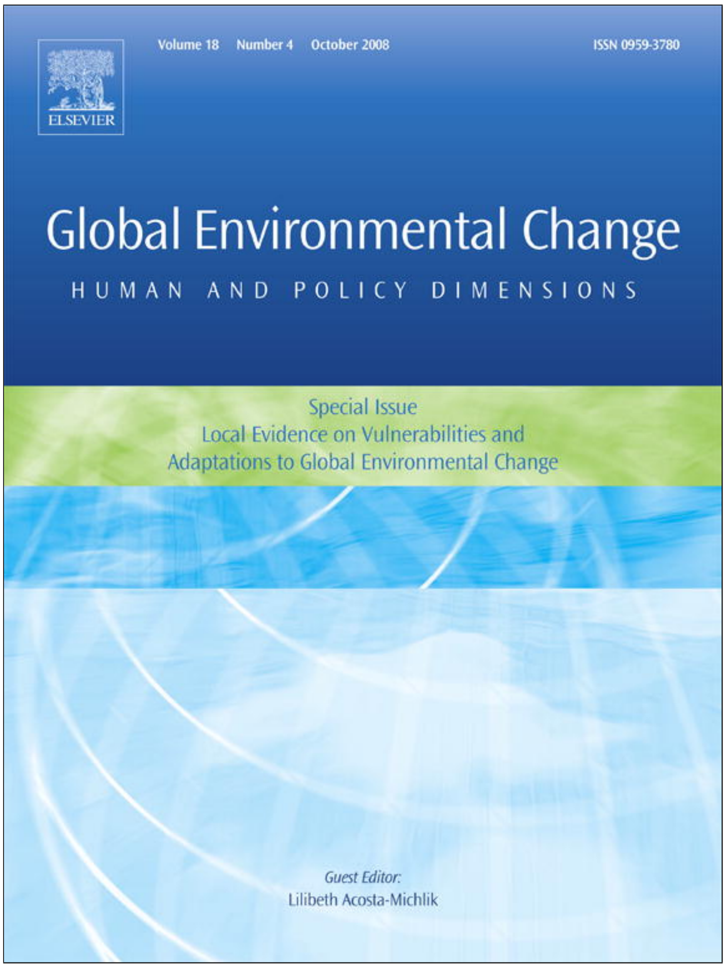
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Fragmentation of rangelands: Implications for humans, animals, and landscapes

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A B S T R A C T

Fragmentation of the ecosystems of the earth into spatially isolated units has emerged as a primary component of global change. Often, fragmentation results from actions that are intended to enhance human livelihoods and well-being; however, there are often costs to ecosystems and human economies that are not considered. We describe the three general categories of processes causing fragmentation of rangelands worldwide: dissection, decoupling, and compression. We show that access to heterogeneity of landscapes is an important attribute of grazing ecosystems worldwide, and that fragmentation of these systems, even when it proceeds in the absence of habitat loss, can limit options of people and animals, options that are particularly important in temporally heterogeneous environments. We discuss the consequences of fragmentation for people, livestock, wildlife, and landscapes and describe potential adaptations that can mitigate its harmful outcomes. We close by reviewing policy options that promote re-aggregation of landscapes and adaptation to fragmentation.

1. Introduction

Habitat fragmentation, the dissection of the earth's surface into spatially isolated parts, rearranges the structure of ecosystems and shapes their function worldwide. In so doing, fragmentation has emerged as a central force driving global change. However, the preponderance of scientific studies of fragmentation has treated humans as causes of fragmentation of the earth's ecosystems without trying to understand their responses. Rather, the focus has been on the biota, on the ways that plants and animals are affected by loss of connectivity within landscapes (see reviews of Niemela, 2001; Chalfoun et al., 2002; de Blois et al., 2002; Schmiegelow and Monkkonen, 2002; Cushman, 2006, but also see Galvin et al., 2008a). However, it is clear that the state of the earth's ecosystems cannot be fully understood without carefully considering the coupling between human societies and biological and physical processes. To that end, revealing the effects of fragmentation on people, as well as their roles in driving it, emerges as a critical part of understanding global change (MEA, 2005).

Most studies of fragmentation have been conducted in forests or in agricultural lands, places where the impacts of humans on landscape connectivity are particularly evident as a result of large-scale conversion of one land cover type to another. Agricultural systems have a long history of fragmentation—the conversion of forests and grasslands to cropland by its very nature creates fragmented environments. In contrast, fragmentation in rangelands has received only recent attention. People and animals have co-evolved with intact, unfragmented rangelands in most of the drylands of the world, where pastoral economies have existed for thousands of years. These ecosystems comprise between one-third and one-half of the land area in the world (Whittaker, 1975; World Resources, 1988; Asner et al., 2004), and support the livelihoods of over 20 million households (Galaty and Johnson, 1990). In most of these areas, there is insufficient rainfall to sustain agriculture, and as a result grazing by large herbivores offers the only sustainable way to turn sunlight into food for people. Climate warming and tropical deforestation promises to expand these lands and, in so doing, will amplify the importance

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of grazing animals to human economies and to human well-being worldwide (Asner et al., 2004).

Fragmentation of the world's rangelands is occurring largely as a result of a mainstream body of thought based on two ideas that have exerted strong influences on policy and management (Sandford, 1994). The first idea is that exclusive use of land and its manifestation in systems of land tenure will promote human welfare, increase livelihood options, and enhance ecosystem function by preventing "tragedy of the commons" (Hardin, 1968) situations. Banks (2003) and Banks et al. (2003) describe how such perceptions inform national rangeland policy in Western China, while Kabubo-Mariara (2003, 2005) recommends privatization in Kenya's Kajiado district's communally held rangelands, for example. The second idea is that compartmentalization of rangelands into small units provides control over movement of animals, which, in turn, enhances options for managing the timing and duration of grazing and, in so doing, promotes rangeland productivity and health (Sandford, 1994).

