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Biophysical Variability and Pastoral Rights to Resources: West African Transhumance Revisited

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Abstract This paper focuses on a conundrum that has dominated the literature on pastoral mobility and institutions in dryland regions of the world, where livestock production is the main livelihood system. High spatiotemporal variability of rainfall and forage resources are seen to require flexible rules and porous social boundaries to facilitate pastoral mobility—characteristics that run counter to conventional views of the requirements for effective common property institutions. We seek to explore this paradox by investigating the spatiotemporal variability of forage availability (using satellite derived vegetation indices as a proxy for green forage) in four transhumance zones ("transhumance sheds") in Mali, West Africa. For each transhumance shed, three characteristics with important institutional implications are evaluated over an eleven-year period between 2000 and 2010: the inter-annual variability of forage phenology, seasonal changes in connectivity of green forage patches, and the degree to which key forage locations exist in the form of consistently early green-up and/or late senescence. Periods of vegetation green-up and senescence, which determine the timing of transhumant livestock movements, are found to be sufficiently regular from year to year to be governed by conventional institutions. Seasonal changes in the north-south connectivity of green patches are sufficiently rapid for customary systems of sharing of pasture information to be effective (rather than more technologically sophisticated systems of pasture information). Moreover, transhumance sheds contain key pastoral forage sites, which because of their consistently early greening or late senescence, are strong candidates for territorial protection from alternative land uses such as agriculture. These findings support local herders' views of transhumance as composed of regular patterns of herd movements along prescribed corridors between key pastoral sites. The seasonal regularity of key pastoral resources has been obscured by an overemphasis on environmental unpredictability that characterizes dryland systems at certain spatial and temporal scales. This paper suggests that policies directed at improving pastoral resource governance must focus instead on securing pastoralists' access rights to movement corridors, specific pastures and water points.

Keywords Pastoral mobility · Transhumance · Resource access · Sudano-Sahelian West Africa · NDVI · Spatial analysis

Introduction

Current understandings of livestock husbandry in dryland regions of the world focus on the importance of livestock mobility across various spatio-temporal scales. Livestock mobility allows for flexible response to ecological variability which is seen to reduce pastoralist vulnerability to climatic change and the likelihood of overgrazing (Scoones 1994; Swallow 1994; Niamir-Fuller 1999; Thébaud and Batterbury

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2001; Adriansen 2006; Fernandez-Gimenez and Le Febre 2006; McCarthy and Di Gregorio 2007; Galvin 2009). Such mobility requires flexibility in resource access that places great demands on common property resource (CPR) institutions, which are seen to be most effective if based on clearly defined social group membership and territorially-bound resources (Ostrom 1990). This strategy is typically carried out through the establishment of small-scale resource user groups that hold legal rights over resources that have been delineated and mapped. A classic example of this from West Africa is the transfer of rights over gazetted forest areas to user groups or municipal governments established through broader processes of political decentralization (Benjamin 2008). Without such rights and boundaries, “local appropriators face the risk that any benefits they produce from their efforts will be reaped by others who have not contributed to those efforts” (ibid: 91). In agropastoral regions of dryland Africa, such appropriations have often occurred through the expansion of crop agriculture (Niamir-Fuller 1999).

In terms of pastoral resources, the need to secure rights through relatively fixed territorial and social boundaries seems to run counter to the spatio-temporal variability of the resources on which livestock in dryland regions depend (Marty 1993; Painter *et al.* 1994). Livestock need to be moved in response to constantly shifting availabilities of water and forage. This mismatch between the biophysical requirements of pastoralism and of conventional CPR institutions has been described by Fernandez-Gimenez (2002) as the “paradox of pastoral land tenure,” which has contributed to the confusion among policy makers and pastoral scholars with respect to the need for flexibility and security of pastoral resource rights. This has led to incoherent policy frameworks that emphasize measures such as pastoral resource information provision and livestock corridors with little if any coordination on the ground (de Jode 2010). As a result, there has been limited progress around the world in improving pastoral management and in securing rights to key resources required for viable pastoral systems (Fernandez-Gimenez and Le Febre 2006; Turner et al. 2011). The high variability and low predictability of spatio-temporal distribution of pastoral resources (water and forage) is the major factor behind the apparently intractable nature of the pastoral paradox. Building from early and important initiatives with respect to non-equilibrium range ecology (Ellis and Swift 1988; Behnke *et al.* 1993; Scoones 1994), there has been an embrace of the variability and unpredictability of resource availability within the pastoral literature.

The premise of this paper is that spatio-temporal variability of forage access has multiple dimensions displaying different levels of variability and predictability. This renders the paradox less intractable than is assumed by an embrace of environmental variability in the abstract. In certain circumstances, regularities in some biophysical features of highly variable environments may form the basis for the establishment of conventional institutions and rules governing mobility. Such institutions have been implemented locally in agropastoral West Africa (Hochet 2005; de Jode 2010) but rarely if ever at the larger scale required for seasonal livestock mobility. This paper compares specific biophysical characteristics of pastoral resources required for large-scale mobility with the requirements of conventional CPR institutions, reflecting the call by researchers subsequent to Ostrom (1990) such as Berkes and Folke (1998) and Gunderson and Holling (2002) to emphasize cross-scale social-ecological linkages in CPR research. Substantial research has since been done on the complexity of these linkages yet the pastoral land tenure question has remained a paradox for lack of empirical, scale-sensitive investigation.

In order to make this biophysical-institutional comparison, we constructed an empirical measurement of spatio-temporal variability of livestock forage based on NDVI data—a remote sensing-based proxy of green vegetation—and applied it to four important zones of pastoral livestock production in Mali, West Africa. We then relate our findings of forage variability to the institutional demands of governing seasonal livestock movements. These institutional requirements are then related directly to the present policy context in Mali in particular and West Africa more generally.

Common Property Institutions and Livestock Mobility

The livestock and climate variability of drylands have served as a poignant case in the development of ideas about common property resource management theory. A common pasture was used by Hardin (1968) to illustrate how the divergence between individual and group interests could lead to overgrazing and resource degradation unless resources are placed under private or government control. Others have countered that undermining local resource users’ control through privatization or government-led schemes increases the vulnerability of resources and their users (Ostrom 1990; Swallow and Bromley 1995; Mwangi and Ostrom 2009). For example, privatization of common resources in dryland areas such as pastures and their subsequent division into smaller endowments has been shown to increase resource degradation and the experience of scarcity among users as patches of productive resources shift continually across space and time (Mwangi and Ostrom 2009). Subsequent work focusing on the nature of the social boundaries that mediate CPR access has demonstrated that pastoral institutions may lack such rigid exclusions of people from pastures, water points, and salt licks but they nonetheless govern access to these resources effectively through flexible political mechanisms based on reciprocity (Casimir and Rao 1992; Niamir-Fuller 1999; Turner *et al.* 2011). For example, customary pastoral institutions in both East and West Africa typically operate through clan structures that tend to overlap with one another at multiple scales. This system ensures that access boundaries remain porous and reciprocal, which allows access to be granted to "outsiders" who are not members of the clan or group that controls the resource in question (Peters 1987; Niamir-Fuller 1999; Cleaver 2000; Robinson 2009). Such arrangements are typical along regional pastoral livestock corridors where herders act as hosts in their home area and guests elsewhere (Heasley and Delehanty 1996; Turner 1999a; De Bruijn and van Dijk 2003).

