Synthesis

Assessing the resilience of a real-world social-ecological system: lessons from a multidisciplinary evaluation of a South African pastoral system

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ABSTRACT. In the past decades, social-ecological systems (SESs) worldwide have undergone dramatic transformations with often detrimental consequences for livelihoods. Although resilience thinking offers promising conceptual frameworks to understand SES transformations, empirical resilience assessments of real-world SESs are still rare because SES complexity requires integrating knowledge, theories, and approaches from different disciplines. Taking up this challenge, we empirically assess the resilience of a South African pastoral SES to drought using various methods from natural and social sciences. In the ecological subsystem, we analyze rangelands' ability to buffer drought effects on forage provision, using soil and vegetation indicators. In the social subsystem, we assess households' and communities' capacities to mitigate drought effects, applying agronomic and institutional indicators and benchmarking against practices and institutions in traditional pastoral SESs. Our results indicate that a decoupling of livelihoods from livestock-generated income was initiated by government interventions in the 1930s. In the post-apartheid phase, minimum-input strategies of herd management were adopted, leading to a recovery of rangeland vegetation due to unintentionally reduced stocking densities. Because current livelihood security is mainly based on external monetary resources (pensions, child grants, and disability grants), household resilience to drought is higher than in historical phases. Our study is one of the first to use a truly multidisciplinary resilience assessment. Conflicting results from partial assessments underline that measuring narrow indicator sets may impede a deeper understanding of SES transformations. The results also imply that the resilience of contemporary, open SESs cannot be explained by an inward-looking approach because essential connections and drivers at other scales have become relevant in the globalized world. Our study thus has helped to identify pitfalls in empirical resilience assessment and to improve the conceptualization of SES dynamics.

Key Words: *drought; empirical resilience assessment; globalization; institutions; monetary resources; pastoralism; rangelands; social-ecological system*

INTRODUCTION

Within the last century, dryland social-ecological systems (SESs) have undergone dramatic transformations due to social, land-use, and institutional change (Reynolds et al. 2007). These changes manifest themselves on various scales and may have considerable consequences for rural livelihoods (Turner et al. 2014). Moreover, climate change projections predict that most drylands will face increased frequency and intensity of drought (IPCC 2013). Spurred by these projections, the effect of drought on livelihoods has been subject to extensive research (Ayantunde et al. 2015, Müller et al. 2015, Martin et al. 2016). Nevertheless, it is still poorly understood under which environmental and social conditions a meteorological drought may be converted into a socioeconomic drought, threatening livelihood security (Thurow and Taylor 1999, Martin et al. 2016). Resilience thinking offers promising conceptual frameworks (Gillson and Hoffman 2007, Vetter 2013). Resilience is the capacity of the SES to change and adapt continually yet remain within critical thresholds (Folke et al. 2010). Resilience has also become a key concept for analyzing the effects of global change stressors (Ifejika Speranza et al. 2014).

Livestock is a major source of income in most drylands (Gillson and Hoffman 2007). Hence, drivers modifying characteristics of pastoral households are of particular importance (Martin et al.

2016): social change may alter income needs; economic change may lower the dependence on livestock-generated income and foster the ability to cope with phases of shortage; and land-use change may alter mobility patterns and thus pastoralists' ability to track spatio-temporal variation in forage resources (McAllister et al. 2006b). Likewise, changes in herd management may alter the connectivity between herds and rangelands (Li and Li 2012, Linstädter et al. 2013).

An empirical assessment of SES resilience in the face of drought, however, is challenging. First, SES complexity requires integrating knowledge, theories, and approaches from different disciplines (Ostrom 2009b, Schlüter et al. 2014). An empirical resilience assessment should thus be truly multidisciplinary and apply broad sets of indicators (Quinlan et al. 2016). In practice, though, such an assessment is still often developed from the perspective of a single discipline and tends to oversimplify either the ecological or the social subsystem (Schlüter et al. 2014). Further challenges are to delineate an SES and its subsystems (Berkes et al. 2003) and to specify interdependencies. The latter challenge is prerequisitive for understanding how cross-scale interactions affect the coupling between subsystems (Allen et al. 2014), and the implications this has for overall SES resilience (Bodin and Tengö 2012). Finally, resilience needs to be assessed against an appropriate baseline such as the system's desirable state

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(Carpenter et al. 2001, Liu 2014). Hence, the question, "resilience of what to what?" (Carpenter et al. 2001) needs to be addressed in a stringent manner (Challies et al. 2014).

Taking up these challenges, we assess the resilience of a rural SES, particularly its livestock-rearing component, toward drought while also considering social, economic, and land-use change. Our study gives equal weight to an assessment of the ecological and social subsystems to avoid oversimplifying either of them (Schlüter et al. 2014). It involves expertise from natural sciences (soil science, vegetation ecology), social sciences (agronomy, economics, history, social anthropology), and cross-cutting fields (political ecology, rangeland ecology).

The focal SES experienced considerable institutional transformations in the past century, including rigid governmental interventions. We mainly evaluate how these interventions shaped interdependencies, and assess consequences for the resilience of livestock-owning households toward drought stress. We envisage that our multidisciplinary approach will help identify potential pitfalls in empirical resilience assessment and improve the conceptualization of SES dynamics in the face of external drivers and shocks.

