Paleoenvironmental Framework for Understanding the Development, Stability, and State-Changes of Ciénegas in the American Deserts

Thomas A. Minckley
Department of Geography and Program in Ecology, University of Wyoming, Laramie, Wyoming
Andrea Brunelle
Department of Geography, University of Utah, Salt Lake City, Utah
Dale Turner
The Nature Conservancy, Tucson, Arizona

Abstract—*As persistent wetlands in arid regions, ciénegas represent important resources for the maintenance and preservation of regional biodiversity. The history of ciénegas in the American Southwest over the last 8,000 years provides information on the dynamics of growth, longevity, and stability of these habitats under previous climate conditions. Proxy data such as sedimentology, pollen, charcoal, and isotopes preserved in ciénega sediments provide information on the formation, disturbance, resilience and state changes within these systems. This long-term perspective is compared to the recent history of degradation observed in the region. Once formed, ciénega surfaces alternate between wetland and dryland phases, identified by changes in pollen preservation and isotopic signatures. These phase changes are hypothesized to be controlled by groundwater-table depths. The degraded state of many extant ciénegas may be similar to the dryland phase, but may also require active management to initiate the natural hysteresis of wetland and dryland phases. We present a conceptual model on the controls for different ciénega states and how the paleoenvironmental record of change can be used in conservation, restoration, and management of these critical habitats.*

Introduction

Arid and semi-arid environments occupy 40% of the terrestrial land area and represent regions with the highest human population growth rates (18.5% between 1990 and 2000; Hassan and others 2005). This population growth places great pressure on the natural environment and the ecosystem services it provides, particularly in terms of water provisioning and water and erosion regulating services. Additional future pressure will come with warming temperatures projected to reduce global streamflow by 15% with every 1°C of temperature rise due to the combined effects of increased evaporation and decreased precipitation (Henderson-Sellers and McGuffie 2012). Beyond fundamental ecosystem services, wetlands (ciénegas) of the American Deserts have long been identified as regions of high conservation concern (Abell and others 2000; Hendrickson and Minckley1985; Leopold 1949; W. Minckley 1969, 1992).

High endemism associated with some ciénegas, most famously the wetland complexes of the Cuatrociénegas Valley, Coahuila Mexico (Abell and others 2000; Badino and others 2004; W. Minckley 1969, 1992), have made these environments a conservation priority. Less considered are smaller ciénegas across the Chihuahuan, Sonoran, and a lesser extent Mojave deserts. For example, in Arizona where wetland environments occupy ~2% of the land area they are critical habitat for at least 19% of the threatened, candidate, or endangered species within the state (Baker Jr. and others 2004; T. Minckley and others *in review*). However, beyond species of concern, simply by providing different habitat in otherwise arid regions, desert ciénegas and riparian corridors may increase regional biodiversity by up to 50% (Sabo and others 2005).

At present, there is no systematic understanding of the dynamics that promote the natural formation and resilience of ciénegas as a biogeomorphic unit within fluvial systems. However, the literature on ciénega establishment, development, and resilience has increased in recent years (Brunelle and others 2010; Heffernan 2008; Heffernan and others 2008; Heffernan and Fisher 2012; Minckley and Brunelle 2007; T. Minckley and others 2009, 2011). Here we present the current understanding of ciénega growth and development in the American Deserts. We focus on the paleoenvironmental record of ciénega origination and use those data to construct a model of natural ciénega dynamics compared to their current degraded state, which form the basis for the management and restoration challenges we presently face.