We offer an alternative view, proposing that the benefits of exclusive land tenure and rangeland compartmentalization may come at significant costs to human and natural systems in arid and semi-arid rangelands. Here, we examine fragmentation of these systems worldwide. We offer evidence showing that fragmentation of arid and semi-arid ecosystems can restrict access of people, livestock and wildlife to spatial heterogeneity in resources, primarily forage and water, which, in turn, prevents them from using spatial variability in resources to buffer effects of resource variation in time (Fig. 1). As a result, the ultimate effects of fragmentation of arid and semi-arid rangelands can include harm to human livelihoods and degradation of ecosystems.

This paper is organized as follows. We first discuss in some detail what we mean by fragmentation and describe the ways in which it occurs on the rangelands of the world. We then explain why rangelands are becoming fragmented. Next, we describe the consequences of fragmentation for wildlife and livestock, for landscapes, and for people. We close by exploring adaptations and responses to fragmentation that have implications for local and national policy.

2. What is fragmentation and how does it occur?

Fragmentation has been widely studied by ecologists, generating a large, diverse literature (see reviews of Niemela, 2001; Chalfoun et al., 2002; de Blois et al., 2002; Schmiegelow and Monkkonen, 2002; Cushman, 2006). In keeping with this literature, we use the term fragmentation to imply the disconnecting of areas of the landscape from one another. As a result, fragmentation restricts access of people and animals to heterogeneity in resources, particularly vegetation and water.

Rangelands become fragmented in three ways—dissection, decoupling, and compression (Fig. 2). Landscapes are dissected into multiple, distinct parts by the creation of barriers that limit movement. These barriers may be physical, social, or administrative. Physical barriers to movement on rangelands can take many forms (e.g., hedge rows, stone walls, and use of natural

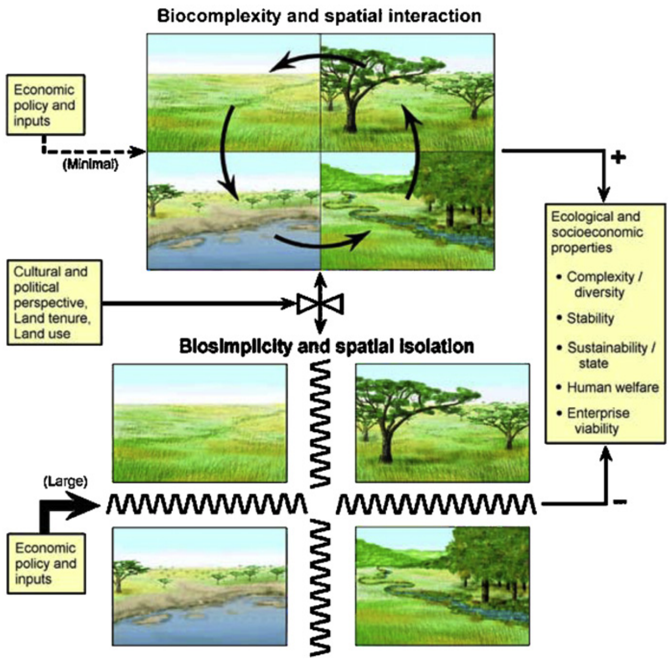

Fig. 1. Spatial complexity plays a central role in the structure and function of grazed arid and semi-arid ecosystems, but modern human land use tends to deplete spatial biocomplexity through ecosystem fragmentation. Ecosystems are simplified by breaking up interdependent spatial units into separate entities, compartmentalizing ecosystems into isolated sub-units. The result is a reduction in the scale over which complex interactions among landscapes, large herbivores and human management take place (with kind permission of Springer Science and Business Media from Galvin et al., 2008a).

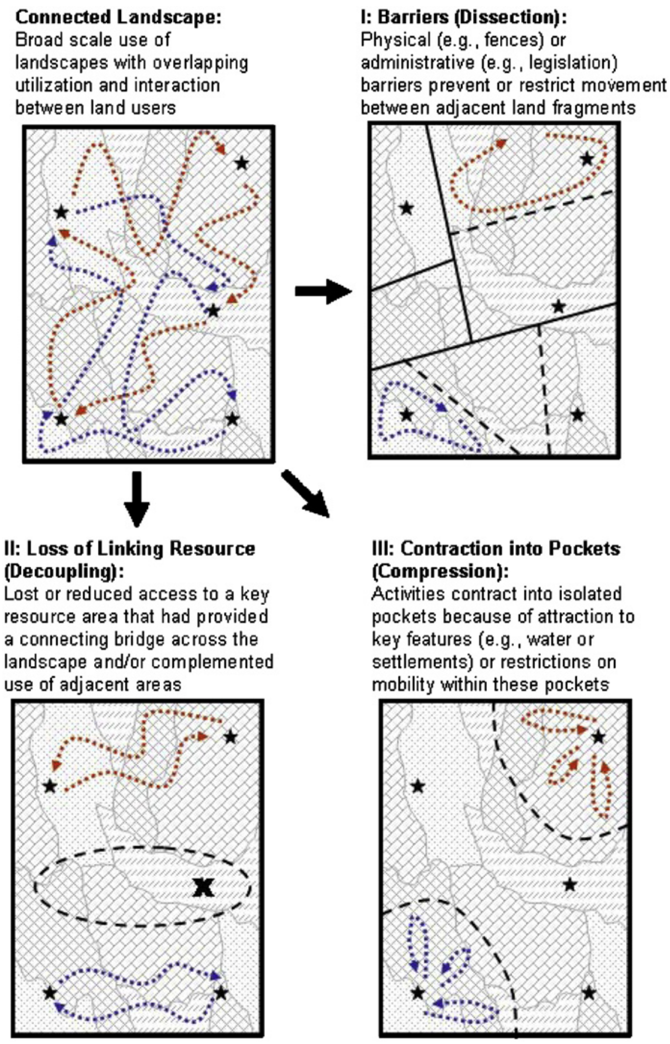

Fig. 2. Processes by which landscape connectivity and access to resource heterogeneity is eroded, fragmenting land use and diminishing interactions among land users. "*" Represent key resources (e.g., water), and landscape patches represent heterogeneity in resources (e.g., different sources of forage that vary in quantity, quality and temporal patterns of availability).

topographic features), but are most commonly represented by fences (reviewed in Boone and Hobbs, 2004). The dissection of landscapes by fences can be functionally significant, despite the fact that fencing does not change the amount of habitat available. Even small fenced parcels can cause substantial fragmentation (Reid et al., 2008). The extent of fencing within an area tends to increase over time following the privatization of communal lands (Kristjanson et al., 2002). Landscapes can also be partitioned by land tenure policy and social sanctions that limit scales of movement.

