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11 Rangeland Ecology

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Executive Summary

The problem

Sub-Saharan Africa rangelands are vital to the livestock economy of the subcontinent. They cover roughly 9 million km^2 or about 40% of the areas with potential for livestock production. The majority of African livestock – chiefly cattle, sheep, goats, camels and donkeys – live on rangelands at some point during the annual production cycles. Most of the range is managed by mobile groups who constitute perhaps one-fifth of poor livestock owners in sub-Saharan Africa. Grazing areas have limited vegetative production because of low and variable rainfall – they receive less than 600 mm annual rainfall – shallow and eroded soils, and inadequate forage due to reduction and fragmentation of the rangeland areas resulting from cropland and urban expansions. For all these reasons, it has been difficult to make sustained improvements in range productivity, even under controlled management, despite several decades of research and development interventions.

ILRI's role in the global context

The International Livestock Research Institute (ILRI) and its predecessor, the International Livestock Centre for Africa (ILCA, 1974–1994) have worked for more than 40 years on rangeland ecologies of sub-Saharan Africa. ILCA's rangelands research focused on the monomodal rainfall areas of the West African Sahel in Mali, the inner delta of the Niger River in Mali, Niger and Senegal. ILRI's historical sites in East Africa were the bimodal rainfall areas of Kenya and Ethiopia. A novel feature of ILRI research since the 1990s has been integrative studies on the rangelands of southern Kenya, in areas of intensive livestock–wildlife interactions in Amboseli National Park, Nairobi National Park, the Mara Reserve and the Serengeti in Tanzania (with collaborative tasks on rangeland management in southern Ethiopia/Borana region).

Impacts of ILRI's research

Scientific impacts

There were a number of scientific impacts of ILRI's range research:

- Integrated studies of domestic livestock, vegetation, water, crop and management interactions with original data from field conditions.
- Identification of determinants of plant and animal productivity under arid and semi-arid conditions.
- Definition of constraints to growth of pastoral systems.
- Development and refinement of research methods – for animal counts, techniques for vegetation surveys, participatory household surveys, application of remote sensing to African environments, and joining of biophysical process models to agent-based household models.
- Extension of range science methods and models to problems of climate change.
- Extension of range science methods to problems of interactions between wildlife and livestock.

- Elucidation of the economic and biological rationale of transhumant pastoralism.
- Refinement of estimates of greenhouse gas emissions from range components (animals, plants, soils, water and infrastructure).

Development impacts

The chief development impact of range science followed from the defence of the economic and biological rationale of extensive pastoralism. This defence, made on theoretical grounds following the emergence of density-independent models in the 1980s, and on empirical grounds following the ILCA/ILRI studies of pastoralism, has prevented bad policies (such as certain forms of group ranges and grazing reserves) from being imposed on pastoral groups. As it has done so, it has preserved pastoral livelihoods and limited rising inequality; an example of this scientific and development impact can be seen in the Kenyan Mara Community Conservation Planning Framework.

Introduction

This chapter summarizes the impact of research by ILRI[1] and collaborators on rangeland ecology in East and West Africa.

In East Africa, the research topics included identifying the drivers of rangeland vegetation, such as rainfall, animal density, bush and crop encroachment, and increased landscape fragmentation. A second group of topics was establishing the importance of wildlife–livestock interactions in Kenya and Tanzania, given the significant and diverse wildlife populations in those countries. This led to a process to foster innovations in conservation area management, better incorporating pastoral livestock production with wildlife. Simultaneously, modelling of coupled systems was ongoing to better capture multiple drivers of change in rangelands and examine both the impacts of landscape fragmentation and the growth of agriculture on livelihoods and ecosystem services. These results highlighted the need to view humans, cattle and wildlife as integrated components of ecosystems when making management decisions

In West Africa, ILCA research focused on comparative evaluations of pastoral and agropastoral systems in central Mali (Niono) and the inner delta of the Niger River (Macina) in the mid-1970s, which led to an understanding of seasonal vegetation growth under the influence of rainfall, flooding, grazing and cropping. The impact of the most severe drought in history that hit the Sahel in 1982–84 was assessed on the pastoral systems of the Gourma region in northern Mali in 1983 and was followed by a monitoring of the rangeland recovery over a decade. Later West African studies documented the impacts of grazing on pastures, including through recycling of nutrients via excretions, based on long-term research in the Fakara region of Niger. Related studies of herder decisions about animal movements, in response to changes in rainfall, cropping intensity and wage opportunities, built on the characterizations of rangeland productivity and its determinants.

Main Trends in African Range Systems

Map 2 (see p. xviii) shows the main research areas of ILRI and its predecessors. General trends around those areas can be described for human populations, livestock populations, climate, vegetation, mobility and grazing access.

Arid and semi-arid pastoral systems are found across much of sub-Saharan Africa. In Kenya, Mali, Niger, Nigeria and Sudan, they are the largest livestock systems by land area. Although sometimes considered 'marginal' in terms of public expenditure priorities, these systems contribute significantly to agricultural gross domestic product, household food and nutritional security, and to ecosystem maintenance in dry areas. In Kenya, over 80% of domestic meat consumption is produced in pastoral systems; Sudan has been exporting around 1.8 million animals annually for decades; and in the Horn of Africa, livestock and meat export values may have exceeded US$500 million by 2010 (Catley *et al.*, 2013, p. 7). In West Africa, these pastoral systems contribute many of the young males and interact with more intensive and sedentary livestock production systems via seasonal mobility.

Human populations

Significant increases in human populations are noted in East and West Africa alike. In West Africa, Touré *et al.* (2012) estimated an increase of 2.6% per year in the overall rural population of the drylands between 2005 and 2010, with 3.6 times more people in 2010 than in 1960. de Haan *et al.* (2016) assumed a 2.5–3% annual increase for the future.

Livestock populations

After the severe losses during the droughts of the early 1970s and early 1980s (Toulmin, 1987) livestock populations have increased rapidly as well, with the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) showing rates of growth of between 3.1% and 4.4% from 1980 to 2010. In both East and West Africa, the small-ruminant population has grown faster than cattle. Detailed data on national level species distributions are lacking in most places; however, unique data from Kenya based on 30 years of aerial surveys shows that cattle numbers have declined as camel and small ruminants have increased (Ogutu *et al.*, 2011). The same study found significant declines in wildlife numbers.

Climate

West Africa is characterized by a south–north climate gradient ranging from humid/subhumid on coast lines to semi-arid/arid in the north. Transhumant pastoralism has dominated in the arid Sahelian zones, with herders migrating among rangelands and water sources. At the end of the rainy season, herders move to areas with available grass or crop residues, often southwards or in wetlands but also more opportunistically. Over the past three decades, 'these movements have become longer and more dispersed' (Touré *et al.*, 2013, p. 14) and conflicts with sedentary farmers and in protected areas have increased (Turner *et al.*, 2011). This is for various reasons, including changes in traditional land uses around water points and increased livestock numbers. Although many transhumance corridors have been legally recognized since colonial times, transhumance corridors are not always respected (Niamir-Fuller, 1999; Turner *et al.*, 2016) and failure to respect them sometimes leads to violent conflicts among herders and between herders and crop farmers.

In East Africa, with bimodal rainfall in some areas, dry-season movements are shorter and more opportunistic. Increased fragmentation of rangelands due to expansion of cropping and other activities and exclusion from dry-season water and grazing further limit seasonal mobility. The observation of range fragmentation was a motivation for much of ILRI's research as scientists sought to understand its impact on rangeland, livestock and wildlife productivity.

Vegetation

Long-term trends are extremely difficult to detect in the East African rangelands. First, the cost of long-term field studies of vegetation and land use make them infeasible in some instances. Second, the high temporal and spatial variability of precipitation and vegetation make it problematic to project from shorter periods and smaller study areas (Homewood, 2008; Oba, 2013). Third, changing drivers such as drought frequency, recent fragmentation and the spread of invasive plant species disturb historical patterns of land use. As Homewood (2008, pp. 65–72) explains, dryland rangelands go through periods of vegetation fluctuation in response to different drivers, in particular climate variability. In East Africa, there is no consistent long-term evidence or trend in rainfall, although heavy grazing from sedentarization or restriction of mobility can degrade rangelands (Galvin *et al.*, 2002), and hence increased fragmentation is a threat to the sustainability of rangelands.

