Landscape Ecol (2020) 35:2433–2447
https://doi.org/10.1007/s10980-020-01068-8

REVIEW ARTICLE

Landscape sustainability science in the drylands: mobility, rangelands and livelihoods

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Received: 22 January 2020 / Accepted: 7 July 2020 / Published online: 17 July 2020

Abstract
Context The global drylands cover 41% of the terrestrial surface and support millions of pastoralists and host diverse flora and fauna. Ongoing socioeconomic and environmental transformations in drylands make it imperative to understand how to achieve the twin goals of food security and ecosystem health.
Objectives The review focuses on examining the patterns of rangeland vegetation dynamics and livelihood transformations associated with changes in pastoralist mobility.
Methods We conducted a comprehensive review of literature on dryland sustainability based on the coupled systems framework and through the lens of mobility, which reflects not only human and livestock movements but also the unique lifestyles and cultural identities of people in drylands.
Results We find that mobility, which is critical for pastoralists to survive and thrive in the drylands, is generally in decline and has significant implications on dryland sustainability. Reduced mobility exacerbates bush encroachment and land degradation, as sedentarized pastoralists use the rangelands more recursively. Associated with declining mobility is livelihood intensification and diversification, but such livelihood transitions may carry both socioeconomic and environmental risks.
Conclusions We argue that to advance landscape sustainability science and reconcile concerns over environmental conservation and human well-being across the global drylands, we must better understand the underlying mechanisms of coupled systems transitions through the lens of mobility, and integrate the perspectives of multiple stakeholders with fundamentally different interests and priorities.

Keywords Dryland · Mobility · Rangeland · Livelihoods · Landscape sustainability

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Introduction

Globally, dryland systems cover 41% of the terrestrial surface, provide over $1 trillion in ecosystem goods and services to 38% of the global population (FAO

2001; Reynolds et al. 2007), and house over one-third of the global biodiversity hotspots (Myers et al. 2000). Ongoing socioeconomic and environmental transformations in drylands make it imperative to examine the tradeoffs and co-benefits between the twin goals of food security for those dwelling in drylands and the ecosystem health of the rangelands themselves. These two goals, while intersecting with multiple United Nations Sustainable Development Goals (SDGs), are directly aligned with #2 Zero Hunger and #15 Life on Land, because drylands not only support the livelihoods of millions of pastoralists (Galaty and Johnson 1990; Dong et al. 2011), but also host diverse flora and fauna (MEA 2005). However, ongoing socio-environmental changes threaten the long-established resource-use patterns and alter the vegetation states and transition pathways in drylands (McCabe et al. 2010; Wu et al. 2015; Hauck and Rubenstein 2017). Climate change causes the fragile dryland ecosystems to experience more frequent and prolonged drought (Asner et al. 2004; Behnke and Mortimore 2016). At the same time, socioeconomic changes such as rapid population growth, urbanization, sedentarization, land-tenure reforms, and cropland expansion fracture drylands into spatially isolated pieces, accelerate rangeland degradation and wildlife habitat loss, and discourage mobile livestock herding (Reid et al. 2004; Li and Huntsinger 2011). These pressing challenges have made dryland sustainability a globally urgent issue.

Livelihood and vegetation dynamics in drylands are strongly coupled because resource-use patterns of pastoralists have substantial implications for rangeland vegetation, and changes in vegetation in turn shape pastoralist livelihoods (Reid 2012; Briske 2017). Although mobility is a core strategy for pastoralists to survive and thrive in drylands (Adriansen 2005; Turner and Schlecht 2019), its measurement remains ambiguous, and its role in determining system coupling and driving system transitions needs greater elucidation. Understanding mobility and socio-environmental system transitions in the drylands requires not only an interdisciplinary approach, but also a shared overarching theoretical framework (Levin et al. 2013). Meanwhile, it is necessary to develop context-specific and use-inspired science for achieving synergistic outcomes in ecosystem services and human well-being in dynamic landscapes under rising uncertainties (Wu 2013). Ostrom's nested framework (Ostrom 2007, 2009) allows us elaborate the coupled nature of dryland socio-environmental system components as also to integrate different disciplinary approaches for an improved understanding of the processes, feedbacks, dynamics, and transitions characterizing specific dryland systems (Fig. 1).

In the coupled systems framework we adopt to analyze dryland sustainability, social components include resource users (pastoralists and their livelihood strategies) and governance system (herding regimes). Food security, a key outcome variable of dryland sustainability, is subject to interactions between resource users, customary and state institutions, and a range of exogenous events. Mobility and institutions governing it are central to dryland system dynamics. Socio-institutional interventions such as sedentarization initiatives tend to undermine prevalent pastoral resource-use principles, negatively affecting livelihoods (Fratkin and Roth 2005). Institutions resting on reciprocity and planned grazing can nonetheless facilitate positive livelihood outcomes (Dixit et al. 2013; Odadi et al. 2017).