METHODS AND ANALYTICAL FRAMEWORK

Social-ecological system delineation
The focal SES has the town Thaba Nchu as an urban center. The area belonged to South Africa's homeland Bophuthatswana and is today part of the Mangaung metropolitan municipality, located ~20 km from the township of Botshabelo. The SES is situated at ~1400-1500 m above sea level and covers 1290 km² (Naumann 2014). The climate is semiarid, with mean annual precipitation of 570 mm. The soils are mainly Lixisols (Kotzé et al. 2013). The vegetation is grassland (Linstädter et al. 2014) dominated by C_4 bunchgrasses such as *Themeda triandra* and *Eragrostis obtusa.*

The SES includes 37 villages (Naumann 2014); adjacent land is used as communal rangeland for cattle, sheep, and goats, and access is restricted to village residents. In addition to its economic value, livestock is used for ritual purposes and indicates household wealth. Crop cultivation is practiced in small gardens (Naumann 2014). The focal SES can be clearly delineated because it is spatially and politically well defined and consists of a single user group (with multiple actors) using a set of natural resources (see Redman et al. 2004, Bodin and Tengö 2012).

Resilience assessment in the ecological subsystem

Resilience of what to what?
The resilience of grazed dryland ecosystems toward drought can be defined as their ability to buffer drought effects on forage provision (McAllister et al. 2006a). This ability to retain a healthy and productive state in the face of disturbances is termed "ecological resilience" (Holling 1996) or "ecological stability" (Donohue et al. 2013). Prominent constituents are resistance and recovery (Hoover et al. 2014), both of which can be substantially modulated by grazing-induced changes in soil and vegetation (Koerner and Collins 2014, Ruppert et al. 2015). Hence, soil and vegetation resilience toward (over-)grazing needs to be assessed first. Then, the implications for rangelands' ecological resilience toward drought can be evaluated. Dryland ecosystems may experience catastrophic shifts toward a desertified state,

characterized by a switch to predominantly bare soil conditions (Schlesinger et al. 1990). Desertification greatly decreases dryland ecosystems' ability to deliver key ecosystem services such as forage (Reynolds et al. 2007). Hence, it needs to be evaluated if the focal ecosystem has passed a desertification tipping point.

Baseline
We use vegetation and soil on commercial farms as an ecological baseline because commercial farmers in the study region specifically manage for a dominance of palatable perennial grasses such as *T. triandra* (Snyman et al. 2013). The aim is to ensure sufficient forage provision, particularly for the dry-season forage depletion bottleneck, which characterizes dryland pastoral SESs (Hempson et al. 2015). A dense cover of perennial grasses also reduces soil erosion and increases ecosystem resilience in the face of catastrophic shifts toward a desertified state (Maestre and Escudero 2009, Zimmermann et al. 2015).

From an ecological point of view, communal rangelands and commercial farms mainly differ in their disturbance regime, i.e., duration, frequency, and intensity of grazing disturbances (Linstädter 2009). On commercial farms, rangelands are managed by allowing resting times. This is done by adapting the intensity and duration of grazing disturbances to the recovery rates of perennial forage grasses via rotational grazing in fenced paddocks. On unfenced communal rangelands, cattle are collected daily near watering points, and grazing is continuous throughout the year (Brüser et al. 2014). Commercial farms were allocated to individual owners during the late 19th century (Kotzé et al. 2013), and boreholes were subsequently drilled. In 2011, average stocking rates were 6.4 ha/livestock unit (LSU) on commercial farms and 4.3 ha/LSU on communal farms (Kotzé et al. 2013).

Scales and levels
We consider pasture, farm, and landscape as levels of spatial analysis (following Huntsinger and Oviedo 2014). To maximize the gradient of grazing pressure, we also consider the small piosphere around water points in which the high and regular abundance of livestock leads to a zone of degraded vegetation (Andrew 1988). We use the term "pasture" in a spatial sense to delineate a spatial unit of rangeland (Huntsinger and Oviedo 2014). On commercial farms, a pasture corresponds to a fenced paddock; on communal farms, it corresponds to the area that cattle forage from watering points, which has a maximum radius of 3–4 km (Frank et al. 2012). The farm level is set analogous to a village's grazing area, and the landscape level (the SES area) is addressed via spatial extrapolation and synthesis. On the time scale, grazing-induced changes in vegetation are usually observable within years; for soils it takes years to decades (Snyman and du Preez 2005, Linstädter and Baumann 2013). Because of a lack of historical data, we only assess the subsystem's current state, and we evaluate drought resistance and recovery using an indirect approach.

Resilience assessment in the social subsystem

Resilience of what to what?
Social resilience is the capacity of a social subsystem to cope with and adapt to stressors and disturbances induced by social, political, and ecological change (Adger et al. 2005). In our case, the social subsystem is represented by livestock-owning households, the social networks to which they are tied, and the

communities to which they belong. We focus on the social subsystem's resilience to mitigate adverse effects of forage shortages (Thurow and Taylor 1999) on herd dynamics and livelihood security, and evaluate the viability of institutions governing natural resource use.

Baseline
Practices and institutions in the focal SES are compared to those in a "traditional" pastoral SES, including historical institutional arrangements in the focal SES. The underlying rationale is that traditional pastoral SESs offer suitable standards of comparison for sustainable range management (Bollig and Schulte 1999, Müller et al. 2007, Turner et al. 2014) because long-term and close interactions with the ecological subsystem have shaped actors' skills, technologies, norms, and institutions (Fernandez-Gimenez 2000). Economic aspects of livestock-keeping in the contemporary SES (such as selling prices) are compared to market-oriented farming practices. The profitability of livestock, which has important consequences for the livestock-generated income in a pastoral SES (Tyler et al. 2007), can thus be quantified.

