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Alejandro de las Heras, Mario A. Rodriguez, Marina Islas-Espinoza*

Water appropriation and ecosystem stewardship in the Baja desert

Abstract: The UNESCO San Francisco Rock Paintings polygon within El Vizcaino Biosphere Reserve in the Baja California Peninsula derives its moisture from the North American monsoon. There, ranchers have depended on the desert since the 18th century. More recently, the desert has depended on the environmental stewardship of the ranchers who have allayed mining exploitation and archaeological looting. Using a Rapid Assessment Procedure (RAP), climate data, and geographical information, sustainability was assessed and foreseeable risks identified, on behalf of the Reserve. The results showed that the costs of stewardship were in terms of water appropriation and livestock herbivory. The socio-ecological system also faced hydrological risks derived from runoff, high evaporation rates and climate change. Additional risks stemmed from the increasing global demand for minerals, including hydrocarbons, found in the Reserve. These external drivers could substantially alter the attitudes of the ranchers or the land tenure. Land abandonment might become possible as children and women seemed to out-migrate from the polygon. Solutions were identified based on the supply and demand for water and should enhance resilience via watershed management and in-ranch water appropriate technologies.

Keywords: Baja Peninsula desert, water, stewardship, resilience, appropriate technologies

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***Corresponding author: Marina Islas-Espinoza:** Inter-American Center for Water Resources, Engineering Department, Mexico State University, Toluca, E-mail: marinaislas@ymail.com
Alejandro de las Heras: Independent researcher, aheras38@hotmail.com
Mario A. Rodriguez: Independent consultant, Former director of El Vizcaino and Sierra La Laguna Biosphere Reserves, mariorod54@hotmail.com

1 Introduction: from planetary concern to local stewardship

Stewardship is emerging as a late recognition that ecosystems are life support systems. The future is viewed as uncertain and upcoming change as warranting immediate action to enhance resilience [1]. Stewardship as currently conceived is planetary in scope, implying global governance [2,3]. However, local action calls for a precise definition of stewardship as the mutual dependency of a human group and the land: neither can survive without the other. Globally and locally, nature has to be imitated in rethinking human activities to improve the circulation of water, carbon and nitrogen [4].

Biodiversity and agrobiodiversity determine resilience. Biocultural heritage, local knowledge, local paratoxonomy, and sense of place link human survival and natural regeneration [5,6,7]. This is never clearer as when in-migrants or corporative interests replace long-established dwellers, accelerating environmental degradation. This is why, despite the impacts of goats and cows, the ranchers studied here are held by the Biosphere Reserve authorities as stewards. There is concern however that in addition to current local pressure, external drivers might dominate livelihood development and alter the imperfect balance between stewards and dryland [8]. In desert environments, the chief characteristics of resilience, self-reliance and self-organization [9] may in the near future be subjected to global and regional shocks.

Deserts collectively have high reptile, avian and mammal diversity, high amphibian endemism [9], but they depend on extremely patchy vegetation. All of them are sensitive to precipitation variability, in turn inversely related to total rainfall and directly to El Niño events [9]. Aridization, the downward trend in rainfall, is of special concern in the emerging field of dryland ecosocial systems [9,10,11]. Desertification (a process running the gamut between replacement of grass by shrubs and formation of dunes) is a vegetational consequence of aridization. Vegetation losses in turn can reduce monsoon rains [9].

Global shocks will likely include water, ore and hydrocarbon mining in wildernesses [12], climate change [13], and cultural change in the wake of globalization. Global shocks may alter the attitudes of desert ranchers, eliciting increased water use and grazing intensification, with impacts on the interrelated cycles of water, carbon and nitrogen. Local ecosystem stressors might then follow several courses: In often nitrogen-limited drylands, chronic N-enrichment may induce loss of plant species via competitive exclusion, thereby reducing resistance to droughts and ecosystem stability [14]. Conversely, random hydrologic variability may augment the resilience of dryland ecosystems by increasing biodiversity [15]. And even the crucial role of climate in controlling plant productivity, might be exceeded by the effects of herbivores and detritivores [16].

We argue that in deserts the intricate links between climate, biogeochemical cycles, wildlife and humans can be wrapped around water, the main limiting factor. Accordingly, this study aimed firstly at identifying the shocks and stressors affecting stewards which may lead to increasing their pressure on the environment. And secondly, predictors of the stewards' transition to enhanced water resilience were identified, to ascertain possibilities of changes in water use technology, and the continuation of their role in the future.

