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A typology for complex social-ecological systems in mountain communities

Mark Altaweel¹, Arika Virapongse², David Griffith², Lilian Alessa², & Andrew Kliskey²

¹ Institute of Archaeology, University College London, 31-34 Gordon Square, London, WC1H 0PY UK (email: m.altaweel@ucl.ac.uk)

² Center for Resilient Communities, University of Idaho, Moscow, ID 83844 USA (email: avirapongse@neoninc.org; griffith@uidaho.edu; alessa@uidaho.edu; akiskey@uidaho.edu)

Effective and standardized assessment of social-ecological systems is crucial for supporting increased resilience of human communities and for developing adaptation strategies. However, few analytical frameworks exist to assess the social-ecological resilience and vulnerability of different landscapes. To help fill the gap in this literature, we investigated the utility of a conceptual social-ecological systems typology by assessing 21 mountain communities in the western United States. Our results show that larger cities or urban areas are generally more resilient than smaller communities, but the variation is not particularly notable. Resilience differences are found most often among communities of different population sizes. In our sample, no community was deemed to be highly vulnerable to social-ecological change. More broadly, development of standardized social-ecological systems typologies can be applied toward accommodating unique environmental niches while allowing for cross-comparisons among regions on a broader continental scale.

KEYWORDS: classification, local communities, montane environments, ecosystem resilience, environmental sociology

Introduction

Classification of social-ecological systems is an important first step for identifying and assessing factors that affect resilience and vulnerability of communities and their resources (Alessa et al. 2009; Ostrom, 2009; Ostrom & Cox, 2010) and determining potential interventions, such as those intended to enhance a system's resiliency (Cumming et al. 2005). A social-ecological system (SES) consists of human and biophysical components that are interconnected and linked through complex system feedbacks and dependencies (Berkes et al. 2003). Mismatch in the scales of SESs, in whole or in part and ranging from community- to landscape-level systems, is often an obstacle to comparative studies (Cumming et al. 2006; 2013). Existing typologies focus on SESs at such a broad level that it is not clear if unique qualities of environmental niches and community specificity can be easily addressed (e.g., Alessa et al. 2009; Ostrom, 2009; Ostrom & Cox, 2010). Information derived from large-scale studies is often not informative when assessing community resilience in specific regions, such as mountainous areas that are varying and complex landscapes characterized by large biophysical gradients and great fluxes in resource quality and quantity. Without robust tools to comparatively assess the resilience of communities located in spe-

cific types of landscapes, it remains a challenge to sustainably manage available valuable natural resources and the social and environmental changes that are expected in the near future.

Typologies of SESs have been developed as practical tools that can be used to classify SESs by applying information generated through conceptual models and existing datasets. By testing such conceptual models in the real world, typologies can help identify key characteristics, drivers, and dependencies within and among systems (Blair et al. 2014; Buergelt & Paton, 2014). Typologies allow for standardized characterization by using specific metrics, so that characteristics (e.g., vulnerability to environmental change) can be compared among communities and management decisions and planning can be conducted with greater standardization. Standardizing the metrics used to assess SESs makes possible scaling up from community to landscape levels so that cross-comparisons can be conducted at broader scales. As an analytical framework, SES typologies are effective in contrasting communities located in specific landscapes with shared biophysical features (e.g., mountains) as well as among landscape types (e.g., mountains and coastal areas) on much broader scales. To develop such a tool, existing SES typologies must be examined and refined in accordance with specific landscapes (e.g., Alessa et al. 2009; Ostrom, 2009).

This article's main goal is to evaluate the resilience of mountain-system communities using a modified version of the "Messy SES" typology (Alessa et al. 2009) and to offer recommendations for further development of typologies as a framework. The unit of analysis used to characterize SESs is a community and its associated resources. We apply the typology in this study to evaluate the resilience of 21 mountain communities located in the western United States. Based on our analysis, we offer recommendations for how the SES typology can be further refined for use in specific types of landscapes. With more enhancement and development, such typologies can be valuable for conducting cross-comparisons among different landscapes so that assessments of SESs can occur on a continental and global scale.

Background

Why Typologies?

Human-environmental interactions are integral components of interconnected, large-scale systems—the "ecological macrosystem" (Brondizio & Chowdhury, 2013; Heffernan et al. 2014). Such macrosystem processes, for instance climate change, have been linked to accelerating rates of natural disasters, economic crises, and livelihood vulnerabilities (Alley et al. 2003; Skoufias, 2003). To improve social preparedness for large-scale change, scientists have formulated high-level frameworks to address community resilience in practice, such as toolkits that enable resilience self-assessment (e.g., U.S. Climate Resilience Toolkit, 2015). Offering a more region-specific framework, typologies provide a template for researchers and managers to systematically identify resilience/vulnerability levels for communities in a comparable and scalable manner.

The most challenging aspect of developing an SES typology is to identify appropriate social, biophysical, and integrated metrics for capturing resilience or vulnerability, as well as finding accessible long-term datasets to support such metrics. Typologies for community-level resilience have focused on aspects of social metrics, such as change in settlement structure, institutions, and livelihoods (Carney, 1998; Berkes et al. 2003; Krausmann et al. 2008). They also can investigate relationships among stakeholders, decision makers, and sociocultural values regarding economic concerns (Wallace, 2007; Reed et al. 2009). Biophysical metrics used in typologies have included presence of different ecosystems, land-cover change, and availability of ecosystem services (Adger et al. 2002; de Groot et al. 2002; Lambin et al. 2003). Integrated metrics include activities of rural landholders and land use (Emtage et al. 2006; Nuissl et al. 2009). To address community-level adaptation

and resilience, different social scales (e.g., individual to community level; Buergett & Paton, 2014), relationships between governance and ecosystem services (Ostrom, 2005; 2009), and community size and resource connectivity (Alessa et al. 2009) are assessed and included in typologies. The applied typology considered here studies the heterogeneity that exists across SESs in their given landscapes by investigating different SES elements.