Scales and analytical levels
We assess social resilience at the household and community levels (Goldman and Riosmena 2013). To address the relevant temporal scale of years to decades (Bollig and Menestrey Schwieger 2014) and to reconstruct practices and institutions in the baseline situation of the traditional pastoral SES, we combine a contemporary with a historical perspective, focusing on changes in the past century. Government interventions, i.e., cross-scale interactions from a higher organizational scale, are explicitly addressed.

Conceptual framework for synthesizing partial assessments
To conceptualize how governmental interventions shaped interactions within the focal SES, we use the SES motif proposed by Bodin and Tengö (2012). This motif is particularly helpful for defining various types of interdependency.

Empirical details

Ecological subsystem
We assessed soil resilience against overgrazing using physical, physico-chemical, and biological indicators. Indicator selection was motivated by their sensitivity toward degradation processes in South African grassland soils (Snyman and du Preez 2005, Lauer et al. 2011). We compared soil resilience around four focus villages of the pastoral SES with that on four adjacent commercial farms. At each site, a representative pasture (a paddock containing one artificial water point, or an area ≤ 4 km from an artificial water point) was identified. We sampled in the small, overgrazed piosphere around the water point (with a maximum radius of 70 m; Moreno García et al. 2014) and on the pasture outside the piosphere. Topsoil samples (bulked over 10 subsamples) were taken from 0–5 cm. For aggregate sampling (0–10 cm), one soil block (> 1 L) per location was prepared in the field (see Kotzé et al. 2013 for details).

We determined bulk density and aggregate structure as indicators for physical soil disturbance and soils' abilities to absorb water and sequester carbon (Bird et al. 2007). Among aggregate size-fractions, large macroaggregates (> 2000 μm) are particularly

vulnerable to breakdown (Seybold et al. 1999, Kotzé et al. 2013), accompanied by losses of soil organic matter. As a physico-chemical indicator, we selected organic carbon (C) stored in aggregate size-fractions. Organic C is closely correlated with soil organic matter, which is a main factor in soil resilience because of its ability to store and provide nutrients, improve soil structure, enhance water infiltration, and prevent erosion (Parton et al. 1987). As biological indicators for element cycling, we quantified amino sugars as markers for microbial residues in topsoil samples (0–5 cm; see Zhang and Amelung 1996 for methodological details). The contribution of amino sugars to C served as a marker for the amount of C sequestered in microbial residues (Amelung et al. 2008). The ratio of fungal- to bacterial-derived amino sugars, as reflected by changes in the ratio of glucosamine to muramic acid (GlcN/MurA), was used as an indicator for soil disturbances. We applied ANOVAs followed by Tukey's HSD (α of 0.05) to test for differences between piosphere and pasture topsoils from the focal SES and from commercial farms using Statistica 9.1 (StatSoft 2010).

We assessed vegetation resilience against overgrazing using a species-based approach, focusing on floristic composition and the relative abundance of *T. triandra,* a palatable native bunchgrass sensitive to overgrazing (van der Westhuizen et al. 1999). Declining abundances of *T. triandra* are typically accompanied by declining rangeland condition (Snyman et al. 2013). Two of the focus villages (Sediba and Middeldeel) were contrasted with four adjacent commercial farms. We sampled five plots (5 × 5 m) per piosphere, and 10–14 plots per pasture. Plant species abundance was estimated as cover. To evaluate differences in floristic composition between piosphere and pasture vegetation of the focal SES and the baseline system, a detrended correspondence analysis (DCA) was performed with species' relative abundance using default settings in CANOCO version 4.5 (Ter Braak and Šmilauer 2002). We plotted contour levels in the DCA diagram, using LOESS smoothing with a span of 0.67 and a degree of 1. Contours delineate rangeland condition classes based on the relative abundance of *T. triandra* (van der Westhuizen et al. 1999). We also tested for differences in the relative abundance of *T. triandra* on piosphere and pasture plots of the two management systems (ANOVAs followed by Tukey's HSD; α of 0.05) using Statistica 8 (StatSoft 2007). We used pasture plot data to generalize our findings to the state of the ecological subsystem.

In a second step, we assessed rangelands' drought resistance and recovery via the rain-use efficiency (RUE), which is the ability of rangelands to convert rainfall into aboveground plant biomass. Mean RUE (RUE_{mean}) decreases and RUE variability (RUE_{var}) increases with rangeland degradation (Le Houérou et al. 1988, Ruppert et al. 2012), indicating a lower drought resistance and a slower recovery. Because long-term RUE data were not available, we used an indirect approach, taking advantage of the fact that drought resilience is closely connected to floristic composition (Koerner and Collins 2014). We obtained RUE_{mean} and RUE_{var} from a 19-year experiment adjacent (< 60 km) to the study sites, where three experimental vegetation states (good, moderate, poor) were monitored, resembling grazing effects on floristic composition (O'Connor et al. 2001).

Social subsystem

We used agronomic indicators to assess the profitability of livestock production and households' dependence on livestock-generated income. We also assessed the potential of management strategies to mitigate drought effects on herds based on the size and temporal stability of herds. We conducted a household survey in the four focus villages and collected detailed data from all cattle-owning households ($N = 230$) via a living standards measurement study (Grosh and Glewwe 2000). The questionnaire included modules on household structure, livestock production and management, income, assets, expenditures, credit, and savings. Data were analyzed with SPSS version 21 (IBM, Chicago, Illinois, USA).

