
GIS	Geographical Information Systems
GPS	Global Positioning Systems
IJI	Interspersion and Juxtaposition Index
INSD	Institut National de la Statistique et de la Démographie
NDVI	Normalized Difference Vegetation Index
NLSI	Normalized Landscape Shape Index
PLAND	Percentage of Landscape
RAF	Reforme Agraire et Foncière (Land and Agrarian Reform)
RS	Remote Sensing
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
UTM	Universal Transverse Mercator
WGS	World Geodesic System

1 Introduction

1.1 Background

Mankind's exploitation of ecosystems for services such as food, shelter, fuel and fresh water has had profound effects on the natural environment for millennia (Achard *et al.*, 2002; Bottomley, 1998). Further, since the 1800s, humans have had increasingly dramatic effects on the global environment following massive increases in the global population coupled with intense agrarian and industrial development. Indeed, man has become the most powerful, universal instrument of environmental change in the biosphere today (Meyer & Turner, 1994; Miller, 1994; Ojima *et al.*, 1994). This has resulted in global climate change, forest and soil degradation, and loss of biodiversity, among other changes, to the extent that the sustainability of our planet's ecosystems is threatened (Lambin *et al.*, 2003; Sala *et al.*, 2000; Trimble & Crosson, 2000; Vitousek *et al.*, 1997). Very little landscapes on the earth's surface remain that have not been significantly modified in some manner by humans. Understanding and predicting the impacts of environmental change in the future is essential to avoid potentially catastrophic damage, and for this, long-term monitoring of land use and cover changes at global, regional and local scales is required (Lambin *et al.*, 2003; Ramankutty & Foley, 1999).

1.2 Land use and land cover change

1.2.1 Definition

Land use refers to the purposes for which humans exploit land cover (Agarwal *et al.*, 2002), which is defined as the layer of soils and biomass, including natural vegetation, crops and human structures that cover the land surface. Land cover change is the replacement of one cover type by another, while land use dynamics refers to any modification of land cover type, such as the intensification of agricultural use, that may not necessarily involve a change in overall land cover classification (Turner II *et al.*, 1993). Land use is thus the manner in which human beings employ the land and its resources such as agriculture, urban development, grazing, logging, mining, etc. In contrast, land cover describes the physical state of the land surface. Land cover categories include croplands, forests, wetlands, pastures, roads, and settlements. The term land cover originally referred to the kind and state of vegetation, such as forest or grass cover, but it has broadened in subsequent usage to include human structures such as buildings or pavement and other aspects of the natural environment, such as soil type, biodiversity, and surface water and groundwater (Bottomley, 1998). Land use is determined by the interaction in space and time of biophysical factors, such as soils, climate, topography, etc., and human factors including population, technology and economic conditions (Veldkamp & Fresco, 1996). Land use affects land cover and changes in land cover in turn affect land use. Riebsame *et al.* (1994) categorize changes in land cover driven by land use into two types: modification and conversion. Modification is a change of conditions within a cover type; for example, a shift from unmanaged forest to a forest managed by selective cutting; while conversion is a change from one cover type to another, such as deforestation to create cropland. Change in land use and land cover is a worldwide issue, but the magnitude of change differs from one place to another.

1.2.2 Land use in the tropics

The tropical zone occupies a wide belt of the globe, including the entire African continent, Latin America, South Asia, and Australia. The type of vegetation in the tropics varies widely (according to the latitude, altitude, and the seasonal variation of the rainfall), and includes numerous types of forest types, *inter alia* various kinds of evergreen rainforest, deciduous forest and dry deciduous woodland (Figure 1). However, in recent decades increasingly large areas of grasslands, woodlands and forests have been converted into croplands and pastures (Mayaux *et al.*, 2005; Lambin *et al.*, 2003; Reid *et al.*, 2000; Houghton, 1994). In 2001 the Food and Agriculture Organisation (FAO) estimated the total loss of tropical forest during the 1990s at 15.2 million hectares per annum, and the annual loss of humid forest alone was estimated at 5.8 million hectares (Achard *et al.*, 2002). Tropical dry forest, representing 42% of the forest in the tropics, has been severely fragmented, disturbed, and in many areas it has been severely depleted (Hartter *et al.*, 2008). While in Latin America, large-scale forest conversion and colonization for livestock-based agriculture are the main causes of forest degradation, cropland expansion by smallholders is the prevailing cause in Africa (Drigo *et al.*, 2009; Drigo, 2006; Lambin *et al.*, 2003). In Asia, intensified shifting agriculture, migration into new areas, the gradual change of existing areas towards more permanent agriculture and logging are believed to be the main causes of deforestation (Achard *et al.*, 2002; Geist & Lambin, 2002).

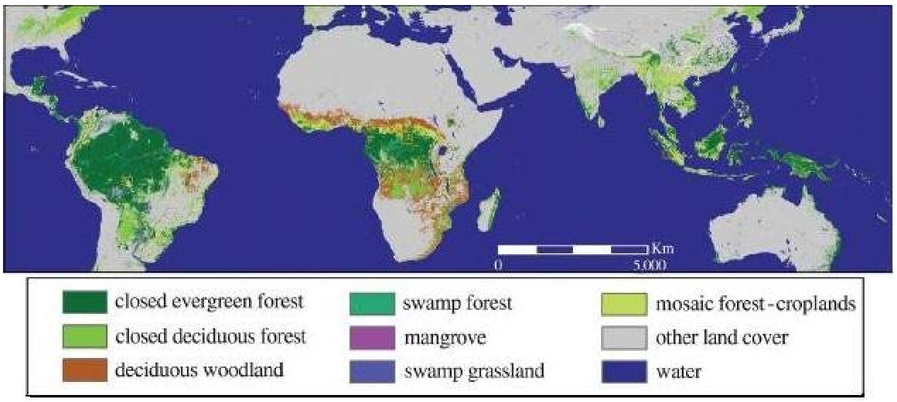

Figure 1. Tropical forest distribution derived from Global Land cover 2000 map (adapted from Mayaux *et al.*, 2005)

Agricultural land expansion is the primary cause of land cover change in the tropics. In the 1990s, African and Latin American countries increased their food production through both agricultural intensification and expansion. In addition to agriculture, natural vegetation cover has given way to pasture, defined as land used permanently for herbaceous forage crops, either cultivated or grown wild (Lambin *et al.*, 2003). More than 60% of pasture in the world is located in Africa, Asia and Latin America. Urbanization has also played an important role in land cover change in the tropics. According to the United Nation Population Division (Lambin *et al.*, 2003; Warren-Rhodes & Koenig, 2001), the number of megacities (cities with more than 10 million inhabitants) has increased from one in 1950 to 17 in 2000, the majority of which are in tropical countries. Doos (2002) estimated that one to two million hectares of agricultural land were converted to housing, industry, infrastructure, and recreational areas in tropical countries from 1990 to 2000.

Drigo *et al.* (2009) studied trends in tropical forest cover from 1990 to 2005 based on the results of the FAO's Global Forest Resources Assessment and estimated that the net change of tropical forest area, defined as total manmade and natural afforestation minus total deforestation, amounted to a loss of 11.8 million hectares during the five year period 2000-2005, compared to a loss of 11.65 million hectares per annum during the ten year period 1990 to 2000. Countries with a large net change and types of land cover during the period 2000-2005 are shown in Figure 2. In Africa, progressive deforestation dominates the overall process of change, characterized by successive conversion from closed forest to open forest, then to fragmented forest and finally to other land use. This is mainly driven by rapid population growth (both in urban and rural areas), poverty and inadequate economic development, wars and conflicts, insecurity of land tenure and desertification/climate change (Drigo *et al.*, 2009; Drigo, 2006; FAO, 2006; Lambin *et al.*, 2003; FAO, 2001). Among direct causes, FAO (2001) cited poor farming practices, conversion to cash crops, increased clearing and tree cutting for fuelwood and charcoal, poor logging and overexploitation, mining and desertification.

In Latin America, the dominant transition is from closed forest to other land use, resulting in a high loss of biomass, mainly from direct conversion of the original forest to cattle ranching and permanent agriculture (Drigo *et al.*, 2009). Tropical Asia presents the highest rates of deforestation and forest degradation in the tropics (Drigo *et al.*, 2009; FAO, 2006). These rapid changes are caused mostly by rural population pressures, intensification of permanent agriculture in traditional shifting cultivation areas, and the expansion of subsistence farming into forest areas. Such changes are a source of damage at several levels.

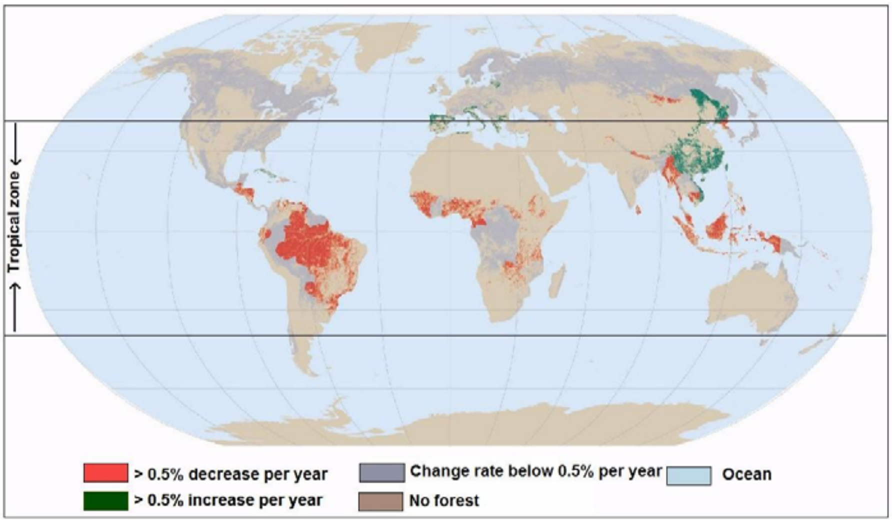

Figure 2. Countries with large net change and types of land cover for the period 2000-2005 (adapted from FAO, 2006).

1.2.3 Consequences of land use and cover change

Humankind has transformed and continues to transform the earth with serious implications for the physical well-being of the planet and its inhabitants. Land use activities, whether converting natural landscapes for human uses and needs, or changing management practices on human-dominated land, have transformed a large proportion of the planet's land surface (Ouedraogo, 2006c). Bottomley (1998), Loveland *et al.* (1999) and Foley *et al.* (2005) report that land use activities, while varying greatly across the world, ultimately result in the same outcome; namely the acquisition of natural resources for immediate human needs, often at the expense of degrading environmental conditions.

Local land use and land cover changes are fundamental agents of global climate change and are significant forces that impact biodiversity through the loss, modification, and fragmentation of habitats, degradation of soil and water resources, and overexploitation of native species (Wezel & Lykke, 2006; Kristensen & Balslev, 2003; Lambin *et al.*, 2003; Riebsame *et al.*, 1994), as well as radiation budgets, trace gas emissions, and perturbation of hydrological and biogeochemical cycles (Sala *et al.*, 2000). At the local and regional levels, land cover change can have profound impacts on aquatic systems due to the implementation of new land use practices that adversely affect water quality and sedimentation. According to Ojima *et al.* (1994), such changes can modify the composition of plant communities through fragmentation, removal and introduction of species, the alteration of nutrients and water pathways, and the alteration of disturbance cycles.