Mountain System Communities

Mountain SESs require special attention because of their position in the upstream-downstream gradient, unique ecosystem characteristics, changing human demographics, effects on resource and management decisions, and cultural and political aspects. As the location of intensive exploitation or as the source of renewable and nonrenewable resources—such as timber, minerals, and water—mountainous regions and their associated watersheds are critical for most societies (Messerli et al. 2004; Winkler et al. 2007; Emelko et al. 2011). As in other systems, mountain-based human communities are subject not only to pressure from macro-environmental drivers such as climate change, but also from human-driven factors such as population growth/decline, economic development, migration, and urbanization. In contrast to other types of SESs, however, extreme biophysical gradients within mountain landscapes can create unique vulnerabilities to disturbance, availability of ecosystem services, and patterns of ecological and natural-resource exploitation (MtnSEON, 2015).

Considered unique and understudied from ecological and biogeographical perspectives (Beniston, 2003), mountain landscapes are defined by high-contrast biophysical and ecological characteristics, such as steep physical gradients (e.g., elevation, precipitation, temperature), ecotones (abrupt ecological transition zones), and highly varied ecosystems and physical characteristics (Haslett, 1997; Gardner & Dekens, 2007). Mountains have extreme and varying topographies along a large continuum; for example, consider the differences between Snowdon in Wales (high precipitation, heavily forested, anciently volcanic, and standing 1,085 meters) and Mount Kilimanjaro in Tanzania (dry, sparsely forested, many endemic plants, actively volcanic, and standing 5,149 meters). Extreme, but local, spatial heterogeneity also differentiates mountains from surrounding lowland areas, so that mountainous regions are often defined according to relative prominence (vertical differentiation from surrounding landscapes). For example, the town of Browning, Montana (USA) is considered to be on the "high plains" at 1,334 meters; this can be contrasted with Mount Rogers in Virginia (USA), identified as a mountain at 1,746 meters, and the

forementioned Snowdon in Wales, unquestionably a mountain at only 1,085 meters.

High-contrast biophysical characteristics also subject mountain landscapes to hazards that are unique or more pronounced than in other landscapes. For example, landslides, avalanches, flash floods, forest fires, and extreme cold events are characteristic of mountain SESs, but largely absent from lowland temperate regions where most of the world's populations resides (Gardner & Dekens, 2007; Hewitt, 2014). Due to the great biophysical, microclimatic, and ecological variability of mountain areas, their ecosystems are reservoirs for biodiversity and highly vulnerable to global change. Prominence and separation of peaks by lowlands with inhospitable biophysical characteristics results in many mountains acting as ecological "sky-islands," with unique fauna and flora that are susceptible to environmental and climate change and physically unable to migrate to more suitable habitat as conditions change (Holycross & Douglas, 2007). Mountains also serve as refuges for many endangered species, such as large carnivores (Weaver, 2001). Global climate change is predicted to have greater effects on mountain ecosystems, and other high-latitude ecosystems, than on most landscapes (a prediction that is actually beginning to occur) (Kullman, 2004).

The biophysical and geographical characteristics of mountainous landscapes contribute to pronounced cultural, socioeconomic, and political diversity and significance for these regions. Mountain ecosystems, especially in Europe, have been modified, molded, and tended by self-organizing and self-regulating cultures at the fringes of larger polities and societies (Rescia et al. 2008). Due to historical patterns of forest use and resource extraction in many mountainous regions of the world, mountain landscapes and associated communities experience (and in some instances engage in activities that directly cause) more deforestation, related flooding, and extreme erosion than comparably sized lowland SESs (Gibon et al. 2010). Mountain ranges have been used to define political frontiers between nations (Stoddard, 1991), and the enforcement of law and effective governance by states is typically weaker in mountainous regions (Ratner, 2000). Often, in mountainous areas minority groups are isolated (e.g., India), natural resources are heavily exploited (e.g., logging and mining), and military conflict persists (e.g., Afghanistan, Yemen; Blaikei & Sadeque, 2000). In addition, mountains regularly serve as sacred sites of cultural importance and these features have been correlated with higher biodiversity (Anderson et al. 2005). As a result of different or unique characteristics for mountain systems and communities, researchers and stakeholders have suggested specific guidelines for protecting the

biological and cultural diversity of these regions (Wild et al. 2008).

Mountain systems are critical for understanding watersheds and their connectivity from high elevation to the sea (Kaneshiro et al. 2005). This importance is exemplified in the ancient Hawaiian managed landscape, or *ahupua'a*, a land division stretching from upland mountains to the near shore that formed the basis for agro-ecological management and acted as a foundation for local cultural and political economies (Kamehameha Schools, 1994; Kliskey et al. 2009). In temperate environments, mountain-to-sea connectivity has been extended to icefield-to-ocean linkages, given changes in elevation and moisture, similarly highlighting the critical roles of downstream connectivity, transitions, and gradients for mountain landscapes in entire watersheds (O'Neel et al. 2015).