As indicators at the community level, we selected the flexibility and interdecadal stability (persistence) of institutions, especially those that govern natural resource use (Herrfahrdt-Pähle and Pahl-Wostl 2012). The viability of joint resource management was assessed via the level of mutual trust (Ostrom 2009*a*), focusing on the present. Data were collected from all cattle-owning households using semistructured interviews. Institutional stability was assessed via qualitative in-depth interviews with village elders in Sediba and Middeldeel ($N = 21$), and via archival research in the national archive in Pretoria and the provincial archives of Mmabatho and Bloemfontein. During semistructured interviews, we also recorded local knowledge on desirable rangeland management strategies and discussed requirements for their implementation.

RESULTS

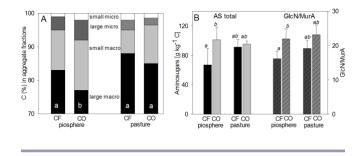### Resilience assessment in the ecological subsystem

Soil resilience

Soils clearly responded to differences in the duration and intensity of grazing. The continuous grazing in the focal SES resulted in significantly higher bulk density in piosphere topsoils ($F_{1,22} = 14.54$, $P = 0.001$) than did rotational grazing on commercial farms. Losses of macroaggregates and the carbon stored therein were also more pronounced in piospheres of the focal SES (Fig. 1A). The contribution of amino sugars to soil C and the ratio of fungal- to bacterial-derived amino sugars were also elevated in the focal SES compared to commercial farms, but differences were only significant in the piosphere (Fig. 1B). Hence, soils in the focal SES were degraded in the piosphere, whereas adjacent areas and commercial farms were not degraded.
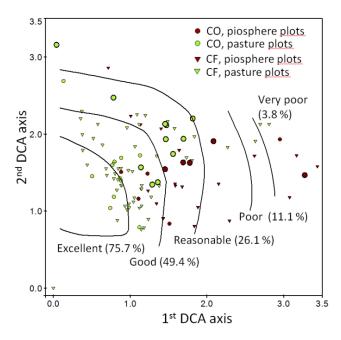
Vegetation resilience

Vegetation responses to grazing were clearly discernable. Almost full turnover in floristic composition occurred along the first DCA axis (3.7 SD, Eigenvalue = 0.41). Plot arrangement along this axis reflected a grazing gradient, with most pasture plots having at least a "reasonable" rangeland condition (Fig. 2). Mean relative abundances of the indicator species *T. triandra* differed among pasture plots ($F_{6,75} = 4.99$, $P = 0.002$), but not among piosphere plots ($F_{6,14} = 2.20$, $P = 0.105$; Appendix 1). For both SES villages, floristic composition and relative abundances of *T. triandra* on pasture plots resembled the "good" compositional state in the 19-year study by O'Connor et al. (2001), whereas piospheres resembled the "poor" state. The study reported the RUE_{mean} of the poor state to be 75.2% lower than that of the good state, whereas the RUE_{var} increased by 46.7%.

Fig. 1. Differences in topsoil condition of piospheres and pastures, comparing the focal social-ecological system with communal management (CO) to the benchmark of commercial farms (CF). (A) Organic carbon content (C) in aggregate fractions, expressed as percentage of total C in the respective aggregate class. (B) Total amino sugar concentration (AS total) and ratio of fungal- to bacterial-derived amino sugars (glucosamine to muramic acid, GlcN/MurA). Different letters indicate a significant difference (Tukey's HSD; $P < 0.05$).

Fig. 2. Detrended correspondence analysis (DCA) diagram visualizing differences in floristic composition and rangeland condition. Piosphere plots (brown) and pasture plots (green) under communal management (CO) in the focal social-ecological system (small circles: Middeldeel, large circles: Sediba) are compared to those in the benchmark system of commercial farms (CF; triangles). Contours delineate rangeland condition classes (excellent to very poor) based on relative abundances of the bunchgrass *Themeda triandra*.

Table 1. Historical perspective on the resilience of the social subsystem, indicating state interventions, institutional changes, and resulting socioeconomic dynamics during the 20th century.

Resilience aspect	Phase of the social-ecological system			
	Pre-betterment (until 1930s)	Betterment (1940s–1960s)	Homeland (1977–1994)	Post-apartheid (after 1994)
Interventions and legislations of the state	Land Acts of 1913 and 1936; declaration as betterment area	Livestock culling; restriction of resource access; forced resettlement	High subsidization and mechanization of agricultural sector	Discontinuation of subsidization; land reform program
Institutional arrangements of land use	Enclosed camps for winter grazing; agricultural production; patron-client relationships	Rotational grazing system enforced by rangers; increasing monetization of reciprocal arrangements	Rotational grazing system enforced by rangers; agricultural production in cooperatives	Institutions of rangeland management collapse
Households' livelihood basis	Subsistence agriculture and pastoral production; additional seasonal off-farm income	Undermining of subsistence agriculture; increasing number of households depend on labor migration	Migration as main income source; agriculture supplements wages; cash crop production by wealthy households	High dependence on social transfers and wage labor; pastoral production for ritual purposes and as supplementary income

Resilience assessment in the social subsystem

Household level

Household economy in the traditional SES was mainly based on subsistence agro-pastoral production. Land was used for rain-fed cultivation of mainly sorghum, maize, and beans, as well as for livestock farming with cattle and sheep. Since the 1930s, the apartheid government intervened massively in regards to land use, and in 1939, defined the region as a betterment area. Initially, betterment aimed at a reduction of livestock numbers by compulsory culls. After two decades of culling, 20% of the households had no animals, and 90% of livestock-owning households possessed < 10 LSU. In the subsequent decades, livestock-based income and agricultural production lost importance for rural livelihoods (Table 1).