Turner II and Butzer (1992) distinguish two types of contemporary global change: systematic and cumulative. Systematic change operates directly on the biogeochemical flows that sustain the biosphere and, depending on its magnitude, can lead to global change, e.g. fossil-fuel consumption increases the concentration of atmospheric carbon dioxide. It is largely associated with, but not limited to, the industrial age, and thus has become especially important in the more recent past. Cumulative change, on the other hand, has been the most common kind of human-induced environmental change since antiquity. Such change is geographically limited, but if repeated sufficiently can become global in magnitude. Changes in landscape, such as changes in forest cover, cropland, grasslands, wetlands, or human settlements are some examples of cumulative change. Such changes are driven by multiple factors.

1.3 Drivers of land cover change

Land use change is always caused by multiple interacting factors originating from different levels of organization of the linked human-environment systems (Lambin *et al.*, 2003). These driving forces vary tremendously in time and space, according to specific human-environment conditions. Drivers of land use change have been widely identified and studied at the global level (e.g. Foley *et al.*, 2005; Meyer & Turner, 1994; Ojima *et al.*, 1994; Turner II *et al.*, 1993; Turner II & Butzer, 1992), the regional level (e.g. Drigo *et al.*, 2009; Geist *et al.*, 2006; Lambin *et al.*, 2003; Geist & Lambin, 2002; Geist & Lambin, 2001) and the local level (e.g. Ouedraogo *et al.*, 2009; Alo & Pontius, 2008; Braimoh, 2004; Kok, 2004; Serneels & Lambin, 2001; Mertens & Lambin, 2000). All identified biophysical and human induced drivers can be grouped into proximate and underlying causes and/or systematic and random drivers, which are described in the subsequent sections.

1.3.1 Proximate causes

Proximate or direct causes of land use change encompass human activities and immediate actions that originate from land use and directly affect land cover (Lambin *et al.*, 2003; Geist & Lambin, 2002; Lambin *et al.*, 2001). They generally operate at a local level and involve a physical action on land cover. They may also originate from spontaneous natural phenomena that could affect land cover. Agricultural expansion represents one of the most important direct causes of land use change. From large scale permanent cultivation and cattle ranching systems in developed countries, to small scale subsistence farming systems associated with traditional shifting cultivation and extensive grazing practices of developing countries, agricultural expansion has been by far the most important driving force of land cover change. Wood removals from forests (deforestation) for sawmill industry or for domestic uses, such as fuelwood, pole or charcoal production, have contributed to the conversion of a large proportion of tropical forest into savannas and grasslands. The most recent human induced direct cause of land use change is the expansion of infrastructure. This involves road and railway development for transportation, the creation or development of public and private markets, urbanization and rural settlements, mining and oil exploitation, water lines, electrical grids and pipeline development. In addition to the abovementioned proximate causes of land use change, some important biophysical factors can contribute to huge changes in land use and land cover. Examples include earthquakes, which frequently disturb the environmental equilibrium in Japan, North and South Koreas and more significantly in Latin America; and bush or forest fires destroying large forests in tropical Africa, Australia and Mediterranean regions. Drought, flood and storms, recently intensified by global warming, are further factors that have led to natural disasters, and are likely to continue to do so.

1.3.2 Underlying drivers

Underlying drivers of land use change (indirect or root causes) are fundamental forces that underpin the more proximate causes of land cover change (Lambin *et al.*, 2003; Geist & Lambin, 2002). They operate more indirectly, by altering one or more proximate causes and are formed by complex interacting demographic, economic, technological, political and cultural factors.

The environmental issues that confront the world today largely derive from attempts to feed and otherwise raise the standard of living of an immense number of humans (Weeks, 1999). In coping with an ever-increasing number of people, we are causing damage to the lithosphere, the hydrosphere, and the atmosphere, which consequently leads to global warming. The world is a vast system in which the immense complexity of human society interacts with the natural system. The amplitude of this interaction varies from one place to another, and in all places it changes over time (Harrison, 1993; Harrison, 1990). Therefore, the role of population in environmental degradation differs from place to place, and from time to time. Environmental degradation can be viewed as the combined result of population growth, economic development and technology improvement. Population growth as a primary cause of changes in land cover and depletion of the world's natural resources and systems has been demonstrated by many authors, from Malthus (1798) to Harrison (1993) through Hardin (1968), Ehrlich (1968), Meadows *et al.* (1972), Ehrlich and Ehrlich (1990; 1972) and Harrison (1990). According to these authors, population growth is an exploding bomb with imminent catastrophic consequences. Therefore, population control must be part of any development strategy, or else, that strategy will fail. The impact of population growth on the environment is the product of the total size of the population, the affluence of the population (per person income), and the environmentally damaging properties of the particular technologies by which goods are produced (Harrison, 1993; Ehrlich & Ehrlich, 1990). The global population is growing rapidly (Figure 3); it was estimated at 791 million in 1750, 1.7 billion in 1900, 2.5 billion in 1950, 6 billion in 1999 and is expected to reach 8.9 billion in 2050. Consequently, land cover change is an important contributor to the environmental degrading which without careful management could lead to world environmental collapse in the near future.

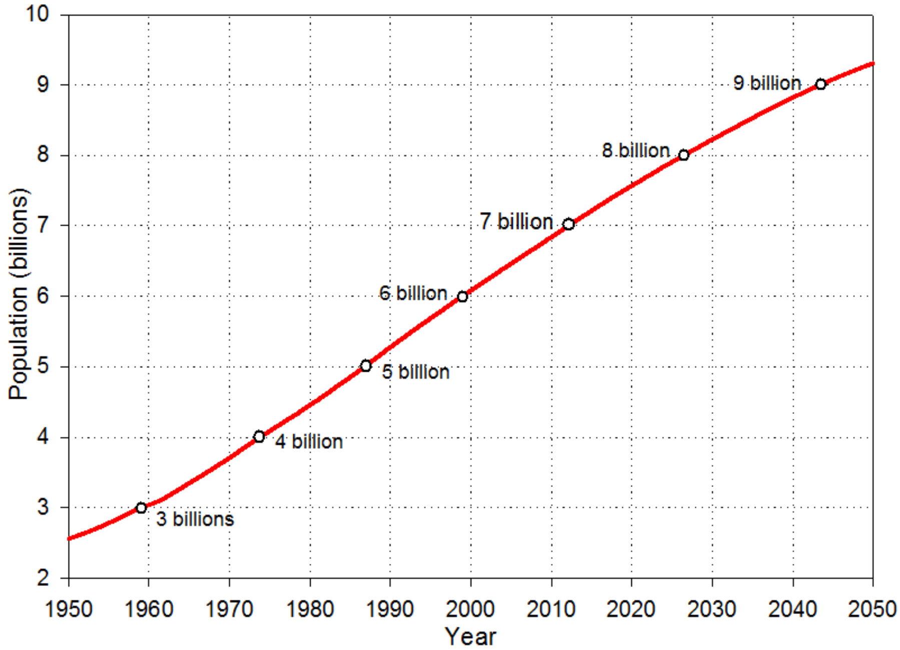

Figure 3. Estimate of world population for the period 1950-2050 (Source: U.S. Census Bureau, International Data Base, December 2008).

The role of technology and economy in land use change must be discussed in relation to agriculture and investments, in particular to increases in the productivity of the factor inputs, land and labour (Meyer & Turner, 1994). Since the 1930s, world agriculture has been transformed from a resource-based to a technology-based industry and from subsistence-based to commercial-based production. Technology has provided new farming techniques, new plant varieties, fertilizers, machinery, and equipment. With the contribution of applied biology, new hybrid crop varieties and new plant species have increased while the increased diffusion of crops between continents has opened new export markets or improved and diversified local diets. Industrialization of factor inputs to agriculture in the form of commercial energy, man-made fertilizers, and pest control substances have removed most constraints on increasing agricultural output. Mechanization, symbolized by the farm tractor, is the most visible representation of agricultural industrialization (Meyer & Turner, 1994). The substitution of inanimate power for animal and human power has removed another constraint on increases in agricultural output, making available large areas for crop production. However, according to Weeks (1999), almost every step of improving agricultural productivity has environmental costs, from irrigation to the use of fertilizers and pesticides to the creation of energy sources and the production of machinery. Technology and market developments also accelerate the urbanization process, because under an improved production system the agricultural sector does not require a large labour force in rural areas; while in towns, factories provide employment opportunities. This has contributed to a large expansion of urban areas in many countries at the expense of other land cover types.

Policies, institutions and local culture usually guide access to land, labour, capital and technology. Therefore, in addition to technological and economic variables, it is equally important to consider political and cultural factors when attempting to explain land use and land cover changes and to understand resource use and management, since these factors interact with individual decision making (Coulibaly-Lingani *et al.*, 2009; Lambin *et al.*, 2003; Agrawal & Yadama, 1997). Institutions include property-rights regimes, environmental policies, decision-making systems for management strategies such as decentralization, democratization, and the roles of the public, civil society, and of local communities in the decision-making process. Institutions also include information systems related to environmental indicators, social networks representing specific interests related to resource management, conflict resolution systems concerning access to resources, and institutions that guide the distribution of resources and thus control economic differentiation (Lambin *et al.*, 2003). Misguided or conflicting policies and institutions relating to landholding and management systems are sources of land and forest degradation in most developing countries. Therefore, recent processes observed in developing countries such as the consolidation of landholdings and the shift from traditional to modern land tenure regimes and to decentralization and devolution, may contribute to the alleviation or reversal of the deterioration process of the natural resources.

1.3.3 Systematic versus random drivers

Factors leading to changes in land use and land cover can also be classified into systematic and random drivers. Systematic drivers are those responsible for regular or common processes of change. They evolve in a consistent, progressive or gradual manner dictated by the processes of natural cycles such as global warming and population increases with their subsequent factors of dynamism. Random factors are coincidental or unique processes of change, operating in the short term and characterized by rapid and abrupt change accompanied by either a recovery or non-recovery of the affected ecosystems, depending on the systems' resilience and feedback mechanisms (Versace *et al.*, 2008; Braimoh, 2006; Lambin *et al.*, 2003; Tucker *et al.*, 1991). These episodic factors include uncontrolled settlements (by migrants or refugee), floods, storms, etc., which are sometimes, implicitly caused or accelerated by systematic drivers.

1.4 Human-environment nexus

Since 1972 and the publication of the Club of Rome's report, "Limits to Growth", the environment has assumed an increasingly important position in the theory and practice of international development. In the same year, the Stockholm Conference on the Human Environment was held. In 1987, an independent Commission on Environment and Development, headed by the then Prime Minister of Norway, Gro Harlem Brundtland, presented its report, "Our Common Future", to the Secretary-General of the UN. Five years later, in 1992, world leaders gathered in Rio de Janeiro for the Earth Summit. A decade on, it was surpassed in scope by the 2002 World Summit on sustainable development in Johannesburg, which discussed poverty and North-South issues. Recently, in October 2009, the United Nations Climate Change Conference in Copenhagen produced the "UN Framework Convention on Climate Change". From these summits and conferences, a large number of reports on environmental crises, over-population, global warming, and economic collapse, etc. have been published, which overwhelmingly conclude that the world's natural resources, the fundamental basis of life on Earth, are under serious threat.