Environmental components in dryland systems include the resource system (rangeland vegetation) and resource units (forage). Rangeland vegetation states and transition pathways are influenced by both broad- and fine-scale socio-environmental factors. At broad spatial scales, climate variables (temperature and precipitation) control the distribution and dynamics of rangeland vegetation types. At finer spatial scales, mosaics of forage resources suggest that climate and vegetation are decoupled (Staver et al. 2011a, b), leading to divergent rangeland transition pathways that are primarily determined by local livestock herbivory (Liao and Clark 2018).

Complex feedback mechanisms within the coupled socio-environmental systems determine system outcomes. On the one hand, characteristics of pastoralists and rangeland governance institutions strongly shape mobility strategies and herd portfolio (process 1 in Fig. 1), in turn determining rangeland vegetation dynamics (process 2 in Fig. 1). As pastoralists sedentarize and herd livestock near and around their settlements in response to external sedentarization initiatives, rangelands can shift into bare ground or shrublands with minimal grazing value (Liao and Clark 2018). Many such transitions are largely irreversible even if herding practices are altered

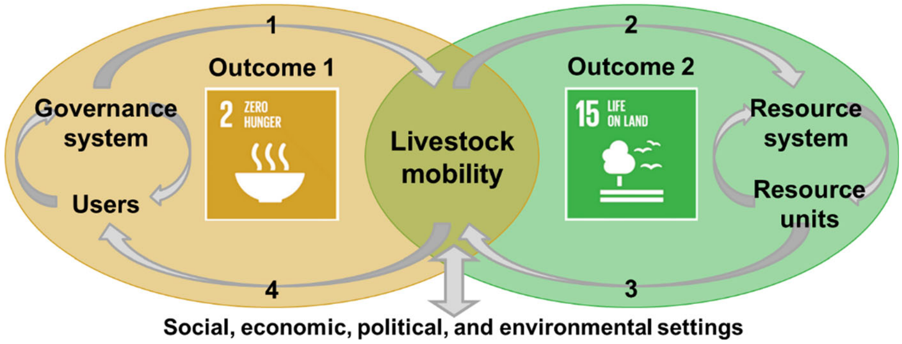

Fig. 1 Social and environmental components of dryland systems with complex feedbacks between resource system, resource units, users, and governance system

(Westoby et al. 1989; Cingolani et al. 2005). On the other hand, the spatiotemporal heterogeneity of forage resources strongly affects livestock mobility and resource-use behaviors (process 3 in Fig. 1), and thereby livestock production outcomes and food security (process 4 in Fig. 1) (Behnke et al. 1993; Odadi et al. 2018). Forage quality and quantity also affect herd size and portfolio management. In cases where rangelands are heavily degraded, pastoralists are likely to adopt non-pastoral livelihoods, but the effects of such adaptations on well-being remain unclear (McPeak et al. 2012; King et al. 2017).

In this paper, we argue that it is crucial to adopt a coupled systems framework to examine how pastoralist mobility affects rangelands and livelihoods, as well as the interactions and feedbacks within the socio-environmental system. Given the significance of mobility to Zero Hunger and Life on Land in the drylands, we must understand the role of mobility to achieve the twin goals. Specifically, we explore three questions: (1) how do pastoralists employ mobility strategies at different spatiotemporal scales in the drylands and how is their mobility affected by socio-environmental characteristics and shifts; (2) how do macro- and micro-scale variables affect rangeland vegetation dynamics and regime shifts; and (3) how do pastoralists adjust their livelihood strategies in response to rangeland vegetation transitions?

In the remainder of this paper, we first offer a synthetic discussion on the significance of mobility in drylands, the institutions that support mobility, measurement of mobility at different scales, and trends of mobility change. Then we examine major trends of rangeland vegetation regime shifts and their determinants, and apply the state-and-transition model to interpret changes in rangeland vegetation dynamics as a result of changes in institutions and resource-use patterns. After that we elaborate the major transformations in pastoral food production in drylands, namely intensification and diversification. We also examine the how alternative strategies resting on traditional ecological knowledge and institutions can contribute to food security and rangeland sustainability. At the end, we discuss the implications of dryland systems in transition, and highlight future research priorities.

Pastoralist mobility

Mobility is arguably the most important strategy adopted by millions of pastoralists worldwide to survive and thrive in the drylands (Adriansen 2005; Homewood 2008; Reid 2012; Turner and Schlecht 2019). Practicing mobility not only meets the nutritional demands of livestock and ensures pastoral food security, but also redistributes grazing pressure, reduces rangeland vulnerability, increases ecosystem resilience, and promotes land sharing with wildlife (Briske et al. 2011; Niamir-Fuller et al. 2012; Crawford et al. 2019). On the one hand, the quality and quantity of forage resources within a single patch of dryland can vary vastly both intra- and inter-annually in response to changes in precipitation and other environmental conditions (Behnke et al. 1993). Rather than fixed control of a specific piece of land, pastoralists in drylands typically require flexible access to multiple pastures in well-dispersed and strategic locations. On the other hand, pastoralists have to constantly negotiate with their neighboring counterparts, sedentarized communities, and the state governments in order to maintain access to pastures at different locations (Kassam 2010; Moritz 2010). In this sense, mobility is also a result of how and who controls resources and over what spatial and temporal expanse.