In 2010–2011, cultivation was mostly restricted to home gardens. Stocking density in Sediba was 4.85 ha/LSU in 2011, i.e., 24.4% above recommended densities for long-term sustainable management (DARD 2003). However, stocking density in 2010–2011 was considerably lower than in the mid-20th century. This is because of a reduction in total cattle numbers (from 785 in 1959 to 547 in 2011) and the discontinuation of cultivation on fields, which enlarged the village's grazing area.

Approximately 50–60% of households were still involved in pastoral production in 2010–2011, with a median herd size of 3.0 animals. Those 8.7% of households possessing ≥ 10 cattle mostly belonged to the local elite and did not rely on their herds for subsistence (Appendix 2). Productivity of cattle herds was low: 45.4% of respondents reported that their cows usually calved annually, and 47.1% stated a calving interval of two years. Herd stability was also limited by high average calf and adult mortality of 30% and 9%, respectively, resulting in average herd losses of 11.4%.

Management strategies to improve forage and water provision to livestock were rare. Most importantly, supplementary feeding was rarely provided; 79% of cattle owners did not plant fodder crops, and 56% never produced hay. Only 42% of cattle owners provided drinking water during the night, and 81% did not take any action to increase animal fertility. The poor herd management was reflected in low slaughter weights and selling prices (approximately 3800 ZAR/steer, ~30% of what commercial farmers usually receive). Low selling prices combined with low herd reproduction negatively affected livestock-generated income. Together with high levels of social transfers from pensions, child grants, and disability grants, this led to livestock husbandry only contributing 9% to average household income.

Community level

The history of Thaba Nchu's communities and their institutions is characterized by transformations induced by external and internal forces (Murray 1996, Naumann 2014). Four phases are distinguishable (Table 1). In the pre-betterment phase, institutional arrangements included communal access rights to rangelands and water, nonmonetary reciprocal labor arrangements, and patron-client relationships, with wealthier men lending cattle to poorer households. In the betterment phase, governmental interventions were the most important top-down driver for changing institutional arrangements of land use. Authorities controlled rangeland use by fencing off paddocks and applying rotational grazing, which was enforced by salaried rangers. In the 1960s, rehabilitation measures were introduced, including resettlement of households in centralized villages (Naumann 2014). In the homeland phase, starting in the 1970s, top-down interventions continued to change institutional arrangements. To achieve self-sufficiency, the Department of Agriculture and the para-statal organization Agricor subsidized cultivation and livestock production.

In the post-apartheid phase since 1994, subsidization was discontinued (Murray 1996), and institutions of rangeland management collapsed (Table 1). Approximately 95% of livestock owners would strongly welcome the reintroduction of these institutions but thought that this would require the support of an (external) ranger, which they could not afford. The viability of joint resource management was also impeded by low levels of mutual trust. Approximately 57% of respondents agreed with the statement, "households in the village are only concerned about their own well-being," whereas 31% were neutral and only 12% disagreed. Asked whether a lost wallet would be completely returned to its owner, 13% disagreed and 78% strongly disagreed.

Table 2. Resilience of the current ecological subsystem, specified for relevant analytical levels on the spatial scale. For soil and vegetation resilience to overgrazing, observations are benchmarked against the rangeland state on adjacent commercial farms. Results from the spatial level of pastures (outside piospheres) are used to generalize findings to the landscape level. Drought resilience is benchmarked against a desirable (experimental) pasture state. Positive signs (+) represent small differences compared to the benchmark state and thus comparatively high resilience; negative signs represent large (−) or very large (−−) differences and thus low resilience.

Spatial scale	Analytical level	Soil resilience to overgrazing			Vegetation resilience to overgrazing		Rangeland resilience to drought	
		Physical indicators	Physico-chemical indicator	Biological indicator	Species-based indicators		Integrative indicators	
		Bulk density, aggregate structure	Carbon stored in aggregates	Amino sugars	Floristic composition[†]	*Themeda triandra*[‡]	RUE_{mean}[§]	RUE_{var}[ǀ]
m²	Piosphere	−−	−−	−−	−	−−	−−	−
ha	Pasture	+	+	+	+	+	+	+
km²	Farm, landscape	+	+	+	+	+	+	+

[†]Floristic composition of vegetation according to detrended correspondence analysis.
[‡]Relative abundance of the palatable bunchgrass *Themeda triandra,* an indicator species sensitive to overgrazing.
[§]Mean rain-use efficiency.
[ǀ]Coefficient of variation in rain-use efficiency.

DISCUSSION

Our multidisciplinary resilience assessment of historic and contemporary phases in a South African pastoral SES showed that different factors have influenced the resilience of its subsystems to drought. In the following, we first discuss the partial assessments, and follow with a synthesis of them.