While cutting through the ideological accretions of recent years, it is still useful to embark upon an analysis of population-environment relationships with a discussion of the positions of Thomas Malthus on the one hand, and Adams Smith, Karl Max, and Emile Durkheim on the other. Although up to three centuries separate us from their writings, their different positions serve as the twin poles of debate with which many interlocutors still align themselves. These lively debates on population, environment and development could be grouped into two main streams: the pessimists (doomsters) on the one hand, and the optimists (boomsters) on the other hand.

1.4.1 Pessimists' theories on global ecosystems

Pessimistic visions of the human-environment nexus was initiated by Malthus (1798). Malthus was concerned with the relationship between population and food supply under conditions in which technology and the resources of the land remain constant. He postulated that human numbers would outstrip the capacity to produce sufficient food and that "positive checks" such as poverty, disease, famine, war and natural disasters would impose downward pressure on the rate of population growth in the absence of fertility control. Malthus' philosophy was subsequently promoted by Neo-Malthusians, exemplified by Hardin (1993; 1968), Ehrlich (1968), Ehrlich and Ehrlich (1990) and Meadows *et al.* (1992; 1972).

In his famous book "The Tragedy of the Commons", Hardin (1968) uses the metaphor of a village common pasture that suffers from overgrazing because each villager puts as many cattle on it as possible, since the cost of grazing is shared by everyone, but the profits go to the individual. He concludes that freedom in the commons brings ruin to all, and maintains that this metaphor applies to global ecology. As a prominent biologist and ecological philosopher, Hardin (1993) argued that we must accept the limits of the earth's resources and make hard choices to live within them. In his book, "Living Within Limits", he focuses on the neglected problem of over-population, making a forceful case for dramatically changing the way we live in and manage our world. Our world itself, he wrote, represents a "lifeboat dilemma": it can only hold a certain number of people before it sinks, and not everyone can be saved. He concluded that the earth has a limited carrying capacity (defined as the number of people in an area relative to its resources and the capacity of the environment to sustain human activities) and that sentimentality should not cloud our ability to take the necessary steps to limit population.

In his book "Population Bomb", Ehrlich (1968) argued that the battle to feed all of humanity is over. For him, the policy choices are clear; population control must be part of any development strategy, otherwise that strategy will fail. For Ehrlich, population control is the conscious regulation of the number of human beings to meet the needs, not just of individual families, but of society as a whole. The solution is to oblige all states to adopt programmes that combine agricultural development and population control. While this is being done, we must take action to reverse the deterioration of our environment before population pressure permanently ruins our planet. Ehrlich and Ehrlich (1990) go further and argue that the population bomb is exploding. Based on the concept of carrying capacity, they conclude that Africa is overpopulated because its soils and forests are being rapidly depleted; the United States is overpopulated because it is depleting its soils and water resources, contributing greatly to the destruction of global environmental systems; Europe and Asia are also overpopulated because of their massive contribution to the carbon dioxide build-up in the atmosphere.

Meadows *et al.* (1972) used a system dynamics theory and a computer model (World3) to design ten human-ecology scenarios for the future up to the year 2100 and came to a pessimistic prediction; if the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth in this planet will be reached sometime within the next 100 years. Twenty years later (in 1992), they applied the same model using the technology and policies in force at that time and came to the conclusion that, in spite of the world's improved technologies, greater awareness, and strong environmental policies, many resource and pollution flows had already grown beyond their sustainable limits. Much must be changed if the world is to avoid the serious consequences of overshoot in the 21st century. The most obvious limit of food production is land. Millions of acres of cultivated land are being degraded by processes such as soil erosion and salinization, while cultivated areas remain roughly constant (Meadows *et al.*, 1992).

1.4.2 Optimists' theories on human ecology

Optimistic views on population, development and environment have historical roots in diverse economic and social theories and may be traced back to the seminal work of Smith (1750), Marx and Engels (1846) and Durkheim (1893). In his concept of the economy of scale, Smith (1750) specifies the need for a growing population that will permit more efficient production through the division of labour. Marx's concept of "verkeher" also refers to the need for population growth and a minimum density that allows for productive action (Marx & Engels, 1846). Similarly, Durkheim (1893) proposes a threshold dynamic density of population that will support the necessary division of labour and more efficient production. More recently, these theories have been supported by Boserup (1981; 1972; 1965) and Simon (1990; 1981; 1980) among others.

Boserupian theory focuses on the relationships between population, environment, and technology. Her concept of technology refers to a wide range of agricultural tools (e.g. tractors), techniques (e.g. fallow patterns), and inputs (e.g. fertilizer). Her theoretical understanding of the relationship between population growth and agricultural change is based on historical Europe. Due to periodic famines and plague in Europe prior to the 18th century, the population was not large enough for the long-term benefits of more intensive agriculture. For that reason, more intensive methods such as irrigation were used in a few more densely populated areas. Boserup asserts that agricultural intensification, or the gradual change towards patterns of land use that creates the opportunity to crop a given area of land more frequently than before is an important mechanism for increasing production. In describing this development, she states that small sparsely distributed populations use fallow to retain soil fertility. They farm different plots in different years and allow the most recently used land to lie unused to regain fertility. However, with increased density, a growing population can use land more frequently and increase output by substituting technological inputs such as fertilizer or irrigation for fallow to retain soil fertility. On the basis of the interrelation between population dynamics, agricultural technology, and production, she defined six different food systems with increasing technological levels and their associated population density. Although defined discretely, Boserup stresses that the strategies used by any population, particularly a growing population, is an evolving mixture of these levels.

Simon's works (1990; 1981; 1980) represent a concentrated attack on neo-Malthusians thinking on population, environment and development. "False bad news about population growth, natural resources, and the environment is published widely in the face of contradictory evidence" (Simon, 1980). According to him, there is a funding incentive for scholars and institutions to produce bad news about population, resources, and the environment because bad news sells books, newspapers, and magazines, while good news is much less interesting. Simon appeals to the unlimited power of technology to increase the services yielded per unit of resource as evidence of the essentially non-finite nature of resources. He argues that the key factor in natural and world economic growth is our capacity to create new ideas and to contribute to knowledge. The more people alive who can be trained to help solve the problems that confront us, the faster we can remove obstacles, and the greater the economic inheritance we shall bequeath to our descendants. In conjunction with the size of the educated population, the key constraint on human progress is the nature of the economic-political system; talented people need economic freedom and security to bring their talents to fruition (Simon, 1990; Simon, 1981; Simon, 1980). To challenge the false news about resource scarcity, he uses the example of a single communication satellite in space that provides intercontinental telephone connections that would otherwise require thousands of tons of copper. He emphasises the vital importance of the contribution of human imagination to adaptive invention. In any way, be it pessimist or optimist views, continuous monitoring of human-environment nexus is paramount to revise policies and practices that will ensure environmental sustainability. The advent of satellite and computer technologies enables us to detect change in land use and land cover with higher accuracy.

1.5 Change detection

Land use and cover change has become a central component in current strategies for managing natural resources and monitoring environmental change. Since the middle of the twentieth century, the rapid development of the concept and technology of vegetation mapping has led to an increase in the study of land use and land cover change worldwide. Accurately mapping the extent and the dynamics of each cover type has become an important priority for each level of governance. Remote Sensing (RS) and Geographic Information Systems (GIS) coupled with Geographic Positioning Systems (GPS) are powerful tools for advanced ecosystem monitoring and management.

Remote sensing is the science and art of obtaining information about an object, area or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area or phenomenon under investigation (Lillesand *et al.*, 2008). The collection of remotely sensed data facilitates the synoptic analysis of ecosystems' functions, patterns and dynamics at local, regional, and global levels over time (Brink & Eva, 2009; Congalton & Green, 2009; Bottomley, 1998). Such data also provide fundamental information with regard to the potential impacts of change and can be used to draw the attention of decision-makers to such impacts at national and international levels (Mayaux *et al.*, 2005).

Prior to image processing for change detection, the calibration of the images to a common radiometric reference is required. This involves the transformation of the digital numbers to physical values of radiance or reflectance, even though the required information for that purpose is sometimes unavailable (namely meteorological data at the precise time of the capture of the images). The response to this lack of information is to perform a relative calibration between imagery from different dates (Lillesand *et al.*, 2008; Tso & Mather, 2001; Hall *et al.*, 1991). This is done by using a linear transformation in which the additive component corrects for differences in atmospheric path radiance and the multiplicative component corrects for differences in detector calibration, sun angle, earth-sun distance, atmospheric attenuation and phase angle conditions.

Several techniques are used for land cover and land use change detection. The most commonly used are: comparative analysis of independently produced classifications and simultaneous analysis of multitemporal data (Tso & Mather, 2001; Loveland *et al.*, 1999). Simultaneous analysis techniques include image differencing, rationing, principal component analysis, and change vector analysis. The most widely used method for change detection is to compare the classification of land cover from two dates. The use of an independently produced classification compensates for the varied atmospheric and phenological conditions between dates, or even the use of different sensors between dates, because each classification is made independently and mapped to a common thematic reference (Loveland *et al.*, 1999). Image differencing techniques are also commonly used for change detection. This procedure consists of taking the mathematical difference between geo-registered images or digital numbers of the images from two dates. The input data can be radiometrically calibrated raw imagery, or transformed data such as normalized difference vegetation index (NDVI) imagery. This is commonly used for coastal change detection, monitoring forest change and urban expansion. Other approaches often used for change detection include surface change, analysis which represents the direction and magnitude of change between specified dates; and spectral mixture modelling, in which a multispectral image is decomposed into spectral end members.

While image processing must be done with much caution, it is also necessary to assess the accuracy of the outputs produced. Congalton and Green (2009) argue that there are many reasons for performing an accuracy assessment. Accuracy is needed to increase the quality of the map information by identifying and correcting the sources of errors; it is needed for comparing various techniques to test which is best, and finally to check whether the information derived from the remotely sensed data is good enough to be used in any decision-making process. Accuracy assessment can be qualitative or quantitative, expressive or inexpressive, quick or time-consuming, well-designed and efficient or haphazard (Congalton & Green, 2009), but the overall purpose is to identify map errors. A standard accuracy assessment procedure for baseline land cover products involves the use of an error matrix (Congalton & Green, 2009; Liu & Zhou, 2004; Loveland *et al.*, 1999). An error matrix is an effective descriptive tool for organizing and presenting accuracy assessment information and should be reported whenever feasible. Error matrices are used to compute both the producer's accuracy and the user's accuracy, combination of which gives the overall accuracy.