A second cause of fragmentation of rangelands is conversion of one land cover type to another which decouples a formerly intact landscape. Spatially selective conversion of land fragments to other uses, particularly cropping (FAO, 2001; MEA, 2005) has occurred on rangelands throughout the world. In other places, access to rangelands can be lost through habitat transformation due to residential and urban development, bush encroachment, forestation, or degradation that renders land unproductive. Even where there is minimal modification of habitat, land use may be altered by changes in land policy, tenure and administration (e.g., establishment of conservation areas), such that fragments become unavailable for humans or livestock (Boone et al., 2006). Disease may also restrict access to fragments within landscapes. For example, in the Ngorongoro Conservation Area of Tanzania, livestock have to be removed from the Serengeti Plains in the wet season to prevent infection from wildebeest (McCabe, 1992; Mduma et al., 1999; Galvin et al., 2008b).

The final type of fragmentation, compression, occurs when the activity and mobility of animals or people contracts to isolated pockets within landscapes in the vicinity of settlements (Roth and Fratkin, 2005), a process generally referred to as sedentarization. Sedentarization occurs when formerly nomadic or transhumant peoples give up customary patterns of movement. These changes have occurred widely in rangelands, as a result of such factors as government policies, interventions from philanthropic organizations and through individual choice for lifestyle near settlements (Niamir-Fuller, 1999; FAO, 2001; Fratkin, 2001). Mobility may be further constrained by a lack of sufficient resources (e.g., boreholes, labor or transportation) required to utilize landscapes at broad scales (Dyson-Hudson and Dyson-Hudson, 1980; Schareika, 2001; Kerven et al., 2004).

Fragmentation of rangelands occurs most often as a result of changes in systems of land tenure. These changes are made for a variety of reasons—to facilitate protection or control of some key portion of the ecosystem, to implement private property rights, to promote economic intensification, or to enforce sedentarization of nomads (Galaty and Johnson, 1990; Perkins and Thomas, 1993; Starrs, 1998; Behnke, 1999; Ellis, 1999; Ellis and Lee, 1999).

3. Consequences of fragmentation for livestock and wildlife

Emerging evidence suggests that the productivity of populations of wild and domestic herbivores depends on access to heterogeneity in landscapes. Boone and Hobbs (2004) and Boone et al. (2005) conducted simulation experiments to examine the effects of fragmentation of ecosystems on livestock performance in east Africa. In these simulations, total area of landscape was held constant, but the landscape was dissected into progressively smaller parcels, as would occur from changes in land tenure without changes in land use. The total number of animals that could be supported declined as parcel size declined (Fig. 3). Wang et al. (2006) provided data showing that feedbacks from population density to population growth rate were weakened by increasing spatial heterogeneity in vegetation, implying that increased access to heterogeneity was associated with increased

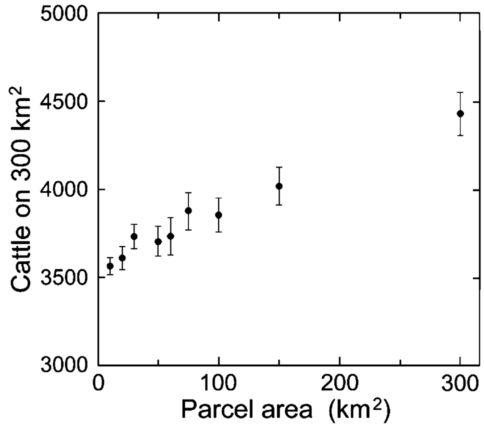

Fig. 3. The effect of declining parcel area on the number of cattle that may be supported on a 300 km^2 arid South African landscape, summing animals supported on parcels spanning from the single intact landscape to thirty 10 km^2 parcels. Standard error bars were generated using 12 simulations with randomized weather patterns (reprinted with permission from Boone and Hobbs, 2004).

carrying capacities. Similarly, Ash et al. (2004) suggested that in large, heterogeneous paddocks animal production is buffered in response to increasing stocking density, but at small, homogenous spatial scales of management there is a much stronger density dependent decline in animal performance. Local extinction of populations of wild ungulates in the Serengeti region of East Africa was predicted to result from restriction of access to spatiotemporally variable vegetation (Fryxell et al., 2005). Similarly, simulations have suggested that access to heterogeneous resources dampens temporal variability in large herbivore abundance in the Serengeti, while fragmentation creates instability (Owen-Smith, 2004).