The dryland locations where vegetation is available are seen to vary significantly over time—both within and between years—due to shifting monsoonal rain events. In northern Kenya, livestock movements have been shown to respond to these events and their effects on vegetation productivity rather than on the overall density of vegetation and livestock (Ellis and Swift 1988; Ellis *et al.* 1993). Although the Turkana of northern Kenya practice regular north-south transhumance, they will also move their cattle several times in a single season in response to monsoon events and pasture availability as part of a strategy to increase the sizes of their herds (McCabe 2004). Therefore, restrictions on the timing and direction of livestock movements that are based on conventional CPR-based rules of well-defined user groups and resources are seen to increase the vulnerability of dryland livestock production.

We argue that this paradox and resulting ineffective policies stem from an overly simplified embrace of the spatio-temporal variability of pastoral resources (e.g., water, forage) in Sudano-Sahelian West Africa. It is oversimplified due to the implicit assumption that all the ecological parameters that are important to pastoral production are uniformly characterized by high variability whereas some parameters may in fact display a certain level of regularity and thus predictability at certain scales. This position on variability is consistent with current scholarship on dryland ecology that argues for a continuum between equilibrium and non-equilibrium conditions that often coexist within the same system (Vetter 2005; Derry and Boone 2010). Although research such as the South Turkana Ecosystem Project has demonstrated the multi-scaled nature of dryland variability, important questions remain in terms of identifying specific scales of regularity and applying them to the institutional dilemmas that stem from the pastoral paradox. Moreover, important differences exist between dryland regions that call into question blanket assumptions about the connection between ecological variability and the institutions that are appropriate to sustain pastoral resource access. For example, Ellis and Galvin (1994) demonstrated that lower inter-annual rainfall variability in dryland West Africa compared to East Africa contributes to important differences in land use and production systems between the two regions. The most notable difference is a higher degree of overlap between pastoral and agricultural land use in West Africa.

This paper builds from this prior work through an empirical analysis of several parameters of the spatio-temporal variability of forage availability with particular institutional implications at the scale of four specific transhumance zones in Mali (Fig. 1). It then connects an analysis of these parameters and their variability to current pastoral resource policies in West Africa. We posit that different parameters that shape livestock mobility may display different levels of regularity, which may serve as a basis for more effective transhumance resource governance based on the conventional CPR approach of strict territorial protection and implemented by institutions operating at appropriate geographic scales. This is a pressing issue as livestock mobility in agro-pastoral West Africa is increasingly restricted by the ongoing expansion of crop agriculture. Croplands are off limits to livestock during critical times of the year and the expansion of agriculture into former grazing areas arguably represents the greatest threat to pastoral livestock production in the region. Moreover, while academically it may be interesting to consider territorially-porous systems of pastoral tenure (e.g.,Turner 1999b), these are much more demanding on systems of governance, so much so that their viability under current political conditions in the region can be questioned. This is especially true in the case of longer-distance mobility known as transhumance, which necessarily involves a high degree of coordination and cooperation across rural communities.

Transhumance in West Africa

The climate of Sudano-Sahelian West Africa is monsoonal with a single rainy season of variable length between the months of April and October. A latitudinal gradient in rainfall leads to sharp north-south changes in vegetative productivity, nutritive quality, and phenology in the region (Penning de Vries and Djitèye 1982; Le Houérou 1989). Long-term average annual rainfall within the four study areas declines significantly from north to south. Along this gradient, the average growing season shortens by 14 days per latitude degree, the average date of vegetation green-up is delayed by 9 days/degree, and the average date of the onset of senescence is advanced by 5 days/degree (Butt *et al.* 2011). These *relatively regular* climate-induced patterns in vegetation have historically shaped the dominant south-north transhumance systems in Sudano-Sahelian West Africa (Beauvilain 1977; Benoit 1979; Breman and De Wit 1983; Santoir 1983; Gallais 1984; De Bruijn and van Dijk 1995;Thébaud and Batterbury 2001; Bassett and Turner 2007). During the rainy season, livestock will move to northern rangelands (> 16° north latitude) where cultivation is sparse to nonexistent and annual grasses have higher nutritional content (Penning de Vries and Djitèye 1982). These movements generally occur during the period of germination and initial growth of herbaceous vegetation