1.6 Burkina Faso in brief and relevance of the study

Burkina Faso is a land-locked country located in the centre of West Africa in the transition zone between the South Sudanian and Sahelian regions. It is bounded to the north and west by the Republic of Mali, to the South by the Republics of Cote d'Ivoire, Togo, Benin and Ghana, and to the East by the Republic of Niger (Figure 4). The country extends 625 km from north to south and 850 km from east to west and covers an area of around 274,000 km^2. The geological history of the country is marked by Precambian volcanic activities, Eburnean faulting and folding, and fluctuations of sea levels, notably those contemporary with Hercynian movements (Anonymous, 1998). These geological events, followed by successive erosion cycles, gave rise to the basis of the relief, which comprises an immense peneplain and sandstone plateau, weathering of which formed the present soil types in the country. According to Boulet (1976), Fontes and Guinko (1995), and Anonymous (1998), eight main soil types are present in the country. Leached ferruginous soils are located in the central part of Precambrian peneplain, poorly evolved eroded soils are mostly found in the northern half of the country; the hydromorphic soils are found on river alluviums or on weathering material in the west of the country; brown eutrophic soil is found in patches throughout the country; vertisols have developed in the south-east and south-west; raw mineral soils on bed-rock or ferralitic pans; halomorphic soils are found in the north of the country; and ferralitic soils, are mainly found in the south of the country.

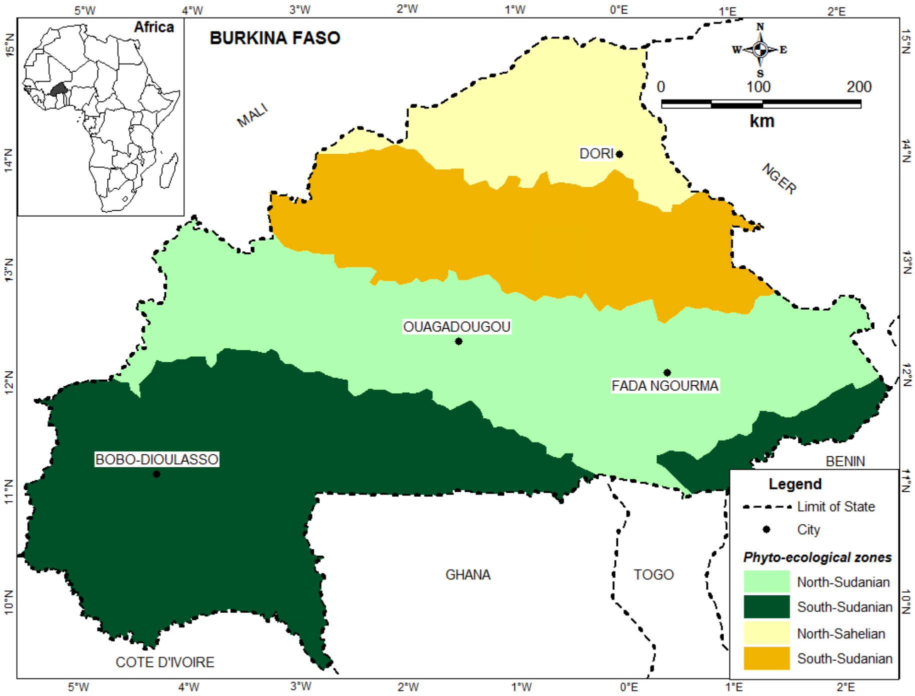

Figure 4. Location of Burkina Faso, together with the agro-ecological zones (adapted from Fontes and Guinko, 1995)

Burkina Faso has a dry tropical climate dictated by the seasonal alteration of moist air from the monsoon deriving from the oceanic high pressure, and dry air from the Sahelian latitude. According to Fontes and Guinko (1995), the climate is marked by two rotating seasons (rainy and dry), a unimodal rainfall curve, a total absence of cool season (the temperature is always higher than 16ºC), and decreasing aridity from the north to the south of the country. The climate is divided into two broad zones based on the isohyets and the length of the dry season: the Sahelian zone and the Sudanian zone, each of them in turn divided into north and south (Figure 4). The agro-ecological conditions follow the climatic division of the country. The south-Sudanian zone receives rainfall of over 900 mm/year and occupies about 36% of the territory, and is dominated by dry forest and tree savanna communities. The south-Sudanian zone possesses a large proportion of the most fertile arable land of the country (more than 35%) with a very low population density (about 20 inhab/km²). The north-Sudanian zone covers the middle part of the country with rainfall of 700 to 900 mm/year. This area covers 33.7% of the country and has 50% of the population with only 32% of the arable land. This is also the region where the highest population density in the country is found. The pressure on land is very high in this zone due to high density of the population. The soils and agro-climatic conditions are less favourable to agriculture than in the South-Sudanian zone. The south-Sahelian zone is located between the north-Sudanian zone and the north-Sahelian zone and receives an annual rainfall of 500 to 750 mm. This zone is home to 19% of the population with a density varying from 36 to 50 inhabitants per km². The prevailing pedoclimatic conditions here (insufficient or irregular rains combined with low soil fertility) constitute a serious constraint on the development of agriculture. The north-Sahelian zone occupies the extreme northern part of the country where rainfall is between 200 and 500 mm/year. It makes up 11% of the country with a population density of 5 inhab/km². It is primarily a region of livestock husbandry.

Estimated at 5,638,203 people in 1975, the population of Burkina Faso reached 7,964,705 inhabitants in 1985, 10,312,609 inhabitants in 1996 and 13,730,258 people in 2006 (INSD, 2007). Thus, in 30 years, the population almost tripled. The population is 85% rural, practising small scale farming and livestock production, which provides nearly 70% of the export earnings and 46% of the GDP (Krämer, 2002). The geographic distribution of the population is very uneven, with population densities ranging from 335 to 6 inhab/km² (Figure 5). Migration has long played an important role in the demographic distribution of Burkina Faso (Henry *et al.*, 2003; Breusers, 1998). Internal migration from rural to urban areas is a commonplace event, but the vast majority of migratory movements are still from one rural area to another. Rural to rural migration essentially involves farmers and herders moving from the Sahelian agro-ecological zones (due to persisting aridity) and from the densely populated provinces of the centre of the country to the south-Sudanian zone (essentially the west and south), in search of arable and grazing lands (Ouedraogo *et al.*, 2010; Ouedraogo *et al.*, 2009). The environment of the attracting regions is undergoing change due to the effects of migratory pressures and extending production systems. This population migration is a source of conflict, including conflict between human population needs and the sustainability of forest resources.

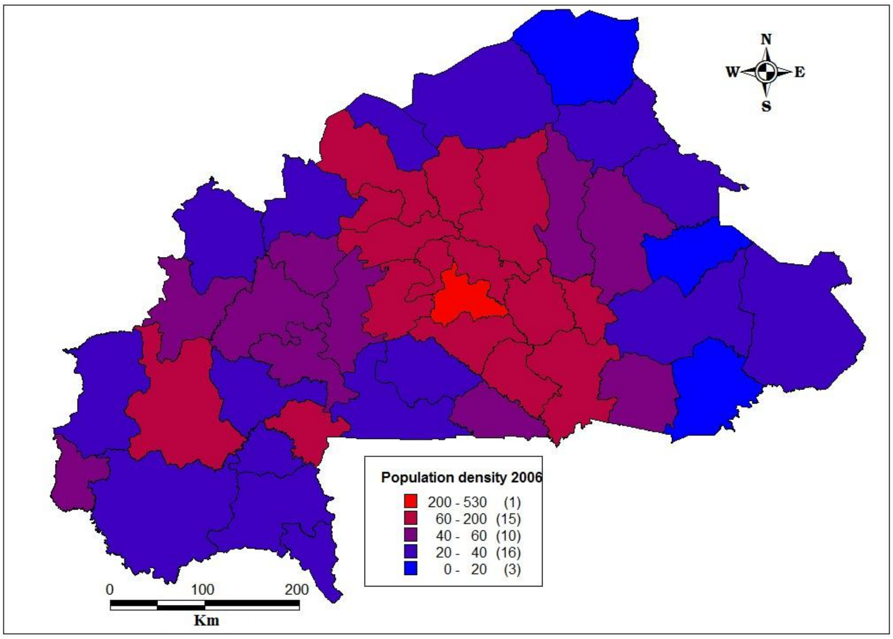

Figure 5. Population density of Burkina Faso in 2006 (from data of INSD, 2007)

A few studies, on a very restricted scale, have investigated environmental changes due to demographic pressure in the zones that attract migrants in the east (Reenberg & Lund, 1998), the west (Gray, 2005; Gray, 1999) and the south (Paré *et al.*, 2008; Ouedraogo, 2006b; Howorth & O'Keefe, 1999). However, large-scale studies that relate long term land cover change to the pressure of both indigenous and migrant people in these zones are lacking. Information on these phenomena is essential for regional and national land use planning, revising or drafting land use or environmental policies, and providing supporting evidence for recently developed methodologies for land use/cover change analysis. Therefore, the studies this thesis is based upon were conducted in southern Burkina Faso with the specific objectives discussed in the following section.

2 Objectives and hypotheses

The main objective of the studies this thesis is based upon was to generate knowledge to support sound and informed decision making for sustainable management of the natural resources in Burkina Faso. The studies explore various aspects, such as land cover change at provincial, district, and village levels; cover change trajectories and transitions; population growth as a result of both natural increases and migration; and related land-based socio-economic activities. The specific objectives were to:

(1) Examine the relationship between population growth and land cover change at a provincial level (**Study I**);

(2) Analyse to what extent land use patterns can be ascribed to rural to rural migration (**Study II**);

(3) Assess the trajectories of land cover change and measure the landscape metrics of the change trajectories in order to understand the processes of change more fully and to predict long term changes (**Study III**);

(4) Determine whether land cover changes in the region studied are driven by systematic or random processes of change (**Study IV**).

The overall hypothesis of the studies was that the rapid forest degradation in the south of Burkina Faso could be explained by the recent population increase in this area. Four specific hypotheses guided the study:

(1) Forest degradation in the Sissili province has been caused by rapid population growth since the 1980s (**Study I**);

(2) Rural migration is the main source of the rapid population increase and the production systems used by migrant populations have been environmentally harmful (**Study II**);

(3) Measurements of landscape metrics can help to understand the processes of change more fully and to forecast long term changes (**Study III**);

(4) Systematic change processes are the dominant type of change in southern Burkina Faso (**Study IV**).

3 Materials and methods

3.1 Study area

All studies (**Studies I, II, III, IV**) were carried out in Sissili province, located in the south of Burkina Faso and bordering the north of Ghana (Figure 6). The province lies between latitudes 10º 58'N to 11º 52'N and longitudes 2º 40'W to 1º 12'E, and is characterized by low relief with an average altitude of 300 m a.s.l. Phytogeographically, the area is situated in the Sudanian regional centre of endemism in the South-Sudanian zone (Fontes & Guinko, 1995). The natural vegetation comprises mostly dry forest and tree savanna community types. The climate is tropical with a unimodal rainy season, lasting for about six months from May to October. Based on data collected from the nearest *in situ* mini-weather station at Leo, the provincial city of Sissili, the mean (± SE) annual rainfall from 1976 to 2007 was 883 ± 147 mm. Mean daily minimum and maximum temperatures ranged from 16 to 32 ºC in January (the coldest month) and from 26 to 40 ºC in April (the hottest month). According to the FAO soil classification system (Driessen *et al.*, 2001), the most frequently encountered soil type is Lixisol (tropical ferruginous soils), which is poorly to fully leached, overlying sandy, clayey-sandy and sandy-clayey material.