2 Methods

2.1 Study area

The study area was the UNESCO World Heritage San Francisco Rock Paintings polygon, in El Vizcaino Biosphere Reserve (the second largest in the Americas after the Galapagos) (Figure 1). Several rainless years may be followed by torrential rainfall typical of the North American Monsoon. Aridity is high (precipitation:potential evapotranspiration ratio of 5-8%). The scrub vegetation is adapted to climate, coarse soils, rocky seasonal riverbeds and riparian corridors. Geology, biodiversity, archaeological and cultural heritages are outstanding and as yet far from fully described.

2.2 RAP information

RAPs help assess water management issues when fast-paced changes occur and opportune decisions are required. RAPs in drylands have allowed for participation of different stakeholders [17]. Adequately carried out, RAPs' advantages include low costs, timely onsite analysis, induction of participative resource management, ease of replication, and cross-validation with ancillary data.

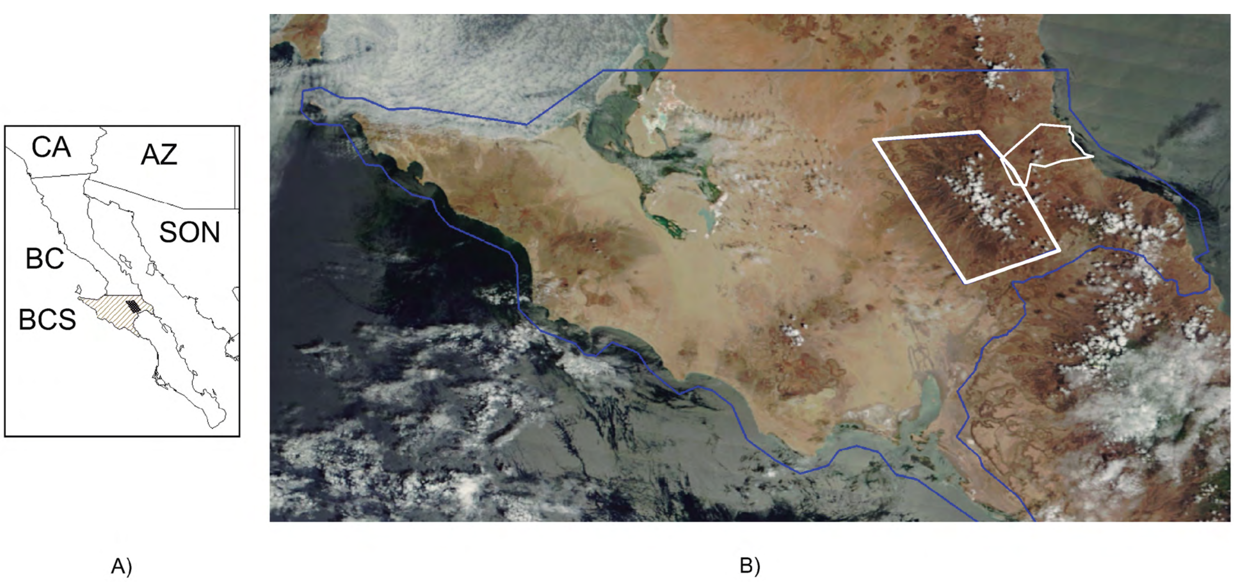

Figure 1: Study area. A) Southwestern US (California, CA and Arizona, AZ) and northwestern Mexican states (Baja California, BC, Baja California Sur, BCS and Sonora, SON) comprise the Sonoran desert. The hatched area is El Vizcaino Biosphere Reserve and the dark polygon is the UNESCO World Heritage San Francisco Sierra Rock Paintings polygon. B) The white regularly shaped outline is the Rock Paintings polygon (206 800 ha), and the irregular white outline is the eastern Biosphere protection core area, where protection is maximal and human use is restricted. The status, rugged topography and location of the Rock Paintings polygon act as a buffer protecting the core area (23 July 2009 Terra satellite image, early North American Monsoon season).

The Baja sustainability RAP was a questionnaire investigating water, land and husbandry management as well as socio-demographic conditions resulting from the economic output of the ranches. This tool drew on experience from Sierra La Laguna Biosphere Reserve, 1000 km farther south in the Baja peninsula, which successfully involved the ranching population and allowed for durable allocation of subsidies and training resources, leading to economic diversification and, allegedly, resilience enhancement.

Response load, or the time and difficulty of questions asked, was calibrated in the Sierra La Laguna experience. Stressors identifiable by RAP would include population growth and commercial orientation in ranch economy. Anthropogenic water appropriation and water requirements of wildlife were discussed with the ranchers during the survey interviews.