Long-term dry matter (DM) production per hectare above the 600 mm isohyet in West Africa is in the order of 600–2400 kg DM/ha. Rainfall and vegetation improved after the droughts of the 1970s and 1980s, and the subsequent 'regreening' of parts of the Sahel has been notable (Hiernaux *et al.*, 2009c; Dardel *et al.*, 2014b) including for the woody population in rangelands (Hiernaux *et al.*, 2009b; Brandt *et al.*, 2016a) and agroforestry parklands (Reij *et al.*, 2009; Sendzimir *et al.*, 2011).

Galvin *et al.* (2002) summarized the research, concluding that woody plants have expanded across most rangelands globally, in response to both grazing management and global increases in carbon dioxide and nitrogen emissions.

Mobility and grazing access

Associated with the growth in population density in East and West Africa has been an expansion of cropping. The area expansion of cropped fields reduces grazing areas on average and typically limits seasonal grazing, such as on wetlands, even more sharply (Haywood, 1981; Marie, 2000; Schlecht *et al.*, 2001).

Increased private ownership and enclosure of rangelands, particularly in East Africa, including 'land grabbing', and the erosion of some traditional practices governing common lands has restricted grazing even more. The loss of mobility and grazing access through public use planning, enclosures and urbanization (Galaty, 2013a) ultimately threatens rangeland integrity (Galvin *et al.*, 2008a,b). Formal tenure is now more important as a tool for pastoralists to secure rights to access lands; however, this poses challenges, because Hobbs *et al.* (2008) has argued that fragmentation results from modern land tenure.

The Central Problems of Tropical Range Ecology

A summary of the central problems of tropical range ecology would be the following questions:

- What are the technical and economic feasibility of measures to raise plant productivity under arid conditions?
- What is the technical and economic feasibility of raising livestock at given levels of feed resources?
- What are the short- and long-term effects of climate and climate change in primary and secondary range productivity?
- What are the effects of rangeland use for livestock, crops, wildlife and tourism on soils, nutrient flows and transfers, vegetation, water and greenhouse gas emissions?
- How have land rights evolved under pressure from competing uses in crops and other sectors, and what are their effects on the seasonal, annual and spatial mobility of livestock?
- What is the appropriate use of equilibrium and non-equilibrium models as explanatory frameworks and policy guides?

This chapter first presents these issues schematically before discussing the evidence produced about them by the studies of ILRI, its predecessors and its collaborators in sub-Saharan Africa.

The technical and economic feasibility of measures to raise primary productivity under arid conditions

Efforts to raise pasture yields in dry areas without added water have failed systematically. Pratt and Gwynne (1977, pp. 100–128) showed that the economics of range improvement – by water development, fencing, overseeding of the range, managed grazing and seeding with new species of grasses – were unfavourable in drier conditions and risky in wetter ones. These findings were generally confirmed in Le Houérou's (1980) book on browse and in Sandford's (1983) global review of pastoral development.

Le Houérou (1989, pp. 149–155) synthesized the Sahelian experience with native pasture improvement over many years and concluded:

- Irregular rainfall, a long dry season and competition from native grasses and forbs made the introduction of higher-yielding plant species unsuccessful.
- There had been no commercial success in reseeding pastures at rainfall around the 550 mm isohyet, with local or introduced grasses or with legumes; the same was true of 'rotational or deferred grazing'.
- '...of the 80 herbaceous tropical arid zone species of forages which have been tried at Niono (550 mm) in Mali in 1977–1980, not one single species became established and amenable to produce a grazing impact'.
- There was one success – with *Acacia tortilis* and *Acacia senegal* near M'Bidi, Senegal – in establishing browse species at rainfall less than the 400 mm isohyet in West Africa.
- The high cost of fencing, firebreaks and water made it nearly impossible to achieve higher plant yields, even if browse and

pasture production could be improved under experimental conditions (see also Montgolfier-Kouèvi and Le Houérou, 1980).

The short- and long-term effects of climate

Climate is the key determinant of rangeland productivity, especially in the arid and semi-arid areas where extensive animal production predominates. In East Africa, these systems receive no more than 600 mm of rainfall annually and often only 200–300 mm (Ellis and Swift, 1988; Oba, 2013). Higher aridity means greater rainfall variability in time and space, and in much of East Africa, the rainfall is bimodal. Inter-annual variability in precipitation is a major driver of herd and grazing management. In East Africa, rainfall is the primary driver of vegetation, with vegetation growth closely following rainfall amount, frequency and duration (Coppock, 1994; Coppock *et al*., 2017).

In West Africa, the monsoon drives a climate gradient from subequatorial humid in the south to desert margins in the north. In the arid and semi-arid Sahel, rainfall varies from 100 to 600 mm annually in a period of 1–4 months, with the more southerly regions receiving from 600 mm to more than 1200 mm over periods of up to 8 months. Although the monsoon occurrence is predictable, it occurs only in one season and the distribution of rain across this season is unpredictable (Hiernaux and Le Houérou, 2006). There is a marked contrast in the Sahel between fodder quality in the wet and dry seasons.

Forage availability and quality are the primary drivers of variability in livestock production. Primary production, in turn, is highly variable over time and space because the major determinant of plant growth is available soil moisture and fertility. Shortages in forage availability arise from drought, constrained access (e.g. due to disease, distance and access to water, or to conflict) or changes in palatability. Most rangelands include a mix of vegetation types including an herbaceous layer and scattered woody plants. These rangelands return quite rapidly to peak production after drought once the rains return, as documented by long-term research (Hiernaux *et al*., 2009a,c; Miehe *et al*., 2010).

Major livestock losses do occur, with severe droughts, which is one reason why herd sizes need to be large enough so that production can return to trend within 3–5 years (Ellis and Galvin, 1994). These droughts are often cumulative, with several successive 'failed' seasons ultimately leading to major hardship and loss of animals, as lack of feed and water plus diseases lead to mortality (Toulmin, 1987). Drought recovery is mostly related to levels of herd die-off, as population is mostly related to lagged rainfall variation; however, drought intervals are also important (Lesnoff *et al*., 2012). Long-term shifts in climate, compounded by persistent growth of human populations and of cultivated areas into rangelands, explain some of the shift in West Africa into small stock in western Niger (Turner, 1999).

The effects of rangeland activities

Pastoralists have for centuries managed the spatial and temporal variability of water and pasture by moving animals annually and seasonally, as shown in the early compilations of Monod (1975) and ILCA (1975). Seasonal mobility in West Africa follows the monsoon along the south to north gradient, while in East Africa, the movements are more opportunistic and local owing to variability in altitude and in the bimodal rainfall regime. Pastoralists also move to avoid seasonal disease outbreaks, often caused by vectors influenced by rainfall patterns. Traditionally, pastoral and agro-pastoral producers managed access to and availability of grazing and water through complex rules and agreements, sometimes including specialized institutions, so that in drought years reserves would still be available (Gallais, 1984; ODEM/CIPEA, 1983). In addition to the ecological drivers, security and access to markets also influence movements. Homewood (2008) noted that the need for flexibility made pastoral systems vulnerable to land loss and exclusion from customary ranges; losses of land access to fragmentation threaten the viability of pastoralism.

Equilibrium and non-equilibrium models

Equilibrium models from temperate systems (on which many of the papers in ILCA's first major book relied; ILCA, 1975) influenced the early studies of tropical arid and semi-arid rangelands. These equilibrium models focused on livestock densities and carrying capacities, and blamed livestock for overgrazing and environmental degradation.

The early ILCA studies in Mali (Hiernaux, 1983; Wilson *et al.*, 1983; Wilson, 1986; Wilson *et al.*, 1988) and later work in the Gourma in northern Mali (de Leeuw *et al.*, 1992), and further in western Niger (Hiernaux *et al.*, 2009a) formed some of the empirical basis of non-equilibrium models, which became dominant in the 1980s and 1990s (e.g. Ellis and Swift, 1988; Behnke and Scoones, 1993; Scoones, 1995).