Resilience of the ecological subsystem

Soil resilience
Soil resilience partly depends on intrinsic soil properties such as texture, but can be substantially altered by management (Seybold et al. 1999). We found distinct responses of physical, physico-chemical, and biological indicators to grazing management. Soils in the focal SES's piospheres were highly degraded, indicated by soil compaction attributable to animal trampling, aggregate disruption, and associated decomposition of soil organic carbon, and a decoupling of biological soil processes (Lauer et al. 2011). Physico-chemical and biological degradation were most likely caused by low litter production due to the removal of biomass (Angassa et al. 2012). Comparatively high soil temperatures due to a high proportion of bare ground may have accelerated the decomposition of soil organic matter (Parton et al. 1987, Amelung et al. 2008).

Most indicators suggested that grazing-induced soil degradation was constricted to the overgrazed piosphere (Table 2) and was particularly pronounced in the focal SES. Because piospheres only occupied a small proportion of the studied rangelands (Moreno García et al. 2014), detrimental effects of overgrazing on soils were locally limited. On the spatial levels of pastures and landscapes, which are of higher relevance for animal nutrition, soil degradation was of minor importance. Hence, the current soil state in the focal SES (outside the piosphere) is not inferior to the ecological baseline of commercial farms.

Vegetation resilience
Rangeland vegetation is the most important interface between meteorological drought and fodder scarcities (Gillson and Hoffman 2007). Species-based indicators showed that vegetation

in the focal SES was roughly in the same state as on commercial farms: Piospheres were highly degraded, whereas adjacent rangelands were not. Remarkably, the palatable bunchgrass *T. triandra,* which is critical to livestock production (Snyman et al. 2013), was almost lost from piospheres, but dominated on pasture plots. Its high relative dominance implies good rangeland condition in the focal SES (van der Westhuizen et al. 1999). Our findings are in contrast to those for soil, where marked differences were observable for piospheres. The good condition of rangeland vegetation is also contradictory to studies from communal areas in South Africa's grassland biome (e.g., Vetter et al. 2006). However, our results are corroborated by three parallel studies focusing on functional trait responses (Moreno García et al. 2014), functional type responses (Linstädter et al. 2014), and intraseasonal vegetation dynamics (Brüser et al. 2014).

RUE_{mean} and RUE_{var} data from an adjacent rangeland experiment (O'Connor et al. 2001) indicate that with decreasing rangeland condition, the vegetation's ability to convert rainfall into forage biomass decreases considerably, as does its ability to buffer effects of rainfall variability on biomass production. This can be explained by the fact that nondegraded vegetation usually has higher functional diversity (O'Connor et al. 2001) and is dominated by perennial plants, which have an intrinsically better ability to cope with temporary water scarcities than do annuals (Stafford Smith and McAllister 2008, Ruppert et al. 2015). Outside the piospheres, rangelands of the focal SES were nondegraded and dominated by perennial grasses, and thus should have comparatively high resistance to, and quick recovery after, drought (Table 2).

Resilience of the social subsystem

Household level
Rangeland management through controlled herd mobility is an adaptive practice to match fluctuating forage availability and needs (McAllister et al. 2006a, Martin et al. 2014). We detected dramatic changes in management practices over the past century. With top-down enforcement of access rules during the betterment phase, households were forced to abandon their traditional, well-

Table 3. Resilience of the current social subsystem to drought, specified for the analytical levels of household and community, based on agronomic and institutional indicators. The resilience assessment focuses on the potential of management practices to mitigate drought effects on herds, and on the viability of institutions governing natural resource use. Practices and institutions in traditional pastoral social-ecological systems are used as a baseline. Profitability is compared to market-oriented farming practices. Positive signs (+) represent high resilience compared to the baseline; negative signs represent low (−) or very low (−−) resilience; n/a = not applicable.

Dimension	Analytical level	Agronomic indicators				Institutional indicators			
		Herd size	Herd stability[†]	Profitability	Dependence[‡]	Rangeland management	Flexibility	Persistence[§]	Mutual trust
Small	Household	−	−−	−	+	−	n/a	n/a	n/a
Large	Community	n/a	−−	−	+	−−	−	−−	−−

[†]Temporal stability of herds, including drought-induced livestock population crashes.
[‡]Dependence of households on livestock-generated income.
[§]Resilience of social institutions to political and economic changes.

adapted practices. After the fall of the apartheid regime and the discontinuation of subsidization, neither the original nor enforced management strategies were applied. This resulted in strategies aimed at individual cost-minimizing use of the common-pool resource system, with negative consequences for the temporal stability and size of herds, and for profitability (Table 3). As in other communal areas in South Africa (Vetter 2013), current calving rates are well above the interval of 12 months, which is the norm on commercial farms (George et al. 2001). Small herd sizes and low temporal stability of herds are typical for low drought-resilience of livestock production (Martin et al. 2016).

Because household income portfolios have been substantially diversified away from livestock production toward migratory labor and social transfers, livestock husbandry is currently an economically marginal activity, which implies that households have become economically independent from their herds (Table 3). However, livestock has retained a safety-net function (Rasch et al. 2016a), strengthening household resilience toward unforeseen expenses. Income portfolios in Thaba Nchu resemble those in other former homelands (Eastwood et al. 2006), but differ from those in other parts of sub-Saharan Africa (Berhanu et al. 2007, Lay et al. 2009).