2.3 Ancillary information

Maps (1:250,000 soil, vegetation and topography maps), metadata of faunal and geological maps, and census data from the National Statistics and Geography Institute provided RAP's sampling framework or helped cross-validate and analyze RAP data. This information was part of the basic Reserve information portfolio used to design and implement the Reserve's management and zoning strategy [18].

Climatic data from meteorological stations in or around the Sierra were used to identify changes in temperature, precipitation and potential evaporation. This allowed for a basic water balance estimate comparing atmospheric supply to human and livestock water requirements.

3 Results

Intense VHF radio communication among the ranches induced a high response rate in the RAP survey: 23 ranches out of 35; respondents were mostly heads of households. Treks of up to 40 and 52 km were traveled to answer or conduct the questionnaire. Two ranchers were interviewed in town and two over the radio. Non-response in ranches could be attributed to non-occupancy or intermittent occupancy due to old age or a main economic activity in town. The age and sex distribution of the ranching families was similar to and prolonged the demographic trend in recent censuses, so that no bias was found.

3.1 Hydrological stress

Widespread torrential runoff and landslides stemmed from rugged topography and summer monsoon (Figure 2). The ranches have coped by settling on the landslide-risk area rather than the torrential-risk one, so that 73% are deprived of flat lands and 50% of them have steep slopes.

Moisture was very limited in the coarse and medium-coarse soils of the Sierra (Online Supplementary Material Figure 1 and Table 1): lithosols are shallow, with continuous hard rock underneath. Yermosols have a thin and poor humus layer. Calcic yermosols in particular are highly saline, constricting water retention and halophilic vegetation. Chromic vertisols had the only fine texture in the polygon, but have little organic matter and a high clay content which limits water penetration; they are sometimes highly sodic. Finally, fluvisols in some riparian corridors are very poorly developed soils made up of material transported by water runoff.

Physical water scarcity was heterogeneous. Half the ranches relied on seeps and springs at a mean 4-km distance and 25% were 10-16 km off their water source, entailing considerable time and effort to locate and fix leaks in the 1-inch PVC pipes. Other ranches carted water manually, on mule back or on pickup trucks. Up to 6 ranches shared a well; and 2 ranches only got rainfall water. These arrangements provided good quality water in 17 out of 23 ranches; inadequate water quality could be due to high mineral contents, especially in the proximity of the Tres Virgenes volcano, or biological contamination. Oases in riparian corridors were hydrologically better endowed (by resurgences of seasonally buried streams) but more isolated and subjected to tropical storm vegetation damage.

Water use affected key aquatic habitats: seeps, springs, and perennial diminutive streams were channeled into dams and perennial tanks. Pressure on water and vegetation mostly came from humans (125 persons), goats (2505 head) and bovines (887 head but with a larger biomass). Mules and burros (342 equines in total) were used for human and cargo transportation during treks to the rock paintings. Roaming livestock water, browse and graze over close to 2068 km^2 since the ranches are widespread in the Rock Paintings polygon. This is more than 50 times the 38 km^2 extent of the ranches.

3.2 Water, flora and fauna

Plant water content is essential for wild herbivores, including bighorn sheep (*Ovis canadensis*) and mule deer (*Odocoileus hemionus*), especially under anthropogenic