The 'Synthesis Paper' of Ellis and Swift (1988) (Table 11.1) contrasted equilibrium and non-equilibrium systems in four domains. Equilibrium systems operate through biotic feedbacks, such that rangelands have a density-dependent carrying capacity. Non-equilibrium systems are density independent and respond to stochastic events such as rainfall and fire, rather than to livestock populations. Semi-arid rangelands in bimodal rainfall systems such as in southern Ethiopia behave more as equilibrium systems (Coppock *et al.*, 2017), while the behaviour of Sahelian rangelands under monomodal rainfall regime clearly affiliates to non-equilibrium (Hiernaux, 2004).

Vetter (2005) summarized the equilibrium/non-equilibrium debate over arid and semi-arid rangelands. She concluded that: 'most arid and semi-arid rangelands encompass elements of both equilibrium and non-equilibrium behaviour, and management must account for the high temporal variability and spatial heterogeneity'.

The African Rangelands Research Environments

East Africa (southern Ethiopia, Kenya, Tanzania)

The rangelands of Kenya, Tanzania and southern Ethiopia are noted for bimodal rainfall, which heightens the seasonal, inter-annual and spatial variability characteristic of arid and semi-arid areas. The short rains occur in October–December, with the long rains in March–May. The lowlands of Ethiopia and northern Kenya are arid and semi-arid, while southern Kenya and northern Tanzania are semi-arid to dry–subhumid with patches of greater humidity.

Historical rangelands research at ILCA focused on the Borana Plateau of southern Ethiopia (Coppock, 1994). The Borana areas have a semi-arid climate (400–600 mm of rain) with a complex mix of vegetation consisting mainly of perennial grasses and shrubs.

ILCA's initial range research in Kenya was in Maasailand in Kajiado County of south-eastern Kenya (Solomon Bekure *et al.*, 1991). ILRI's later work concentrated on the rangelands of southern Kenya, especially areas of intensive livestock–wildlife interactions in Amboseli National Park, Nairobi National Park, the Mara Reserve and the Serengeti in Tanzania. The rangelands of northern Tanzania and southern Kenya are more varied in terms of rainfall (400–1200 mm), with national parks occupying some of the wetter areas (Amboseli National Park and Maasai Mara National Reserve). These parks are among the most popular for wildlife tourism, and the challenges of integrating

Table 11.1. Contrasts between equilibrium and non-equilibrium systems. (From Ellis and Swift, 1988.)

Domain	Equilibrium systems	Non-equilibrium systems
Abiotic patterns	Vegetative conditions relatively constant; wetter	Highly variable conditions; typically, drier; monomodal rainfall
Plant–herbivore interactions	Deterministic from livestock to vegetation with limited feedback	Weak determinism from livestock to vegetation; plants under 'abiotic control'
Population patterns	Density-dependent carrying capacity; animal 'populations track carrying capacity'	Density independent; 'abiotic cycles'; carrying capacity random
Ecosystem characteristics	Typically more humid and densely populated	Typically more arid and less densely populated than equilibrium system

wildlife tourism with livestock production remain significant. Vegetation in the Mara is more productive than in more arid Kajiado, but both areas are predominantly tall- and short-grass plains interspersed with woodlands and shrubs. Some of ILRI's research focused on the Athi-Kaputiei Plains, in northern Kajiado district and bordering Nairobi National Park (Reid *et al.*, 2008). Rainfall ranges from 500 to 800 mm. The soils are derived from phonolitic lava and contribute to a nutrient-rich savannah with both grasses and trees that can support considerable wildlife biomass. For at least 400 years, Maasai have occupied this area. Over the 20th century, this pastoral–wildlife system has become more fragmented and compressed, which was the subject of ILRI's research.

Further south in Kajiado, on the border with Tanzania, the Amboseli ecosystem has long been considered a conservation jewel. However, its ongoing transition from extensive pastoralism to intensive pastoralism carried out on individual land parcels is threatening both wildlife in and around the Amboseli National Park and livestock production by the communities (Burnsilver *et al.*, 2008). The constraints on mobility and fragmentation of the resource base has altered the landscape, modifying wildlife habitat and increasing competition among wildlife and livestock for pasture and water.

Over to the west in Narok County, the Mara ecosystem is one of the wettest pastoral savannahs in East Africa and is the northern site of wildebeest, zebra and Thomson's gazelle migration from the Serengeti in Tanzania. The Maasai Mara National Reserve is limited to wildlife tourism but is surrounded by group ranches to the north and east. It receives relatively high rainfall (up to 1200 mm annually) and is a productive range that supports a high density of wildlife, especially from July to October when animals migrate north from Tanzania. Some research also occurred in the Ngorongoro Conservation Area adjacent to the Serengeti, which is a designated multiple-use area with important objectives for both wildlife conservation and human welfare. Over 50,000 Maasai pastoralists and their livestock live in the area (Boone *et al.*, 2002). The Tarangire–Simanjiro–Manyara pastoral ecosystem, south-east of the Serengeti in Tanzania, was also a site for some of ILRI's work.

West Africa (central Sahel in Mali, Inner Delta, Gourma, western Niger, northern Nigeria, Senegal and Gambia)

Rangeland production in the Sahel occurs under monsoon conditions and is characterized by high spatial, seasonal and annual variability (Ayantunde *et al.*, 1999; Hiernaux and Le Houérou, 2006). The Mali studies of the late 1970s to the early 1990s would have occurred in a period of exceptionally low Sahel rainfall, which would not have been true of the East Africa studies (Nicholson, 2000; Nicholson *et al.* 2018). Mean primary production ranges from 600 kg DM/ha in the northern Sahel with 200 mm of rainfall to 2400 kg DM/ha in the southern Sahel with 600 mm rainfall, but there is no linear relationship between rainfall and herbage production (Hiernaux *et al.*, 2009c; Dardel *et al.*, 2014a).

Herbage production is characterized by a wide local variation due to differences in soil type, runoff water patterns based on topography and geomorphology, and dominant plant species (Hiernaux and Le Houérou, 2006). The feed quality of herbage is often inversely proportional to the amount of water infiltrated in the soil during the growing season, at least for a given soil texture and fertility (Breman and de Wit, 1983). Free-ranging ruminants are selective in choosing their diets (Ayantunde *et al.*, 2007), and therefore spatial heterogeneity in herbage mass and quality affects the spatial distribution of grazing animals (Turner *et al.*, 2005; Schlecht *et al.*, 2006).

ILRI's pastoral research in West Africa has focused on the Sahel, in view of the importance of these arid rangelands to livestock production. ILRI research on rangeland ecology started in Mali in the 1970s in Niono (central Mali) and then expanded to Macina (the inner delta of the Niger River). In 1983, 25 rangeland sites were established in Gourma and were monitored by ILCA from 1984 to 1993, and then irregularly until 1998. The site monitoring continued from 2000 to 2009 under the African Monsoon Multidisciplinary Analysis (AMMA) project (Mougin *et al.*, 2009) and is still going on under the AMMA-CATCH (Coupling the Tropical Atmosphere and the Hydrological Cycle) research network (www.amma-catch.org; accessed 25 March 2020) although the observations had to be scaled down from 2012 because of civil insecurity. In Niger, 71 vegetation monitoring sites were established in Fakara and were monitored from 1994 to 2006 under ILRI research activities. The monitoring of these sites is continuing within the AMMA-CATCH network (Cappelaere *et al.*, 2009). In addition, there were grazing studies conducted on-station at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Centre in Sadoré, Niger, and at the Niger government cattle ranch in Toukounous.

The Gourma monitoring sites are spread along the south–north bioclimatic gradient from Boulakessy at the border with Burkina Faso to Gourma Rharous on the Niger River via Hombori and Gossi. Gourma is in the Sahelian agroecological zone with average annual rainfall of between 200 and 500 mm (Hiernaux *et al.*, 2009b,c). It is dominated by annual herbaceous plants and a few tussock perennials towards the driest end, with widely scattered shrubs and small trees.

Fakara is a small natural region of western Niger covering about 6000 km^2 between the confluent valleys of the Niger River to the West and the fossil valley of the Dallol Bosso to the East (Hiernaux and Ayantunde, 2004). The study site covers 500 km^2 (included within latitude 13°20′–13°35′N and longitude 2°35′–2°52′E) all falling within the central Sahel bioclimatic zone with annual precipitation of between 400 and 500 mm.