Community level
For the social subsystem, resilience is mostly conceived as a synonym for economic and social stability and persistence (Bollig 2014). From a historical perspective, three issues are remarkable. First, a forced transformation (Folke et al. 2010) had negative effects on the flexibility and persistence of original local institutions (Table 3). By restricting households' access to pastures, reciprocal and patron-client arrangements were undermined. In consequence, the social resilience of communities decreased. Second, new practices such as rotational grazing were not maintained or adapted after the end of apartheid. We assume that their top-down enforcement has undermined their acceptance. Third, the forced resettlement disrupted residential patterns and thereby violently reorganized social structures. Our results suggest that these enforcements had negative effects on social cohesion, indicated by low levels of mutual trust. As in other pastoral SESs (Hausner et al. 2012), this probably impeded joint resource management, which requires internal monitoring and sanctioning, and prevented the delegation of responsibility to rangers.

The lack of adequate local institutions responsible for rangeland management has been frequently reported to be an outcome of South Africa's betterment interventions (Moyo et al. 2008, Vetter 2013). Indicators for the state of institutions and trust imply a low resilience of Thaba Nchu's livestock production system toward temporary fodder shortages (Table 3). Accordingly, a modeling study parameterized with data from the focal SES showed that a lack of cooperation between households increased the likelihood of livestock population crashes (Rasch et al. 2016b).
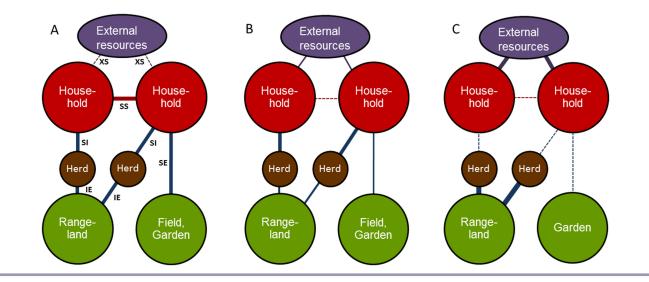
Synthetic assessment of social-ecological system resilience

The modified social-ecological system motif as a conceptual framework for synthesis
To formalize interdependencies between and within subsystems, we use the SES motif, a conceptual framework proposed by Bodin and Tengö (2012). It represents a simplified SES consisting of two social actors and two ecological resources. In the focal SES, livestock-owning households are the social actors of interest, and local pastures and fields are the two main resource types. To this four-node motif, we add an external node representing external resources to account for their importance in the focal SES, and an interface node representing herds (Fig. 3). The interface node is motivated by common characteristics of pastoral SESs. First, herds may constitute a mixture of exclusive and shared resource use: In our study, while each household has exclusive access to its herd, livestock herds in communal settings share the ecological resource of pastures. Second, conceptualizing herds as an interface overcomes the difficulty of assigning herds to a subsystem; previous studies have either assigned them to the ecological subsystem (e.g., Bodin and Tengö 2012) or the social subsystem (e.g., Ostrom 2009b). Third, the connection between social actors and ecological resources is not direct, but is mediated by livestock population dynamics. Thus, herds constitute a complex and indirect social-ecological link. An interface node accounts for this indirect coupling: Herds could be tightly coupled to the ecological subsystem, the social subsystem, or both.

Coupling within and between subsystems
In the traditional (pre-betterment) SES, the strong dependence of livestock on local forage resources and the strong dependence of pastoral households on livestock-generated income implied a strong coupling between subsystems through their livestock interface (Fig. 3A, SI and IE interactions), and a livestock-

Fig. 3. Novel social-ecological system (SES) motifs (modified from Bodin and Tengö 2012) of three major phases in the focal SES: pre-betterment (A), betterment and homeland (B), and post-apartheid (C). Livestock-owning households (red nodes) are social actors in the social subsystem; rangelands and fields and gardens (green nodes) are natural resources in the ecological subsystem. To this original four-node motif, herds (brown nodes) were added as an interface between subsystems, and a node of external resources was added to account for the open character of the focal SES. Link types show interactions between nodes: external to social (XS), social to social (SS), social to interface (SI), interface to ecological (IE), and social to ecological (SE). Ecological-to-ecological interactions (EE) were not of relevance in the focal SES. Line width illustrates the strength of interactions; dotted lines indicate weak interactions.

mediated shared access to rangelands. Fields were exclusive resources, providing an additional, direct interaction between subsystems (Fig. 3A, SE). Within the social subsystem, households were closely coupled through social networks and institutions (Fig. 3A, SS), whereas nonfarm resources were of minor importance (Fig. 3A, NS). Because similar patterns have been reported for other traditional pastoral SESs (Li and Li 2012, Goldman and Riosmena 2013), we deduce that high levels of connectivity and asymmetric access to resources could be critical resilience mechanisms in pastoral SESs.

Top-down interventions of the government's betterment schemes initiated various decoupling processes within and between subsystems. This decoupling continued in the homeland phase (Fig. 3B, weak interactions illustrated by thin or dotted lines). Low rates of supplementary feeding in the post-apartheid phase imply that currently, herds are again closely coupled to local rangeland resources. Concurrently, livelihoods became decoupled from livestock-generated income because of the increased importance of external resources (Table 3, Fig. 3C). In the nomenclature of Ostrom (2007, 2009b), the decoupling of users (households) from resource units (herds) triggered a recoupling of the resource system (rangelands) to the resource units (herds). Our finding that top-down processes have triggered strong decoupling processes is corroborated by other studies from pastoral SESs (Li and Li 2012, Goldman and Riosmena 2013). In contrast, recoupling processes between social and ecological subsystems have rarely been observed (but see Bollig and Menestrey Schwieger 2014).