Prior to EuroAmerican settlement, the American Deserts contained many ciénegas, near piedmonts, as in Cuatrociénegas, or as emergent features within regional river systems as is seen in many ciénegas in Arizona and New Mexico (fig. 1) (Hendrickson and Minckley 1985;

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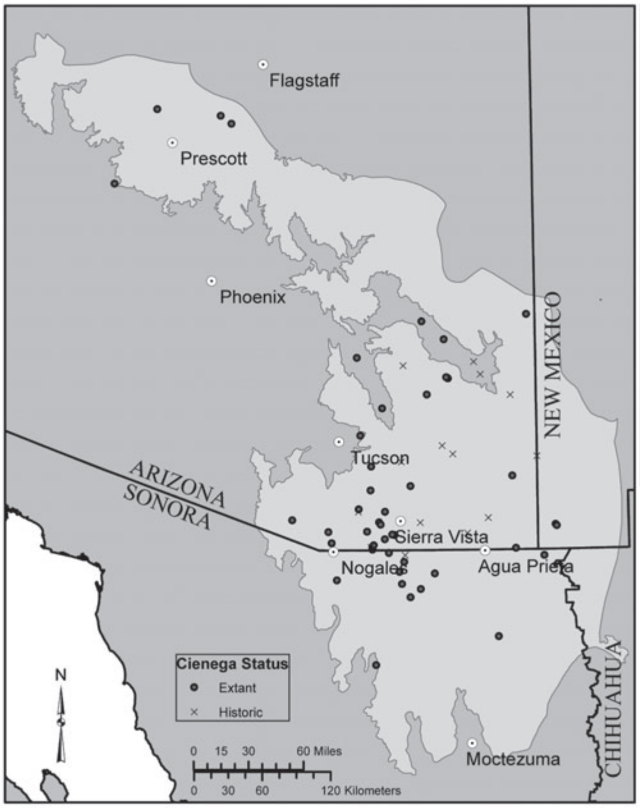

Figure 1—The distribution of the Apache Highland Grasslands and historic and extant ciénegas in southern Arizona, USA, southeastern New Mexico, USA, northern Sonora, Mexico, and northeastern Chihuahua, Mexico.

T. Minckley and others, *in review*). The loss and degradation of these habitats increased rapidly with human settlement, influenced by removal of beaver and their associated dams, draining and conversion to pasture and agricultural fields, down-cutting along nick points in wagon and rail roads, and active channelization and draining to reduce regional malarial threats in the late 19th and early 20th centuries (Bryan 1925, 1928; Fonseca 1998; Hendrickson and Minckley 1985; Leopold 1949). Later impacts on ciénegas include headcuts resulting from artificial dam installations, which concentrated flood pulses and increased associated erosive force of those events (fig. 2). Current threats are associated with both these legacy impacts and groundwater overdrafts that result in a loss of surface connectivity between the water table and root zone. The pattern of regional ciénega degradation is shown by comparison of historic vs. extant ciénegas in southeastern Arizona (fig. 1). Many of these former ciénegas are located in the major agricultural region of Cochise County, AZ (fig. 1). Cumulatively the activities associated with settlement have resulted in a general degradation of ciénegas by converting many into grasslands and shrub-lands dominated by mesquite (*Prosopis* sp.) and other desert trees and shrubs.

Geomorphic Settings Of Ciénegas

Ciénega refers to a set of freshwater environments in the North American deserts and semi-arid grasslands that are typically permanently wetted, either by springs or by water forced to the surface by channel constrictions or sub-surface features such as bedrock or sills (Heffernan 2008; Hendrickson and Minckley 1985; T. Minckley and others, in review). Flow of subsurface water is distributed laterally and longitudinally, allowing ciénegas to occupy areas 100's of meters wide and long. For example, the San Bernardino Ciénega, spanning the border between Arizona and Sonora, is estimated to have been 1.0-3.4 km wide and 6 km long (Rosen and others 2005), while Canelo Hills Ciénega is 0.1-0.14 km wide and ~2 km long . Because the subsurface controls of ciénega formation are not well known, the proposed spring classification system of Springer and others (2008) presently best describes these environments as 'low gradient wetlands with indistinct or multiple [water] sources.' Ciénegas, though aggradational (Minckley and Brunelle 2007; T. Minckley and others 2011), do not appear to be formed through anastomosing streams with associated terracing (Leopold and others 1994). Rather, ciénegas appear largely planar, occupying nearly the entire widths of valley bottoms with little large-scale morphology to distinguish sub-units within these surfaces. However, preferential flow channels can exist across the surface between hummocks of grasses, sedges, and other herbaceous taxa. Aerial photographs of extant ciénegas show that these features within low-ordered streams and rivers have distinguishable paleo-stream channels disappearing above and dendritic channels emerging below permanently wetted ciénega, creating a more deltaic-like form than a distinct channel form.