In all of these cases, it appears that access to vegetation heterogeneity shapes population dynamics by enhancing the number of animals that can be supported on a landscape or by reducing the variance in animal numbers over time. Two mechanisms are believed to cause these effects. In the first mechanism, heterogeneity enhances the ability of pastoralists, livestock, and wildlife to track resources that vary over time and space, and in particular, to use resources that buffer populations from episodes of resource scarcity (Perevolotsky, 1987; Illius and O'Connor, 1999, 2000; Owen-Smith, 2004). Arid and semi-arid ecosystems are characterized by temporal variability in precipitation, which, in turn, creates variability in the quantity and quality of forage available to herbivores (Ellis and Swift, 1988; Coughenour et al., 1990; Illius et al., 1998). Buffering occurs when non-preferred resources remain lightly used when vegetation production is high. These non-preferred resources can then be used when production is low, thereby stabilizing population numbers (Illius and O'Connor, 1999; Owen-Smith, 2004). In addition, foraging herbivores respond to this spatial variability in resources by moving among areas of the landscape, seeking conditions where forage is abundant and nutritious (Perevolotsky, 1987; McNaughton, 1988, 1990; Coughenour, 1991). Movements occur at several scales (Senft et al., 1987; McNaughton, 1989; Scoones, 1995). In response to seasonal variation in resources, people and animals undertake large-scale migrations; for example, movements between winter and summer ranges in temperate ecosystems, and movements between dry and wet season ranges in tropical ones (Breman and de Wit, 1983; Coughenour, 1991). Within seasons, temporal variation in forage quality is created by plant phenology—immature, rapidly growing plants are more nutritious than mature plants (Van Soest, 1982). Plant phenology is rarely synchronized across the landscape, rather varying asynchronously as a result of spatial variation in elevation, aspect, and fine scale heterogeneity in weather (Coughenour et al., 1990; Albon and Langvatn, 1992; Wilmshurst et al., 1999; Mysterud et al., 2001; Fryxell et al., 2004, Hebblewhite et al. 2008). Wild herbivores, pastoralists and their livestock respond to gradients and pulses in forage quality by matching their distribution to spatially variable peaks and gradients in forage quality (Coppock et al., 1986; Coughenour et al., 1990; Scoones, 1995; Fryxell et al., 2004; but also see Baker and Hoffman, 2006; Hebblewhite et al. 2008). The value of access to heterogeneity has also been recognized in commercial pastoral situations where maintaining a mix of land types is often considered desirable, allowing asynchronous forage responses to rainfall (Ash and Stafford Smith, 1996).

In the second mechanism, heterogeneity helps herbivores to obtain resources that are not substitutable for one another. Herbivores require energy, nutrients, and water. These resources are often available at different locations on the landscape; concentrations of minerals may occur at places distant from water, and water may not be found in areas with the most nutritious forage. Mobility allows herbivores to obtain these non-substitutable resources by selecting diets from different locations on the landscape (Coughenour, 1991, 2008).

Clearly, the magnitude of the effect of fragmentation depends on the way in which resources are juxtaposed in space. If the full variety of resources can be found in all areas of the landscape and at all times, then the landscape can be dissected into spatially isolated units with nominal effects, but this is rarely the case in arid and semi-arid rangelands (Scoones, 1995). When different areas of the landscape contain different resources, then restriction of mobility of people and animals can prevent herbivores and pastoralists from matching their distribution to the resources they require to survive and reproduce. These effects can be profound—interruption of migratory pathways, for example, can render landscapes effectively unsuitable for people and animals, whereas connected landscapes provide viable habitat (Fryxell et al., 2005). In African grazing systems, large-scale animal movements are important to sustaining both domestic and wild herbivores during droughts (Coughenour et al., 1985; Homewood and Lewis, 1987; Walker et al., 1987) and access to a range of grazing areas is crucial in reducing mortality rates (Desta and Coppock, 2002). This is particularly true when animals are confronted by multiple drought events (Ellis and Swift, 1988; Illius et al., 1998; Oba, 2001).

4. Consequences of fragmentation for landscapes

Many of the world's rangelands are believed to be degraded as a result of excessive livestock grazing (Breman and de Wit, 1983; Milton et al., 1994). According to Illius and O'Connor (1999), the degree to which herbivores influence land condition and degradation is closely linked to the degree of coupling between animals and plants, climate variability, and the inherent resilience of the system. These authors developed the idea that spatial heterogeneity is a strong determinant of this coupling between plants and animals in semi-arid and arid grazing systems because of the dependence of animals on particular parts of the landscape during times of drought. Fragmentation of landscapes will therefore affect animal productivity and dynamics as well as landscape condition. The scale at which animals utilize landscapes and the scale of vegetation heterogeneity interact to determine the influence of animals on rangelands. As fragmentation compresses this scale of interaction, spatially localized coupling between plants and animals increases, raising the potential for the impacts of animals on the land to be expressed as land degradation.

At large scales, unfragmented landscapes allow mobility of animals across entire regions, permitting them to exploit many different resources. Asynchronous and spatially variable patterns in rainfall and localized disturbances like fire amplify spatial heterogeneity in soil and plant resources, further encouraging animals to move around the landscape (Fuhlendorf and Engle, 2001). This movement allows recently grazed areas to recover from grazing events as animals move from areas where resources are depleted to areas that have not been exploited. In addition, the risk of overgrazing and degradation may be low because there is a relatively weak coupling between animals and plant resources. In systems characterized by large-scale nomadic grazing, few, if any, inputs are used to keep animals alive during droughts. As a result, animals tend to die off during extended droughts before they adversely affect the plant–soil system (Ellis and Swift, 1988). Scoones (1994, pp. 1, 2) summarized this weak coupling as "livestock, under such conditions, do not have a long-term negative effect on rangeland resources." However, Illius and O'Connor (1999) argued that animals depend on "key resources", that is, resources that usually remain available during episodes of resource scarcity. Examples of key resources include swamps and riparian areas that remain productive during droughts (Scoones, 1995) or winter ranges where forage remains unobstructed by heavy snowfall (Hobbs, 1989). The existence of these resources means the system is not entirely uncoupled and there is, thus, the potential for landscape damage despite variability in the population size of herbivores (Illius and O'Connor, 1999).

At moderate spatial scales of grazing (e.g., large paddocks or pastures in commercial grazing systems) considerable spatial heterogeneity in plant and soil resources may remain after fencing, resulting in heterogeneity that may confer some benefits for animal production as described above. However, in most situations animals have access to the whole grazing area and they can continue to graze preferred areas even when they become resource depleted. The result can be degradation that commences in the most preferred parts of the landscape but then sequentially spreads to other parts (Ash and Stafford Smith, 1996). Management interventions such as burning to redistribute grazing or strategic resting of the paddocks can overcome risks of degradation at this scale (Andrews, 1986). Another fragmenting influence at this large paddock scale is isolated waterpoints, which can create a piosphere effect due to concentrated grazing at those locations (Lange, 1985). This leads to overgrazing and degradation and loss of biological diversity close to the water, while more distant areas remain ungrazed (James et al., 1999).