The province covers 7,111 km² (about 3% of the country surface area), with a population growing from 119,352 inhabitants in 1986 to 212,628 inhabitants in 2006. The population is composed of four main ethnic groups: Nuni, Wala, Mossi and Fulani. The Nuni and Wala groups have been living in the area for centuries and are considered indigenous, while the Mossi, who originate from the Central Plateau in Burkina Faso, and the

Fulani, herders from the northern region of the country, are considered migrants. The latter two groups were attracted to the southern region during the 1980s in search of arable land and green pasture, respectively (Howorth & O'Keefe, 1999). The dominant agricultural production methods in the study area are traditional subsistence farming systems with cereals (such as sorghum, millet and maize), tubers (yam and sweet potatoes) and animal husbandry. However, over the last ten years, there has been intense competition for land between the traditional farming systems and more lucrative production systems. These systems include extraction of fuelwood, poles and non-wood forest products, production of cash crops (cotton and fruit-tree plantation e.g. *Anacardium occidentale, Mangifera indica*), and ranching (Paré *et al.*, 2008). Southern Burkina Faso provides fuelwood and charcoal for the important nearby towns of Ouagadougou and Koudougou, located 80 km and 150 km away, respectively. Non-timber forest products, such as fruits, leaves, tubers, perennial grass straw and hay, are also harvested from the forest (Kristensen & Lykke, 2003; Lykke *et al.*, 2002) for multiple uses.

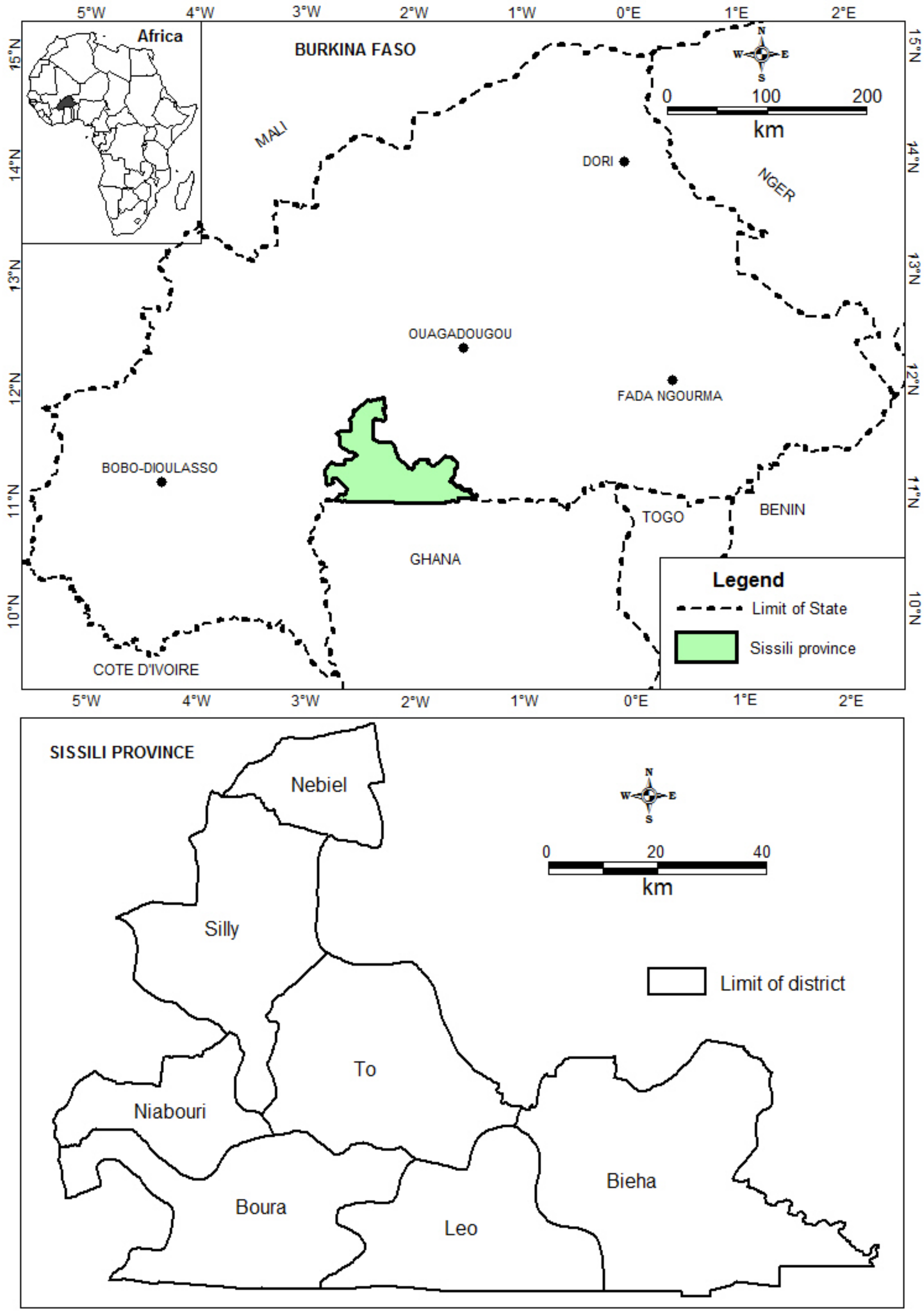

Figure 6. Location of the study area

3.2 Detection of land cover change

Cover change detection for all studies (**Studies I, II, III, IV**) was based on processing Landsat and ASTER (Advanced Space-borne Thermal Emission and Reflection Radiometer) images from different periods. The processing procedures were the same in all studies, with priority given to geometric correction and a relative calibration between imagery from different dates, as an alternative to radiometric rectification. Each image was geo-rectified to UTM WGS 84 Zone 30 North coordinates using ground control points, yielding a root mean square below 15 m for Landsat images and below 7.5 m for ASTER images. Land cover classifications for all images were based on training sites, topographic maps, high resolution panchromatic aerial photographs, *in-situ* observations, and cross-checks with local inhabitants to clarify issues for which a clear relation between spectral signatures and field features could not be established. The maximum likelihood classifier was used for all supervised classifications and nomenclature for cover types were based on those recently defined by Lamprecht (1989) which are more detailed and best fit the vegetation context of the study area. Several vegetation classification nomenclatures exist for Africa, among which the most authoritative document is *The vegetation of Africa*, produced by White (1983) for United Nations Educational, Scientific and Cultural Organization (UNESCO). However, this document was strongly criticised because its classification was based on the combination of chlorological and physiognomic characters in the vegetation nomenclature (Lawesson, 1994), while vegetation types are generally distinguished by physiognomic categories (Eiten, 1992). Stratified random sampling methods were used to collect an optimum number of sample reference points for the classification accuracy assessment. They were generated and transferred to a GIS programme, in which they were overlaid with the classified image. Field checks served as a basis for the accuracy assessment. All image processing was done using ENVI Version 4.2 (Copyright 2005, Research Systems, Inc. 4990 Pearl East Circle) and the vectorized data were processed with MapInfo Professional Version 7.5 (Release Build 23, Copyright 1985-2003 MapInfo Corporation).

3.3 Population dynamics and land cover change

Studies I (Sissili province) and **II** (Neboun village in Sissili province) were based on the use of both satellite data and population data. In Burkina Faso, the first national population census was done in 1975. Since that date, population censuses have been conducted approximately every ten years (1985, 1996, and 2006). To estimate the population size for each individual district of Sissili province (**Study I)** during the inter-census times (1986, 1992, and 2002), we used the population projection method according to Weeks (1999) as follows:

$$P_{0+t} = P_0\left(1 + G_r \times t\right) \quad (1)$$

$$G_r = \left[\left(R_b - R_d\right) + \left(I_m - O_m\right)\right] \quad (2)$$

where P_{o+t} is the total population estimated from the previous census year to the t next years, P_o is the total population at the census year, G_r is the growth rate, R_b and R_d are the birth and death rates at the census date, respectively, I_m and O_m are the immigration and out-migration rates and t is the number of years after the census date.

In the national population census reports, data relating to population size at the village level are missing and, furthermore, data relating to internal migration for each ethnic group are not reported. To estimate the current population and migration data at Neboun village (**Study II**), we have organized a complete local population census in August 2007. All necessary information was recorded in the census form. The historical data (1976, 1986, 1992, and 2000) were estimated based on cohorts of the *in-situ* population at the census date. The data was subsequently adjusted to take into account birth, death and migration parameters using Eqs. (1) and (2).

In both **Studies I** and **II**, repeated measurement ANOVA was performed to determine the statistical significance of the inter-annual variability of land cover types, migrant and indigenous populations. To relate land cover change to population dynamics, Pearson correlation analysis was performed for each land cover type using the SPSS 16 software package (Copyright SPSS for Windows, Release 2007 Chicago: SPSS Inc.).

3.4 Trajectory of forest cover change

The trajectory of forest cover change (**Study III**, covering To district) refers to the successions of land cover types for a given sample unit over more than two observations (Zhou *et al.*, 2008a; Zhou *et al.*, 2008b; Liu & Zhou, 2004; Petit *et al.*, 2001; Mertens & Lambin, 2000). The number of trajectories (T) is given by Eq.(3) where n is the number of land cover classes and x the number of observations (time series image analysis).

$$T = n^x \tag{3}$$

Three observation periods (1976, 1992, and 2006) with four land cover classes (cropland, shrubland, woodland, and dense forest) were used to build 64 trajectories. All 64 trajectories were merged into five unified classes (old cultivation, old forest, agricultural deforestation, non-agricultural deforestation, and reforestation) to simplify spatial pattern metrics analysis. Four landscape metrics commonly used in ecological studies and supported by Fragstat (Spatial Pattern Analysis Program Quantifying Landscape Structure, version 3.3 build 5) were measured to sustain the trajectory assessment. These were namely the Percentage of Landscape (PLAND, Eq. (4)), the Normalized Landscape Shape Index (NLSI, Eq. (5)), the Interspersion and Juxtaposition Index (IJI, Eq. (6)), and the Area Weighted Fractal Dimension Index (FRAC_AM, Eq. (7)).

$$PLAND = P_i = \frac{\sum_{j=1}^{n} a_{ij}}{A} \times 100 \tag{4}$$

$$NLSI = \frac{e_i - \min e_i}{\max e_i - \min e_i} \tag{5}$$

$$IJI = \frac{-\sum_{k=1}^{m} \left[\left(\frac{e_{ik}}{\sum_{k=1}^{m} e_{ik}} \right) \ln \left(\frac{e_{ik}}{\sum_{k=1}^{m} e_{ik}} \right) \right]}{\ln(m-1)} \times 100 \tag{6}$$

$$FRAC\_AM = \sum_{j=1}^{n}\left[\left(\frac{2\ln(0.25p_{ij})}{\ln(a_{ij})}\right)\left(\frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}}\right)\right] \qquad (7)$$

where i is the class of interest; j is the patch number of class i; P_i is the proportion of the landscape occupied by class i; a_{ij} represents the area (m^2) of patch ij; A, the total landscape area (m^2); e_i is the total length of edge (or perimeter) of class i in terms of number of cell surfaces (including all landscape boundary and background edge segments involving class i); $\min e_i$ represents the minimum total length of edge (or perimeter) of class i in terms of the number of cell surfaces, while $\max e_i$, the maximum total length of edge (or perimeter) of class i in terms of the number of cell surfaces; e_{ik} is the total length (m) of edge in landscape between classes i and k; m is the number of classes present in the landscape, including the landscape border, if present, and p_{ij}, the perimeter (m) of patch ij.