Customary pastoralism involves both flexible institutions and constant negotiations for gaining and securing access to seasonally variable forage resources (Blewett 1995; Mwangi and Ostrom 2009). While pastoralists are engaged in community-based governance in which they create and adapt rules regarding the agreed-upon harvesting strategies and community member obligations, politics is also ubiquitous in the interactions between pastoralists and their neighbors and state officials, in their exchanges in markets and with farmers, and in their internal relations as a community (Agrawal 1999). In order to deal with spatio-temporal heterogeneity of forage resources, commercial ranchers on the drylands of Australia often purchase grazing rights on more productive land. This practice, known as agistment, relies on mutual trust because hosts of temporarily transferred herds are responsible for taking good care of them and only easy-to-manage livestock should be sent by owners (McAllister et al. 2006). However, in places where herders lack cash to practice agistment, multi-scale reciprocity of resource sharing among pastoralist groups and with agricultural communities play a significant role in facilitating large-scale movement (Dixit et al. 2013). Therefore, institutional developments that support community capacity building, improve resource management, and promote distributive equity are fundamental to the practice of seasonal migration and camp relocation (Coppock et al. 2011; Leslie and McCabe 2013). Meanwhile, as the state attempts to extend its capacity to transform pastoralist lifestyle towards sedentarization through various development intervention and conservation programs, pastoralists will have to adjust their mobility and livelihood strategies (Liao and Fei 2017), and the continual exercise and negotiation of power relationships will shape how institutions are constructed, reproduced, and changed in pastoralist communities (Fratkin and Roth 2005).

Pastoral mobility can be generally considered as cumulative livestock movement on the rangelands within a given time period. At different spatio-temporal scales, there are two main types of mobility: (1) broad-scale movement that involves changing camp locations from one site to another across seasons, which is also understood as travel mobility, and (2) fine-scale daily movement within one-day reach from camps, also known as grazing mobility (Adriansen 2008; Turner and Schlecht 2019). According to broad-scale movement features, subsistence livestock herding can be classified as nomadism, transhumance, and sedentarized pastoralism (Dyson-Hudson and Dyson-Hudson 1980). Nomadic pastoralists search for forage extensively throughout the landscape, while transhumant pastoralists migrate seasonally along an environmental gradient. These two types of pastoralists exhibit a higher degree of broad-scale mobility than sedentarized pastoralists, who have at least one permanent settlement around which production activities are primarily practiced. According to whether nomadic herds are kept or not, sedentarized pastoralists can be further differentiated as settled herders with nomadic herds and sedentary herder-farmers who graze their livestock around settlement year-round (Reid 2012).

Because of the variation of mobility across spatio-temporal scales, mobility measurement needs to capture both broad- and fine-scale patterns, and should be quantified in quite different ways. Turner and Schlecht (2019) summarized a wide of range of indicators to measure mobility. At the fine-scale, the indicators include (1) daily cumulative travel distance, (2) daily maximal distance of movement from camp, (3) daily duration of grazing, (4) frequency of movement while grazing, and (5) frequency of watering. At the broad-scale, the indicators include: (1) annual cumulative movement distance, (2) frequency of camp relocation throughout the year, (3) maximal distance between base camp and satellite camps, (4) weighted density of transitional camps visited during the year, and (5) average distance travelled between adjoining transitional camps.

Various approaches have been adopted in collecting data to study pastoral mobility. For example, interviews, observations, participatory mapping, and household surveys have been used to gather original information on how pastoralists move (Homewood and Lewis 1987; Brottem et al. 2014; Liao et al. 2014a, b). Data collected using these approaches, however, are often of limited accuracy and reliability. Although findings based on such data shed light on broad-scale seasonal migration practices, they barely reveal fine-scale movement details and resource-use patterns. The emergence of GPS-tracking technology and evolving spatial analysis capacity have advanced the study of pastoral mobility. Portable GPS units installed on livestock provide highly detailed information on fine-scale mobility (Butt et al. 2009; Moritz et al. 2010; Wario et al. 2016). However, extensive movement behaviors (e.g. camp relocation) are insufficiently captured in many GPS-tracking efforts due to short battery lifespan and intensive labor requirement.

Thanks to the development of low-cost, long-lifespan GPS-tracking technology (Clark et al. 2006), more frequent, continuous, and cross-season data can be collected to quantify pastoral mobility at both broad- and fine-scales. For example, Liao (2018a, b) developed a metrics system, and used intensive, cross-season GPS-tracking data (Liao et al. 2017) to evaluate multi-scale mobility across five communities in southern Ethiopia. The metrics system includes both seasonal indicators such as home range and number of camps, and daily indicators such as herding loop length, maximum distance from camp, and angular distribution of observed cow locations (Fig. 2). The findings suggest that due to variations in population density, precipitation, and presence of government development intervention programs, pastoral mobility patterns are highly heterogeneous even within the same region, ranging from sedentary herder-farmers who completely gave up camp relocation to settled herders who keep nomadic herds (Liao 2018a, b). Rather than generalizing mobility pattern according to any single indicator, comprehensive across-scale evaluation is necessary to understand pastoral mobility as a critical strategy to manage herds in the drylands.