The study site in Toukounous is a 4474 ha ranch situated in the central Sahel, 14°33′N and 33°17′E, at an altitude of 290 m above sea level. The ranch is fenced into 30 paddocks, varying in size from 49 to 283 ha. The local climate is typical Sahelian semi-arid tropical with monomodal rainfall from July to September. The long-term annual rainfall (mean±standard deviation) is 336±105 mm. Like any other Sahelian site, the vegetation is dominated by annual herbaceous species. The study on the effect of grazing regimes on cattle performance was conducted between 1995 and 1997 (Ayantunde *et al.*, 1999).

The study site in Sadoré (13°14′N, 2°16′E) at the ICRISAT Sahelian Centre in Niger is situated about 45 km south-east of Niamey. The climate is typical south Sahelian with an annual precipitation of between 450 and 600 mm. Most grazing studies were carried out at an enclosure that was established in 1982.

Key predecessors and partners

The early ILCA work in Niono, Mali, was developed alongside a Malian–Dutch research programme called ‘Primary Production in the Sahel’ (Penning de Vries and Djiteye, 1991). Pierre Hiernaux was among the first to set up systematic monitoring of rangeland sites for long-term analysis, complementing others in Senegal (Valenza, 1984; Gaston and Boerwinkel, 1982; Miehe *et al.*, 2010). ILCA researchers contributed early studies on livestock productivity, mobility and transhumance within the Macina flood plain (ODEM/CIPEA, 1983) and in central Mali. Toulmin *et al.* (2002) and Cotula *et al.* (2004) conducted research on pastoralist mobility and conflicts over land, especially between herders and farmers, in the 1990s, which highlighted changing land-use dynamics in response to different legal and administrative changes. Turner (1992, 1999, 2017) contributed to this line of research by examining how community resource management to ‘clarify rules’ of access actually runs the risk of increasing local ecological and economic vulnerabilities, given both the agro-ecological realities and the range of resources needed to sustain both crop and livestock production. Turner highlighted the trend of a greater year-round presence of livestock in the former ‘agricultural’ zone as a significant factor changing resource access and needs and leading to conflict.

In East Africa, key researchers who were working at the same time as ILRI (and in some cases were ILRI collaborators) on issues of land use and livestock included Peter Coppolillo, Lane Coppock, Solomon Desta and Katherine Homewood. Galaty (1994a, 2013b) noted in particular the negative trends towards excluding livestock or selling lands for other, crop-based, purposes. McCabe found similar issues in Tanzania in long-term research on Maasai livelihood diversification (McCabe, 2003; McCabe *et al.*, 2010), as did Homewood (2008) and collaborators from ILRI. Coppolillo (2000) described factors affecting the distribution of animals across landscapes and found that the distribution of dry-season water was a major influence throughout the year, not only in the dry season. He also noted variability in herder practice and cattle productivity.

Desta and Coppock (2002, 2004) summarized the long-term data on cattle populations, rainfall and changing access to rangeland resources in the Borana region of southern Ethiopia. Their 2002 study convincingly demonstrated the 'boom-and-bust' cycle of livestock losses associated with periodic rainfall deficits. Their 2004 study documented a trend of declines in per-capita livestock holdings due to resource pressure/population increase and reduced access to key grazing areas (similar to trends documented in southern Kenya by Solomon Bekure *et al.*, 1991, and Galaty, 1994b, among others). This was leading some families to try cultivation as well as privatizing some grazing areas. They suggested that these patterns are broadly predictable and hence development interventions should reflect these system dynamics and respond to growing resource pressure.

Homewood *et al.* (2001) summarized long-term changes in land cover in Serengeti–Mara focused on wildlife rather than livestock per se. Comparing the Kenyan side to the Tanzanian side, they found a marked decline in species and rapid land-cover change only on the Kenyan side. Their analysis concluded that the Kenya–Tanzania differences were primarily due to landowners responding to market opportunities for mechanized agriculture and less to cattle numbers or to population growth. Homewood went on to collaborate with ILRI and other colleagues on the book *Staying Maasai: Livelihoods, Conservation and Development in East African Rangelands* (Homewood *et al.*, 2009), which focused more on livelihood diversification in the context of changing land-use dynamics.

Gufu Oba conducted long-term research in southern Ethiopia and northern Kenya on rangeland dynamics, exploring herder management of grazing areas and herder perceptions of land-use change and responses to these changes (Angassa and Oba, 2007, 2008; Oba *et al.*, 2000). His research contributed evidence on the interactions among rainfall, plants and grazers, and documented herder management of rangelands for animal and rangeland performance.

The main research questions in ILRI

The research was organized into four main areas: (i) quantitative assessment and monitoring; (ii) effects of grazing regime and intensity; and (iii) grazing access and mobility; and (iv) interactions among people, livestock and rangelands.

Quantitative assessment and monitoring

Quantitative assessment and monitoring of rangeland resources included detailed mapping in the large study zones of central Mali, the Macina flood plains, the Niono ranch, Gourma and later in the Fakara of Niger. The assessment and subsequent monitoring in the 1970s and 1980s were important to document how vegetation behaved in response to rainfall and soil properties. These studies also contributed to a broader understanding of the variation between rangeland types in different parts of Africa, again in relation to soil properties (fertility) and rainfall. To date, the monitoring and assessment of rangeland resources in Gourma, Mali (1984–2006), and in Fakara, Niger (1994–2006) (which have then continued under AMMA and AMMA-CATCH) are the only such long-term studies in the West African Sahel. Other investigations were mainly short-term studies of grazing or of conflict between farmers and herders.

Grazing regimes

A second area of research sought to explain the effects of grazing regimes and grazing intensity on animal performance, rangeland vegetation and forage production, and on the physical and chemical properties of soil. ILRI researchers sought to understand the relationships between animal productivity and rangeland management, including the impacts of livestock grazing on rangeland properties and cropped areas (e.g. through nutrient redistribution). The answers to the first two questions also contributed empirical evidence to the debates about whether arid and semi-arid African rangelands behave as equilibrium or non-equilibrium systems (Behnke *et al.*, 1993). These debates and the evidence underlying them has significant implications for rangeland management (see Homewood, 2008, Chapter 4, and Vetter, 2005). They also contributed to the related debates about whether the Sahel was under a process of desertification and if livestock systems had particular responsibility in the process (Hiernaux *et al.*, 2016).

Access to grazing resources

The third area was research on access to grazing resources and livestock mobility in relation to vegetation resources and the livelihoods of pastoralists and agropastoralists. These studies led to an understanding of how livestock keepers used mobility to actively manage their herd productivity, given the high temporal and spatial distribution of vegetation in the rangelands. In West Africa, reciprocal relationships with croppers have historically been important for the mutual benefits that pastoralists received by grazing their animals in wetter areas and croppers received from the manure deposited by transhumant animals.

Interactions among people, livestock and rangelands

A common area of research in East and West Africa was to document interactions among people, livestock and the range. This research built upon the characterization, assessment and monitoring work in West Africa to take into account the new dynamics, especially changes in cropping patterns, increased fragmentation, livestock population dynamics and the impact of declines in previously reciprocal arrangements and the failures of formal land tenure. In East Africa, the research combined modelling with ground observations, resulting in key findings about the impacts of fragmentation (in particular) on rangeland, wildlife and livestock performance (Galvin *et al.*, 2008c). This also resulted in the development of several modelling exercises to better understand the impacts of changing rangeland dynamics, and a new model. In addition, Reid *et al.* (2004, 2008) sought to understand complementarities between livestock production and wildlife management in southern Kenya, leading to significant innovations in land management around the Nairobi National Park and the Maasai Mara National Reserve.

Principal Findings

East Africa

ILRI hosted the Land Use Change, Impacts and Dynamics (LUCID) network, beginning in 2000. The general goal was to promote biodiversity conservation and prevent land degradation through research to provide tools for understanding key changes. The network specifically sought to 'examine the causes and consequences of land degradation and the biophysical systems that underlie changing patterns of land use within East Africa land-cover/land-use changes in response to multiple drivers' (www.lucideastafrica.org; accessed 25 February 2020). Three foci were: (i) the drivers and impact of agricultural expansion into grazing areas; (ii) the transition of agro-pastoral systems in semi-arid areas; and (iii) the impacts of land-use change on biodiversity.