At small scales of grazing, that is, when landscapes are fragmented into very small units, there is very tight coupling between animals and plant resources (Baker and Hoffman, 2006). Managing the balance between animal numbers and forage can be difficult in semi-arid and arid environments because of the large climatic variability that results in large fluctuations in primary production from year to year. As a result, overgrazing can be a common occurrence and unless management intervenes to reduce the grazing pressure, deleterious changes in vegetation composition, primary productivity and soils, might ensue (Hudak, 1999). These changes in vegetation and soils usually require both drought and high grazing pressures to occur together (Hodgkinson, 1995). Drought on its own can alter species abundances and the vigor of plants; however, it rarely changes long-term species composition. In commercial grazing situations in particular, it is possible to maintain animals in small, fragmented landscapes through supplementation using fodder and/or protein and energy feeding strategies (Ash et al., 2002; Lackett and Hobbs, 2008). These external inputs have the effect of decoupling the animal–plant system and allowing animals to be maintained on land where they would have otherwise died or been removed. The risk of land degradation is especially high in this situation because there may be no feedback of vegetation condition on animal performance. Similarly, in highly fragmented communal grazing lands, where the main goal is livestock keeping rather than livestock production, the feedback effect of vegetation condition on animal condition is not a strong incentive to intervene until there is a strong likelihood of mortality (Scoones et al., 1996; Campbell et al., 2000). Consequently, the risk of degradation is high.

5. Consequences of fragmentation for livestock enterprises

Human actions cause landscape fragmentation not as an end in itself, but as a result of changes in land tenure and land-use practices that are usually aimed at achieving regional-scale policy objectives (e.g., reallocation of land rights; Hannam, 2000). Care is therefore needed to distinguish between the consequences of fragmentation per se, and the effects of accompanying changes in land tenure and land use. For example, when land is subdivided to accommodate a greater density of land users, the effects of fragmentation (smaller size of land units) need to be distinguished from those of increased pressure on land resources. We consider two ways in which fragmentation can affect how people use and benefit from rangelands: (1) where communal access to rangelands is replaced by exclusive rights to parcels of land; and (2) where private land tenure units are subdivided into a larger number of smaller units for reallocation. In both cases, as argued in the previous sections, one of the main consequences of fragmentation is that it breaks down spatial buffering of rangelands by coupling animal production more tightly to localized fluctuations in forage availability. Land users in fragmented landscapes are therefore exposed to greater risks from variability in animal production and an increased chance of degrading the long-term productive capacity of the land (McAllister et al., 2006).

Policies aimed at privatizing land and settling transhumant populations have had some success in achieving narrowly defined benefits for users of arid and semi-arid lands (Sandford, 1994). For example, the allocation of private land rights in communal pastoral systems can lead to more equitable access to land, whereby previously marginalized individuals are provided with direct control over parcels of land (Lesorogol, 2003, 2005; Reid et al., 2008). These land rights have allowed for the possibility of selling land, as well as securing access to loans (Grandin, 1986). In some cases, economic empowerment has been enhanced. Lesorogol (2005), for instance, shows how land privatization in a Kenyan pastoral area has increased prospects for income diversification and wealth. This has also promoted the installation of fences (Rutten, 1992; Kimani and Pickard, 1998; Reid et al., 2004) which, while fragmenting landscapes, has proved useful for controlling movements of domestic and wild animals, protecting crops and settlements, controlling animal disease, and improving herd and grazing management (Boone and Hobbs, 2004). Finally, privatized land tenure has also facilitated settlement (BurnSilver and Mwangi, 2007; Reid et al., 2008), which may allow landholders to benefit from greater access to services and greater participation in local economies.

However, these benefits have been accompanied by some unintended, negative effects of fragmentation. First, subdivision and privatization of formerly communally accessible land has altered access to forage and water (Boone et al., 2005; BurnSilver and Mwangi, 2007). People endeavor to enhance their economic state by, for instance, fencing or diversifying their livelihoods through agricultural production, but the result may affect neighboring herders and wildlife trying to access the resources they require. The allocation of key resources, such as formerly shared water, to individuals can disrupt land use for other landholders. Furthermore, this disparity may widen over time as those who received advantageous allocations of land prosper and compound their advantage by taking over less-viable land units (Rutten, 1992; Kabubo-Mariara, 2005; Mwangi, 2007). Second, fragmentation replaces flexible, broad-scale communal land-use arrangements (e.g., reciprocal access to grazing lands to escape localized drought) with more rigid land options, constrained within small private land units (Turner, 1999; but see McAllister et al., 2006). This loss of flexibility undermines the capacity of individual landholders to cope with drought and other risks (McAllister et al., 2006). Privitization and settlement can become further entrenched by a loss of social memory, and preferences for the increased access to services and economic participation that the new lifestyle affords. This can make it increasingly difficult to restore the mobility and broad-scale access to landscape complexity within these pastoral systems (Fernández-Giménez and Le Febre, 2006).

The second consequence of fragmentation occurs when privately owned units of land are subdivided for reallocation, such as what is planned under the South African land redistribution program (Zimmerman, 2000; Hall, 2004). Another example is offered by the early stages of pastoral settlement in Australia, during which land was subdivided to accommodate the demand for land, promote the growth of rural populations, distribute land more equitably and stimulate pastoral development (Hannam, 2000). These benefits, however, have not been achieved without cost. Where subdivision has progressed to the extent that land units are too small for land users to derive a livelihood, the reduction in income and loss of options for adaptation undermine the viability of enterprises (BurnSilver et al., 2003). Although this problem is chiefly due to a greater density of land users, rather than fragmentation, it can create a poverty spiral from which it is difficult to escape without strong policy intervention.