In modern pastoralism, mobility has been increasingly compromised at the broad scale (Turner and Schlecht 2019). Erosion of customary land claims, creation of new administrative boundaries and land tenure, and development of new state institutions structured primarily to serve sedentary populations have compromised both pastoral mobility and institutions supporting pastoralist livelihoods over the long run (Fernandez-Gimenez and Le Febre 2006; Li et al. 2018). The expansion of crop cultivation and the promotion of environmental conservation through payment for ecosystem services schemes, coupled with rapid population growth and urbanization, exacerbate the competition for land and water and constrain the scope of seasonal movement (Georgiadis et al. 2007; Liao et al. 2014a, b; Zhang et al. 2019). Furthermore, rangeland degradation and environmental change have diminished the natural resource base of livestock herding, forcing pastoralists to reduce effort in mobile pastoralism and seek alternative livelihood strategies (Pricope et al. 2013; Unks et al. 2019). In particular, climate change is expected to threaten pastoralist livelihoods, as both modeling and empirical results suggest that reduced amount of annual precipitation and increasing drought frequency would substantially reduce the supply of forage resources, and negatively affect subsistence mobile livestock herding and household income (Ellis and Lee 2005; Martin et al. 2014; Gongbuzeren et al.

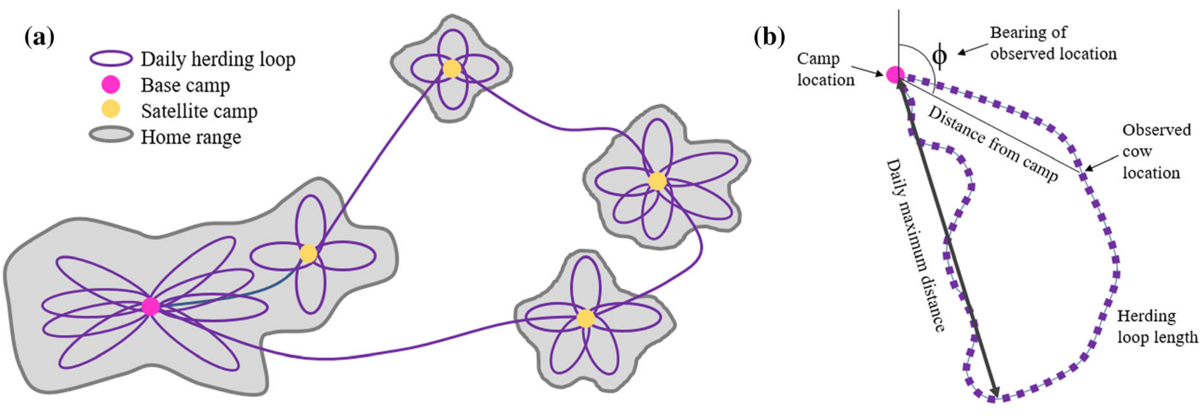

Fig. 2 Pastoral mobility metrics at the seasonal (**a**) and daily (**b**) levels. Seasonal metrics include home range (determined by a threshold of probability of utilization distribution) and number of camp locations. Daily metrics include daily maximum distance from camp, herding loop length, and angular distribution of observed cow locations (Liao 2018a)

2018). Consequently, subsistence pastoralists have to explore forage resources in nearby commercial ranches or conservation areas at during environmental stress, or adapt their livelihood strategies to the requirements of sedentarization and diversification associated with compromised broad-scale mobility.

At the local scale, however, pathways of mobility transition can be divergent. On the one hand, pastoralists may reduce their daily travel efforts in livestock herding as a result of diversification into non-pastoral livelihoods such as crop cultivation or small business. On the other hand, emerging evidence suggests sedentarized pastoralists are engaged in more intensive fine-scale movement on a daily basis than those practicing camp relocation. In contrast to nomadic or transhumant pastoralists who can set up satellite camps in under-utilized rangelands farther away from settlement areas, sedentarized pastoralists must increase their daily herding loop length as the dry season approaches so as to reach suitable grazing areas which become increasingly distant as nearby forage is incrementally consumed. In this sense, sedentarized pastoralists demonstrate greater movement intensity than their nomadic or transhumant counterparts. For example, in the East African savanna where subsistence pastoralism is challenged by woody plant encroachment and socio-political pressure towards sedentarization, pastoralists increase their daily herding route distance to compensate for forage gap after they stop practicing seasonal migration (Liao et al. 2017). Similar problems face Samburu and Masaai pastoralists in central-northern Kenya (Hauck and Rubenstein 2017).