Over 48 working papers were published covering 30 years of land-use change across East Africa, primarily in subhumid and semi-arid zones where cropping, livestock production, protected areas and wildlife commonly overlapped. The main findings on the agro-pastoral systems transition and the impacts of land-use change on biodiversity (Maitima *et al.*, 2004) included:

- Causes of land-use change in agro-pastoral systems: the research found that the fluidity of land-tenure arrangements and quite major changes around who has rights to use land and decide how it should be used was most marked in agro-pastoral areas. The trend was a movement away from common management to private and individual arrangements such as subdivision of former group ranches (Olsen *et al.*, 2004), including fencing and smaller grazing areas, as well as more crop-based agriculture.
- Beneficial impacts of grazing on rangeland vegetation: moderate grazing was found to support native vegetation and local diversity.
- Impacts of the increased competition for key land and water resources: this was resulting in the restriction of herding and an increase in cropping and transition of some households to agro-pastoral production. In addition, there were restrictions on movement of wildlife and loss of access to wetland areas and key migration corridors and resources (Reid *et al.*, 2004; Lamprey and Reid, 2004).
- Impacts of restrictions on wildlife and livestock movement: despite the gazetting of national parks and reserves, dispersal of

> animals into adjacent areas or for seasonal movements was still critical. Unfortunately, the increased competition for land also increased human–wildlife conflicts.

Extending the LUCID work while adding unique data on wildlife and livestock populations over time across Kenya, Joseph Ogutu and colleagues documented the impacts of pastoralism and protected areas on wildlife numbers. The first studies focused on the Mara ecosystem, where they documented the decline in a number of wildlife species, which corresponded with habitat deterioration and in some cases increased numbers of people and settlements (Ogutu *et al.*, 2009). This trend was continuing by 2011, but they noted the importance of ranches around the park as wildlife dispersal areas, which led to a recommendation that land use and poaching needed to be regulated (Ogutu *et al.*, 2011). The finding on the importance of pastoral areas to support protected areas emerged again, as these areas provide corridors between seasonal grazing areas (Ogutu, 2013; Ogutu *et al.*, 2017). The 2017 study estimated that Kenya's communally and privately protected pastoral areas support 65–70% of the country's wildlife population. This is because the national parks and reserves are too small for many of the large wildlife who must access areas outside the protected areas either seasonally or year-round. This research influenced the support community conservancies around the Maasai Mara National Reserve, Nairobi National Park and Amboseli National Park through the Reto-o-Reto project.

ILRI researchers engaged in over a decade of research on land-use change, land management, biodiversity and livestock across the arid and semi-arid regions of southern Kenya and northern Tanzania. This collaboration produced a book in 2008, drawing on some of the LUCID studies and others, entitled *Fragmentation in Semi-Arid and Arid Landscapes* (Galvin *et al.*, 2008d). This edited volume is a comprehensive overview of why and how fragmentation has occurred across a range of arid and semi-arid ecosystems and the implications of this fragmentation for people and animals. An increase in the 'exclusivity of use' across rangelands has restricted movements across landscapes, limiting access to resources. Given that mobility is key to managing the temporal and spatial heterogeneity of water and forage resources, the research found that limitations on mobility were having serious impacts on rangeland ecology as well as on livestock and people. Their thesis was that fragmented landscapes are less productive than unfragmented ones. They attributed fragmentation to modern systems of land tenure, which are not suited to arid and semi-arid rangelands (Hobbs *et al.*, 2008).

Reid *et al.* (2008) describe the Athi-Kaputiei Plains near Kitengela, Kenya, which they studied intensively on the ground and in aerial surveys during the period 1977–2002. The area is an unusual example of a fragmented pastoral ecosystem that still supports migration of large wildlife despite its proximity to Nairobi. At present, the fragmentation is exacerbated by fencing of land parcels. Fences had a particularly negative impact on livestock movements and grazing/foraging. This research informed the Wildlife Conservation Lease Program, which paid Kitengela residents to allow free movement of wildlife on their lands, to avoid poaching and to avoid fencing of land. Initiated in 2000 and expanded in 2007, the programme had the potential to be a promising innovation, but it fell short of success. Although Osano (2013) found some positive impacts, for example in terms of more lions and payments to beneficiaries, the programme stopped in 2012 when the donor funds closed.

The conflict between wildlife and livestock

Reto-o-Reto sought solutions to land-use change and wildlife conservation problems with a more action-oriented approach. It engaged pastoral communities in solutions to balance poverty alleviation and wildlife conservation in pastoral systems. The research approach described in Reid *et al.* (2016) was one of 'continual engagement' between scientific researchers and community members which produced new knowledge and solutions. They intentionally used collaborative research-facilitator teams to better engage with communities and bridge across nested institutions from community up to the global level. This approach produced several key pieces of hybrid knowledge, from the Kitengela conservation payments to the Amboseli modelling work on the impacts of subdivision and the Mara Community Conservation Planning Framework.

Community-based conservation has emerged as a promising approach for resolving conflicts stemming from wildlife–livestock–pastoralist interactions, and the Reto-o-Reto approach supported the establishment of a network of conservancies around the Maasai Mara National Reserve. This began with four in 2009, which expanded to 14 by 2013 when the Mara Wildlife Conservancies Association was formed. At the heart of the conservancy model is that payments from tourists are used to compensate pastoral communities for adhering to rules about when and where they are permitted to graze their animals, in order to ensure that wildlife have enough area and forage. The community management model offered by the conservancies was strengthened by the 2013 Wildlife Conservation and Management Act and the 2016 Community Land Act. Today, all conservancies across Kenya are members of the Kenya Wildlife Conservancies Association and strive to offer a sustainable model that protects both wildlife and pastoral livestock production.

The final outcome for which the Reto-o-Reto work is known was the 2010 Greater Kitengela Land Use Master Plan, the first ever for a pastoral area. This plan evolved with support from research that showed, for example, that compensating pastoralists for loss of access to grazing lands could increase their resilience. The multiple pressures on land in Kitengela, and the cessation of funds for the compensation scheme, have compromised the objectives of the plan. As discussed at the end of the chapter, participatory land-use planning with communities is still one of the most promising solutions for improved management of rangeland ecosystems.

Modelling

The Colorado State University (CSU)/ILRI collaboration also led to innovations in modelling rangelands and pastoral households. Research spanning the 1990s and early 2000s sought to quantify different alternatives in the rangelands of sub-Saharan Africa resulting from the increasing pressures on natural resources owing to human population growth and the resultant conflicts among wildlife, cattle and agriculture (Galvin and Thornton, 2001). The major research questions were the effects of landscape fragmentation (in the case of southern Kenya, the subdivision of group ranches) and the growth of agriculture (Thornton *et al.*, 2003, 2006; Boone *et al.*, 2005, 2006) on livelihoods and ecosystem services. The coupled model was subsequently used to explore the possibilities of schemes of payment for ecosystem services in areas of southern Kenya where agriculture is expanding rapidly, to compensate pastoralists for losses arising from more wildlife-compatible forms of land use (Bulte *et al.*, 2008). A third set of studies investigated the impacts of climate variability on livelihoods and on the economic benefits of using weather forecasts (Galvin *et al.*, 2004; Thornton *et al.*, 2004). This work was later extended to more generalized studies of the relationship between fragmentation and rainfall variability (Boone, 2007; Boone and Wang, 2007).

The CSU/ILRI collaboration on integrated assessment modelling was founded on the SAVANNA model, originally developed by Coughenour (1985, 1992) for Turkana District, Kenya, but further developed and applied in many other settings in Africa, Asia and North America since. SAVANNA models primary ecosystem interactions, simulating functional groups for plants and animals over periods from 10 to 100 or more years in a spatially explicit way.