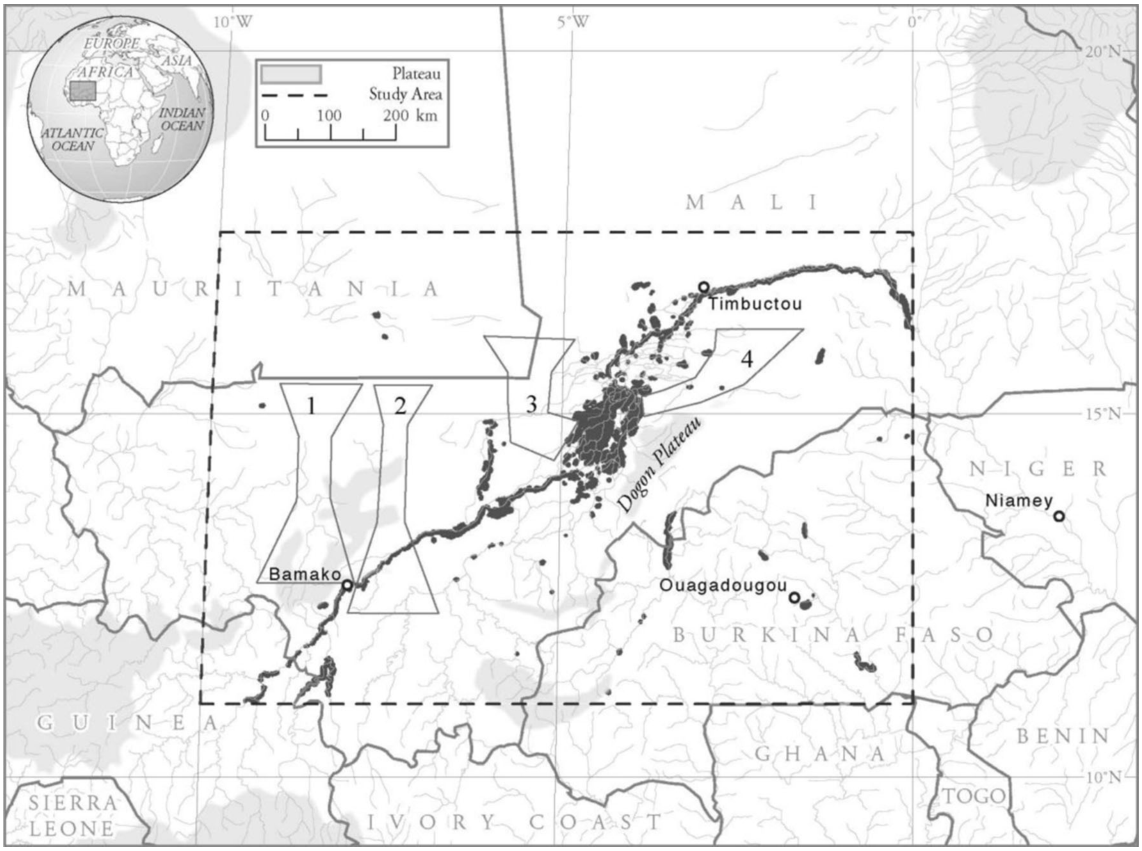

Fig. 1 Location of four transhumance sheds in central Mali. Phenology parameters were estimated from MODIS imagery covering the study area (outlined by *dotted line*) after the masking of floodplain areas (*dark shaded areas*). Plateau areas are represented by grey shading

(green-up period). The rate of movements (km/day) is limited by the poor nutritional status of livestock at the end of the dry season (Diallo 1978). Movements south occur at the beginning of the dry season driven by declines in the availability of surface water and green forage. Because of the much higher nutritional status of livestock, their southward movements are typically more rapid than their northward movements at the start of the rainy season (ibid: 1978).

Transhumance is comprised of a succession of north-south travel movements along a network of resting points that are located near water sources (Fig. 2). Livestock rest for periods ranging from 1 day to several weeks (Schmitz 1986; De Bruijn and van Dijk 1995; Turner 1999a). At these resting points, calves are separated from their mothers to facilitate milking. Livestock move away from these resting points to graze, returning when cows rejoin their calves at milking (see inset of Fig. 2). Daily grazing movements are necessarily circular with a much higher fraction of the time spent grazing compared to travel. The attractiveness of a resting point in any given year is therefore strongly affected by the availability of forage in its vicinity (<=3 km radius). As cultivation pressure increases, transhumance movements become increasingly restricted to a reduced number of paths—braided paths under conditions of medium-to-heavy cultivation pressure evolving to distinct single paths under conditions of very heavy cultivation pressure. A "transhumance shed" is an area characterized by a particular web or parallel set of transhumance corridors connecting a northern pasture dispersion area with a an area to the south where rainfall is higher and dry season resources are more favorable. A transhumance shed does not delineate a single "corridor" but the total area within which livestock rely on a particular corridor system. The long axes of these sheds are situated along a north-south axis and they display an hour-glass shape with their widths increasing at the northern and southern ends (Fig. 2). The widening at the northern end reflects the dispersion zone within extensive pasture areas and the widening of the southern zone is due to higher levels of cultivation pressure, which force livestock herders to rely on a reduced set of major paths moving north.

Regularity of Livestock Mobility in West Africa

A review of livestock mobility within West African transhumance systems reveals more regularity than is typically portrayed by most outside observers, farmers, government officials, and in some cases, livestock herders themselves (Gallais 1984; Bassett 1986; Turner 1999a; Bassett and Turner 2007; Moritz *et al.* 2010). In contrast to portrayals of

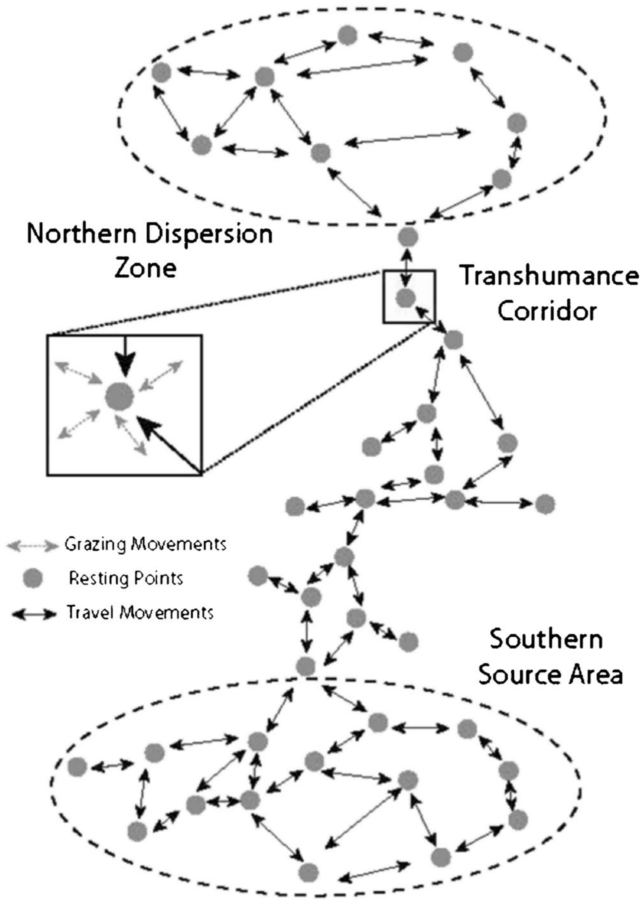

Fig. 2 Geographic characteristics of a West African regional transhumance shed showing the case of a well-defined transhumance corridor connecting a spatially broader source area to the south and a dispersion area to the north. Livestock move between resting points (travel movements), often associated with water sources, from which they disperse to graze (grazing movements)

chaotic or responsive but highly variable livestock movements, we see that transhumance movements by livestock within a particular area following similar trajectories every year. While the length of stay at a particular resting point will vary significantly from year to year, all herders can name the resting points that they rely upon at the beginning and end of the rainy season as they travel to and from the northern dispersion zone of a particular shed.

Herders have arguably benefited from the ignorance of state and local actors about their mobility patterns because it has helped them prevent interventions and control by these actors that have tended to undermine their livelihoods (Bassett 1988; Moritz 2006; Turner *et al.* 2011). Today, under conditions of agricultural pressure and the need for more direct protection of their access to resources, there is a growing recognition among pastoralists that this strategy of exploiting and perpetuating the ignorance of others is no longer effective and has ultimately contributed to an erosion of their rights to the key pasture and water resources as well as the passage corridors that connect them. It has also reinforced notions of pastoral backwardness and ungovernability—notions that have only served to further erode pastoral rights within agropastoral landscapes (Niamir-Fuller 1999).