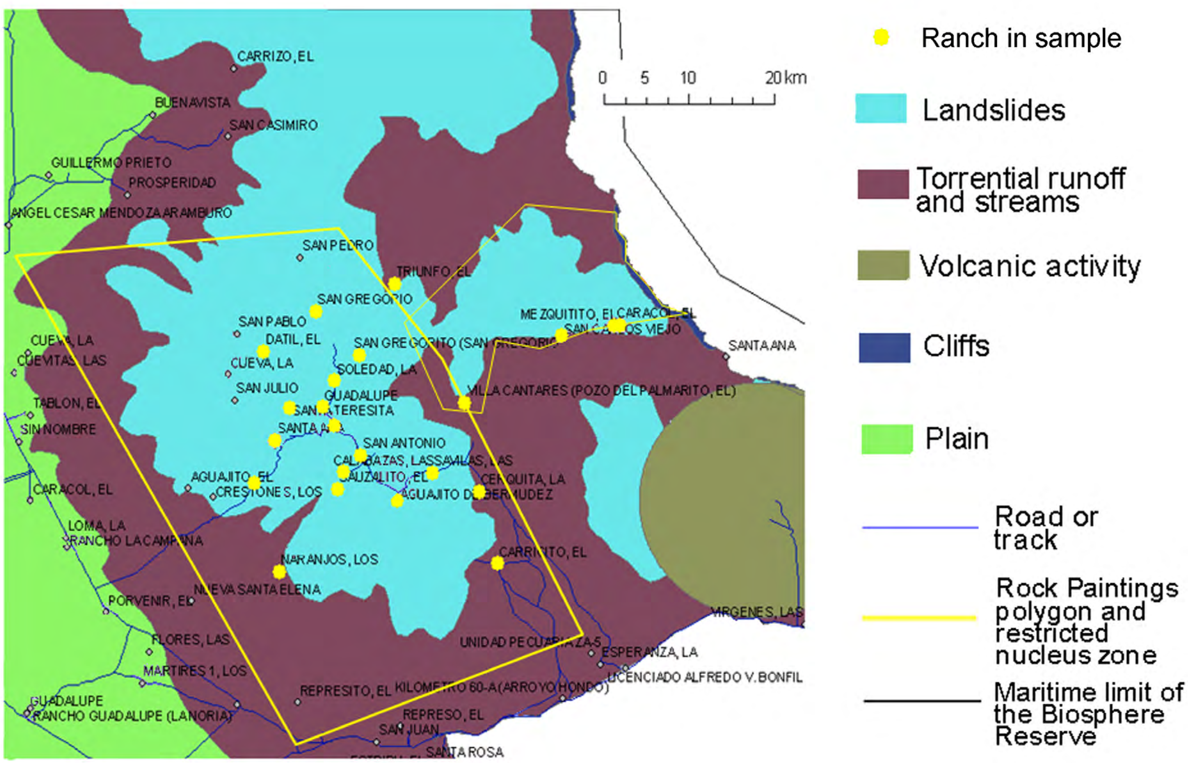

Figure 2: Geophysical risks. The study area is mostly susceptible to landslides and extreme torrential runoff events. Most ranches are in the landslide-risk area so as to avoid torrential events. Volcanic risks from the Tres Virgenes volcano remain a possibility; a geothermal energy plant in the vicinity of the volcano is a testament to telluric activity.

water appropriation. Wildlife and livestock rely on sarcocaulescent vegetation dominated by bushes with thick and fleshy stems, and sarcocrasicaulescent bush with cacti such as cardón (*Pachycereus pringlei*), sour pitahaya (*Stenocereus gummosus*) or cholla (*Cylindropuntia cholla*). Microphillic scrub is composed of a few species with very small leaves. Yucca (*Yucca valida*) patches are also present. Tree communities include mesquite (*Prosopis glandulosa*, *P. articulata*, *P. palmeri*, with great affinity for nitrogen-fixing bacteria), oak (*Quercus oblongifolia*) patches at the top of the sierra and riparian corridors (Online Supplementary Material Figure 1 and Table 1).

Dead vegetation is the chief source of soil organic matter, essential to water penetration and retention in soil. However, dry vegetation and palm leaves were a leading material in houses and corrals, and cooking woodfuel (Online Supplementary Material Figure 2). This reduced vegetation decay. Weekly woodfuel collection was 50 kg on average per ranch (ranging between 4-200 kg), either as dead wood or cut from living trees. Half the firewood was from the hills and a third from arroyos (seasonally dry riverbeds). There was also indication of plant parasites (affecting less than 5% of the landholding area) with little severity for the study area as a whole, but significant local severity.

3.3 Diminishing human population as a future issue

The ranchers' ancestors lived in isolation since the 18th century, suggesting a distinctly resilient lifestyle. However, a recent trend of declining population was suggested by a high masculinity ratio, low proportions of married men, low proportions of people between 20-29 years old (especially women, Online Supplementary Material Figure 3), a low proportion of children, an aging population and lack of in-migration. These indicators were associated with gender-specific labor in the ranches, and out-migration (of women, children and elderly people) reportedly for economic, educational or health reasons. There seemed to be recent back-and-forth migration to the towns of the Biosphere Reserve (Santa Rosalia with a tradition of mining and fishing, the horticultural oasis of San Ignacio, the intensively-irrigated horticultural town of Vizcaino, and the saltworks-dominated Guerrero Negro), at different stages of a person's lifecycle.

Isolation was also a likely driver of out-migration indicated by an average 3.2 families per settlement, and the 45-km average distance to the nearest town. Some ranches lacked a trail to even the nearest ranch. Trails were manually carved by ranch members over several years. However, at least one VHF radio set was owned by each family, a fundamental social and economic cohesion element, as all could listen to the messages, organize shared goods transport, and know who is working alone in the outdoors.

An additional vulnerability element might be genetic erosion in the human population: among the 125 persons in the surveyed ranches, one surname was clearly dominant (it was present in 76 persons from the father line and 47 from the father and mother lines). A co-dominant surname appeared 11 times. The combinations of the dominant and co-dominant surnames appeared 33 times. Nineteen couples shared one or two surnames. The foregoing pointed to the ranches as being both a population isolate and a tightly knit kinship community.