Methods

Analytical Approach

We use the "Messy SES" typology as a starting point to assess community-level resilience in the western United States mountain system (Alessa et al. 2009). Resilience and vulnerability are designated as two ends of a continuum in this typology, which emphasizes community size, resource use, and community connectivity, acknowledging that SESs are inherently difficult to categorize or assess (Folke, 2006). In comparison to the SES typology proposed by Ostrom (2005; 2009), Alessa et al. (2009) requires fewer proxies, so it is more manageable in practice. Our analysis assessed the Alessa et al. (2009) typology to improve its utility for providing information helpful to making management and community-planning decisions. The unit of analysis in our study is a community, defined as an area and population associated with an organized and commonly governed collection of households.

To assess the typology, we first selected 21 communities from the western mountainous region of the United States (Intermountain and Rocky Mountains) as a sample group (Figure 1). We defined a mountainous region as a landscape with significant prominence, sloping terrain, valleys, and human communities. We studied communities located in such landscapes in the states of Colorado, Idaho, Montana, Oregon, Utah, Washington, and Wyoming, with population sizes ranging from 204 people (Washtucna, Washington) to 663,900 residents (Denver, Colorado).

We next considered the eleven resilience proxies used in Alessa et al. (2009) and their relevance to our mountain-system communities (see the next section). Resilience proxies are diversity, distance, retention, distribution, persistence, collectivism, variability,

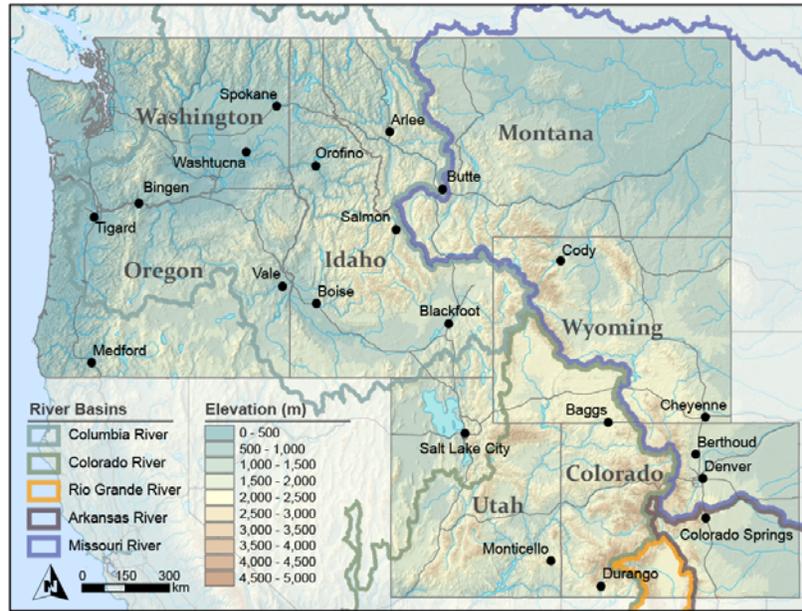


Figure 1 Location and elevation of sample communities.

substitutability, communication, and risk. We identified specific metrics for each proxy (Table 1), based on the availability (e.g., open source, freely available) of quantitative datasets. Where possible, we identified both social and biophysical metrics for each proxy. Metrics that were only available at large scales (e.g., state level) were scaled down to the community level based on population proportions. In other words, we took the state-level data and applied it to the community.

After all data were collated, we calculated the range for each metric for the sample group. We then divided the range into three parts (Table 1, column “Metric Defined”). Qualitative identifiers were given for each part (e.g., low, middle, high) to describe their relationship to the metric. These identifiers were then assigned numeric values that reflected the metric’s contribution to resilience. For most metrics, the transformation was 1 = low, 2 = middle, and 3 = high. Some categories, with more quantitative data that allowed for fine-scale treatment, also apply 0.5 intervals. For other metrics, an inversion was needed. For example, “distance to freshwater” was considered 1 = high, 2 = middle, and 3 = low, as a shorter distance to water is associated with higher resilience. After all results were described numerically, data in each proxy were averaged. We then translated the averages into categories A, B, and C (resilient to vulnerable, respectively), where the bottom-, middle-, and top-third of averaged results correspond to A–C categories, respectively. Resilient communities (A) are those which are most likely to withstand distur-

ance, transitional communities (B) respond unevenly to disturbance, and vulnerable communities are those least able to resist the negative effects of disturbance (c.f. Alessa et al. 2009).

Size (i.e., population) is considered separately from the proxies (Alessa et al. 2009), because the scale of social organization is a strong discriminator with respect to environmental change and response (Wilbanks & Kates, 1999; Marston, 2000). Size offers the opportunity to scale resilience assessments for cross comparisons among communities. For example, the number of residents is associated with aggregated benefits (e.g., tax revenue) and costs (e.g., resource use; Dasgupta, 1995). In mountain regions, size is particularly important because the human-carrying capacity is often limited by topography. Small communities are often located in canyons or on sloped land, with larger population concentrations situated in valleys or at the edge of mountainous areas (Cohen & Small, 1998).

Our analysis defines community size by estimated population, ranging from small ($3 < 2,500$), medium ($2 = 2,500–50,000$), to large ($1 > 50,000$) according to the United States Census Bureau’s (2010a) urban-rural classification for towns (data are collected from U.S. Census, 2015a). The resilience classification (A, B, or C) is combined with the size classification (1, 2, or 3) so that nine different categories for community resilience are possible (i.e., Types 1A–3C).