For household modelling a simple structure was built – the Pastoral Household and Economic Welfare Simulator (PHEWS). This tracks the flow of cash and dietary energy in pastoralist households using a simple set of management rules that describe a reasonably realistic hierarchy of goals at the household level. PHEWS was used to model households of varying sizes and assets and with different access to natural resources. PHEWS was built using survey data regarding household size, structure and income; species, numbers and sexes of livestock held; and cultivated area (Thornton *et al.*, 2003). A coupled SAVANNA–PHEWS model was calibrated for sites in northern Tanzania and southern Kenya (Thornton *et al.*, 2006, 2007; Galvin *et al.*, 2006) using ecosystem and household data collected in the previous decade.

SAVANNA–PHEWS was innovative in at least two ways. First, it is worth noting that SAVANNA itself is a complex and sophisticated model, and even now represents a summit of the ecosystem modeller's art. PHEWS, on the other hand, occupies the other end of the spectrum: it is simple, requires relatively few data to calibrate, was developed very quickly and can easily be adapted to new situations. PHEWS was an early example of a 'disposable' model: because the builder invests only limited time and energy in assembling it, the model can easily be thrown away and a new start can be made, as there is little lost. The nature of the relationship between model complexity and model utility is probably not as straightforward as is often imagined; this is borne out by recent trends in some quarters towards model simplification. Second, despite the disparities in the detail and elegance of the models, SAVANNA and PHEWS were tightly linked, and were run as part of the same simulation. At each time step modelled, SAVANNA passed information about livestock to PHEWS, and PHEWS passed information about the sale or purchase of animals back to SAVANNA, where herd sizes were adjusted accordingly.

PHEWS was essentially a population-based model, and it was used as the basis for developing an agent-based approach to investigate similar questions. Like PHEWS, the DECUMA model (Decisions under Conditions of Uncertainty by Modelled Agents) was tightly linked with SAVANNA to represent livestock-owning and cultivating households. As an agent-based model, DECUMA simulates in a relatively complex way individual households on a landscape in a spatially explicit way (unlike PHEWS), adjusting livestock distributions on a weekly basis and making other household decisions on a monthly basis (Boone *et al.*, 2011; Boone and Lesorogol, 2016). One potentially important document from all this work, unwritten as yet, is a comparison of SAVANNA–PHEWS and SAVANNA–DECUMA simulations for the same situation: we have calibrated applications of both coupled models for the same part of Kajiado district, Kenya. Such a comparison would throw light on the added value of a more complex household model (DECUMA) compared with a very simple model (PHEWS).

Beginning in 2012, ILRI worked with CSU on a simulation tool that could be used to project global rangeland changes in response to trend climate and climate variability. This led to a process-based simulation model that is spatially explicit and of moderate complexity, called G-Range. Several needs guided the design of G-Range:

- A simulation tool for global rangelands that captures main primary production and its dynamics.
- A tool of moderate complexity – one that could be useful to a new user in a week or less.
- A monthly time step, with simulations that run for 5–100 years or more.
- Representation of global vegetation at least at the scale of herbaceous, shrubs and trees.
- The ability to include natural or management modifications to rangelands, such as fire and fertilization.
- Programming structures and portable code, allowing the software to be run on different platforms including multiprocessor clusters or networks.
- Output mostly as straightforward spatial surfaces, without complex summary analyses that are more readily done in other packages.

The idea was not to program G-Range from scratch but to use components from published models. The Century model (Parton *et al.*, 1993) was used as the core of the soil modelling and physiological aspects of the G-Range model, given Century's wide use in rangelands over the past 20 years or so. Other aspects of G-Range were influenced by SAVANNA. G-Range does contain some new contributions, notably in modelling plant populations.

There are several insights from the CSU/ILRI collaboration on the modelling of coupled systems. An early synthesis of the coupled modelling work supported the hypothesis that a household's capacity to stresses is governed by flexibility in livelihood options (Thornton *et al.*, 2007). Households cope with stresses through intensification, diversification and off-farm economic activities. Viable options depend on household objectives and attitudes as well as on access to natural resources, inputs and output markets. The study also highlighted the fact that generally it is the poorer households that can gain the most from implementing risk-management options. Furthermore, there are limits to the adaptive capacity of households in the absence of access to off-farm resources, and these limits likewise depend on local context. Much of the CSU/ILRI work around rangeland fragmentation has been summarized in Hobbs *et al.* (2008) and Galvin *et al.* (2008b,c) as discussed above.

A general insight from the modelling work was the view of humans, cattle and wildlife as components of an integrated ecosystem (Galvin *et al.*, 2008a), if technical, advisory and policy-related interventions are to be appropriately targeted. A thread that remains to be unravelled is the appropriate use of integrated models to resolve conflicts between conservation and people in the rangelands (Galvin *et al.*, 2006).

Simulations with G-Range summarized projected climate change impacts on livestock across Africa, using a review of literature and model results (Thornton *et al.*, 2015; Boone *et al.*, 2015). While there are many options that can help livestock keepers adapt, there appear to be no widely applicable and unconstrained options (Boone *et al.*, 2018; Thornton *et al.*, 2019).

West Africa: assessment and monitoring of rangelands

This was one of the major areas of research begun by ILCA in Mali, as a contribution to the study of livestock production in a diversity of pastoral and agro-pastoral systems (Wilson *et al.*, 1983, 1988; ODEM/CIPEA, 1983) continued in Niger by ILRI (Hiernaux and Ayantunde, 2004; Hiernaux and Turner, 2002). ILCA researchers invested large efforts to characterize, quantify and spatially assess forage resources across different regions. Field observations of 331 sampled sites across central Mali from 1976 to 1980 (Wilson *et al.*, 1983) encompassed a large area in order to include most of the seasonal movements of herds managed by Macina Fulani pastoralists as well as a diversity of livestock production systems. The observations defined bioclimatic zones and noted how the forage species composition varied with these zones (Hiernaux and Le Houérou, 2006). Within the zones, the distribution of woody plant species depends on soil texture first and then moisture regime and terrain topography (Sankaran *et al.*, 2005). Beyond that, land-use history, especially clearing for cropping, was found to modify the composition of woody plant species (Cissé and Hiernaux, 1984; Achard *et al.*, 2001). The distribution of herbaceous species, which are mostly annuals, is less consistently sensitive to these same factors as well as to the shadow of woody plants. This is due to large inter-annual variations in species composition in relation to variations in rainfall distribution as well as changing soil seed stocks (Hérault and Hiernaux, 2004). Analysis of aerial photographs confirmed the match between geomorphology and vegetation type (Hiernaux and Haywood, 1978).

Additional observations of 169 sites across the Macina floodplains from 1979 to 1983 (ODEM/CIPEA, 1983) demonstrated that biogeographic zoning only affected unflooded islands or edges, along with land-use history including cropping and wood exploitation. In the flood zones, the perennial herbaceous vegetation is determined by the inter-annual variations in flooding regime (Hiernaux and Diarra, 1986). Although poor in species diversity, they were highly productive. The patchy distribution required large-scale mapping, which was also a methodological innovation (Marie, 2000).

Observations across the 25 sites in the Gourma transect (Hiernaux *et al.*, 2009b,c) following the 1983/84 drought confirmed the earlier Mali findings that vegetation is organized by bioclimatic zones and then based on edaphic conditions within these zones. Land-use history had little impact. Soil type and rainfall distribution determined where herbaceous and woody plants were located and distributed. Analysis of satellite images for the same region also indicated that vegetation types can be mapped to edaphic zones and surface hydrology and soil type (Breman and de Ridder, 1991; Gal *et al.*, 2016). Field observations supported the building up of a novel primary production model, STEP (Sahelian Transpiration, Evaporation and Productivity model) to simulate annual herbaceous growth relying mainly on a soil water balance and meteorological control of plant photosynthesis (Lo Seen *et al.*, 1995). The model was validated with field monitoring data on the Ferlo and Gourma rangeland vegetation (Mougin *et al.*, 1995; Tracol *et al.*, 2006). The herbaceous vegetation decay and decomposition with or without grazing is also simulated in STEP and has had a number of applications in assessing seasonal fodder resources (Diawara *et al.* 2018) and impact on the environment (Delon *et al.*, 2015; Pierre *et al.*, 2015). STEP was further adapted for particular perennial grasses growing in flood plains (Léauthaud *et al.*, 2018).