3.4 Income diversification as a low priority

No relationship existed between herd size and ranch size, because of free roaming beyond property limits (ten ranches spanned 5 or less Ha, ten 20-50 Ha and three 737-1755 Ha, but the stock roamed over tens of kilometers away from the ranches). No simple relationship existed between income on the one hand and household, ranch or herd sizes on the other hand (R^2 among these variables was 0.01-0.03). But collectively the bulk of the ranchers' income came from livestock products (Online Supplementary Material Table 2), and income was scarcely diversified. In other words, free roaming and herd size seemed to determine environmental impacts but not income.

Some ranchers could use more grazing land neither incurring monetary costs nor internalizing environmental costs (a pooled goods issue). This might explain income inequality: the yearly per capita income was 50-19800 USD with 10 ranches < 584 USD and 3 ranches > 8000 USD.

Livelihood diversification was not a widespread goal: 87% of the ranches expressed development needs related to traditional activities (Online Supplementary Material Figure 4) and especially to further water exploitation (Figure 3). A mere 0.06% of the 3812 Ha ranch area have at some point been used for horticulture. Some fertile areas had steep and dry slopes, limiting agriculture. Nevertheless, a few ranches were interested in agriculture or livestock stalling despite their lack of experience, showing an innovative attitude.

3.5 Attitudes toward agrobiodiversity and the Biosphere Reserve

Twenty one wild medicinal plants were used and their properties acknowledged. Only five ranches did not mention any medicinal plant usage. The informants were also aware of degradation calling for reforestation, restoration or protection, reportedly involving 247.55 Ha, mostly with mesquite tree or cacti losses due to root worm

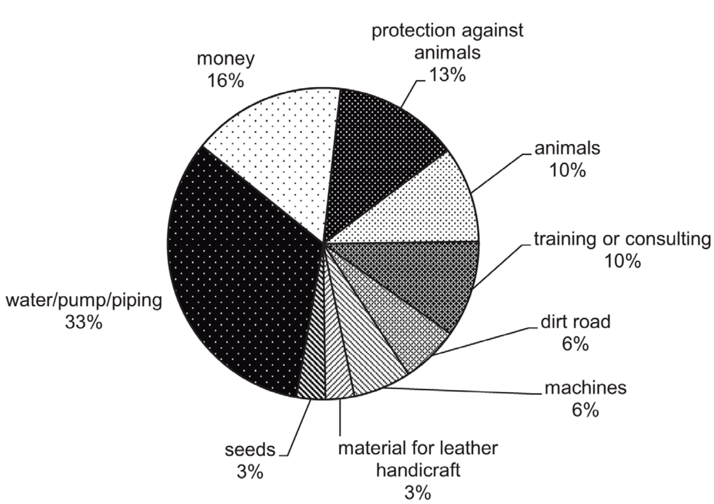

Figure 3: Support needs. Foremost among these were water equipment and money. If supported, these could lead to increased dependency on already scarce water and an external source of money, making the ranchers more vulnerable in the long-run. Conversely, seeds for crop and fruit production were regarded with caution due to lack of water, land, knowledge and experience, as well as destruction by livestock. Diversification albeit desirable is also seen as a risk.

attack; dipú trees browsed by burros (*Equus africanus asinus*) and mules (*Equus mulus*); palm trees (*Washingtonia filifera, Washingtonia robusta, Erythea armata*) knocked down by Hurricane John but with plenty of saplings, as well as trees dying because of lack of rain for several years. Some ranchers also claimed to protect vegetation, birds and rock paintings. As to livestock-wildlife conflicts, losses to carnivores (puma, *Puma concolor*; golden eagle, *Aquila chrysaetos;* and coyote, *Canis latrans*) were mentioned but the right of wild animals to live was acknowledged; cattle loss was also explained by their straying for long periods.

Horticulture had been practiced by 11 ranches cultivating 29 species over a minuscule 2.3 Ha total area mostly in the oases, with water and suitable land as limiting factors. Alfalfa (*Medicago sativa*), a preferred feed plant due to its superior protein content, was cultivated in only one ranch but was purchased outside the sierra by several ranches.

As to the attitudes toward the Biosphere Reserve, three quarters of the ranches were willing to collaborate with the Biosphere Reserve office, although they ignored the mechanisms for this. Half the ranches gave a number of household members that could engage in collaborative conservation (Online Supplementary Material Figure 5).