The fact that animal nutrition has recently become recoupled to rangeland resources might also explain why vegetation outside piospheres is currently in a good (nondegraded) state. This observation is somewhat surprising because communal land tenure in South Africa is often associated with high livestock densities and continuous grazing, typically leading to undesirable vegetation changes (Vetter et al. 2006). We assume that rangeland vegetation has recently recovered because stocking densities were (unintentionally) reduced and because unsustainable practices of supplementary feeding were abandoned (see Müller et al. 2015). In other words, the current low-input management has reestablished a rangeland system in which livestock populations are dynamically coupled to their stochastically fluctuating dry-season forage resources, thus avoiding rangeland degradation (Hempson et al. 2015). Our results support the idea that grazing-induced vegetation changes under communal land tenure do not necessarily have to be stronger than those under freehold tenure (Palmer and Bennett 2013, Linstädter et al. 2014).

Our study also underlines that the tragedy of the commons (Hardin 1968) only holds for contested resources. Although a lack of social connection between users sharing the same ecological resource (Fig. 3B and C) usually suggests overharvesting and degradation (Bodin and Tengö 2012), we found that natural resources are currently in a comparatively good state. However, this state is not due to solutions imposed by the government or self-organization of users (Ostrom 2009a), but is simply because the resources have become less contested.

CONCLUSIONS

We empirically assessed the resilience of a pastoral SES to drought based on various methods from natural and social sciences that were applied in an integrated way. This makes our study one of the first with a truly multidisciplinary approach, avoiding oversimplification of either the ecological or the social subsystem (Schlüter et al. 2014). Our conflicting results from partial assessments underline that measuring a narrow set of indicators may impede a deeper understanding of SES dynamics (Quinlan et al. 2016). The results also show that the resilience of an SES's subsystems is not easily synthesized into overall SES resilience because of complex interactions between subsystems (Lade et al. 2013, 2015). Moreover, we found that decoupling processes do not necessarily decrease the resilience of either subsystem or the overall SES, as concluded earlier (Li and Li 2012, Domptail et al. 2013, Goldman and Riosmena 2013). On the contrary, the resilience of contemporary livestock-owning households to drought is higher than ever before. The reason for this resilience is that physical and monetary losses in livestock production only have negligible effects on livelihoods because of the high importance of external resources. We have integrated these findings in our novel SES motif (modified from Bodin and Tengö 2012), in which external resources are considered explicitly.

Our findings have important conceptual implications. In open SESs with a high importance of external resources, resilience cannot be explained by looking inside the focal SES. Studies and conceptual frameworks that tend to be inward-looking, such as those focusing on common-pool resource management (e.g., Bodin and Tengö 2012), may miss essential connections and drivers at other scales. Such connections become increasingly relevant in modern developing economies, where isolated SESs are rare (Young et al. 2006, Fischer et al. 2015). Moreover, the idea of resilience as being conjointly ecological and economic is misleading in such open, globalized SESs: Even if the local capacity to adapt to local conditions is strengthened, adaptations may be overwhelmed by changes in external drivers. The critical importance of teleconnections and fungible monetary resources makes the resilience of globalized, open SESs qualitatively different from that of isolated SESs (Challies et al. 2014). Future studies should consider these radically diverging trends in cross-scale linkages when choosing conceptual frameworks and methods for resilience assessment.

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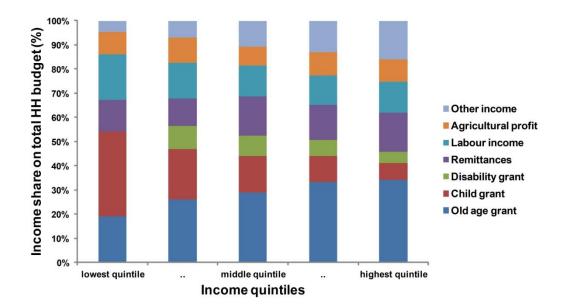
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Appendix 1. Contribution of income sources towards total household income in the village Sediba along income quintiles.

Appendix 2. Comparison of vegetation condition on pastures in the Thaba Nchu SES (continuous grazing practice) to pastures on adjacent commercial farms used as benchmark system due to rotational grazing practice. Rangeland condition on piosphere and pasture plots is derived from the relative abundance (rel. %; mean ± SD) of the palatable bunchgrass *Themeda triandra*, following van der Westhuizen et al. (1999). Letters indicate significant differences between sites (Tukey's HSD; $P < 0.05$). Note that only the three piosphere plots closest to the water point were considered to stay congruent with the assessment of soil resilience.

SES; tenure	Site	Piosphere			Pasture		
		n	*T. triandra* (rel. %)	Rangeland condition	n	*T. triandra* (rel. %)	Rangeland condition
Thaba Nchu; communal	Sediba	3	2.28 ± 3.85	Very poor	10	42.7 ± 19.1[a]	Reasonable
	Middeldeel	3	6.06 ± 10.41	Poor	11	77.5 ± 17.2[b]	Excellent
Benchmark; commercial	Lieftefontein	3	5.62 ± 6.96	Poor	13	58.7 ± 19.9[ab]	Good
	Rustdam	3	17.4 ± 16.99	Poor	12	73.6 ± 18.9[b]	Good
	Hellerfontein	3	2.17 ± 4.29	Very poor	11	73.0 ± 15.2[b]	Good
	Ems	3	4.10 ± 3.18	Poor	14	74.4 ± 15.3[b]	Good