Proxies and Metrics for the Typology

The eleven proxies considered in the typology are intended to capture a range of social-ecological factors affecting community-level resilience and vulnerability (Alessa et al. 2009). Proxies address components of vulnerability including root causes (e.g., factors that produce unequal distribution of resources among people), dynamic pressures (e.g., processes and activities such as environmental change), and unsafe conditions (e.g., spatial location and the built environment; Wisner et al. 2004). We evaluated the

proxies according to: 1) relevance to mountain systems and 2) metrics and available datasets to inform the proxy. Table 1 lists the specific proxies that we applied. A total of nineteen metrics and eighteen different sources for datasets informed our typology. Table 1 also indicates the thresholds of metrics employed to evaluate communities by identifying the range within the sample group (column “Metric Defined”). We identified relatively informative metrics and good quality datasets for most proxies. Data were all derived from free, publicly available sources on

Table 1 Descriptions, definitions, and datasets for metrics used for each proxy.

Proxy	Metric	Metric Description ¹	Metric Defined ²	Data Set Citation
Diversity	Industry diversity	Range across percent of participation of top three industries of the town (%)	High (3) < 5, Medium (2) 5–10, Low (1) > 10, Range: 0–15	U.S. Census (2013a)
Diversity	Biodiversity	Biodiversity of plants, fungi/lichens, animals, by state (number of species)	Low (1) < 6,915, Medium (2) 6,915–7,827, High (3) > 7,827; Range: 6,003–8,739	Nature Serve (2013)
Distance	Ocean distance	Distance from the ocean (km)	Low (3) < 603, Medium (2) 603–1,107, High (1) > 1,107; Range: 100–1,510	Google Earth (2015)
Distance	Water distance	Distance from main water source for community use (km)	Low (3) < 60, Medium (2) 60–115, High (1) > 115; Range: 5–170	Google Earth (2015); community websites
Retention	Renewable energy use	Energy used from renewable sources (wind, solar, hydro, geo, biomass) by state (%)	Low (1) < 34, Medium (2) 34–67, High (3) > 67; Range: 0–100	USDOE (2013)
Retention	Recycling activity	Number of people per recycling center (individuals/center)	Low (3) < 10,374, Medium (2) 10,374–20,748, High (1) > 20,748, communities with no centers identified as “high”; Range: 0–31,122	RecyclingCenters.org (2015)
Distribution	Airport distance	Distance to international airport (km)	Low (3) < 258, Medium (2) 258–503, High (1) > 503; Range: 13–748	Travel Math (2015)
Distribution	Conduits available	Connection points to Interstate highways (Number of connection points)	Google Earth (2015) Range: 0–5	Google Earth (2015)
Persistence	Establishment age	Founding year for community (year)	Older (3) < 1,863, Medium (2) 1,863–1,880, Young (1) > 1,880; Range: 1,847–1,896	Wikipedia (2015)
Collectivism	Union affiliation	Employed and salary workers with union affiliation by state (%)	Low (1) < 9, Medium (2) 9–14, High (3) > 14; Range: 4.60–18.40	BLS (2014)
Collectivism	NGO participation	Number of people per NGO by community (individuals)	Low (3) < 153, Medium (2) 153–256, High (1) > 256; Range: 50–360	IRS (2015)
Variability	Precipitation range	Range in precipitation record per year (inches)	Low (1) < 20, Medium (2) 20–30, High (3) > 30; Range: 9.4–41.7	Western Regional Climate Center (2015)
Variability	Population change	Change in community population from 1990 to 2015 (%)	Low (3) < 121, Medium (2) 121–154, High (1) > 154; Range: 88–187	City Data (2015)
Directionality	Export-import difference	Difference between exported and imported goods by state (US\$)	Low (3) < 8,944, Medium (2) 8,944–23,774, High (1) > 23,774; Range: –5,887–38,605	U.S. Census (2015b)
Substitutability	Commuting activity	Change in daytime population due to commuting, by county (%)	Low (1) < 5.2, Medium (2) 5.2–16.1, High (3) > 16.1; Range: –5.7–27	U.S. Census (2010b)
Substitutability	Growing days	Number of growing days for cultivated plants per year by state (days)	Low (1) < 115, Medium (2) 115–156, High (3) > 156; Range: 74–197	Farmer’s Almanac (2015)
Communication	Internet access	Percent of people with computer and Internet access, by community (%)	Low (1) < 81, Medium (2) 81–85, High (3) > 85; Range: 8–89	U.S. Census (2013b)
Risk	Social Vulnerability Index	Vulnerability measurement 1–4	Low (1) < 1.33, Medium (2) 1.33–2.66, High (3) > 2.66; Range: 1–3	HVRI (2013)

¹ Qualitative description of metrics, including the scale of the dataset and unit of analysis (in parentheses).

² Quantitative categorization of the metric, including a qualifier describing the town’s metric in relation to the sample group (low to high); numeric designation describing the metric’s contribution to the town’s resilience (in parentheses, 1: negative, 2: neutral, 3: positive); and range of actual values within the sample group.

the Internet.

Diversity (the first of the eleven proxies), which considers a community's varying access to both local and distant resources, is a measure of a community's social and biophysical options for meeting livelihood needs, such as mechanisms for accessing resources (e.g., livelihood activities) and availability of resources (e.g., timber, energy deposits). Economic diversity, such as the presence of different industries, helps to inform how communities might adapt to shifts and stresses arising from evolving economic circumstances (Chapin et al. 2004). Diversification promotes livelihood security by helping households overcome crises and abrupt change (Shackleton & Shackleton, 2004). Similarly, biophysical diversity, such as biological, ecological, and natural resource diversity, offers a great range of options and alternatives for communities to be more adaptive to change (Adams et al. 2004, Reyers et al. 2012). In mountain systems, diversity is linked to distance and distribution and provides different options for livelihood strategies.