3.5 Systematic and random cover transition

Systematic and random land cover transitions in Sissili province (**Study IV**) were detected by in-depth analysis of the transition matrix obtained from the cross-tabulation of two raster maps of the province (1986 and 2002) using a methodology presented by Pontius *et al.* (2004).

Parameters measured included Swap (Eq. (8)) and the Vulnerability to Transition (Eq. (9)). To detect whether the transitions were brought about by a systematic or a random process, the transition categories were computed in four steps: the expected gains (Eq. (10)); the differences between observed and expected gains; the expected losses (Eq. (11)), and the differences between the observed and expected losses. Statistically, a land cover category is said to gain randomly from others if the gains are in proportion to the availability of the categories which are losing. Conversely, a land cover class is said to lose randomly to others if such losses are in proportion to the size of the classes which are gaining. Any large positive or negative deviation from these proportions is referred to as a systematic transition (Braimoh, 2006; Pontius *et al.*, 2004). Systematic transitions involve regular or common processes of change and tend to be dictated by population growth, increased commercialization, frontier development or lack of environmental awareness. In contrast, random transitions are those influenced by coincidental or unique processes of change (Braimoh, 2006; Pontius *et al.*, 2004; Lambin *et al.*, 2003).

$$S_j = 2\min\left(C_{j+} - C_{jj}, C_{+j} - C_{jj}\right) \tag{8}$$

$$N_p = G_p - L_p \tag{9}$$

$$G_{ij} = \left(C_{+j} - C_{jj}\right)\left(\frac{C_{i+}}{1 - C_{j+}}\right), \forall i \neq j \tag{10}$$

$$L_{ij} = \left(C_{i+} - C_{ii}\right)\left(\frac{C_{+j}}{1 - C_{+j}}\right), \forall i \neq j \tag{11}$$

where S_j is the vulnerability to transition, $2\min\left(C_{j+} - C_{jj}, C_{+j} - C_{jj}\right)$ means two times the minimum between $C_{j+} - C_{jj}$ and $C_{+j} - C_{jj}$. $C_{j+} - C_{jj}$ is the total loss of class *j*; $C_{+j} - C_{jj}$, the total gain of class *j*; N_p is the net change-to-persistence, G_p and L_p, respectively the gain and loss to persistence. G_{ij} is the expected gain of class *i* from class *j*; L_{ij} is the expected loss of class *i* to class *j*. C_{i+} and C_{+j} are respectively the proportion of the landscapes that were occupied by class *i* in 1986 and class *j* in 2002.

4 Results and discussion

4.1 Dynamics and trajectories of land cover in southern Burkina Faso

The dynamics of land cover in southern Burkina Faso were assessed at three levels, namely the provincial, district and village. At the provincial level, there was an increase in the area of cropland at the expense of shrinking forest cover (Table 1, Figure 7). In 1986, cropland occupied 7.5% of the province area while 20 years later (2006), cropland area had increased four-fold, with a mean annual increase of 0.96%. This estimate rate of increase in cropland is much higher than a previous estimation at the country level by the FAO (2001), but is rather close to estimations by Ouedraogo (2006b) and Paré *et al.* (2008) inside Sissili Province, and by Braimoh (2004) in a similar environment in Northern Ghana, which were 0.2%, 1.03%, 0.7% and 1.1%, respectively. The high rate of land clearance for agriculture highlights the recent decrease in forest area in the province, mainly exacerbated by the high demand for cotton and maize at the national and international levels (Ouattara *et al.*, 2008) and the increasing valuable cash plantation systems in the area (Ouedraogo, 2006a).

At the district level, a significant inter-annual and inter-district variation with a constant increase in the area of croplands was observed throughout the study period. In general, there was a remarkable increase in area of cropland in all districts with a differing intensity from one district to another. Bieha district had a spectacular change in area of cropland from 1986 (1%) to 2006 (18% of the district area). This could be the reflection of the recent settlement of migrant farmers from arid regions in search of arable lands in the district, observed since the 1980s (Ouedraogo, 2006b; Henry *et al.*, 2003; Howorth & O'Keefe, 1999). Leo and Niabouri also experienced a rapid increase in the area of cropland. In terms of highest rate of cropland area among districts, Leo came in the first position, followed by To district, with 42% and 35% respectively in 2006. Niebel and Silly had the lowest annual increase in area of cropland. At the very restricted level (village), the detailed time series land use study in Sissili province showed tendencies similar to the change observed at province or district level, with cropland being the cover type gaining most in area to the detriment of forest cover (Table 2). Plantation forestry, mainly dominated by cashew plantation initiated in 2000, could ultimately contribute in halting some of the detrimental effects of deforestation if its recent trend continues unchanged.

Table 1. Cropland area change from 1986 to 2006 in each district of Sissili Province

		Cropland (%)				
District	District area (ha)	1986	1992	2002	2006	Annual increase
Bieha	175447.07	1.11	4.83	6.83	17.90	0.84
Boura	112872.85	6.31	7.81	21.42	27.10	1.04
Leo	95900.26	8.60	13.17	28.72	41.66	1.65
Nebiel	41087.00	13.96	27.57	39.27	21.35	0.37
Niabouri	52517.29	3.26	7.90	22.19	29.82	1.33
Silly	112901.70	10.01	26.88	33.33	18.48	0.42
To	120374.67	14.37	34.45	38.81	34.96	1.03
Total (Sissili)	711100.84	7.50	16.48	24.73	26.62	0.96

Table 2. Change in land use types in Neboun village

	Land use types (%)				
Years	Cropland	Dense forest	Wood savanna	Shrub savanna	Plantation
1976	5.81	35.64	25.91	32.65	0.00
1986	9.60	34.07	24.58	31.76	0.00
1992	12.84	39.86	22.97	24.32	0.00
2000	16.79	24.79	22.27	35.63	0.51
2007	19.63	24.01	20.67	34.19	1.50

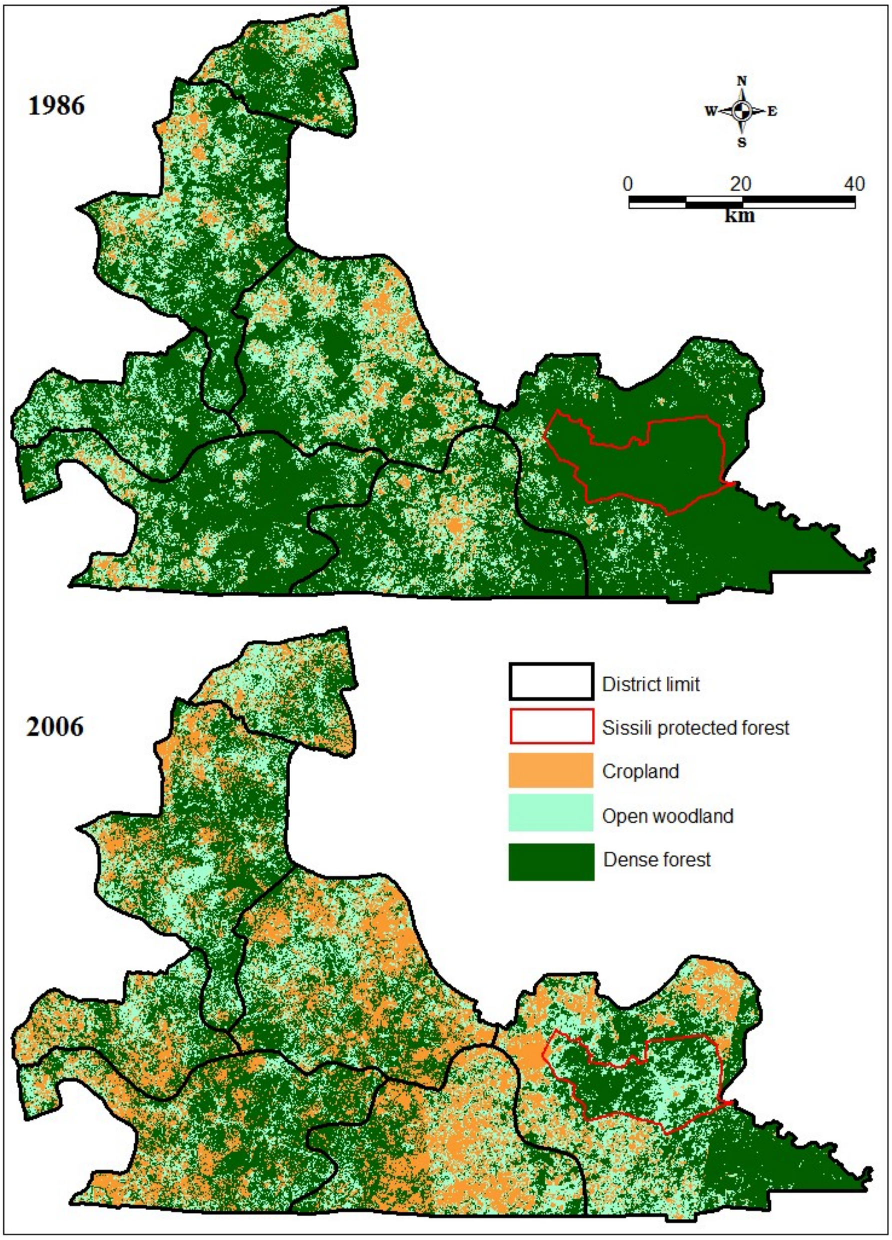

Figure 7. Pictorial representation of land cover change in Sissili Province

Measurements of spatial pattern metrics of land cover change trajectories in To district (Sissili province) from 1976 to 2006 (Table 3) showed a very low proportion of PLAND for old cultivation (0.07%), showing that permanent croplands were lacking. This highlights the prevalence of shifting cultivation in the study area. This system of production is likely to persist in southern Burkina Faso in the near future if nothing is done to discourage it. It is deeply rooted in the region and has a direct link with land tenure systems. In Burkina Faso, land tenure is defined by the Land and Agrarian Reform act (RAF) adopted in 1985 and repeatedly modified. The RAF clearly stipulates that all land in the country belongs to the state. However, its application is not yet widely accepted and at a village level the local land tenure system is still applied. The tenure system in all villages of Sissili province for instance is governed by customary law arrangements between local land chiefs (generally from the indigenous ethnic group) and those asking for land to farm (Ouedraogo, 2006b; Howorth & O'Keefe, 1999). The flexibility in the tenure system is one of the factors pulling landless farmers.