As mobility is crucial for achieving synergies between subsistence livestock herding and rangeland sustainability, future development of institutions should cater to the needs of mobile pastoralists rather than merely emphasizing on sedentarization and disregarding pastoralists' customary access to resources. Recognizing the reality of shrinking space for migration, negotiated movements and planned grazing are becoming essential to achieve synergies in subsistence livestock herding and environmental conservation (Dixit et al. 2013; Odadi et al. 2017). For example, in order to promote wildlife conservation while ensuring local food security, dozens of community conservancies have been established by the Northern Rangeland Trust (NRT) since 2004 in Kenya. Like other community-based natural resource management institutions (Nelson and Agrawal 2008; Ulambayar et al. 2017), community conservancies aim to give local people more control over the management of communal lands and natural resources (NRT 2018). One rangeland management strategy created by NRT is planned grazing, which is to be implemented at the zonal/settlement level by opening small blocks sequentially to control livestock movement. As pastoralists sedentarize, the next best strategy to prevent overgrazing is rotational grazing with a fallow period, as bunched rotational grazing leads to disproportionate consumption of the less palatable forage species (Crawford et al. 2019). In addition, land sharing via leasing the land and paying a management fee also seems to be commonly adopted (McAllister et al. 2006). Future research needs to investigate the role of such new strategies to advance our understanding of how changes in rangeland governance institutions affect pastoralist mobility, and determine livestock production outcomes and rangeland sustainability.

Rangeland vegetation dynamics

Human society needs dryland ecosystems to provide multiple services effectively, especially as the pressure on drylands increases due to local impacts such as overgrazing to regional and global impacts such as climate change. Throughout the global drylands, a suite of critical ecosystem services, such as net primary production, carbon storage, and provision of nutrient pools, is vital for halting desertification and sequestering carbon (Flombaum and Sala 2008; Cardinale et al. 2011; Zhao et al. 2020). It is estimated that drylands host many endemic plant and animal species (MEA 2005) and include about 20% of the major centers of global plant diversity and over 30% of the designated endemic bird areas (White and Nackoney 2003). Such species richness is crucial for dryland ecosystem function. Among them, plant species richness in drylands enhances their multi-functionality and the ability of ecosystems to provide multiple functions such as carbon gain, carbon storage, and nutrient cycling (Maestre et al. 2012).

Drylands are globally undergoing a range of vegetation regime shifts. Among these changes, woody plant proliferation, commonly known as bush encroachment, has been a growing concern for rangeland management in many parts of the world

(Brandt et al. 2013; Anadón et al. 2014; Gartzia et al. 2014). Bush encroachment substantially suppresses the growth of high-value herbaceous forage species in the understory, reduces indigenous plant biodiversity, and alters rangeland ecosystem functions (Scholes and Archer 1997; Rundel et al. 2014). For example, throughout the East African drylands, woody species such as *Acacia mellifera*, *A. oerfota*, and *A. reficiens* have been proliferating, which outcompete understory grass species such as *Cenchrus ciliaris*, *Chrysopogon aucheri*, *Cynodon plectostachyus*, and *Pennisetum glaucifolium* (Liao et al. 2016). Such vegetation regime shifts not only change the hydrological and biogeochemical processes in the drylands (Asner et al. 2004), but also threaten pastoralist food security that rests on cattle herding (Smith et al. 2000).

While early rangeland management practices was commonly based on equilibrium carrying capacities, findings in the recent decades suggest that the arid and semi-arid rangelands are constantly at disequilibrium (Behnke et al. 1993; Gillson and Hoffman 2007). The dryland ecosystems are subject to multiple stable vegetation states with different species composition and morphological structure (Staver et al. 2011b). Precipitation, temperature, fire, grazing, and soil have all been described as crucial in the origin, maintenance, and shift of vegetation on the global drylands (Lehmann et al. 2011; Stevens et al. 2017). While climatic and edaphic factors primarily determine broad-scale vegetation distribution, complex patches of open and closed canopy rangelands can exist within a single climate zone, suggesting that controls such as fire and grazing are important at a finer spatial scale (D'Odorico et al. 2011; Archibald et al. 2012).

Grazing is a crucial factor in shaping vegetation dynamics in rangelands (McNaughton 1983, 1985). Various efforts have been made to assess its fine-scale quantitative patterns. For example, grazing intensity can be inferred from livestock census data (Staver et al. 2009), comparison between the differences in biomass inside and outside enclosures (Lázaro et al. 2016), the percentage of consumed forage (Ash et al. 2011), or distance from settlement or enclosure (Angassa 2014). In order to better capture the fine-scale spatial variation of grazing intensity, GPS tracking and spatial analysis tools were applied (Butt et al. 2009; Moritz et al. 2012). For example, in southern Ethiopia, with cumulative livestock movement data, researchers find specific spatio-temporal resource-use patterns governed by local rangeland management institutions (Wario et al. 2016; Liao et al. 2017). Pastoralist communities that practice a higher level of broad-scale mobility, namely camp relocation, demonstrate lower grazing intensity throughout the community herding boundaries. Under such indigenous herding regimes, multiple vegetation states occur in the same pastoral community. At the lower end of grazing pressure, rangelands have transitioned into dense thickets, while at the higher end, the landscape is dominated by sparse shrubs with minimal herbaceous cover. However, given moderate grazing pressure, rangelands are maintained as open canopy woodlands characterized by abundant grasses and low woody cover (Liao and Clark 2018).