3.6 Climate change and water balance

Despite incomplete weather data in Mexico, information in and around the Sierra hints at climate change (Online Supplementary Material Table 3). Most evident is a consistent pattern of increasing temperatures in the last decades (maximum, average and minimum temperature increases in the 0.2-0.8°C range). These figures underestimate change as the official time series overlap and so average out past and recent values. Precipitation (with some spatial variation) and especially potential evaporation also seem to shift upwards. The relationship between both parameters is possibly the most important climatic trait as regards survival and resilience; typically, evaporation largely exceeds rainfall. Other water balance parameters can only be appraised qualitatively in the area: Runoff is very intense due to the torrential rainfall regime, very low vegetation interception, steep slopes, and poor water retention of shallow or clayey soils. Infiltration and recharge are thus very low.

3.7 Resilience enhancement and water supply

Given the high evaporation and high energy required for water transport, rainwater and stormwater harvesting could diversify water sources and diminish use of natural sources. With current mean annual rainfall, human and livestock biological requirements could be met with a 72,000 m^2 catchment, equivalent to 0.2% of the ranches' land (Online Supplementary Material Table 4). With 70% of the annual rainfall concentrated in 24 hours, harvesting and storage arrangements need only be made for the short monsoon period. The RAP showed that 8 out of 23 ranches had impoundments and corrals. Another 9 ranches just had corrals. The remaining 6 ranches had neither facility. With 72,000 m^2 to meet yearly anthropogenic needs in the Sierra, an average ranch would need a 3,130 m^2 catchment area and a 625 m^3 storage volume, roughly the same volume as perennial impoundments found a few meters from ranch houses, fed by constant trickling from distant natural sources and constantly depleted by evaporation.

3.8 Future mining

What may complicate matters in the study area are the existence of mineral reserves and the increasing global scarcity of minerals and hydrocarbons (Online Supplementary Material Figure 6). Large-scale mining is already carried out in the Reserve, in the world's largest saltworks, owned by the Mexican government and Mitsubishi Corporation, and El Boleo, a century-old multi-ore mining operation recently reopened. Even water mining may face competition from oil and gas exploitation underneath the Vizcaino aquifer.

4 Discussion

In the Holocene the clearest example of desertification as a consequence of a monsoon switching off is the Sahara. A desertification trend in times of anthropogenic global change is a powerful motive for desert conservation. Large challenges have been met with some success by small stewardship changes: in the Chihuahuan desert's Janos Biosphere Reserve, fifteen years of drought and overgrazing had a knock-on effect on wildlife, leading to severe desertification (replacement of grass by shrub). For people this meant reduction of feed and a setback in livelihood, forcing migration and land sales. However, people have responded by reducing herd sizes, excluding land from grazing and planting native grass [19]. Farther west, the Sonoran desert faces different issues in terms of hydrology and climate, thanks to the North American Monsoon. But it lacks extensive grasslands, making its vegetation more vulnerable to ranching.

4.1 Climate risks and wildlife

The Sonoran desert is the hottest in North America and now exhibits a widespread winter and spring warming trend. This may modify the elevation distribution of species [20]. Flowering in April, a month earlier than a century ago, may impact communities and especially shrubs and migratory pollinators [21]. North American monsoon rains now appear in July after a very dry June [22], and bloom-rainfall asynchrony may lead to fitness loss. Riparian, brush and forest species are already subjected to drought mortality, but extreme droughts seem poised to become more frequent. Since dominant species provide habitat and ecosystem structure, their increased mortality can have cascading effects on communities [23]. Prolonged lack of water creates a void in the xylem (cavitation), interrupting the evaporation process that drives sap circulation and respiration. Riparian species appear to be more vulnerable to cavitation than upland species [24]. A major drought can cause a 55–100% die-off in most perennial species. Stunted adults in a lesser drought fail to survive a more severe one [25]. Most climate models predict more evapotranspiration and less precipitation in North American deserts, affecting riparian ecosystems through increased drought, lower streamflows and shifts in streamflow timing. Plant biomass could be reduced by 70–97%, especially in native compared to exotic species. Elevated CO_2 increases water-use efficiency in many plants, especially under dry conditions, but in N-limited riparian corridors this will not compensate for increased aridity [26].

In the study area, modest winter rains may occur and the Monsoon brings one pulse of torrential summer rain. The remainder of the year is arid, but May and a chronically rainless June are critical for plants. Water stress augments herbivory for plant water content since the most sensitive livestock species can use up to 30% of their total body water pool per day during the dry season [27]. The significant negative impacts of donkeys on native Sonoran desert vegetation are comparatively well documented: they occur mainly near water, as their range does not exceed 4–6 km from water [28]. This is the moment of highest competition between livestock and wild species. Wild species may not compete as much: bighorn sheep use water developments during the day and mule deer during the night [29]. Moreover, some bighorn sheep populations do not seem inclined to drink from manmade catchments and survive without free water during the dry seasons by consuming barrel cacti and other succulents [30]. However, the water consumption of the desert mule deer (below 46°C) oscillates between 1.5 and 6 L every 24 hours [31] and is comparable to livestock water consumption.