However, even where land units remain large enough to support viable enterprises in 'average' years, the constrained scale of land use may expose landholders to increased risk of fluctuations in forage production, such that their ability to cope with droughts is hampered. In Australia, land managers have adapted to these risks by developing agistment networks in which landholders with excess forage allow access to their land to those who have insufficient forage for their livestock (McAllister et al., 2006). These networks can enhance livestock productivity in temporally variable environments, particularly where spatial autocorrelation in resources is low (McAllister et al., 2006). There is also evidence that enterprise consolidation is occurring in some fragmented rangelands in Australia (Stokes et al., 2006) and in the US Great Plains (Lackett and Galvin, 2008). Where this is occurring, enterprises have the opportunity to restore the benefits of broad-scale access to spatial heterogeneity by selecting configurations of spatially dispersed properties with complementary attributes (e.g., properties in different climatic zones that experience different fluctuations in forage production, or properties with different types of forage matched to specialized animal production activities) (Stokes et al., 2006).

6. Human adaptations to fragmentation

Pastoral households, communities and institutions respond to fragmentation in ways that are shaped by the state of the fragmentation process. It is useful to distinguish three states:

(1) Fragmentation of the landscape is increasing, owing to the processes outlined above (increasing fragmentation).
(2) Fragmentation is decreasing, through policy- or market-led

aggregation (often re-aggregation of previously fragmented landscapes, or 'speeding re-aggregation').

(3) Fragmentation is advanced, and there are strong economic and/or socio-cultural reasons why this is very unlikely to be reversed ("chronic fragmentation").

There may be advantages and disadvantages associated with each state, and we imply nothing about the well-being *per se* of pastoralists or the status of natural resources at each state. These states, however, provide a useful framework for thinking about public and private adaptation options, as these will differ depending on the state of the fragmentation process. In broad terms, if fragmentation is increasing, measures might most usefully be aimed at slowing or arresting the increase, unless there are overwhelming advantages to fragmentation. If fragmentation is decreasing, measures that promote re-aggregation may be appropriate. If fragmentation is already highly advanced and unlikely to change, measures are needed that can mitigate the problems caused by lack of mobility, loss of access to forage and water, and possible over-use of natural resources.

Adaptation refers to actions that are taken by individuals, communities, organizations and governments as a response to ameliorate the negative consequences of change (Smith et al., 1996; Smit and Pilifosova, 2001; Smit and Wandel, 2006; Nelson et al., 2007). It is possible to distinguish between public and private adaptations (Adger, 2003; Adger et al., 2003; Kurukulasuriya and Rosenthal, 2003). Public adaptations include such actions as government land-use planning, land tenure policy design and implementation, and conservation of natural resources. Public adaptations may be initiated at the national, regional or local levels, and they often imply a consortium approach that can combine blunt national policy instruments with much more sharply focused landscape-level policies and individual action (Lynam, 2006).

There are several kinds of private adaptation. First, households may intensify existing production patterns, whereby physical or financial productivity is increased (Galaty and Johnson, 1990). Second, households may diversify their livelihood options. This might involve diversification of agricultural activities to spread risk, increased income from off-farm employment, or carbon payments to households, for example. A third adaptive response is to expand the size of managed resources, for instance, through land reform or consolidation of land holdings. Fourth, pastoralists can substitute social capital for natural capital, that is, they may be able to increase the mobility of their livestock and their access to more heterogeneous landscapes by utilizing kinship networks or other customary or legal arrangements that allow their livestock to access key grazing resources (e.g., BurnSilver and Mwangi, 2007; Galvin, 2008). A fifth adaptive response is an exit from pastoralism and agriculture altogether (Rutten, 1992). We give examples of some of these adaptation responses below in relation to the situations where fragmentation is being slowed, where re-aggregation is occurring, and for the case of chronic fragmentation.

Efforts by communities, landowners and local institutions to slow fragmentation (state 1 above) can yield big benefits for landscape connectivity, allowing wildlife (and other organisms) and pastoralists to continue to access landscape heterogeneity. These take the form of land purchases, legal structures such as conservation easements, and social/economic agreements such as grazing associations, wildlife/livestock corridors, and land leases. In Kajiado, Kenya, while herders in Imbirikani Group Ranch want to privatize land holdings to secure ownership, they are also concerned about losing access to larger landscapes during the dry season and droughts if new landowners establish exclusive use rights on their new parcels (Fig. 4a). These communities thus use their social capital to maintain landscape connectivity through grazing associations that assure reciprocal grazing rights (BurnSilver and Mwangi, 2007). Other communities in the same district, in the Athi-Kaputiei Plains, work with non-governmental organizations (NGOs) and the state-run wildlife parastatal, which pay landowners to keep fences down, thus allowing freer movement of animals by keeping migratory corridors for wildlife and livestock open (Kristjanson et al., 2002; Reid et al., 2008). Similar informal arrangements can be seen in the agistment networks of Australia (McAllister et al., 2006).

Commercial pastoral systems in Australia are typical of systems where re-aggregation is occurring (state 2 above; Fig. 4b). In Dalrymple Shire, fragmentation is not very advanced and large properties are still economically viable. Farmers here have recognized the need to increase the scale of operations for economic reasons and to spread climatic risk, so they are using normal market forces to overcome fragmentation through property acquisitions. This is having a spectacular impact on land values in the region, which are increasing (Stokes et al., 2008).