Fire also plays an important role in maintaining alternative stable vegetation states in rangelands. With woody plant cover under 40%, fire is frequent, but it becomes rare in systems with woody plant cover over the 40% threshold (Archibald et al. 2009). The relationship between woody plant cover and fire can be explained by a dynamic model in which woody plant recruitment is typically high given infrequent fire and sparse grass cover, but recruitment rate reduces rapidly near 40% woody cover, and remains low with higher grass cover (Staver et al. 2011a; Touboul et al. 2018). This dynamic model is essentially a state-and-transition model, in which rangeland dynamics are considered as a set of discrete vegetation "states" with changes between states occurring as discrete "transitions" (Westoby et al. 1989; Milton and Hoffman 1994; Briske 2017). Transitions from one state to another often require a combination of climatic circumstances and management actions (e.g., fire or grazing) to bring them about (Mayer and Khalyani 2011).

The state-and-transition model is commonly used to interpret the complexity of rangeland vegetation dynamics in the drylands. Here we use the case in southern Ethiopia to interpret rangeland vegetation dynamics before and after the burning ban. Positive fire feedback had been a major mechanism to promote transitions among alternative states prior to 1970s (Fig. 3a). Infrequent high intensity fire could convert the landscape into open grassland, which would later shift into sparse scrubland due to woody plant recruitment and grazing. Periodically, pastoralists applied low intensity fire to burn shrubs and tree saplings, which would facilitate the transition into

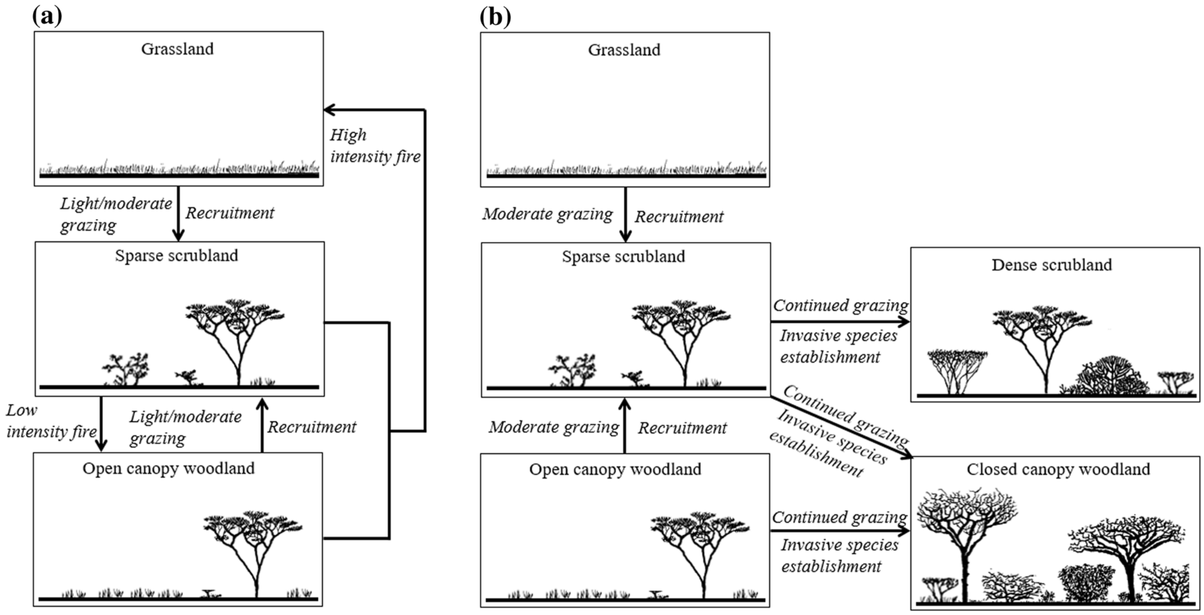

Fig. 3 Rangeland states and transitions with grazing and fire (**a**), and with grazing but without fire (**b**) (Liao and Clark 2018)

open canopy woodland. Continued grazing and woody plant recruitment would then shift the open canopy woodland into sparse scrubland. Such plant-livestock-fire interaction would maintain the stability of open canopy woodland and sparse scrubland until the next high intensity fire (Coppock 1994).

In 1970s, the Ethiopian government imposed a fire ban, leaving livestock grazing the dominant factor that determine rangeland vegetation states and transitions (Fig. 3b). The grassland created from the last high-intensity fire would slowly shift into sparse scrubland. Then due to invasive woody species establishment (Angassa and Oba 2010) and continued grazing, sparse scrubland would transit into dense scrubland. Even open canopy woodland would shift into dense scrubland or closed canopy woodland over time. Although the government lifted the fire ban in 2000s, minimal herbaceous biomass and litter in the understory could barely allow fire to thin the woody layer in the dense scrubland and closed canopy woodland, making it difficult to return to the states of sparse scrubland or open canopy woodland.