Spatio-Temporal Variability of Forage Access

Despite regularities in the basic organization of transhumance systems, the question remains as to whether high spatio-temporal variability of forage resources inhibits the effectiveness of conventional institutional features characterized by spatial boundaries. Green herbaceous vegetation is seasonally variable (Penning de Vries and Djitèye 1982). In the middle of the rainy season it is sufficient for livestock—except during the severest of droughts. During the middle two-thirds of the 8–10 month dry season, green vegetation is largely nonexistent. Rather, it is the 2–4 week periods at the beginning and end of the rainy season that play a critical role in the nutrition of livestock. It is also during these periods that livestock are moving between the southern and northern ends of their transhumance sheds. While species composition of herbaceous vegetation affects its forage quality for livestock, the major factor is phenology. The quality of forage is highest at the onset of growth, declining at a slow rate with growth followed by a precipitous decline with the drying of vegetation (ibid: 1982).

For transhumance, key forage parameters are the spatial and temporal variability of vegetation green-up and senescence (see below and Table 1). A third parameter is the inter-annual variability of the calendar periods when green-up and senescence occur. If inter-annual variability is high, it

Table 1 Institutional implications of parameters of the spatiotemporal variation in forage access

Forage parameter	Institutional features
Degree to which key forage patches are at same location from year-to-year	• Rigid versus flexible rules governing access to pastures • Information networks about current forage availabilities across transhumance shed
The within-year variation in green-up and senescence dates across the transhumance shed	• Mechanisms to improve connectivity between forage resources (e.g. greater web of corridors). • Information networks about current forage availabilities across transhumance shed
Variation in the timing of the green-up and senescence periods from year-to-year	• The nature of rules governing the timing of transhumance movements
The degree to which parameters above vary across transhumance sheds	• The need to adapt institutional features to the conditions of each transhumance shed

will be more difficult to manage the timing of the movements within transhumance sheds. Within the green-up and senescence periods, the range in the timing of greening and browning across the shed will affect the rate of movement along corridors and the need for information about the forage availability. During both periods, the connectivity of green fodder patches will influence the degree to which additional corridors within the shed are protected and whether networks to provide information about forage availability are needed. If there are areas within sheds where green-up is consistently earlier or senescence consistently later, they can delineated as key pastoral resources in need of formal protection from competing land uses. Finally, the degree to which these parameters vary from one shed to another affects the degree to which transhumance rules would have to be tailored to each one.

Methods

Geospatial analysis was performed to characterize the spatial and temporal variability of forage parameters that have important institutional implications (Table 1) according to the following steps: 1) identification of four transhumance sheds in Mali based on fieldwork conducted for other studies (Turner 1992; Brottem 2013) and relevant literature (Fig. 1); 2) calculation of the phenological parameters of green-up and senescence dates using 2000–2010 MODIS NDVI data; 3) determination of the four sheds' green-up and senescence periods; 4) analysis of seasonal changes in the connectivity between green forage patches within sheds as measured by the landscape metric Mean Proximity Index (MPI); and 5) identification of areas within each shed that show rapid NDVI gain during green-up and slow NDVI loss during senescence over the 11-year study period.

Study Area

Each of the four transhumance sheds is tied to one or several documented corridors with their own complex social history and physical geography, which require additional field research to fully characterize their requirements for pastoral mobility. Shed 1 is also described in detail in project literature focusing on the management of the Boucle de Baoulé biosphere reserve (Geerling and Diakité 1988; Boureima 2006,). Shed 2 runs parallel with shed 1; its use and characteristics have been corroborated by Ibrahima Sow, a local pastoralist involved in resource policy, as similar to shed 1. Each shed links semi-arid Sahelian pastures towards the Mali-Mauritanian border that are utilized during the rainy season (June-August) with dry season grazing areas located in the Sudanian and Sudano-Guinean sub-humid savanna zones. Patterns of livestock movement in these sheds have generally shifted south since the drought of 1984. Transhumance sheds 3 and 4 (Fig. 1) serve herds that pass the dry season on the floodplain of the Inland Niger Delta of Mali. Transhumance shed 3 connects the western edge of the floodplain (fed by the Diaka River) to the rainy-season pastures to the northwest (Mema and Sahel). The middle section of the shed passes through the "Dead Delta," an area that historically was flooded and is marked by depressions and fossil water channels. Transhumance shed 4 connects the eastern edge of the floodplain (fed by the Niger River) to the rainy-season pastures to the northeast (Gourma). The middle section of the shed represents a choke point for herds along the southeastern edge of the Delta as it falls just north of the Dogon Plateau (over which livestock movements are very difficult). Livestock movements within these sheds date back to at least the nineteenth century (Ba and Daget 1984) with herd managers with homes on and off the floodplain relying on them (Gallais 1967, 1975; Breman and De Wit 1983; Cissé 1986; Turner 1992; De Bruijn and van Dijk 1995).

Estimation of Phenological Parameters

The timing and rate of north-south movements of livestock within these sheds are shaped by vegetation phenology. Two key parameters are the dates when herbaceous vegetation greens up and senescence at particular places within transhumance sheds. We employed 16-day 1 km resolution MODIS NDVI imagery to estimate these parameters (MODIS science dataset MOD13A2, distributed by the Land Processes Distributed Active Archive Center: lpdaac.usgs.gov). The use of MODIS NDVI imagery at fine spatial (250 m) and temporal scales (16 days) has been well documented to understand how behavioral activities of grazing ungulates are influenced by resource availability in sub-Saharan Africa (Bro-Jørgensen *et al.* 2008; Butt 2010). NDVI is a reliable, robust and proven indicator of the density and greenness of photosynthetic vegetation (Justice and Hiernaux 1986; Chamaillé-Jammes *et al.* 2006), but NDVI is a poor indicator of non-photosynthetic biomass (Gamon *et al.* 1995). Several studies have relied on NDVI to estimate resource availability and utilization among wild ungulates in semi-arid sub-Saharan Africa (Bro-Jørgensen *et al.* 2008; Pettorelli *et al.* 2009). Sixteen-day/1 km resolution data were chosen for two reasons. First, it necessarily reduced the processing time required for 11 years of data, which would have been exceedingly onerous at a resolution of 250 m given the relatively large spatial extent of the mobility patterns under study. Secondly, large-scale studies (e.g., continental) have tended to utilize 8 km resolution AVHRR NDVI data, which were deemed overly coarse for our objectives. Therefore, 1 km resolution provided a balance between practicality and suitability. The four transhumance sheds fall within a single MODIS scene (h17v07) (Fig. 1). For all pixels within the four transhumance sheds, NDVI data were extracted for dates falling between April 1 and November 1 over an 11 year period (2000–2010, 154 image-dates in total).