Distance refers to the physical distance to essential resources (e.g., water, goods, trade). For example, communities located near headwaters have great potential for environmental impact on downstream communities. Mountain communities are often isolated; steep gradients can cause distribution of resources to be more sensitive to change than in more homogeneous topography. Climate change, for example, is expected to affect mountain regions by making some natural resources either physically more distant, scarce, or no longer available (Hope, 2014). Therefore, distance is linked to the proxies of topography, diversity, and distribution.

Retention is defined as efficiency in resource utilization, such as through renewable and recycled materials. In mountainous regions in the western United States, renewable natural resources that contribute directly to livelihoods include, but are not limited to, arable soil, trees and plants, fish and game, and wind for power generation. More varied and numerous renewable resources provide long-term security for mountain communities (Forman, 2008). Security can be measured based on how much renewable energy or how many resources are used in a community, including the capacity and infrastructure for recycling resources. Retention is linked to distance, as isolation can drive higher retention or prevent recycling of materials through lack of infrastructure.

Distribution is a measure of a community's level of connectivity to a broader economy, such as through transportation conduits. In terms of infrastructural resilience, a community with easy access to highways, major airports, and rail interconnections is

more resilient than an isolated community (Cutter et al. 2010). Strong connections to surrounding communities and a broader region enhance community resilience by allowing more access to resources and emergency aid while being responsive to external factors or shocks.

Persistence is measured based on a community's previous history in facing threats and overcoming and adapting to social-ecological stresses (Assche & Lo, 2011). Historical records can form a baseline indicating how effectively communities have dealt with social-ecological stress in the past. For mountain communities, this is particularly important for anticipating and adapting to natural threats, such as floods. This proxy helps to measure a community's experiences recovering from major ecological disturbances such as pine-beetle infestations. As a metric for persistence, community age can be informative, with historical memory being preserved through records and traditional, generational knowledge.

Collectivism represents how community-driven processes and institutions, such as governmental, private, and public organizations, respond to social-ecological change (Buduru & Pal, 2010). This characteristic indicates how well communities are able to respond to endogenous or exogenous stresses through local cooperation and systems of organization. A high number of community-based programs and institutions [such as labor-union affiliation and the presence of nongovernmental organizations (NGOs)] relative to population can determine if organizational systems enable resilience. High levels of collectivism help to shape more rapid and flexible responses among communities through such processes as adaptive governance (Folke et al. 2005).

Variability refers to the consistency of environmental factors and resource availability for a community over time. Environmental variability, for example, has been identified as an important determinant of community vulnerability in traditional agricultural systems throughout the world (Altieri, 2004). Variability can be measured in several ways: the World Meteorological Organization (WMO), for example, has used change in precipitation, river discharge, and air temperature over a minimum of 30 years to monitor environmental variability. In mountain systems, variability is often determined by the location of a community along different gradients (e.g., elevation, location in watershed, slope). As climate change begins to have greater effects on specific landscapes over the next century, variability in environmental factors such as precipitation is expected to increase, greatly affecting agriculture and other activities (Beniston & Stoffel, 2014).

Table 2 Values of the resilience proxy measures for the 21 sample communities, including size and analysis results. Resilience level category ranges are as follows: A = 3.0–2.4; B = 2.3–1.7; C = 1.6–1.0.

Community / Proxy	Size	Diversity	Distance	Retention	Distribution	Persistence	Collectivism	Variability	Directionality	Substitutability	Communication	Risk	Average of resilience proxies	Resilience level	Resilience Type
Denver, CO	1	2.5	2	2	3	3	2	1.5	3	3	2	2	2.4	A	1A
Colorado Springs, CO	1	2.5	1	2	2.5	3	1.5	1	3	1.5	3	3	2.2	B	1B
Durango, CO	2	2	2	2	1.5	1	2.5	2	3	1	2	3	2	B	2B
Berthoud, CO	2	2	2	2	2	2	2.5	1	3	1.5	2	3	2.1	B	2B
Orofino, ID	2	2	3	3	1	3	2	2.5	3	2	2	2	2.3	B	2B
Salmon, ID	2	1.5	2.5	3	1	2	2	2	3	1.5	2	2	2.1	B	2B
Blackfoot, ID	2	2	2.5	3	2	2	1	1.5	3	1	2	2	2	B	2B
Boise, ID	1	1.5	2.5	2	1.5	3	1.5	1	3	1.5	1	2	1.9	B	1B
Butte, MT	2	2.5	2.5	2	1.5	1	2.5	2	3	1	1	2	1.9	B	2B
Arlee, MT	3	2	2.5	1	1	2	3	2	3	1.5	1	1	1.8	B	3B
Tigard, OR	1	3	3	3	2.5	3	2	2	3	2	2	2	2.5	A	1A
Vale, OR	3	3	3	3	1	1	3	2	3	2	2	2	2.3	A	3A
Medford, OR	1	2.5	3	3	2	1	2.5	1.5	3	1.5	1	2	2.1	B	1B
Monticello, UT	3	2.5	2	2	1.5	1	1	2	3	1.5	2	1	1.8	B	3B
Salt Lake City, UT	1	2.5	2.5	2	3	3	2	2	3	2.5	2	2	2.4	A	1A
Washtucna, WA	3	2	3	2	1.5	2	2.5	2	1	1.5	2	2	2	B	3B
Spokane, WA	1	1	3	3	2	2	2.5	2	1	1.5	2	2	2	B	1B
Bingen, WA	3	1.5	3	3	2.5	1	2	2	1	2	2	2	2	B	3B
Cheyenne, WY	1	2.5	1.5	1.5	3	2	1.5	1.5	3	1.5	2	2	2	B	1B
Baggs, WY	3	2	2.5	1	1	2	2	1	3	1	1	2	1.7	B	3B
Cody, WY	2	3	2.5	1	1	1	2	2	3	1.5	1	3	1.9	B	2B