Pastoral food production and livelihoods

Drylands favor pastoral livelihoods revolving around extensive livestock herding, coupled at times with rain-fed agriculture (Blench 2001; Dong et al. 2011). Given heterogeneous distribution of natural resources in space and time, livestock production through mobile pastoralism is key to ensuring access to forage and water throughout the landscape (Galaty and Johnson 1990; Salzman 2004). Consequently, many scholars routinely advocate for the livestock sector as the foundation of future development interventions in the drylands (Fratkin and Roth 2005; McPeak et al. 2012; Liao et al. 2015). How to achieve food production growth with a lower environmental footprint but without sacrificing the livelihoods and economic benefits that livestock bring, has dominated the agendas of those aiming at designing more sustainable patterns of global food supply and demand. Simulation-based findings emphasize that, by 2050 s, transformational changes of livestock systems are necessary to cope with climate change in most of the world, although the nature and extent of the changes required vary across climate change scenarios (Leclère et al. 2014). In fact, transformation of food production in the drylands has been taking place in the past decades, demonstrating two major trends which are not necessarily mutually exclusive: intensification and diversification.

Sustainable intensification of agriculture (Garnett et al. 2013; Rockström et al. 2017; Liao and Brown 2018), a concept derived from successful cropping or mixed crop-livestock systems in relatively humid environments, has been widely promoted for improving livestock production efficiency (Herrero et al. 2010). At the core of intensification in the drylands are using less water and energy, reducing greenhouse gas emissions while producing the needed forage for livestock (Qi et al. 2017). Technological innovations and improved access to resources and markets are critical to meet the growing expectation on drylands to produce more food. One major approach to intensify livestock production is integration with crop cultivation, which can enhance production efficiencies that help spare land for nature and make dryland systems more resilient to environmental changes (Thornton and Herrero 2015). For example, simulated scenarios suggest that transition from mobile livestock herding towards mixed crop-livestock systems represents a cost-effective strategy, which substantially reduces agricultural adaptation costs while halting deforestation on millions of hectares of land globally (Weindl et al. 2015). Empirical evidence also suggests that the uptake of intensification practices such as household feedlot production system will not only improve livestock production profitability, but also reduce greenhouse gas emission intensity (Dahlanuddin et al. 2017). If properly adapted to the particular environmental and socioeconomic contexts, intensification can foster yields in the drylands via improved soil carbon accumulation and water retention (García-Palacios et al. 2019).

However, the sustainability of intensified livestock production in drylands is also a matter of discussion. First, while intensified mixed crop-livestock systems can be more productive, increased productivity is usually based on the use of substantial external inputs such as water, fertilizer, and other capital investments; this is infeasible at a broad scale, especially in developing countries (Fan et al. 2015). Emerging evidence in the drylands of Kenya suggests that unless crop cultivation expansion moves away from flood irrigation that is drying rivers to drip systems, tensions between crop and livestock agriculturalists will continue to rise (Roden et al. 2016; World Vision 2017). Second, converting drylands into more intensified land uses will considerably increase carbon emissions and lead to other serious environmental consequences (Searchinger et al. 2015). Third, the spatiotemporal heterogeneity of drylands predetermines that opportunistic and flexible herding should be the preferred strategy, while diversification into non-pastoral livelihoods is a coping strategy at best (Liao et al. 2015). Many existing practices to boost livestock production in drylands are likely to result in long-term, large-scale rangeland degradation and are thus unsustainable (Qi et al. 2017). Therefore, it is crucial to explore how to balance between crop-based intensification and extensive herding in drylands.

Another major transformation in pastoralist livelihoods is diversification, through which households and communities pursue diverse economic strategies to manage uncertainty and improve their well-being (McCabe et al. 2010; Baird and Hartter 2017). Livelihood diversification is widely promoted and adopted due to its contribution to reducing risk and stabilizing income flows and consumption, which can potentially lead to improvements in quality of life, wealth accumulation, and food security (Coppock et al. 2011). Throughout the global drylands, various empirical evidence has revealed the ongoing trend of diversification, where mobility is in decline and alternative livelihoods revolving around fixed settlements are adopted, which include crop cultivation, wage employment, small business, and switching to feedlot-based livestock production system (Goldman and Riosmena 2013; Wang et al. 2013; Boru et al. 2014).

Although there is ample evidence that diversification can contribute to improved well-being, the translation of diversification into increased incomes or other indications of higher quality of life is far from being automatic. Diversification might occur as a voluntary or compelled response to a certain socioeconomic or environmental crisis (Ellis 1998; Sen 1999). Given specific overarching socio-political and policy context, livelihood diversification can unfold as a process of struggle for survival instead of a chance for transformation and improvement (Liao et al. 2015). Transitioning out of the livestock sector also has negative health implications, as pastoralists seeking for wage labor positions in nearby cities or towns can no longer provide as much milk to their children as do those who remain as pastoral dairy farmers, which led to reduced weight gain (Fratkin and Roth 2005).