The two phenological parameters were estimated for each pixel-year combination using a double-logistic function with green-up date estimated as the maximum of the 2nd derivative of the function (where acceleration of NDVI gain is the highest) and senescence date estimated as the date in which the function falls to 80 % of maximum NDVI is reached as described by Butt *et al.* (2011: 3369–3372). These estimates best capture the point at which grasses and forbs begin to sprout at the onset of the rainy season and vegetation begins to senesce and dry at the onset of the dry season (Butt *et al.* 2011). Pixel-year combinations were excluded from further analysis where: 1) NDVI gain ($NDVI_{max}$-$NDVI_{min}$ across the April 1-November 1 period) is less than 0.1; or 2) there was a poor fit of the double logistic function to the data (e.g., $r^2<0.5$, inverted curve, intractable 2nd derivative). Across the whole MODIS scene, approximately 12 % of the pixel-year combinations were removed for these reasons (Butt *et al.* 2011). Pixels of low NDVI gain were excluded due to the impossibility that instrument error, noise, or other factors could be accurately distinguished from specific areas where vegetation was not greening up during any particular year. Less than 10 % of the pixel-year combinations were removed from transhumance sheds 1–3. For transhumance shed 4, lying further north, 23 % of pixel-year combinations were removed, most from the northern end of the shed due to low NDVI gain (reflecting very low vegetation growth during the year).

Green-Up and Senescence Periods

As noted, long-distance livestock movements respond to the changing availability of high quality forage that is strongly shaped by phenology. The green-up and senescence periods for each shed-year combination were estimated using a series of bi-daily binary grids (1=green, 0=not green) produced from the green-up and senescence dates estimated for each pixel. For the purposes of this study, the green-up period is defined as the time period at the beginning of the rainy season when a minimum of 20 % of the pixels are defined as green until a maximum of 85 % of the pixels are green. This definition was chosen to capture the most rapid and therefore most important phase of landscape green-up over the entire transhumance shed. The same holds true for senescence except in reverse: the period begins at the last day when at least 85 % of pixels were still green and ends at the first subsequent date when the green pixel percentage falls below 20 %.

Connectivity of Green Patches

The rate of north-south movement of herds partly depends on the rates of the northerly movement of the greening front and of the southerly movement of the senescence front at the beginning of the rainy and dry seasons respectively. Other factors such as the avoidance of cropped fields in the south and accessing surface water in the north can lead to earlier movements during periods of green up and senescence. Since the feasibility of these movements depends most critically on the connectivity of green forage patches, we evaluate how connectivity among green patches changes during the green-up and senescence periods. Rapid northerly movements of the greening front will be associated with concomitant increases in green-patch connectivity at the beginning of the rainy season and few fodder restrictions on northward movements of livestock. A more gradual increase in connectivity of green patches along the south-to-north axis may lead to delayed or more rapid movements of herds due to unavailability of green fodder along the way. Similarly, rapid southward movements of the senescence front at the beginning of the dry season will be associated with more abrupt loss of the green fodder availability along the transhumance corridor.

In order to study how green-patch connectivity changes seasonally, the landscape metric Mean Proximity Index (MPI) was utilized to measure the spatio-temporal pattern of green patches over the entirety of each transhumance shed during the green-up and senescence periods. MPI is a measurement of fragmentation and isolation of a particular discrete unit (McGarigal and Marks 1995). A low MPI value indicates a highly fragmented or sparse unit while a high value indicates cohesion or dominance of pixels of the same unit. Thus, the multi-date trend in MPI of green pixels provides a spatio-temporal index of the degree of green-patch connectivity affecting the viability and rate of livestock movements at the onset of the rainy and dry seasons.

Spatial and Temporal Variation of NDVI Change

It is important to understand whether there are areas within each shed that can be characterized as key pastoral resources with respect to quality fodder (Scoones 1994). These would include sites that green up rapidly or senesce slowly compared to other sites within the transhumance shed. Such sites would be candidates for territorial forms of protection that are not found in government strategies typically associated with variable dryland resources. Differences in absolute gain and loss of NDVI are strongly correlated with latitude due to the higher peak standing biomass in the south compared to the north. Since we are interested in the relative NDVI gain/loss within the corridors, we calculated the percentage change in per pixel NDVI during the green-up and senescence periods in each corridor.

The nature of spatio-temporal variability was evaluated by calculating measures of the average *temporal* (average pixel-level variability across 11-year period) and *spatial* (11-year average of the spatial variability within each shed) variability for each shed. These variabilities are expressed as coefficients of variation (standard deviation divided by mean percentage change in NDVI). NDVI change percentage was found to be normally distributed within each shed so a threshold of 1.5 standard deviations above the 11-year mean (green-up period) and below the mean (senescence period) was established to identify high gain/low loss pixels compared with the rest of the shed.

Recognizing that different land covers can influence local differences in phenology, sample points were selected through a spatially stratified sampling process from points identified as high gain during the green-up period, low loss during the senescence period, and points not falling into either category. These sample points were then categorized with respect to the dominant three land-cover types as visually estimated through Google Earth Pro: 1) crop agriculture; 2) depression areas (known in Francophone West Africa as *bas-fonds*); and 3) other land cover types, including areas available for seasonal livestock grazing. A difference of means test was then calculated between the agriculture and depression proportions of the control points and the early green-up and late senescence sample points for each shed.

Results

Three features of the spatio-temporal distribution of forage availability with significant implications for institutions governing livestock mobility are: 1) The inter-annual variability in the timing and length of the green-up and senescence periods; 2) The changing connectivity of green fodder patches at the beginning of the rainy and dry seasons; and 3) The nature of the local spatio-temporal variation in phenology and whether there are key fodder sites that tend to green up sooner or senesce later on average compared to other sites in the shed.

Green-Up and Senescence Periods

The onsets of green-up and senescence are a function of latitude, which is consistent with other studies (Zhang *et al.* 2005) (Table 2). Sheds 1–2, extending further south, display earlier green-up period onsets. Sheds 3–4, extending further north, display earlier senescence period onsets. Inter-annual variations in the onsets and ends of the green-up periods show slightly greater variation than those of senescence periods. Onset variation is highest for the most southern (Shed 1) and northern shed (Shed 4). Still, onset and end dates for green-up periods do not vary widely: standard deviations in these dates across the 11-year period tend to be approximately 7 days. The average length of green-up periods is approximately 30 days (higher for the southern shed) with standard deviations of approximately 7 days as well. Senescence dates generally show less variation than green-up dates with standard deviations of approximately 6 days across all four sheds. Average senescence period length is slightly shorter than green-up period length in each shed with a lower inter-annual variation (standard deviation equal to 5 days).

Connectivity of Green Patches

MPI varies seasonally with consistently low MPI values at the beginning of the rainy season preceding a period of exponential increase or decrease followed by a plateau with a subsequent exponential decline to very low MPI values during the beginning of the dry season (Fig. 3). The periods of steep rise and fall of MPI values are largely bound by the green-up and senescence periods defined by the dates when 20 % and 85 % of shed pixels are green (see Fig. 3 highlighted as black symbols). In certain cases, a plateau or inflection point is reached or the MPI value continues to rise after end of the green-up period (85 % of pixels are green), indicating that connectivity is still being incrementally gained further into the rainy season. MPI values for sheds 1 and 2 rise earlier and fall later during the window periods than sheds 3 and 4, which reflects their relative positions further south. The more gradual rise and fall as well as the lower absolute MPI values for sheds 3 and 4 reflect the higher inherent patchiness of vegetation in these sheds.