Observations a decade later in the Fakara region of south-western Niger, a more densely populated area with more sedentary populations, found that vegetation distribution was explained by both the edaphic environment and land use (Turner and Hiernaux, 2015). The generally poor soil fertility explained the poverty of the vegetation floristic composition. These findings were confirmed by analysis of high-resolution photographs and satellite images, which also were used to distinguish cropping land-use types (Schlecht *et al*., 2006; Tong *et al*., 2020).

The assessments were also combined with monitoring of herbaceous biomass and floristic composition at the same sites, observing variation in vegetation production over time (e.g. before, during and after droughts); across topography (lowlands versus uplands; sandy soils versus clay soils); and in response to burning and grazing. The results confirmed the high spatial heterogeneity of Sahelian rangeland forage resources, in response to rainfall, runoff and soil properties. Land-use change was also found to be a factor in data collected from 1994 to 2006 in Fakara, Niger. Finally, woody plants were also assessed and monitored during the same time and over the same sites to observe how their growth, phenology and distribution were affected by soils and rainfall as well as grazing and cropping (Hiernaux *et al*., 2009a, 2019).

Overall, this body of research was novel in several respects. First was the quantification of forage resources expressed in seasonal capacities per landscape unit (Marie, 2000; Hiernaux, 2005; Auda *et al*., 2012; Hiernaux *et al*., 2015). Second were a number of methodological innovations. The assessment of the contribution of woody plants to livestock nutrition led to new woody plant population survey methods (Hiernaux, 1980; Franklin and Hiernaux, 1991; Brandt *et al*., 2016a,b), development of allometric relationships between woody plant size and foliage and fruit masses (Cissé, 1980), and surveys to characterize the phenology of the main woody plant species (Hiernaux *et al*., 1994b). It also led to a number of methodological advances in systematic field observations (Hiernaux, 1982, 2016; de Leeuw and Hiernaux, 1990), aerial surveys (Milligan, 1982; Milligan *et al*., 1982) and remote sensing using aerial photos and satellite images (Hiernaux, 1988; Hanan *et al*., 1991). One of the principles put forward in field methodology is the stratified random sampling along linear transects (Hiernaux, 2016), as a more efficient strategy to account for the high spatial heterogeneity and patchy pattern of the vegetation. Consideration of the significant seasonality of vegetation growth in arid to subhumid West Africa was a driving principle in screening for more efficient metrics of forage resources assessment by satellite remote sensing such as normalized difference vegetation index (NDVI) metrics used to assess herbaceous and crop production (Hiernaux, 1988; Bégué *et al*., 2014) and also woody plant crown cover and foliage mass (Brandt *et al*., 2016a,b).

Indeed, the strength of the seasonality of the Sahel ecosystems, including the complex situations created by the combination or rainfall and flood seasons in the Macina flood plains (Hiernaux, 1983), forced the assessments to go beyond static survey and to quantify, explain and attempt to predict the seasonal and inter-annual variations in forage resources. Repeated measures of vegetation in rangeland grazed or protected from grazing together with rainfall records, soil moisture and main nutrient (nitrogen, phosphorus) contents were decisive to better understand what the limiting factors of rangeland production were (Buerkert and Hiernaux, 1998; Hiernaux and Diawara, 2014). They led to the development of simulation models of the vegetation growth (Lo Seen *et al*., 1995; Mougin *et al*., 1995), grass tillering under grazing condition (Hiernaux *et al*., 1994) and also of the straw and litter decomposition during the dry season depending on grazing and trampling intensity (Hiernaux *et al*., 2014).

Stratified sampling along a linear transect has been adopted in many rangeland resources assessment and monitoring such as the monitoring by the Centre de Suivi Ecologique in Senegal (Diouf *et al*., 1998), the Institut de l'Environnement et de Recherches Agricoles (INERA) national pastoral resource survey in Burkina Faso (Kiema, 2015), the carbon balance study in Widou Thiengoly in Senegal (Assouma *et al*., 2018). Similarly, the stratification of woody plants when assessing their density by an unbiased distance method known as the 'point-centred quadrant' (Pollard, 1971) with points distributed at regular intervals along the same linear transect, associated with classical dendrometry on woody plants sampled by the method and allometric relationships (Cissé, 1980; Henry *et al*., 2011), is increasingly used to efficiently assess the contribution of woody plant population (Hoffmann *et al*., 2006).

The seasonal curve integral of the NDVI during either the growing season (herbaceous) or the dry season (woody plants) is widely used in satellite remote sensing the vegetation production, as well as metrics based on seasonal NDVI maximum, mean or percentile values (Tucker *et al.*, 1985; Hiernaux, 1988; Fensholt *et al.*, 2004; Dardel *et al.*, 2014a), and based on STI in the dry season (Jacques *et al.*, 2014; Kergoat *et al.*, 2015). Accounting for the woody phenotypes improved the assessment of woody plant cover and foliage masses (Brandt *et al.*, 2016a,b, 2019).

The simulation models developed and calibrated using field data collected by ILRI in Mali, Niger and Senegal have been used to predict vegetation production from rainfall, flood and grazing scenarios (Dardel *et al.*, 2014a,b; Diouf *et al.*, 2016; Diawara *et al.*, 2018), and also to assess the risks of soil erosion by wind (Pierre *et al.*, 2015), carbon sequestration, carbon and nitrogen emissions to estimate (Le Dantec *et al.*, 2009; Delon *et al.*, 2015) and to calculate the main nutrient balance in a pastoral ecosystem (Schlecht *et al.*, 2004; Assouma *et al.*, 2018).

The quantitative assessments of grazing livestock impact on the ecosystem in the short and medium term, and the derived model tools have been used to advocate for protecting and ensuring livestock seasonal and regional mobility in pastoral systems (Hiernaux *et al.*, 2015). They contribute to discussions on the desertification paradigm in the Sahel and policies developed at national and international scales to combat alleged desertification (Dardel *et al.*, 2015; Hiernaux *et al.*, 2016).

Quantifying the carbon and nutrient recycling role of livestock in pastoral and agro-pastoral systems has been used to diagnose the corralling practices of agro-pastoralists in western Niger and suggest improvements (Gandah *et al.*, 2003; Powell *et al.*, 2004; Djaby, 2010; Hiernaux and Diawara, 2014; Coppock *et al.*, 2017). More generally, this knowledge was used to assess the contribution of livestock to cropping intensification with a perspective of ecological sustainability and improvement of agro-pastoralist welfare (Hiernaux, 1996, 2013; La Rovere *et al.*, 2005).

Effects of grazing regimes on animal and rangeland performance

A series of experiments were carried out across the various West African sites to try to address concerns that grazing livestock was a driver of environmental degradation. These experiments were aimed at measuring the impact of livestock grazing regimes on short (within season) and medium (inter-annual) time frames. The ILRI experimental work clearly separated the impact during the short growing season from that during the long dry season (Hiernaux and Diarra, 1986; Hiernaux and Le Houérou, 2006).

Grazing experiments across three sites and over two decades, in fenced paddocks, demonstrated that herbaceous annuals responded to grazing during the growing season with regrowth, but this decreased rapidly in response to repeated grazing on the same plants. The short-term impacts depend on the timing and intensity of the grazing (Hiernaux and Turner, 1996). Grazing during the dry season was found to accelerate the decomposition of straw and litter, so that, at most, livestock intake reaches a third of the herbaceous biomass at the onset of the season (Hiernaux *et al.*, 2015). In the particular case of the Macina grasslands, which are adapted to temporal floods, dry-season regrowth was found to depend on grazing timing and intensity, with an optimum frequency specific to each grassland type (Hiernaux, 1984). The longer-term effects of grazing observed on species composition and vegetation productivity are minor compared with the effect of clearing a land to crop or for forestry exploitation (Hiernaux, 1998; Achard *et al.*, 2001; Hiernaux and Turner, 2002). They depend on the timing and intensity of grazing and involve forage intake but also trampling and livestock excretions (Diarra *et al.*, 1995; Schlecht *et al.*, 1998). Another set of experiments assessed soil seed stocks and germination patterns; these were found to be transient, with most seeds germinating during the wet season following dispersion, particularly due to the capacity of annuals to produce large numbers of seeds, which were rapidly dispersed.