Directionality refers to the input or output of resources due to trade or environmental change. Some mountain communities are more self-sufficient due to local natural resources (e.g., timber), but industrial goods and services needed to capture more value from these resources may be outsourced to other locales. For example, a mountain-ski town imports goods and services to earn revenue through visitors to the resort, gaining resources. A mining town, on the other hand, may extract and export natural resources (removing resources). Directionality informs how (negative or positive) communities are able to accumulate resources that promote resilience and adaptation related to proxies of distance, distribution, and retention (Carpenter & Brock, 2008).

Substitutability measures a community’s range of available resource options and gauges its ability to adapt under social-ecological stress by having access to redundant and multiple social-ecological resources (Folke et al. 2005). Metrics to inform this proxy can include the availability of nearby work opportunities (e.g., percentage of local residents that commute to jobs) and growing days for agricultural and cultivated plants.

Communication relates to a community’s ability to access knowledge to help promote resilience and adaptation, which can be in the form of mass media or social networks that spread ideas (Vogel et al.

2007). Quantifying the population’s level of access to the Internet and other communication (e.g., libraries, archives) informs this proxy.

Risk is important for determining how likely it is that communities will be affected by disturbance events (e.g., flooding, economic crisis, or disease outbreak). Depending on their specific location, higher elevation communities may experience major shocks such as shifts in the quantity and timing of precipitation due to climate change, while lower elevation communities may be less affected. Meaningful risk metrics for mountain systems include predicted change in precipitation and snowpack, which can increase due to storm events. Distance from contamination sources, such as elevation and location along a watershed gradient, can affect pollution spread (Briggs, 2003). While ambient temperature generally varies with altitude and latitude, variation in meteorological conditions due to climate change is expected to be inconsistent across time and space. The Social Vulnerability Index (HVRI, 2015) is a useful measurement of risk that considers susceptibility to environmental hazards by categories such as race, ethnicity, and age, as different cohorts may have greater risk due to socio-economic status.

Based on an SES science approach, all of the proxies inform and affect each other through feedback loops. However, some proxies are more closely

Resilience Rank	C vulnerable			
	B transitional	Colorado Springs, CO Boise, ID Medford, OR Spokane, WA Cheyenne, WY	Durango, CO Berthoud, CO Orofino, ID Salmon, ID Blackfoot, ID Butte, MT Cody, WY	Arlie, MT Monticello, UT Bingen, WA Washutcna, WA Baggs, WY
	A resilient	Denver, CO Tigard, OR Salt Lake City, UT		Vale, OR
		1 - large	2 - medium	3 - small
		Community Size Rank		

Figure 2 Typology results for the communities assessed.

related than others. Diversity, variability, distance, retention, distribution, and directionality are all based on a community’s physical features. Size, persistence, and collectivism focus on social aspects of local history and social organization. Risk stands alone because it is based on the prediction of future events, according to an analysis of all other proxies. Topography is not included as a proxy, although it affects many of the proxies, including size, distance, risk, and distribution.

Results

Table 2 displays the size of the communities and aggregate measures of the metrics for each resilience proxy so that they can be compared across communities. The table also shows the final combined size and resilience score for each community. Communities typed A to C are more to less resilient, respectively; community sizes 1 to 3 are large to small, respectively.

On the basis of our analysis (Table 2 & Figure 2), most sample communities are characterized as transitional (n = 17); however, four communities are classified as resilient. Large communities, or cities, are deemed to be either resilient (n = 3) or transitional (n = 5). Medium-sized communities are all identified as transitional (n = 7). The majority of small towns are transitional (n = 5). Using the framework provided by Alessa et al. (2009), none of the towns in our sample are classified as vulnerable, although Baggs, WY scores very close.

As an illustration of the assessment of SES resilience using the typology it is useful to consider the individual measures for a single community. As an example, the town of Salmon, Idaho, is a small rural community of 3,112 residents located in the Salmon River Mountains of the American Continental Divide in central Idaho—rated as a medium-sized communi-

ty (Type 2). The town is situated at an elevation of 1,202 meters above sea level (ASL), immediately west of Continental Divide-mountain peaks that reach in excess of 3,000 meters ASL, and at the upper headwaters of the Salmon River—a tributary of the Columbia River Basin, and 1,560 kilometers upriver from the Columbia River mouth on the Pacific Ocean (Figure 1). Salmon has a semi-arid climate with cold, dry winters and hot, slightly wetter summers. Historically, the Salmon River valley is home to the Native American Lemhi Shoshone people and notable as the birthplace of Sacajawea, the Shoshone guide for the Lewis and Clark expedition of 1804–1806, and the route taken by that expedition as they crossed the Continental Divide en route to the Pacific Ocean.