In these studies, old cultivation areas exhibited the smallest NLSI and FRAC_AM, and a null IJI, indicating that this trajectory class was aggregated and spatially adjacent to fewer other classes with less complex patch shapes. This confirms results of previous studies, which showed that in the 1970s native Nuni people in Sissili were practicing environmental-friendly subsistence farming around settlements (Howorth & O'Keefe, 1999). Old forest had a PLAND of 9%, meaning that more than 90% of forest cover has been subjected to disturbances, while net deforestation during the study period affected 34% of the study area. This was due to farming activities in association with non-agricultural factors, such as grazing, fires, fuel wood and charcoal extraction, and climatic factors (Paré *et al.*, 2008; Yameogo, 2005). The highest IJI (values above 50) were found for old forest, deforestation and reforestation trajectory classes, implying that they tended to be associated with other classes with highly interspersed patches.

Table 3. Spatial pattern metrics of forest cover change trajectories

Trajectory classes	PLAND (%)	NLSI	IJI	FRAC_AM
(1) Old cultivation	0.07	0.0949	0.00	1.0614
(2) Old forest	8.57	0.1456	50.68	1.0932
(3) Deforestation due to agriculture	30.12	0.2516	61.22	1.2415
(4) Deforestation due to factors different from agriculture	32.50	0.2739	62.10	1.2821
(5) Reforestation	28.74	0.2084	59.17	1.1532

4.2 Population dynamics and environmental impacts

Population dynamics were assessed at the province, district and village levels. The total population of the province increased from 119,352 inhabitants in 1986 to 212,628 inhabitants in 2006 with an approximate growth rate of 2.2% per annum, resulting in an increase of the population density from 17 inhab/km² to 30 inhab/km² (Table 4). In addition to the natural growth rate of the population which is generally considered to be high, the rapid variation of the population size was a function of migration. Migration to southern Burkina Faso started in the 1980s when severe drought hit the Sahel zone and caused substantial losses of farmers' crops and herders' domesticated animals (Ouedraogo, 2006b; Gray, 2005; Henry *et al.*, 2003; Ouedraogo, 2003). Most of the affected people moved towards the south in search of arable land and pasture. At the district level, the population increase was remarkable. Leo and To were the most densely populated, with 53 and 40 inhab/km² in 2006, respectively. The least populated districts were Bieha, Nebiel and Boura.

Table 4. Evolution of the population densities in Sissili Province

	Population density (inhab km^{-2})			
District	1986	1992	2002	2006
Bieha	8.81	9.34	11.76	17.02
Boura	14.35	16.76	22.76	21.77
Leo	27.78	31.57	42.01	52.53
Nebiel	10.93	12.30	16.24	18.82
Niabouri	12.54	16.33	23.79	36.31
Silly	17.80	20.06	26.51	29.54
To	24.84	27.38	35.59	39.60
Total	16.78	18.96	25.11	29.90

At the village level, in-depth analysis of data from the local population census and interviews revealed the importance and origins of migration in the region and its role in degrading the environment. In Neboun village, the total population in 1976 was 194 people, of whom 97% were indigenous and 3% migrants. Remarkably, the population reached 1,926 people in 2007 (44% indigenous and 56% migrants). Migrant people, mainly Mossi (farmers) and Fulani (herders), were originally from the central and northern regions of the country (Figure 8). These two regions have specific demographic and ecological contexts pushing farmers and herders to emigrate. According to the 2006 national population census, the population of the central regions accounted for 46% of the total population (INSD, 2007), of whom more than 90% were farmers. This indicates the population pressure in the region, resulting in a situation in which the arable land could no longer support the required food production and grazing systems (Gray, 2005; Reij *et al.*, 2005; Gray, 1999). In such conditions, migration towards new frontiers is often considered the best option (Bilsborrow & Carr, 2001; Boserup, 1972). The main difficulty in the northern regions (Sahel) was the insufficient rainfall (Reenberg & Lund, 1998), even though some recent studies tend to demonstrate that rainfalls and vegetation covers in the Sahel are gaining improvement (e.g. Hiernaux *et al.*, 2009; Reij *et al.*, 2009b; Reij *et al.*, 2009a). To make up for this insufficiency, farmers developed plant-pit systems (*Zaï* and *Demi-lunes*) to improve the water holding capacity of the land (Sorgho *et al.*, 2005; Slingerland & Stork, 2000). This technique is laborious and still depends on rainfall availability. Therefore, emigration was seen as the ultimate solution (Youl *et al.*, 2008). Among migrants, some were returning from the coffee and cocoa plantations in Côte d'Ivoire due to the politico-economic unrest that began in 2000 in the country.

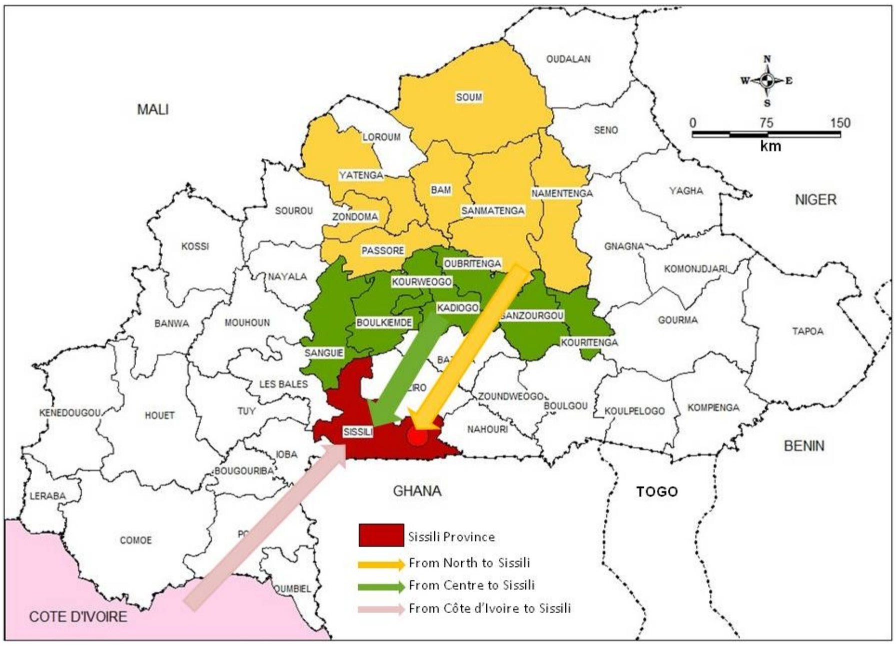

Figure 8. Migration to Sissili province

Correlation tests between population dynamics and land use change revealed that changes in land cover could be related to population growth. At all spatial levels, strong relationships between population and cover changes were found. At the province level, there were strong relationships between population and changes in area of both cropland (r^2= 0.90; $p < 0.05$) and dense forest (r^2= 0.56; p= 0.03). However, population change and change in area of woodland were not correlated (r^2= 0.11; p= 0.42). At the village level, there were strong correlations between land cover types with the entire population, and particularly with the migrant population. Migration was strongly correlated with area of cropland (r^2= 0.91; p= 0.03) and areas of woodland (r^2= 0.93; p= 0.02). The strong correlation observed between population growth and area of cropland suggests that shifting cultivation or slash/burn systems are still dominant in the study area, with continual clearance of forest lands for croplands, rather than the intensification of production systems in the existing croplands. Such practices are still current in most parts of the tropical zone (Ningal *et al.*, 2008; Lambin *et al.*, 2003; Reenberg & Lund, 1998), since people basically rely on small scale farming practices for food and revenue. A new agricultural policy introduced by the government in the 2000s, initiated to increase cotton production at the national level, could have boosted the forest decline in southern Burkina Faso. The policy granted credits to farmers to acquire ploughs and fertilizer for cotton production. In a context of technology and market improvement in the agricultural sector, cultivated land is likely to increase (Lambin *et al.*, 2003; Bilsborrow & Carr, 2001). Furthermore, there has been a growing expansion of agribusiness system in Sissili province, which involves private investors who make use of machinery and casual labour for commercial crop productions (Paré *et al.*, 2008; Ouedraogo, 2006b; Ouedraogo, 2003).

In addition to clear cutting forests for crop production, the strong correlation between forest cover decline and population growth could be explained by energy requirements as well as the grazing methods. The household survey in Neboun revealed that farmers are producing charcoal and extracting wood for fuel on a large scale to supply the capital city (Ouagadougou) where wood and charcoal account for about 90% of the energy requirements (Ouedraogo, 2006a; Krämer, 2002). The grazing methods in use are based on free mobility of livestock in all open forests. In periods of scarcity, some tree species such as *Afzelia africana* Smith ex Pers., *Pterocarpus erinaceus* Engl. & Diels, *Khaya senegalensis* A. Juss and *Adansonia digitata* L are pollarded to feed animals (Ouedraogo, 2006b). Migration has played an important role in the degradation process in southern Burkina Faso. Geist and Lambin (2001), Lambin *et al.* (2003), and Geist *et al.* (2006) argue that migration in its various forms is the most important demographic factor causing land use change both spatially and temporally. During their first years of resettlement, migrant farmers fundamentally rely on charcoal and fuelwood traffic for their survival, as revealed by the survey. They exploit large areas for crop production to secure their income and domestic food, as well as to meet the food shortages and chronic food insecurity that their parents face in their home villages.

4.3 Dominant signals of land cover transitions

Analysis of land cover transition processes revealed that all cover types had a high vulnerability index to transition (Table 5), indicating that forest cover is subjected to conversion to other land use types. The net change-to-persistence ratio (Np) is higher for bare land (20.5), indicating that this class type, even though small in proportion in 2002 (0.5%), has a high potential to increase in the future in southern Burkina Faso. This could be due to inappropriate farming practices that severely degrade the soil by accelerating wind and rain erosions, ultimately resulting in unproductive lands (Forman & Alexander, 1998).

Table 5. Gain-to-persistence (G_p), loss-to-persistence (L_p), and net change-to-persistence (N_p) ratios of the land cover classes in southern Burkina Faso

	Gain (g)	Loss (l)	Persistence (p)	G_p	L_p	N_p
Bare land	0.43	0.02	0.02	21.50	1.00	20.50
Cropland	12.72	4.44	4.31	2.95	1.03	1.92
Shrub-/grassland	20.53	19.08	15.36	1.34	1.24	0.09
Woodland	9.27	32.15	14.78	0.63	2.18	-1.55
Dense forest	17.05	4.35	5.46	3.12	0.80	2.33
Water body	0.04	0.00	0.02	2.00	0.00	2.00

The results also showed that 80% of transitions observed in southern Burkina Faso were due to systematic processes of change (Figure 9). The systematic transitions concerned the conversion from shrub-/grassland to cropland and bare land; conversion from woodland to shrub-/grassland and dense forest land, and conversion from dense forest land to shrub-grassland and woodland. This is a good sign from a planning perspective, since management policies could address well known systematic factors. Results indicated that gains in cropland occurred preferentially from shrub-/grasslands as clearing these is less labour-demanding (Murphy & Lugo, 1986), with very few conversions from dense forest and woodland to cropland. At the regional scale, this suggests that extensive farming activities, although amplified by rural-rural migration, may not be the primary cause of dense forest and woodland decline. Conversely, the gain of shrub-/grassland from dense forest and woodland indicates that the woodlands are the main sources of the firewood and charcoal used to meet the energy demands of the nearby big cities, namely Ouagadougou and Koudougou (Ouedraogo, 2006a; Ouedraogo, 2006c; Krämer, 2002).