Another line of research observed the effects of grazing regimes on diet selection and animal performance. This demonstrated that grazing ruminants selected forages that were more nutritious and digestible than an overall pastural evaluation would suggest. Night-time grazing was found to increase forage intake and hence animal productivity, especially during the dry season, as the quality of available forage decreases in the dry season. Supplementation is necessary for animals to maintain their body weight in the late dry season. The foraging behaviour of free-grazing livestock differs by species, with goats being the most selective and sheep the patchiest.

A domain of the grazing livestock impact on which the ILRI team particularly focused their research, especially when studying agro-pastoral systems, was the recycling of organic material and minerals through faeces and urine excretions. Faeces and urine excretions were studied in controlled conditions, in barns and metabolic cages at Sadoré research station (Fernández-Rivera *et al.*, 2005), but also on grazing cattle on the ranch at Toukounouss (Ayantunde *et al.*, 1999) and on cattle, sheep and goats in village conditions (Schlecht *et al.*, 1998). In the latter case, the results indicated that grazing livestock through their local mobility with grazing–walking and resting–rumination areas achieved a spatial transfer of organic matter and nutrient to the benefit of resting points such as paddocks and corralling spots (Hiernaux *et al.*, 1998). These nutrient concentrations are key to cropping intensification and diversification (Hiernaux and Diawara, 2014).

Turner (1999) and Turner *et al.* (2005) looked at the issue of whether grazing livestock in mixed crop-grazing areas could possibly lead to grazing-induced degradation. Their results indicated this is possible if there is not enough labour/expertise to manage the animals or if they are constrained in finding enough free-grazing areas. Turner and Hiernaux (2002) worked with livestock herders to document how they moved their grazing animals across landscapes. This approach resulted in better information on the spatiotemporal distribution of livestock across agro-pastoral landscapes, as this distribution reflects local land-use patterns, topography, vegetation, settlements and water points.

Mobility and access to grazing

Given the previously summarized evidence that livestock keeper management of grazing is critical to how much feed livestock are able to access as well as the distribution of nutrients across landscapes, the studies that researchers associated with ILCA and later ILRI conducted on mobility and access to grazing resources are relevant.

Research from central Mali (Niono and Macina) in the late 1970s and early 1980s described the daily and regional grazing routes used by pastoralists. The ILCA/ODEM project in Macina mapped transhumance routes and documented the local governance and access rules. In Niono, the researchers found that integrated crop–livestock production was increasing. Contractual agreements and grazing rights and institutions were declining in terms of authority/formal recognition. Similar research in Gourma, Mali, also found diversities of pastoral and agro-pastoral systems and a tradition that fixed grazing rights through access to water points. Research from Fakara in the mid-1990s that was followed up in 2007 found that grazing management of most village livestock depended on movements outside the village territory, especially during the rainy season to avoid damage to crops and to have access to natural pastures as there is always restricted livestock mobility during the cropping season. Second, the presence of extra-village movements of village livestock is higher in areas of higher population density, which is expected due to declining grazing areas as a result of demographic pressure. Third, the perceived advantages of herd mobility are to better provide livestock with pasture and water and, at least during the rainy season, to avoid crop damage. The perceived disadvantages of herd mobility are losing access to milk and other livestock products, not finding dry-season pasture or water outside the village territory and spending more energy trekking the herd.

Research on farmer–herder relationships and conflict management in agro-pastoral systems of Niger from 1995 onwards produced novel findings (Turner *et al.*, 2012; Turner 2017). Community informants stated their preference to resolve conflicts without involving customary or government authorities, particularly at supra-village levels, as they did not believe that higher authorities could settle conflicts in a lasting fashion. Second, most of the farmer–herder disputes occurred during the cropping season and involved active mediation by customary authorities at the local level, resulting in a crop damage fine. These fines were paid by the herding family or livestock owner. These disputes are better managed when there is a convergence of productive interests across herding and farmer social groups and a high perceived degree of interdependence. Later research in Mali (Turner *et al.*, 2014) confirmed that increases in the number of conflicts due to unauthorized grazing of crop residues is a reflection of the change in farmer–herder relationships from that of mutual trust that characterized manure and entrustment contracts to more inherently conflictual relationships based on wage and tenancy contracts.

Conclusions and the Future

Rangelands research in arid and semi-arid sub-Saharan Africa has been reinvigorated by renewed government and donor interest in pastoral livelihoods. The challenges facing productive rangelands remain competition over resources, which has been exacerbated by armed conflict; overuse of some rangelands as fragmentation continues; and the failure of many technical and governance interventions, as summarized by Reid (2012). These challenges cannot be met without a long-term core-funded research investment, as has been achieved in the pastoral areas of the USA, Australia, New Zealand and the Mediterranean Basin.

Despite the recent revival of interest in pastoral problems in the drylands, the Altmetric results highlight the serious underinvestment in African range sciences. Searches for the expressions 'range ecology', 'pasture', 'pastoralism' and 'grazing' show that papers from African sites, of all institutional affiliations, are only about 5% of global papers and barely 4% of global citations.

The unresolved development challenges of pastoralism in East and West Africa make it essential to renew long-term empirical research to understand rangeland dynamics and to develop appropriate public policies. The rangelands research agenda at ILRI focuses on: (i) governance for better rangeland management; (ii) monitoring rangeland conditions to improve development interventions; (iii) understanding the interactions between climate change and the rangelands; and (iv) improving rangelands productivity for pastoral resilience.

Range governance

As most rangelands are common pool resources that are shared by communities, development partners have been testing community-based approaches in different settings. Evidence of what works to make participatory and community-based rangeland management successful is accumulating, but researchers have not yet systematically consolidated this evidence. For example, evidence is emerging to suggest that simple interventions by communities to establish (or re-establish) seasonal grazing patterns can have a quick and significant effect on rangeland condition. In order to convince various investors of the feasibility of rangeland management, however, we need more action research and trials of interventions such as seasonal planned grazing, rangeland rehabilitation and management of bush encroachment. This needs to be coupled with impact assessments of the social and biophysical impacts of past and ongoing management initiatives, as well as cost–benefit analysis of the relative benefits of rangeland management. Finally, we lack evidence of how community-level restoration interventions interact with socio-ecological dynamics and larger landscape scales.

Monitoring rangeland conditions

Quick successes in restoration often build the confidence of community institutions to take on bigger challenges. However, scaling out these local successes often proves challenging, given the seemingly intractable challenge of securing access to resources while also maintaining the flexibility needed to manage these resources. While rangeland management needs to be participatory, this participation may differ by social, institutional and biophysical context. Supporting, validating and disseminating evidence for appropriate models of governance that build on community-based approaches, further enabling them with higher-level institutional arrangements, is thus another priority. While evidence suggests that community governance needs to be enabled by higher-level arrangements, such as national land-tenure policies or district land-use plans, again little systematic analysis of these nested models has been consolidated.

Mitigating climate change and the rangelands

Documentation of the ecosystem services provided by rangelands shows that they can generate a competitive return on new investment. Much of ILRI's previous work on ecosystem services focused on wildlife biodiversity. However, recently, carbon sequestration has attracted more interest, as an option to offset greenhouse gas emissions from other sectors. While the potential for carbon sequestration in rangelands is high, there is little empirical evidence about what is achievable in arid and semi-arid environments (Milne *et al*., 2016).

Adapting to climate change in the rangelands

Adapting rangelands to future climate change is an overarching priority. Climate change will bring hotter temperatures and different rainfall patterns, with accompanying changes in the composition, quantity and quality of forage. Models like G-Range are a major step forward in studies of climate change and rangelands and can advance investigations of adaptation and mitigation options there. Work is under way on coupling G-Range with household models to allow integrated scenarios of ranges, animals and households.

Rangeland productivity

With the increased interest in stimulating more market orientation and commercialization of pastoral and agro-pastoral systems, many development partners are forced to address the question of forage availability. While substantial new fodder production is available from crop residues and potentially from the introduction of new planting materials in mixed systems, it is inevitable that most rainy-season forage will be produced on rangelands. With greater investment in tools such as land-use planning, rangeland management can be stimulated by the commercial opportunities.

Note

[1] 'ILRI' refers to 'ILCA and ILRI' unless a specific distinction is needed.

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