4.2 Collaborative water management

So far, the Sierra ranchers have not participated in wildlife conservation but water conservation would directly impinge on wildlife fitness. This should entail collaborative management of micro-catchments with the Reserve office. Participative solutions should include:

1. Watershed protection in the six sensitive watersheds included in the Rock Paintings polygon. This means attracting livestock to the southern margin of the three eastern, remote, watersheds in the nucleus zone of restricted human activity (Online Supplementary Material Figure 7). Livestock trampling avoidance would protect biological soil crusts (cyanobacteria, fungi, mosses and lichens) thereby decreasing water erosion and sediment loss, especially during storms [32]. To avoid erosion, seeps and dams must be restricted in these watersheds, as should expensive fences which curtail wildlife movement.
2. Protection of riparian and upland vegetation. Allowing for free streamflows and biological soil crusts can result in fine sediment accretion and evolution of geomorphic surfaces, helping enhance biomass productivity in drought-sensitive riparian corridors [26]. Upland vegetation moderates erosion on steep slopes.
3. Connectivity. Creating corridors between moisture or vegetation patches can be a recipe for livestock ubiquity. Patch restoration and preservation around seeps and water sources can be carried out in and away from the ranches.

The identity of people sharing the same livelihood can be enhanced by community conservation. One example is the traditional grazing association and 'cooperative land management and livestock marketing' arrangements in the US Sonoran desert [13]. In southern Mexico, a centuries-long trend of vegetation loss and desertification due to caprine and ovine overgrazing was overcome thanks to social organization, earnings from environmental services and water conservation projects [5].

To effect similar changes in the study area calls for collective action as well as preservation of the self-reliance and self-organization culture consistent with sustainability [9]. Predictors of collaboration with the Reserve office are the apparent concern about vegetation damage; local knowledge of wild medicinal plants; interest for horticulture; and interest for alfalfa which could be produced near the ranches to supply dry-season feed.

4.3 In-ranch water developments

Precipitation, runoff, infiltration and evaporative restrictions dictate a diversification of water sources, storage and a reduction of water consumption and loss. A predictor of resilience-enhancing in-ranch water developments is the presence in most ranches of impoundments, corrals or both, some about the required size to bypass water stress in the driest periods. Impoundments however may need to be protected from heat, radiation and wind, to decrease evaporation. Eventually, each ranch compound ought to be managed as a catchment area. An estimate of the necessary catchment area and storage volume is the annual monsoon rainfall which should be enough for feed growth and livestock dry season demand (Online Supplementary Material Table 4). Currently, rainwater and stormwater harvesting (Online Supplementary Material Table 5) is best approached through a combination of roof collection, tensile structures using textiles like tarpaulin, and ground liners. Appropriate water technologies to reuse wastewater nitrogen, phosphorus and organic matter are recommended by the World Health Organization, inexpensive and easy to learn and adapt [33] to drainfield-irrigated (evaporation-free) horticulture and feed production, if protected from herbivory. Terraces can be created using abundant local material, where applicable. Disinfection of stored water can be carried out with solar UV appliances and filters [33], or using solar stoves to save fuelwood. Water appropriate technologies should gradually substitute gasoline-powered water pumps using (mule) animal power, reduce water transport and piping maintenance.

Husbandry reasons for in-ranch appropriate water developments are as follows. Livestock grazing intensity decreases as a power function of distance from the ranch [9]. Grazing around the ranches would reduce feeding effort and stock dehydration. In-ranch water supply can attract livestock during dry periods which is most important when deserts are most water-limited at the end of droughts, because more overlap exists then between wildlife and livestock diets [34]. In-ranch feed production can be N-augmented by manure; and the increase by ungulates of fungal endophyte symbioses with woody plants can improve tree cover [35,36]. Trampling is intense when livestock is concentrated but it only needs to occur in the driest months; the upside is enhanced C and N cycling [37,38]. Gradual livestock enhancement through crossbreeding should allow for optimal meat and milk production and local adaptation. This is best achieved by stalling than roaming. This would permit added value in every ranch, and herd size diminution in the largest ranches. Finally whenever predator-proof fences are required, they are easier to maintain near the ranches.