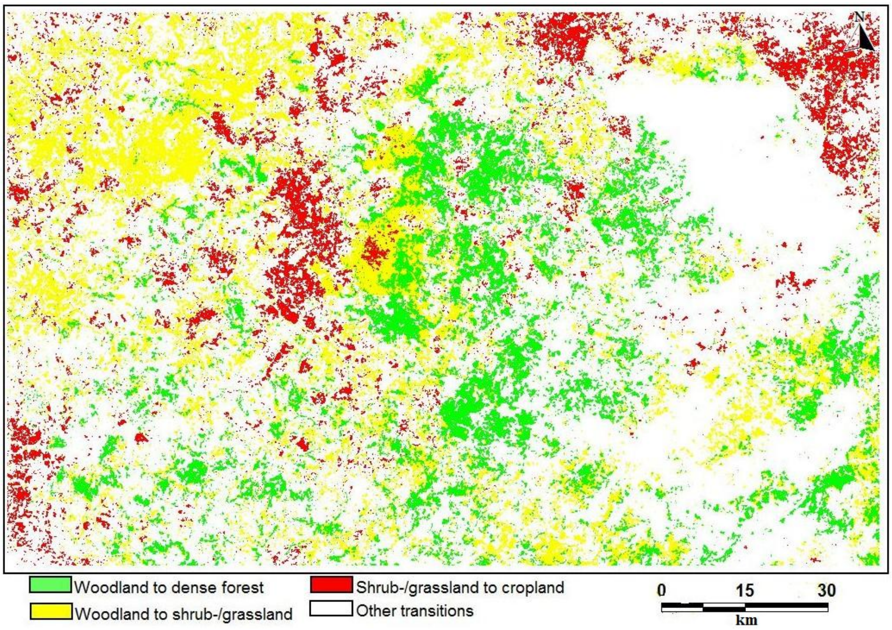

Figure 9. Systematic forest cover transition in southern Burkina Faso

In addition to systematic process of changes, a few changes occurred due to random processes, involving conversions from shrub-/grassland to woodland and dense forest land, and conversions from dense forest and woodland to cropland, as indicated in Figure 10.

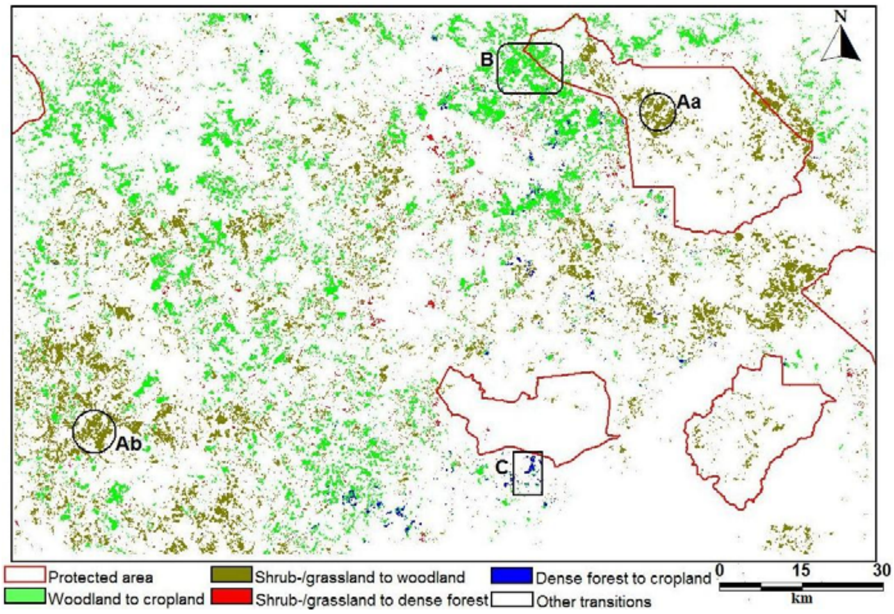

Figure 10. Random forest cover transition in southern Burkina Faso (Aa et Ab indicate improvement of shrub-/grassland to woodland in protected forest and village forest, respectively; B indicates uncommon conversion from woodland to cropland and C, sporadic conversion from dense forest to cropland).

In areas indicated by boxes Aa and Ab in Figure 10, there was an improvement of shrub-/grassland to woodland. This kind of transition mostly occurred in protected areas (Aa) and in village forests (Ab), where vegetation is protected from logging, grazing and farming. In areas indicated by box B, there was a conversion of woodland to cropland. This could be due to the recent massive and uncontrolled migration of farmers from drought-affected areas in the northern and central zones of the country to the southern, western and eastern regions (Gray, 2005; Reenberg & Lund, 1998). Box C indicates areas where dense forest was sporadically converted to cropland, mainly yam plantations, which need deep soils and more humid conditions than other types of crops grown in the area.

5 Conclusion and recommendations

The use of multi-temporal remotely sensed imagery and technologies, together with population data, household and land surveys enabled the detection of land cover trends and transition processes and the role of population dynamics in environmental degradation in southern Burkina Faso. Over the last thirty years, cultivated lands expanded increasingly to the detriment of the forest, and within forest covers, densely forested areas were continuously degrading to open woodlands, shrublands and grasslands. At the province, district and village levels, the human population increased rapidly within the same period, partly as a result of natural growth but most importantly due to the large scale immigration of farmers. The resulting increase in population dictated the change in land cover. Trajectory analysis revealed that prevailing small scale farming practices are associated with slash and burn systems in the study area. These practices were among the primary proximate causes of deforestation and forest degradation and they are likely to persist in the future if nothing is done to discourage the practices. Land cover transition measurements indicated that most changes in land cover were governed by systematic processes of change. Therefore, these processes could be systematically addressed and/or reversed provided that there is political will to do so. Some minor changes occurred due to random processes of change but they could not be the cause of large scale deforestation in southern Burkina Faso.

The picture of southern Burkina Faso as presented above provides a clear illustration of the pessimistic theory of the human-ecology nexus initiated by Malthus in 1798 and promoted by Hardin (1968; 1993), Ehrlich (1968; 1990), and Meadows *et al.* (1972; 1992). However, overpopulation itself is not an issue in southern Burkina Faso, but rather the lack of control of population mobility and use of improved technology for agricultural intensification. In this situation, Marxist views on human-ecology, exemplified by Boserup (1972) and Simon (1980), who argue that a growing population might use man-made technology (machinery, fertilizers, etc.) to increase production instead of opening new fields for agriculture, could have been relevant to southern Burkina Faso.

To minimize the adverse side-effects of the growing population pressure on the environment in southern Burkina Faso, the following strategies could serve as a baseline for the sustainable management of forest ecosystems: (i) population control and more importantly migration control might be the starting point for any resource management plan. Migration control should include reduction of the migration flow and the management of specific sites to settle newcomers, otherwise in addition to deforestation, migration could also become a source of conflict between indigenous and migrant people in the long term. (ii) The land tenure system as defined in the RAF should be implemented in practice. If it is recognized that the land belongs to the state, then the state should take control over it, deciding on access to the land, the extent and conditions of that access. (iii) Policies related to agricultural intensification must be promoted by the government to discourage cropland expansion and its associated fragmentation of forested areas. (iv) Agribusiness activities should be followed up by an organized government structure to avoid clear cutting large space by actors without being able to make good use of it, as it seems to be. (v) Plantation of rapidly growing trees should be promoted to provide an alternative source of energy to the felling of natural forest for fuel wood and charcoal production. (vi) Alternative sources of income should be found and supported by the government's micro-economic policy in order to reduce the pressure on land as the ultimate source of income generation. (vii) Concerted efforts should be made to define appropriate strategies, new policies and institutional arrangements that could balance agricultural production and forest conservation through dialogue with stakeholders. (viii) Finally, further investigations should be made to address policy, socio-economic and climatic contributions to forest cover change in the study area.

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French summary (résumé)

Avec la forte croissance de la population du globe et le remarquable progrès de la technologie, l'homme apparait comme le facteur fondamental le plus redoutable dans le processus de transformation des écosystèmes. Pour comprendre les mobiles et prévoir les conséquences de ces transformations, les études à long terme des changements de l'occupation et de l'utilisation des terres à l'échelle planétaire, régional et local demeurent une condition sine qua non.

L'objectif de la présente étude est de mesurer l'impact de la croissance démographique sur la dynamique du couvert végétal afin de générer des connaissances susceptibles de contribuer à une gestion durable des ressources naturelles par le biais de prise de conscience et de décisions appropriées. L'étude a été réalisée au sud du Burkina Faso, dans la province de la Sissili. La bonne pluviométrie et l'abondance des terres cultivables ont fait de cette partie du pays un pôle d'attraction pour les paysans désespérés des zones arides du nord et des régions surpeuplées du centre, et également une zone d'émergence de l'agrobusiness. La méthodologie utilisée combine la détection de la dynamique de l'occupation des terres à l'aide de traitements d'une série d'images satellitaires de hautes résolutions de 1976 à 2006 ; l'évaluation de la dynamique de la population humaine sur la base des recensements de population; le calcul de métriques cibles du paysage et la détermination des processus de transition (systématique ou aléatoire) qui sous-tendent le changement environnemental. Les résultats ont montré que depuis les années 70s, les superficies des terres cultivées se sont progressivement étendues au détriment des couvertures forestières et, l'expansion des champs et la diminution des forêts sont corrélées à la croissance démographique. Le calcul des métriques du paysage, en particulier l'Index Normalisé de la forme du Paysage (NLSI), l'Index de Dissémination et de Juxtaposition (IJI) et l'Index de la Dimension Fractale de la Surface Pondérée (FRAC_AM) ont révélé la prépondérance de la pratique de la culture itinérante sur brûlis qui demeure nuisible à l'environnement. L'analyse de la transition de l'occupation des terres a montré que la majeure partie des changements est causée par des processus systématiques maitrisables tels que la croissance démographique, l'ampleur des cultures commerciales (coton, maïs, anacardes,…) et l'absence de l'éducation environnementale. Le processus aléatoire de transition est surtout lié à l'immigration brusque et incontrôlée de la population paysanne.

Afin de palier aux effets destructeurs de la croissance démographique sur l'environnement, il est nécessaire de contrôler et d'organiser la migration, de mettre en application la reforme agraire et foncière, de promouvoir l'intensification agricole et la plantation d'espèces forestières à croissance rapide et de diversifier les sources de revenu du monde rural.

Mots-clés : Burkina Faso, image satellitaire, migration, métriques de paysage, transition systématique, changement du couvert végétal.