An example of chronic fragmentation (state 3 above) is afforded by the "post-industrial" land tenure and use situation of the Jackson Valley, Wyoming, USA, which is analyzed by Lackett and Hobbs (2008). Here, a pre-European settlement period of communal land use by both Native-American hunter–gatherers and European fur trappers was followed by a period of fragmentation, as land was converted to private ownership for permanent European settlement and ranching in the 1880s and 1890s (Fig. 4c). Fragmentation was further compounded by the need to mitigate conflicts with wild ungulates, such as elk, whose access to winter ranges was cut off by roads, fences and agricultural development. This period was followed by a period of consolidation, where ranches were expanded to take advantage of economies of scale. As the area is becoming increasingly attractive to the recreation industry, there is again increasing fragmentation; large agricultural holdings are being subdivided into housing tracts for residential and commercial development, to cater to the rising human population. In this region, fragmentation is here to stay. The high level of external labor and capital inputs required to maintain the local elk population, in itself a tourist attraction, bears witness to the local severity of fragmentation.

The adaptations described are applicable to each type of fragmentation. For example, pastoralists may substitute social capital (e.g., livestock associations, formal and informal networks) for natural capital to gain access to resources that have been fragmented by fences (dissection), conversion to cropland (decoupling) or by sedentarization (compression) (Fratkin, 1998; BurnSilver and Mwangi, 2007; Reid et al., 2008).

7. How can public policy support efforts to adapt to fragmentation?

At broad political levels (district, national, regional), public policy can either support or hinder efforts by landowners and communities to adapt to fragmentation at the landscape scale. As shown above, there are compelling reasons for human societies to fragment range landscapes; these include securing ownership of land and water, controlling livestock movements, and establishing controlled use of scarce resources like water or dry season pastures. However, under some circumstances, the costs of fragmentation are high enough that policies that slow further fragmentation or re-aggregate fragmented landscapes can bring significant social and private benefits. In cases where fragmentation is chronic, public policy has a role to play in relieving some of the associated costs. To be viable, the benefits of slowing

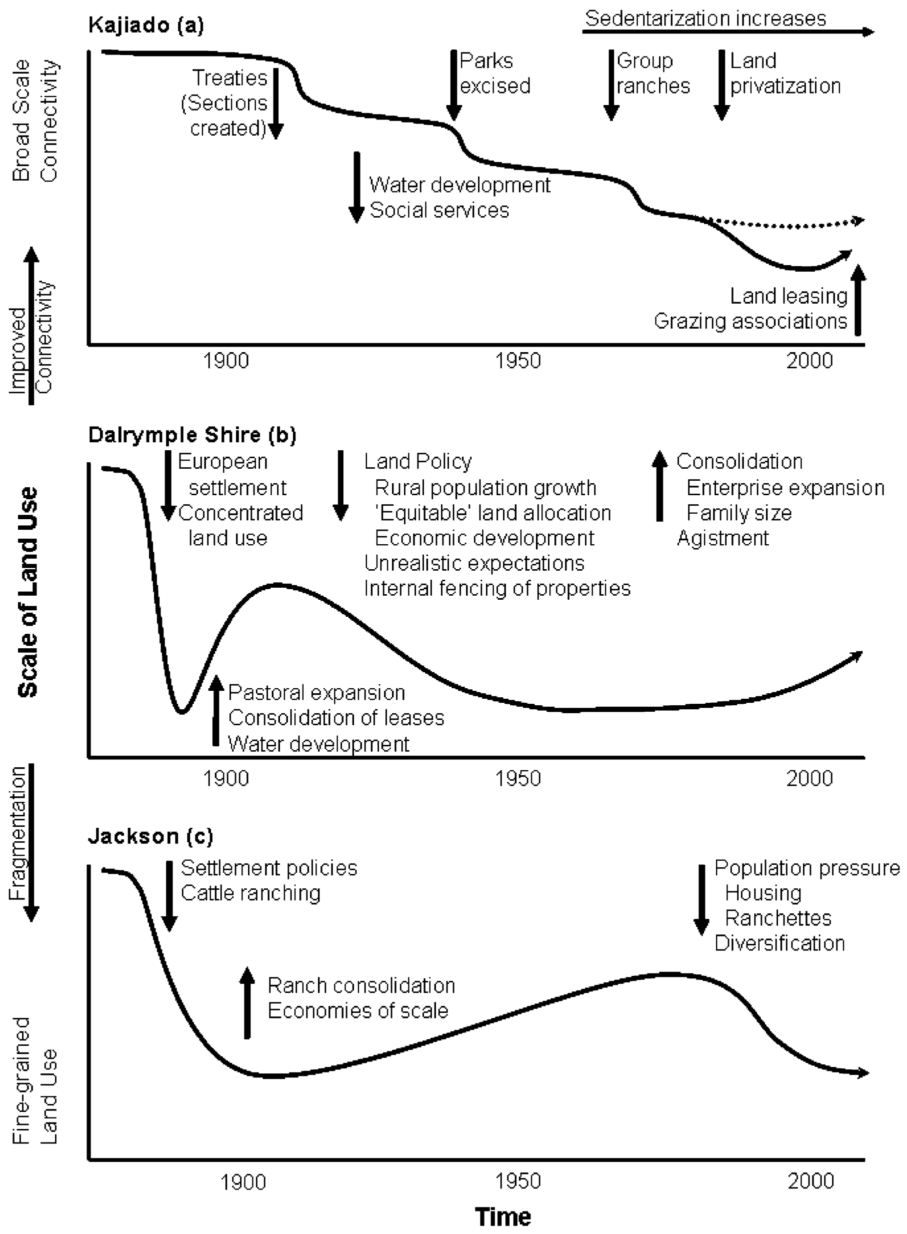

Fig. 4. Historic patterns of fragmentation in three contrasting rangelands around the world in Africa (a), Australia (b), and North America (c) show three states of fragmentation. Downward arrows indicate the diverse set of drivers that have reduced the scale of land use, mobility of land users and access to landscape heterogeneity. Upward arrows indicate drivers that reconnect land fragments, restoring broad scale access to heterogeneous resources.

fragmentation or aggregation need to clearly outweigh its costs—a big win, small loss situation (DeFries et al., 2004). Even better is aggregation that simultaneously delivers access to wider landscapes and some of the same benefits that herders seek through fragmentation, such as secure tenure and controlled access to valuable resources (a win–win situation).