Ciénega surfaces appear to have a strong biogeomorphic control on their formation. Heffernan (2008) proposed that ciénegas represent an alternative stable state to gravel bottom stream channels that

Figure 2—Downstream view from head cut of incised channel near Cloverdale Ciénega, NM. Brown, thin, paleo-ciénega soils are evident on left bank downstream margin. Poorly sorted and angular rocks and cobbles make up the bed material nearest to the head cut.

Figure 3—"Flow-Lines" across the Canelo Hills Ciénega, March 2009.

characterize many of the river corridors of the American Deserts. Heffernan (2008) observed that after 4 years without grazing pressure, wetlands had developed in over 20% of Sycamore Creek, Tonto National Forest, Arizona. Large flood events (>20m^3 s^{-1}) within Sycamore Creek were able to remove up to 76% of the nascent vegetation cover in single events, but most lower magnitude flood events (<20m^3 s^{-1}) only affected 20% of the vegetation cover. How longer established ciénegas respond to floods is not known, but the few analyses in progress argue for long-term surface stability.

Extant ciénegas, such as Canelo Hills Ciénega, show post-flooding evidence of laminar flow avulsing from a "main-channel" that lays aboveground vegetation down across the entire surface with no evidence of scouring to bedrock (fig. 3). This suggests that a combination of lateral spreading of flood-pulses and aboveground biomass attenuates the erosive strength of floods and protects softer sediments of the ciénega surface. Flood events bring in sands, silt and clays, and may be an important source of fine organic detritus from upstream sources (Heffernan and others 2008). During non-flood season, the permanently wetted soils and slow movement of water through the vegetation matrix of a ciénega provides an environment for capturing and retaining pollen and other micro and macro botanical remains that allow for the reconstruction of paleoenvironmental histories (T. Minckley and others 2011). Based on consistencies in organic content from a transect of sediment cores from Canelo Hills Ciénega, it appears that the entire vegetated surfaces of ciénegas may grow synchronously when climatic and hydrologic conditions are right for wetland initiation (Berg-Mattson and others, in prep).

Paleoenvironmental Study

T. Minckley and others (2011) looked to expand upon Heffernan's (2008) multiple stable state hypothesis by applying the interpretation of multiple stable states to the 8000 year long San Bernardino Ciénega paleoenvironmental record. Instead of a gravel bottom stream transitioning to a wetland, stabilization of the sand bottom matrix appears to have occurred ~8.0 ka (ka = calibrated *kiloannum* years before 1950 CE) during a dry phase where pollen was poorly preserved and herbaceous taxa and desert trees dominated (fig. 4). Evidence of perennial water on the surface begins ~7.0 ka and persisted until ~4.0 ka based on pollen preservation and observed aquatic snail shells in the sediments. After 4.0 ka, pollen preservation decreases suggesting aerial exposure of the ciénega until ~2.4-1.6 ka BP. Isotopic analysis of this section confirms that the surface was likely occupied by grassland vegetation (fig. 4) (T. Minckley and others 2009). A return to a wetland state occurs after 2.4-1.6 ka BP based on pollen preservation and isotopic analyses, which likely persisted until the late 19th to early 20th century (Mearns 1907; T. Minckley and others 2011).