Thus, policy makers cannot assume diversification to be a desirable practice for the rural poor. Even if well-intentioned, development intervention efforts to direct rural peoples towards adopting diversified livelihood strategies can bring about negative impacts, especially in locations where the socio-environmental context strongly favors specialization in mobile livestock herding.

In addition to intensification and diversification, indigenous knowledge, which results from a blend of cultural and ecological diversity in specific contexts, has been recognized as being crucial for future adaptation to achieve sustainability goals (Berkes 1998; Kassam 2009). Livelihoods based on indigenous knowledge would bear similarities to traditional pastoralism while adding new elements to adapt to rangeland degradation and woody plant encroachment. Given their diversity and depth of knowledge on the rangelands, pastoralists can make novel contributions to rangeland management policy-making. For example, according to pastoralists' ethnobotanical knowledge, vegetation regime shifts towards denser woody plant cover in the East African drylands would negatively affect the production of cattle and sheep; however, goats would be largely unaffected by while camels could benefit from the ongoing regime shift. Accordingly, pastoralists increase their holdings of goats and camels while cutting cattle herd size to take advantage of woody plant proliferation (Liao et al. 2016; Volpato and King 2018). In addition, pastoralists keep livestock of different age groups, and feed them in different patches of rangelands to better exploit the diversity of vegetation in their communities. In particular, milking cows, calves, and animals under two years old are kept close to settlements, while bulls and immatures over two years old are herded farther away from encampments (Solomon et al. 2007; Liao and Clark 2018). Such dynamic livestock portfolio based on indigenous knowledge not only mitigate the impact of bush encroachment on pastoral food security, but also facilitate adaptive management, and thereby enhance the resilience of dryland systems and pastoralist communities.

System integration

While existing research on dryland sustainability has generated valuable insights to improve human well-being and enhance rangeland resilience, in most cases, there tends to be a reporting bias either in favor of focusing on social outcomes or environmental consequences. In fact, any changes in drylands concern the coupled systems, and will have implications on both social and environmental components. For example, changes in resource-use patterns or environmental conditions have the potential for cascading effects on the entire dryland system: more intensified food production in the drylands may contribute to macro-level economic growth, and have the potential to enhance pastoralist livelihoods; conversely, intensification also carry the threat of appropriation of communal lands and natural resources from pastoralists whose livelihoods depend on such assets, thus raising significant concerns regarding social equity. Transformations in food production can also have major impacts on land cover, with degradation and loss of ecosystem services likely to occur as the 'underutilized lands' are converted into more intensified purpose of utilization.

However, current work on causal mechanisms primarily involves abstract modeling and controlled experiments devoid of socioeconomic processes (Herrero et al. 2009; Briske et al. 2015). Studies either support or condemn pastoral mobility, and which one it is largely depends on whether the research objectives focus on improving livestock production efficiency (Herrero et al. 2013), promoting social equity and justice (Upton 2014), or supporting vibrant wildlife (Macdonald and Loveridge 2010). There is insufficient integrated research to examine the mechanisms that lead to the joint outcomes, and how their interactions affect system transitions in the drylands. This knowledge gap has led to the justification of national governments' development and conservation initiatives in drylands by criticizing customary pastoralism as being irrational and resulting in social conflicts and environmental degradation (Hardin 1968).

Conclusion

This review provides a synthetic discussion of dryland sustainability using a coupled systems framework and through the lens of mobility. With a population projected to grow significantly in the coming decades, we expect a gargantuan appetite for livestock products, and there is a growing concern about how to accommodate this increase in demand with a low environmental footprint and without eroding the economic, social, and cultural benefits that livestock and pastoralism provide on the drylands. We argue that mobility is a crucial strategy for pastoralists to survive and thrive in the drylands. However, broad-scale mobility (e.g. seasonal migration) is in decline as a response to ongoing socio-environmental changes. Loss of broad-scale movement in modern pastoralism has significant implications on dryland sustainability. In terms of rangelands, declined mobility can exacerbate bush encroachment and land degradation, as sedentarized pastoralists are more likely to use the rangelands more recursively. Regarding livelihoods, food production in the drylands is becoming more intensified and diversified; however, such transformations in livelihoods do not necessarily translate into improved well-being, and may carry substantial risks of environmental degradation.

In order to advance landscape sustainability science and reconcile concerns over environmental conservation and human well-being across the global drylands, we must understand the underlying mechanisms of coupled systems transitions through the lens of mobility, and integrate the perspectives of multiple stakeholders with fundamentally different interests and priorities. Future research needs to further explore the new socio-environmental frontiers of interdisciplinary sustainability science in the drylands. It is necessary to develop convergence research by merging ideas (i.e. sustainable development, agricultural intensification, system coupling and transition, governance, mobility), approaches and technologies from widely diverse fields to explore how to achieve the twin SDGs of Zero Hunger and Life on Land, and understand transitions and their determinants in the complex socio-environmental systems.

Funding This research was funded by a startup grant at Arizona State University.

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