In general, evaluating the costs of implementing different policies and the benefits that are likely to accrue to different stakeholders is not easy, however (Prugh et al., 1999). Evaluating policy impacts on livelihoods and the environment is particularly complex: even if the economic impacts can be appropriately estimated, the social impacts associated with particular policies may enhance representation and participation on the one hand or foster exclusion and marginalization on the other (Homewood, 2004). There are other issues associated with trying to understand how different policy options may influence fragmentation at the landscape scale. One is associated with institutions. Few institutions, especially in developing countries, naturally operate at the landscape scale; many function locally and internationally, but not in the 'missing middle' (Tomich et al., 2004). For example, ministries of agriculture tend to focus on the farm and the sector as a whole, but not on the landscape level. When it comes to implementing policy, collective action is more difficult when the actors are heterogeneous (i.e., due to language and geographic barriers and the involvement of many people, communities, or institutions). Action is thus problematic and institutions are weaker in this missing middle and this makes policy action particularly difficult (Reid et al., 2006). A second issue is that making collective decisions is a process with considerable transaction costs (Cousins, 1996; Campbell et al., 2000). While the conditions under which local institutions are likely to emerge to enable such collective decision-making are reasonably well-understood (Ostrom, 1999), most situations are likely to require multiple institutions working at multiple spatial scales, with multiple authorities, and with multiple functions (Niamir-Fuller, 1999). All policies have some transaction costs in addition to any benefits they may have, and their evaluation has to draw on a wide variety of multidisciplinary sources, if promising options are to be identified that have largely positive outcomes for both development and the environment (Homewood, 2004).

We see several ways in which appropriate policy can slow fragmentation or encourage aggregation. Some of these suggestions will require strong adaptation of policies developed for sedentary populations, if they are to break the cycle of further fragmentation. First, public policy can actively support re-aggregation of fragmented landscapes. One example is in south-west Queensland, where property sizes have already been too fragmented and many are sub-economic in scale. Many owners do not have the capacity to expand or to intensify, and costs continue to rise. In this particular region the State Government intervened to provide financial incentives for consolidation and to provide science-based tools to achieve more sustainable carrying capacities (Johnston et al., 1996; Hewitt and Murray, 1999). These incentives have not led to widespread property consolidation and more proactive government intervention may be required to achieve increases in scale that are needed if these pastoral systems are to thrive rather than merely survive against the odds.

Second, there is a need to move from a segregated, sectoral approach to a more integrated systems approach in policy development (Bridging the gulf, 2005). For many range landscapes, there is a tangle of jurisdictions and opposing incentives and disincentives to fragment landscapes. On the one hand, policy for agriculture and market incentives almost always favors intensification of land, labor and capital, which can encourage herders to settle down and substitute inputs for landscape heterogeneity. On the other hand, most policies concerning natural resources encourage conservation of unfragmented landscapes to conserve wild populations of plants and animals. When these policies meet in the same landscape, as they do in rangelands, conflicts arise and a patchwork of public and small landholdings appears (BurnSilver, 2007; BurnSilver and Mwangi, 2007). This highlights the need for a change in the way policy is developed, with a more integrated and negotiated approach to whole systems uniting various sectors. This is the approach adopted by the Reto-o-Reto project, a collaborative research project that focuses on pastoral welfare, ecosystem and wildlife conservation and trade-offs between different land-use strategies in fragmenting rangelands of Kenya and Tanzania. By continually working with policy makers at the local, regional, and national levels, this project has developed actions plans and contributed to the revision of national policies dedicated to issues of pastoral and livestock development, land use and wildlife management (Reto-o-Reto, 2007).

Third, much development policy directly or indirectly encourages pastoral people to settle (Fratkin, 1997), creating a growing nuclei of chronically fragmented landscapes. In wetter rangelands, intensification of production integrated with soil and nutrient conservation can allow settled herders to become productive farmers. This may limit the spread of fragmentation, if returns to land improve. Public policy here needs to support farmer access to inputs and markets to substitute for their lost access to landscape heterogeneity.

In the drier rangelands, for herders who need and want to herd over extensive ranges, there remain strong incentives to settle in one location. Families choose to limit their mobility in order to access social services, such as health care and education, and to access markets by settling around towns (Rutten, 1992; Blench, 2000). Here, public policy can support herders in several ways: by improving returns to extensive pastoralism, for example, through increasing accessibility both to markets and to price information, by substituting mobile services for those usually only available in towns, and by encouraging development of ecosystem service payments and ecotourism in rangelands. Policies in the education, health and veterinary sectors can include novel ways to deliver information and services to families in remote areas to break the cycle of settlement and further fragmentation. Furthermore, as new international markets continue to develop, such as those for organic beef, carbon or biodiversity credits, national policy bodies could serve as brokers to connect communities in extensive rangelands to markets willing to reward them for maintaining open and unfragmented landscapes.

8. Conclusion

Human actions worldwide are fragmenting the ecosystems of the earth into spatially isolated parts. Fragmentation occurs in many ways including dramatic, physical changes in land cover that might occur when forests are cleared for agriculture, as well as more subtle forms occurring when altered systems of land tenure restrict mobility of people and animals. Many of these actions are taken to enhance human welfare, and often measurable enhancements in people's livelihoods and well-being are realized. However, although actions that fragment landscapes may provide benefits, there are accompanying ecological and economic costs that often remain unaccounted for. We have developed the argument that spatial isolation in grazing ecosystems limits the ability of people and animals to exploit a fundamentally important resource: heterogeneity in vegetation. Access to heterogeneous vegetation on intact landscapes increases options for wildlife, pastoralists, and their livestock on these landscapes. These options can be critical in arid and semi-arid environments, allowing consumers to compensate for temporal variation in resources by selective use of spatial variation. In the absence of these options, external inputs are often required to sustain human economies and ecological processes.

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