4.4 Sustainable mining?

Small-scale mining managed by local populations seems utopic nowadays. Allegedly, mining for geothermal energy production could be sustainable but southeast of the Sierra, the Tres Virgenes geothermal facility uses vast amounts of water. In our experience in the Baja peninsula, one mining claim is purchased by a private prospection company from the Mexican government and is successively sold to a string of other companies until the balance of risks and prospects is shown to be favorable and exploitation starts, along with heavy environmental impacts. Water, soils and vegetation are used intensively and polluted in the short and long terms. Mandatory mitigation measures can hardly restore open pits, toxic screes and polluted water mantle. Local populations seldom gain in the process.

Furthermore, as global energy demand is expected to increase 50% between 2007-2030 [12], Mexico's reliance on oil exports may spur oil exploitation of hitherto untapped reserves, including those beneath the Vizcaino aquifer, partially fed by the Sierra. Oil demand may pose the biggest threat to the ranchers' livelihood as their land tenure is not immune to expropriation should the Mexican government assert that this is in the public interest. But even expropriation can be legally stopped. And the organized citizenry has halted mining claims in the Baja peninsula in recent years.

4.5 Demographic, economic and cultural change

The urban members of ranching families were part of the livelihood networks that allowed the ranches to survive, showing that demography and economy are intertwined. Without proper economic sustainability, out-migration can rapidly empty the Sierra. To retain a young population in the ranches, men and women should be trained to enhance the marketing of ranching products. Up till now a few ranchers have monopolized and distributed cheese to the closest cities and meat farther away in northern Mexico. Local brands can be developed to exploit the fact that the Sierra exports organic products made in a Biosphere Reserve in a sustainable and safe way. This would open access to more lucrative markets in southwestern US and perhaps lessen resource use. Exports can diversify incomes, but this can bring market-oriented culture to remote communities.

Subsidies also diversify income but programs are centrally designed in Mexico City to raise production and so clash with local sustainability. Subsidies also destroy the culture of self-reliance and favor better-off ranchers. This is why the Biosphere Reserve funds should prioritize ranches that cumulate disadvantages: physical isolation, distance from water supply and low income. These ranches may be more vulnerable to external shocks and internal stressors, and experience higher transaction costs to access support. Reserve funds should help secure more income that varies asynchronously from rainfall [9]. Although the ranchers have an official monopoly on archeological treks, tourism should rely less on the limited quota decided by archeological authorities. More emphasis is needed on agro-ecotourism in organic ranches, the famed contemporary local culture, interpretive walks, and geotourism tapping the stunning landscapes and geology of the Sierra.

Ongoing cultural change may occur under the influence of the ranchers' urban network and schooling, thereby supplanting aspirations of ranching lifestyle. A workaround is to buttress local sustainability with a knowledge network of diverse stakeholders oriented to technologically inducing sustainability while fully considering local knowledge, as exemplified elsewhere in the Sonoran desert [39]. Emulating experiences from other deserts (e.g. Israel and Iran) can also save learning costs and bolster conservation.

5 Conclusions

As yet very little research has been conducted on water stewardship in desert Biosphere Reserves. Here, the combination of rapid appraisal and ancillary data showed that external shocks (climate change, mining and globalization) hold the capacity to worsen multiple stressors (population decline and increased use of natural resources) and move the socio-ecological system closer to thresholds.

We argue that water supply-demand gaps might be a misreading: water was in fact appropriated in manmade impoundments and left to evaporate. Evaporation thus became the focus of change proposals rather than herd size diminution, because in the long run the latter might entail reductions in income which may lead the ranchers out of the Sierra and allow for more detrimental land and water uses to occur.

Water savings in deserts in an era of climate change are not optional. Enhancing resilience implies a transition from water appropriation to appropriate technologies (e.g. in-ranch stormwater harvesting, improved storage and solar disinfection after storage) and collaborative micro-catchment management. Although very thrifty, water appropriate technologies come at a cost. Allocating funds to water stewardship should depend on demonstrating reduced ranching environmental impacts. The ranchers and the Biosphere Reserve office have an active role to play but probably require an extended knowledge network and commercial network to add value to their organic dairy and meat products.

A dominant interest in more water equipment, existing water and livestock facilities (impoundments and corrals), as well as attitudes (inclination to collaborate in conservation and restoration) were likely predictors of involvement in water appropriate technologies.

Rapid appraisal procedures can initiate participatory processes. Future RAP uses should expand beyond diagnoses and probe the acceptation of water and solar appropriate technologies able to improve water quality while diminishing fuelwood extraction in vegetation-limited environments.

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Conflict of interest: The authors declare that they have no competing interests.

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