Across all cases, connectivity of green pixels increases and decreases rapidly during the green-up and senescence periods and this indicates that the windows effectively capture when transhumance is most viable. The optimal timing of movements is different. During the green-up period, steep increases in MPI result in the rapidly expanding viability of herd movements to the north that allow for livestock, weakened after the long dry season, to graze each day along the transhumance corridor. During the senescence period, steep declines in the

Table 2 Mean start dates, end dates and length (days) for the green-up and senescence periods for four sampled transhumance sheds over an eleven-year period (2000–2010). Standard deviations (days) are presented in parentheses

Transhumance shed	Green-up period			Senescence onset period		
	Start date	End date	Length	Start date	End date	Length
1	May 29 (12)	July 8 (7)	40 (13)	Sept 1 (4)	Sept 23 (6)	23 (5)
2	June 8 (9)	July 9 (8)	30 (8)	Sept 2 (6)	Sept 29 (4)	27 (5)
3	June 26 (8)	July 22 (8)	26 (6)	Aug 23 (7)	Sept 14 (6)	23 (5)
4	July 1 (14)	July 26 (12)	25 (6)	Aug 21 (8)	Sept 12 (6)	22 (5)

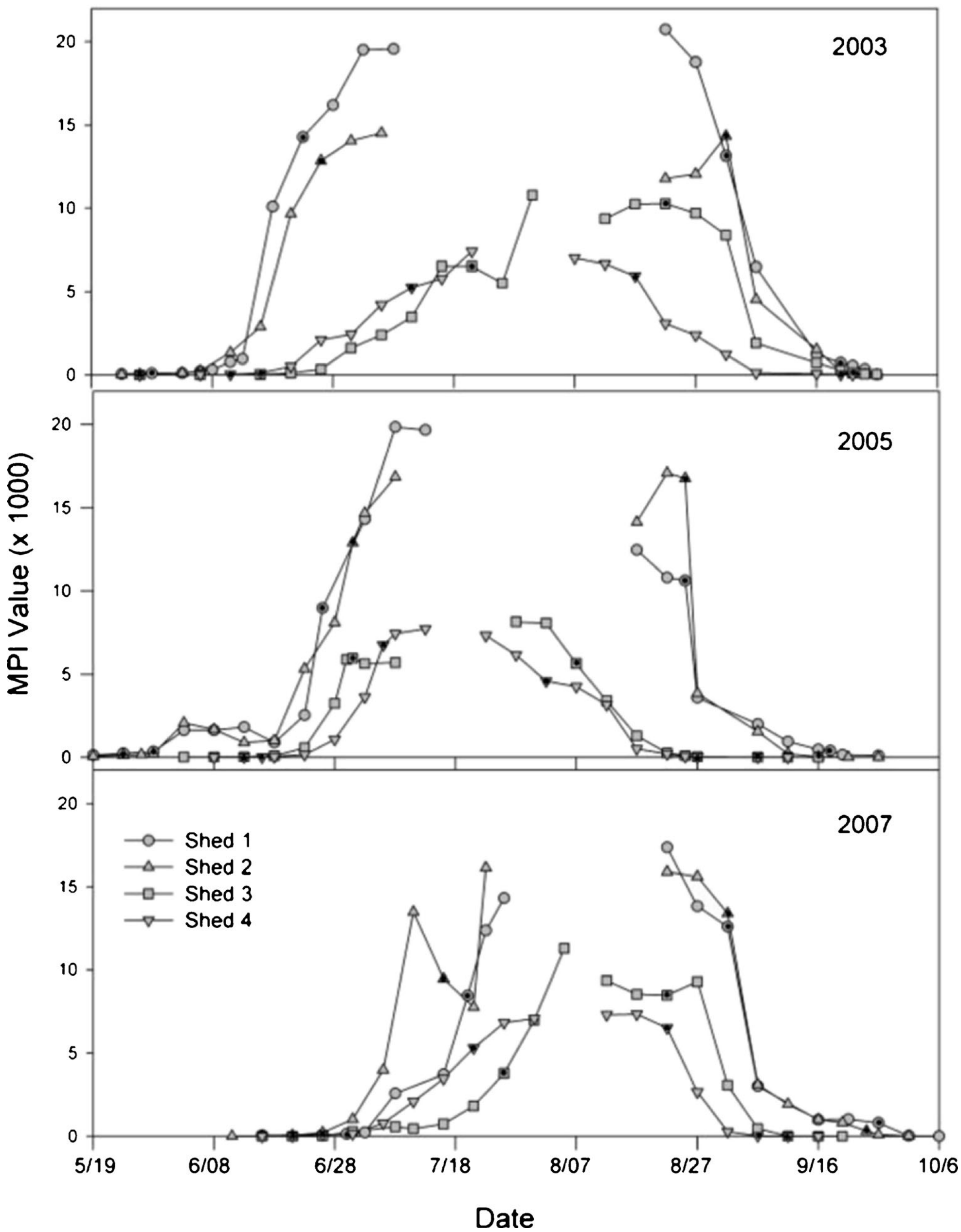

Fig. 3 Seasonal variation of MPI for each of four transhumance sheds in 2003, 2005 and 2007. For each seasonal curve, the data points when 20 % and 85 % of the pixels have greened-up (green-up period) or senesced (senescence period) are marked with black circle. The time periods that fall between these marks are defined as the green-up and senescence periods

availability of green vegetation rapidly reduce the viability of slow, gradual herd movements, which are necessary to prevent livestock from losing significant amounts of weight. These gradual movements are deterred even further by the presence of cropped fields to the south and, as a result, livestock movements at the beginning of the dry season tend to be rapid with long distances covered each day (Breman and de Wit 1983).

Critical Green Fodder Areas

Both spatial and temporal variation of NDVI change is higher during the senescence period (Table 3). No significant differences in spatial or temporal variation are seen across the transhumance sheds although shed 2, which covers the greatest latitudinal range, shows higher spatial variation. Across all four sheds, spatial variation is higher than temporal variation of NDVI change during the green-up and senescence periods. This finding supports the interpretation that there are key sites that green up faster and senesce slower within all four sheds.