Discussion

Extending observations of modern riparian and ciénega dynamics into the past requires placing interpretations of available proxy (pollen, isotopes and sediment characteristics) into a testable framework (fig. 5a, b) where there are three possible ciénega states: historically natural dryland and wetland phases, and a recent degraded phase. Dryland phases and degraded phases appear similar in the pollen record having poor pollen preservation and, therefore, only provide minimal presence-absence vegetation data based on the most hardy pollen grains (T. Minckley and others 2011). These data are not considered quantifiable by the authors. Pollen preservation is enhanced during the wetland phase, providing a first order estimation of whether a surface was saturated in the past. Wetland phases, then, are those that provide the best data for composition of the plant communities for both ciénegas and surrounding uplands.

Isotopic analysis of ciénega sediments provides evidence of state changes based on identification elemental and isotopic sources of organic material (Meyers 1994; T. Minckley and others 2009). Though not taxonomically specific, isotopes and specifically the C:N ratio provide information on past ciénega surface conditions (T. Minckley and others 2009) with lower C:N values indicating wetted conditions (fig. 4). Isotope data are particularly useful for understanding changes in pollen preservation and were instrumental to the identification of state changes in the paleoenvironmental record of San Bernardino Ciénega (T. Minckley and others 2009, 2011).

Reference State Models for Setting Restoration Goals in Desert Wetlands

Based on our observations of recent and past state changes in ciénegas, we propose a process-based ecohydrologic model of state transitions in ciénegas. This model integrates water balance, vegetation structure (above and below ground) and channel form as key variables that influence the trajectory of biogeomorphic change, and provides a framework for ciénega restoration and management. This model is comparable to state-and-transition models used to understand and manage arid-upland sites that have experienced heavy grazing pressure resulting in surface erosion, and encroachment of woody vegetation (Bestelmeyer and others 2003; Laycock 1991).

Depending on historic and present water availability, the potential natural states of ciénegas may be *dryland* or *wetland phases* (fig. 5a,b). Although these phases differ in the relative depth to groundwater and the persistence of surface waters, both states are characterized by surfaces with relatively homogeneous topography, high organic matter content and high resilience to erosion by floods. The current state of many ciénegas may be considered in a *degraded phase*, characterized by an active geomorphic surface, discrete channels, minimal surface water, and encroachment of woody vegetation, especially proximal to incised channel margins.

Throughputs for ciénega development are mainly hydrologic: groundwater (GW) through, surface flow (SF) in and out, and actual evapotranspiration (AE), which should be a net loss from the system