The overall diversity proxy for Salmon of 1.5 (medium) tempers a low industrial diversity, based on over 12% participation in lumber, ranching, and tourism as the top three industries, with a high biodiversity, resulting from close proximity to relatively unmodified forest and riverine environments (Tables 1 & 2). The distance proxy of 2.5 (medium-low) combines a particularly large distance from the ocean (1,560 kilometers) at the very headwaters of the Columbia River, and short distance from the town’s main water source—the entire town is within one kilometer of the Salmon River (Tables 1 & 2). The retention proxy of 3 (very low) combines low metrics for renewable-energy use and recycling activity (Tables 1 and 2). The distribution proxy of 1 (very low) reflects Salmon’s single connection to Interstate 90 which is 226 kilometers away and accessible in Missoula to the north (Tables 1 & 2). Its persistence proxy of 2 (medium) mirrors the founding of Lemhi County and the City of Salmon in 1866 (Tables 1 & 2). The collectivism proxy of 2 (medium) reflects the combination of 12% of employed and salaried workers in union affiliation for Idaho and 165 people per NGO (Tables 1 & 2). The variability proxy of 2 (medium) indicates both a modest environmental variability (range in annual precipitation) and a modest change in community population from 1990 to 2015 (+0.03%). The directionality proxy of 3 (low) for Salmon echoes relatively low self-sufficiency due to the importation relative to exportation of resources (Tables 1 & 2). A substitutability proxy of 1.5 (medium-low) reflects little change in daytime population due to scant commuting (the only other incorporated city in the county being Leadore with only 105 residents some 74 kilometers away, and a medium number of growing days per year (Tables 1 & 2). Its communication proxy of 2 (medium) is due to a moderate percentage (83%) of the community possessing computer and Internet access. And the risk proxy of 2 (medium) reflects a moderate social vul-

nerability index score (2.0) for the community (Tables 1 & 2). The average resilience for Salmon of 2.1 is in the range of transitional resilience—an uneven response to disturbance resulting in an overall rating for the community as a type 2B transitional community (Table 2 & Figure 2).

Discussion

Benefits and Limitations

The Alessa et al. (2009) typology offers descriptions of proxies, but does not specify the metrics that should be used. The categories in the typology are not unique to mountain systems, but mountain characteristics such as precipitation, temperature, transport, and diversity of available resources do affect results by influencing resilience. As such, the typology allows for flexibility to use different region-specific metrics for capturing resilience in mountain systems. By testing the utility of the typology with mountain communities, we were able to assess the challenges, benefits, and limitations of the typology, so that more robust taxonomies can be developed and data gaps identified. Our proxies were not weighted, as the intent was to identify the communities that showed more or less vulnerability within this particular framework.

Datasets are generally available to capture the size and proxies for resilience reasonably well. Since each of our datasets came from a different source, it was time consuming to collect the appropriate data to inform each metric. As other SES studies have noted, the different scales used for each dataset (e.g., county, zip code, state levels) present challenges, because there is a need to scale down some datasets to the town level (e.g., per capita) (Cumming et al. 2006). To improve quantitative capacity to evaluate the resilience of communities, datasets should be collected at the community level.

As an evolving field, resilience science continues to test conceptual SES models that identify metrics of resilience as well as relationships among metrics (Berkley & Gunderson, 2015). In the absence of guidance from a foundation of literature that defines specific metrics to be used in a typology, we select measures that are able to demonstrate the typology's workability using publically available data. Among the proxies, persistence proves to be the least informative in our analysis, as all of the communities were established at roughly the same time. For variability, we use population change from 1990 until the present, which demonstrates that communities can leverage human capital into infrastructure improvement (Short & Mussman, 2014). Although less than ideal, the data were readily available and could be used to highlight the relative ability of communities

to address variable resource or ecological conditions. We use the number of growing days for the substitutability proxy, as this shows the range of crops that can be grown given prevailing climatic advantage. While mountain communities in the United States are not often known for large-scale commercial agriculture, food production does enable local residents to provide for themselves during disruption. For our assessment of risk, we use the Social Vulnerability Index (HVRI, 2013), which we recognize does not include the biophysical aspect of vulnerability, but offers a straightforward way to differentiate risks among communities.

Our typology has potential to be more readily applied using quantitative—rather than qualitative—data, as they provide values that can be directly translated to resilience categories. However, some proxies like collectivism may best be informed through qualitative documentation of activities conducted by government, nongovernmental, and private-public partnerships. The current typology framework is not very conducive for such qualitative datasets. To understand the context that underlies community resilience, better ways to assess qualitative data, such as through the deployment of historical perspectives, are needed to improve typologies. In addition, data sources for metrics are not available in a central repository, so time-consuming online searches in a dispersed and changing digital landscape are needed. We suggest that future typologies consider better ways to include qualitative datasets. While qualitative databases are often inherently difficult to work with, relative measures within such qualitative understanding can at least provide information on what is more or less important from the perspective of resilience.

In this study, we relied only on publically available data rather than community-based information (e.g., local knowledge, unpublished municipal management information). These data, which are labor intensive to collect, could be used in analyses after specific communities of interest have been identified through applying the typology. Depending on open-access data makes the typology useful for managers and planners, who can efficiently allocate their limited resources by more quickly identifying vulnerable communities that may warrant further investigation. In our current study, we emphasize access to data over a more comprehensive approach because we believe that typologies must be easy to populate and implement to be useful in land, resource, and community management. Science often fails to translate results into methodologies that can be utilized by managers and applied researchers, resulting in a research-implementation gap that this study attempts to fill (Walsh et al. 2014).