As measured over a 10 year period (2000–2010), locations of rapid green-up and slow senescence across each of the four sheds are contiguous areas within each shed that provide critical resources during key periods of the pastoral calendar (Fig. 4). These areas tend to be smaller and patchier in the northern sheds (#3, #4) reflecting their more arid conditions

Table 3 Coefficients of spatial and temporal variation of NDVI change during green-up and senescence periods. The average coefficient of spatial variation is derived using the eleven-year average of the standard deviation of fractional NDVI gain (green-up period) or loss (senescence period) across the transhumance shed. The average coefficient of temporal variation is derived using the average of across all pixels in the shed of the standard deviation of fractional NDVI gain (green-up period) or loss (senescence period) for each pixel across the eleven-year period

Transhumance shed	Green-up		Senescence	
	Spatial CV	Temporal CV	Spatial CV	Temporal CV
1	0.56	0.32	2.13	0.79
2	0.57	0.27	3.35	0.48
3	0.49	0.23	1.78	0.71
4	0.65	0.31	1.55	0.61

and larger proportion of bare ground. The results of the point assessment of these key sites indicate that the sites of late senescence in sheds 1, 2, 3 are associated with agricultural land cover—reflecting the fact that crops such as millet tend to senesce later than non-cultivated vegetation (Table 4). This suggests that for end-of-rainy-season key resource areas, an agricultural land cover mask based on higher resolution data (e.g., Landsat) would be needed to create accurate local-scale transhumance resource maps.

Green-up resource areas were not influenced by agriculture. In sheds 1 and 2 green-up areas matched large, non-arable stretches of land in the northern portions of the sheds or in lower-lying areas to the south. In shed 1, green-up areas tend to be within and around a protected area, the Baoulé biosphere reserve, which is consistent with the observed movements and grazing patterns of local livestock herders. In sheds 3 and 4, green-up areas closely matched low lying areas that receive accumulated water runoff. This also

Fig. 4 Key sites within the four transhumance sheds that show: **a**. Significantly earlier green-up over the 11 year period 2000–2010 (> 1.5 standard deviations above a shed's mean NDVI gain during the green-up period); and **b**. Significantly later senescence over the 11 year period 2000–2010 (> 1.5 standard deviations below a shed's mean NDVI loss during the senescence period

Table 4 Mean per pixel proportion of agriculture and depression) for areas of early green-up, late senescence, and areas not designated as either category (control) in sheds 1–4. A Pearson's two-tailed t-test was performed to test the significance of difference between mean proportion for each land cover category (green-up/senescence) and the control points. (Significance at $p<.10$: *, $p<.05$: **)

Shed #1	#_points	Proportion_agriculture	Proportion_depression
Point type			
Early green up	120	.07	.02
Late senescence	141	.28**	.03
Control	38	.12	.03
Shed #2			
Early green up	93	.17	.08
Late senescence	131	.47**	.06
Control	31	.25	.10
Shed #3			
Early green up	50	.00	.93**
Late senescence	46	.21**	.20**
Control	85	.02	.50
Shed #4			
Early green up	52	.02	.72**
Late senescence	49	.01	.53
Control	45	.00	.36

suggests another important dimension of local resource governance. In addition to protecting relatively large patches of grazing resources, as suggested by the results for sheds 1 and 2, connectivity must be protected between low lying resource areas that are dispersed throughout the landscape. Agriculture expansion is more of concern in shed 3 than in shed 4 given in the low rainfall received by the latter.

Discussion

Green-Up and Senescence Periods

Despite the importance of green-up and senescence to the timing and destinations of transhumant movements in Sudano-Sahelian West Africa (Breman and de Wit 1983; Le Houérou 1989), measurable connections between the phenological patterns and actual transhumant movements have been limited in terms of geographic area and empirical evidence. The analysis presented here addresses this research gap by characterizing and measuring the spatio-temporal variability in vegetation phenology over 11 years within four transhumance sheds in Mali. The green-up and senescence periods are surprisingly short (Table 2) given the substantial north-south distance (120–360 km) and latitudinal ranges covered by the four transhumance sheds. On average, these periods (defined as 20 %–85 % green for green-up period and 85 % to 20 % green for senescence period) are, on average, a month long. It is during these periods when transhumance movements take place. The length of these periods reflects both the latitudinal gradients in green-up and senescence onset as well as spatial variability in these dates at given latitudes. Previous work analyzing the latitudinal variation of phenology within the study area at the scale of the 0.5° latitude bands has found that moving north green-up onset is delayed on average 0.09 days/km and while senescence onset occurs earlier by 0.05 days/km (Butt *et al.* 2011). Thus for transhumance sheds 1–2, spanning 320–360 km in a north-south direction, one would expect that the mean green-up and senescence onsets to differ by 29–32 and 16–18 days respectively between their southern and northern ends. On the other hand, the mean green-up and senescence onsets for transhumance sheds 3 and 4 would be expected to differ only 13–18 days and 7–10 days respectively between their southern and northern ends (spanning only 200 and 150 km in a north-south direction respectively). The fact that green-up and senescence periods for sheds 3 and 4 are similar to those found for sheds 1 and 2 (Table 2), despite their lower latitudinal range, reflects the higher spatial variability of phenology in these more northern and overall drier sheds.

Governance Implications of Green-up and Senescence Timing

The implications of these observations for the governance of transhumance are multiple. First, latitudinal variation in the timing of phenological parameters within transhumance sheds is more limited than commonly assumed. If we recognize that most herds utilizing sheds 1 and 2 are only moving across half of theses sheds' N-S ranges, latitudinal variation in green-up and senescence onset in the movement range across all of these sheds is on the order of two and 1 weeks respectively. The maximum rates of transhumance movement of livestock at the onset and end of the rainy season of 15–30 km/day and 20–40 km/day along the N-S axis (Breman and de Wit 1983) are on the order of the movement of green-up and senescence onsets (11 and 20 km/day respectively). This finding calls into question the usefulness of measures that provide satellite-derived information about pasture conditions to facilitate livestock herders' decisions about when to depart or return from transhumance (e.g., the U.S. government famine early warning system). Given how quickly the green-up and senescence onsets spread across the latitudinal range and connectivity between green patches increases, reliance by herders on local conditions to move either north or south is a sufficient strategy. The forage-related information that herders need are the specific locations of better vegetative conditions, in terms of forage density and species composition, at any given point in the transhumance shed. Such information needs to be tied to the local place names used by herders themselves. Remote sensing-based information is generally too spatially coarse and not processed to relate to pastoral geographies and therefore is likely to be of little use.

Second, while the green-up and senescence periods differ from one transhumance shed to another, the inter-annual variability of the start and end dates for these periods is lower than expected, which provides a good basis of the predictability that is needed for developing institutions to manage transhumance during these periods. In this way, rangeland phenology, as the biophysical driver of seasonal long-distance livestock movements, strongly differs from the image of pastoralists "chasing the clouds" in unpredictable ways that defy conventional modes of common resource governance. While the rainfall magnitudes and timing vary significantly from place-to-place, vegetation phenology is more predictable at the scale of the transhumance shed. Still, these features vary significantly from shed to shed, which supports the need to tailor resource management measures to each shed's biophysical parameters.