Another limitation of our approach is that the metric scores are calculated based on our sample. However, we selected this approach because our main goal was to demonstrate the potential utility of the typology as one step in a more encompassing process toward vulnerability assessment of a large number of communities. One benefit of our approach, nevertheless, is that the resilience score is adaptable to changing circumstances within the sample itself. As new resilience typologies and assessments are developed and tested, more rigorous comparisons will be possible. This was attempted for this study but proved difficult for the given data values that were available. In any case, we contend that our analysis offers valuable perspective on advancing SES typologies.

Relevance of Results

Our assessed communities indicate that larger cities are slightly more resilient than smaller communities, where Size 1 settlements average a 2.18 resilience score vs. 2.06 for all other settlements. On one hand, the higher resilience result could be because relatively larger communities generally have more diversified economies; more efficient connections to national and international transportation networks; use of resources; and ability to leverage social, knowledge, and financial capital. In advanced economies, cities tend to have social and economic capacity to develop increasingly resilient infrastructures (Pretty & Ward, 2001; Vugrin et al. 2010; Walker & Cooper, 2010; Smith & Stirling, 2011). In comparison to larger cities, smaller mountain communities, particularly those with populations of less than a few thousand, are slightly more vulnerable (Size 3 communities have a 1.98 resilience average). Interestingly, no communities are classified as Type C (vulnerable). There are a number of possible explanations, such as that no communities in the sample group are vulnerable, the United States is simply relatively wealthier and better able to address resilience, and the typology is not specific enough to inform the resilience context of mountains (e.g., mountain system may represent a nested typology within the typology that we used). Instead of adjusting scores so that some communities are assigned to each of the resilience categories (e.g., centering proxy scores at “2”), we chose to maintain the original protocol, so that the results could be comparable to future typological analyses.

Unfortunately, we were unable to find many other studies similar to the approach that we have employed here, making comparison to previous work difficult. Pickett et al. (2014) propose some relevant ideas of urban adaptation and how it could benefit types (large to small) of communities, but this does

not include a practical implementation of a typology to case studies. Although comparable current research efforts have been produced to investigate cities and their capacity for resilience (e.g., Arup Group, 2015; BRR, n.d.), we find that these studies do not account sufficiently for environmental, geographical, or biogeographic effects.

Future Direction

This study offers yet one more step in improving typologies so that they can provide useful information for stakeholders seeking to make decisions regarding community- and landscape-level resilience. A next step entails more rigorous analysis and identification of appropriate metrics. Even among monitoring initiatives, it is unclear what indicators should be assessed to support improvements in community resilience (Carpenter et al. 2001), a situation that remains a major challenge for the broader monitoring community (Schimel & Keller, 2015).

We applied our typology to mountain communities in the western United States, where data are more available than for less developed nations (Sunderlin et al. 2005). A major obstacle for all managers is data availability, which has led to advocacy for open-access publishing (Fuller et al. 2014). With a new push for large-scale, standardized, and publicly accessible data around the world (e.g., observatories, census data, satellite maps), data will likely become more accessible in the future, making possible global-scale analyses. Remote-sensing data is another attractive and simple resource useful for providing quick proxy measurements until more adequate resources are obtained from ground-based sources.

Based on our experience, we have some concrete recommendations for the next steps needed to develop an effective and useful SES typology. Researchers should strive to:

- Develop a portal that assembles datasets for metrics in one place, so that the mining of data can be made more efficient.
- Define best practices, particularly in regard to the unit analysis and scales used among different datasets, so that the data can be more interoperable and easier to use.
- Increase testing of SES and resilience science theories, conceptual models, and typologies to better define the metrics and relationships among metrics.
- Increase the sample size used to test typologies to better define the range and thresholds for metrics.

- Test the limits of the typology in other mountain systems, ecosystems and landscapes, and geopolitical and sociopolitical contexts.
- Foster better partnerships with data- and informatics-science communities to help overcome data challenges in the typology, such as the need to identify better ways to include qualitative data and community-based data.

Conclusion

We present an application of the Alessa et al. (2009) SES typology to evaluate its utility for assessing resilience of communities located in mountain landscapes. We offer suggestions to further refine a conceptual SES typology so that better assessment of the resilience of communities in specific landscapes can occur. With such refinement, SES typologies can provide useful information for regional planners, for instance at the state level, as a way to compare vulnerability of multiple communities. For researchers, typologies offer a useful tool and approach to better evaluate conceptual SES models and to analyze patterns and causes of resilience or vulnerability to change. Efforts to standardize data and analytical approaches for SESs and resilience science will help to advance these fields toward new frontiers and increase their application in practice.

Our study offers a starting point for further development of typologies. Taxonomic tools are critical for identifying communities and regions or geographic areas that are more or less resilient, but these provide a coarse-level diagnostic, so that more comprehensive assessment and data collection can be applied more efficiently. With growing global population, changing climate, and increasing pressures on limited natural resources and infrastructure, an SES approach is needed in land and natural resource management, so that the landscape and its components can be treated as an interconnected system with shared goals toward greater resilience.

Acknowledgments

This work was supported by the Mountain Social Ecological Observatory Network (MtnSEON; NSF award #DEB 1231233), the Dynamics of Coupled Natural Human Systems: Water-use Decisions in a Dynamic Environment Project (CNH; NSF Award #BCS 1114851), and the Idaho EPSCoR Program (MILES; NSF award #IIA-1301792). The views expressed here do not necessarily represent those of the funders. We also express our gratitude to Kacy Kreiger (University of Alaska Anchorage) for the cartographic design on Figure 1.

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