Third, spatio-temporal analysis shows the existence of sites that show consistently earlier green-up or delayed senescence. Access to these important pastoral sites effectively expands the period of quality fodder available to livestock. Areas of earlier green-up onset are generally found to be depression areas that receive significant levels of run-off at the onset of the rainy season. Areas of later senescence at the beginning of the dry season, particularly for sheds 1–3, correlate with cropped areas. While cropped fields are preferentially located in areas of the high water infiltration, prolonged greenness is associated with phenological differences between crop species and natural vegetation and the crop management strategies practiced by farmers. These areas are off-limits to livestock and understandably are foci of significant farmer-herder conflict. The benefits of depression areas, on the other hand, derive from their geomorphic position. These are increasingly centers of considerable land-use competition with the promotion of market gardens (Thébaud 1988; Marty 1993). The pastoral geography of corridors, encampments and water points are not abstract references to ephemerally-visited locations. These interconnected features have place names and are revisited on at least a yearly basis by mobile herds. This consistent and predictable geography is an additional feature that is consistent with conventional common property institutions. With sufficient political will and capacity, areas of early green-up and late senescence as well as the corridors that connect them can be mapped and protected as key pastoral resources.

Current Policy Context

With limited attention to institutions that manage north-south movements and that protect key pastoral resources, policy support for livestock husbandry has been dominated by programs that seek to disseminate market and pasture information. Such programs are consistent with a view of high, unpredictable variability as a major constraint to livestock husbandry and the need for greater information to adjust livestock populations to fodder availability through livestock movements and market transactions. Two problematic assumptions of such programs are not only that the information, as disseminated in the form of prices and NDVI units, is of use to herders but even if useful, herders are assumed to be able to move freely in response to the new information. Herders may be better informed but blocked to act on this information due to labor and land-use barriers to movements of livestock to greener pastures or markets.

Other rural development programs and policies, promoted concurrently with these information dissemination programs have actually worked to further erode the viability of longer-distance transhumant movements through the promotion of agriculture, irrigation, and decentralization of governance (Marty 1993; Painter *et al.* 1994; Turner *et al.* 2012). While one would be hard-pressed to argue that the state provided effective protections of transhumance corridors prior to the recent surge of decentralization initiatives, the transfer of authority from the state to local levels will likely worsen the prospects for the maintenance of livestock mobility (Brottem 2013). This is due to the "public good" characteristics of the inter-linked landscape features (accessible corridors, water points, and pastures) necessary for transhumance. Local decisions will most likely not account for the broader benefits associated with a particular water point along a transhumance corridor. Therefore, alternative land uses that directly benefit local communities and reinforce existing land rights will tend to be favored. In fact, there is evidence that herders' access to these features erodes unless there are affluent local herders who choose to influence decisions in their favor (Turner *et al.* 2012). In Mali, these situations are exacerbated by land tenure policies, such as the 2006 Agricultural Orientation Law (national law #06–045), that make it even more difficult for local or regional governments to protect the type of large, contiguous pastoral resource area identified in this paper. This law has legally recognized and therefore further strengthened customary tenure rights that are typically held by the traditional heads of agricultural villages or clans. Not only does this favor continued agricultural expansion in areas where it has historically overlapped with pastoral livestock production; it also splinters authority over land use decision making between very small-scale, sub-local institutions. Even though the government of Mali has passed laws to protect livestock resources access, such as the 2001 Pastoral Charter (national law #001–004), implementation of these measures, especially in terms of the territory-based resource areas defined in this paper, lack the institutions that can work effectively at the scale of transhumance sheds and corridors.

Conclusions

Livestock mobility plays an important role in reducing the vulnerability of agropastoral production in Sudano-Sahelian West Africa. While it is characterized by some inherent unpredictable variability, it also has important features that are tractable, governable and can be mapped. More specifically, the following conclusions can be made:

1. The timing of transhumance movements, as they are shaped by the green-up and senescence periods within a transhumance shed are less variable from year to year than is commonly presumed. Therefore, they have a predictability that would allow for planning and rule-making that would accommodate the often competing land uses of livestock husbandry and agriculture. Timing varies from shed to shed and therefore, governance should be tailored to local situations through co-management institutions.
2. Despite the wide latitudinal range of the studied transhumance sheds, greening and senescence spreads rapidly across them at the beginning and end of the rainy season, which are the most important periods of livestock movements. As a result, once greening or senescence is experienced at one area of a shed, it will be very soon experienced elsewhere. Therefore, spatially-coarse systems of detection based on satellite-derived data are not necessary since local experience is an equal predictor of greening or senescence at other latitudes within the shed. What pastoralists need more urgently is information about the specific locations of quality fodder and water at higher resolutions using place names that are recognizable to local people.
3. There are sites that are essential to the viability of transhumance within particular sheds either through the provision of pasture or water. These sites can be identified by herders or, as described above, through appropriately scaled remote sensing-based analysis. Given the importance to livestock nutrition of extending the period of time within a year when livestock graze green fodder, protecting sites of early green-up or late senescence from competing land uses is important. This is important at the beginning of the green-up period when livestock are weak from the preceding dry season and greatly benefit from early growth of forage grasses. This is also important during the senescence period at the end of the rainy season when slowing the rate of movements south into cropped areas will reduce the potential for farmer-herder conflict. Such movements cannot be slowed through the drilling of boreholes but must involve the protection of areas that predictably support green vegetation for extended periods each year.
4. The most vulnerable aspect of the transhumance corridors is that they are inter-connected. The major threat to transhumance systems is not climate variability or drought but the extension of cropped areas at particular points within a shed that block movements between areas where pasture and water can be accessed, thereby reducing the viability of the whole system.

Therefore, we question dominant notions that pastoralism is simply a system that requires more information to allow livestock pressure to equilibrate to the shifting patches of forage and water as driven by highly variable climatic conditions. All production systems in dryland Africa must be responsive to a certain amount of change and variability but there are identifiable features of climate and rangeland ecology that are predictable and regular. A billiard ball world of herders moving across a semi-arid landscape to equilibrium hides the real politics that surround livestock mobility, which depends on corridors, resting points, pasture areas, and water points that are legible, can be mapped, and therefore managed through rules that are enforced at appropriate institutional scales.

Despite the common invocation of terms such as corridor, resting point and water point in any discussion with rural peoples about resource management in agropastoral areas of the region, there is amazingly little high quality and verified information about the locations and legal status of these features of the social landscape. Many academics have traced the paths followed by pastoralists but often without relating these movements to the landscape ecological features that allow such movements. What is needed is to map these as landscape features and gather information along their stretch as to their management, tenure arrangements, phenologies of available forage resources, and the land use pressures that surround them.

The spatio-temporal variation and patterns of forage availabilities will vary from one region to another. We do not suggest that the regularities we observe in the Sahel will be duplicated in other areas of the world. In fact, the uniquely sharp climatic gradient of the Sahel produces some of the regularities that we observe in this study. Still, all pastoral ecosystems have features that vary in the degree to which they are predictable and unpredictable in relation to pastoral needs. Recognizing this variation is important for developing and supporting pastoral institutions and livelihoods.

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