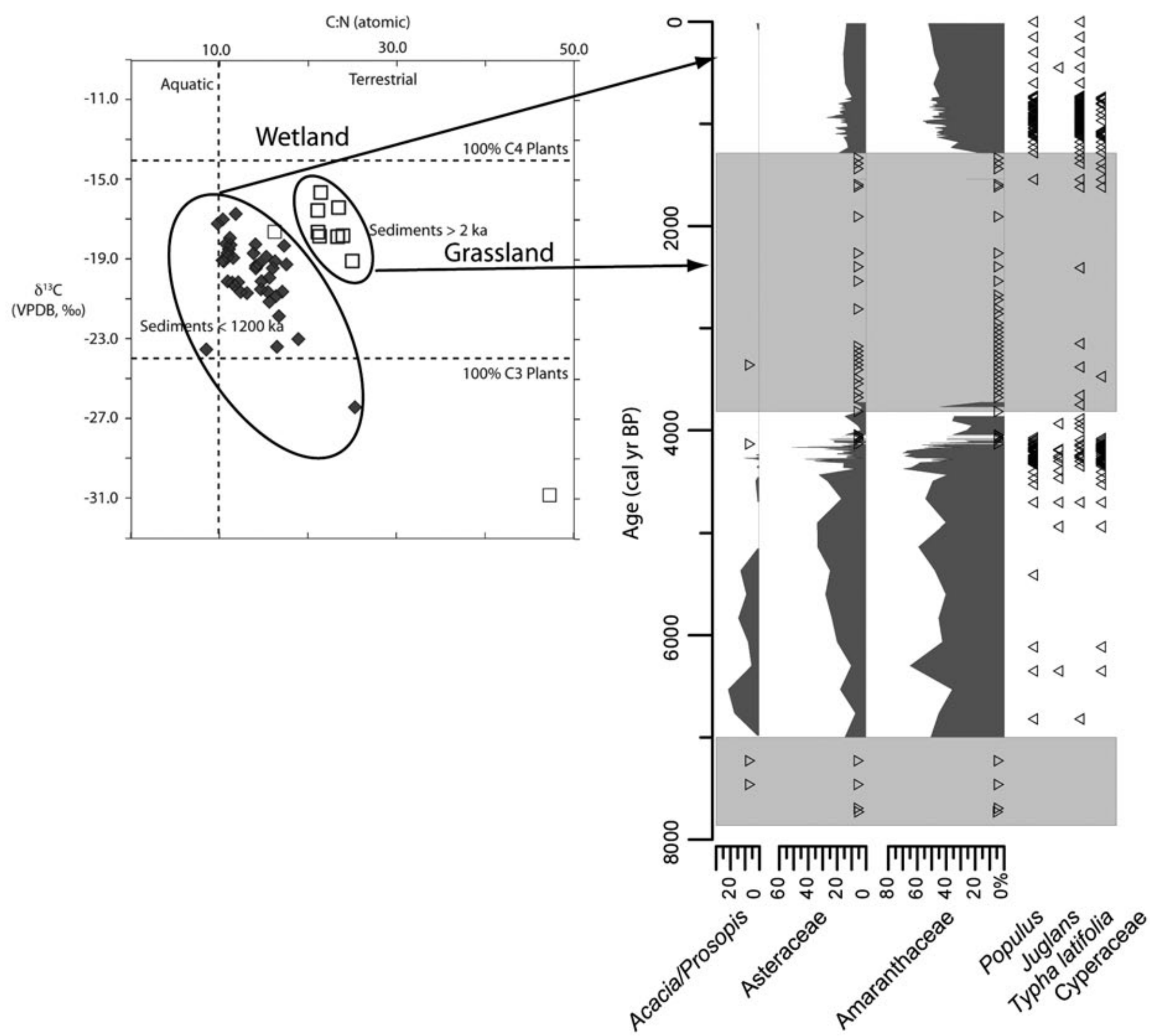

Figure 4—Scatterplot of C:N and δ[13]C isotopic values for the past 4000 years next to the pollen data for San Bernardino Ciénega (T. Minckley and others 2011) showing the isotopic shift in sediments with poor pollen preservation, indicated by triangles in the first three columns, as compared to sediments with good pollen preservation, indicated by shaded pollen abundance curves.

as evaporative potential (PE) is high throughout the year (fig. 5a,b). However, upstream and upland sediment (SED) sources contribute to organic detritus, inorganic carbon, and sand, silts and clays (Heffernan and Fisher 2010; Heffernan and others 2008).

Dryland Phase—The dryland phase is the natural reference state that occurs when groundwater levels have likely decreased >25 cm below the surface for obligate wetland species (Stromberg and others 1996), allowing for grass and woody taxa encroachment (fig. 5b) (T. Minckley and others 2009). Presumably lowered groundwater tables result in no perennial surface flow, which decreases growth rates of the ciénega surface (Minckley and Brunelle 2007; T. Minckley and others 2011). Pollen preservation is reduced during the dryland phase because of the periodic exposure of deposited pollen grains to oxidizing conditions. Groundwater flow out of the system is lowered because of plant usage and evapotranspiration. Flood pulse attenuation occurs in the dryland phase, because surface flow is not channelized. Rather, broad ciénega surfaces disperse seasonal flood pulses into sheet floods, preventing channelization. Sedimentary organic content is high during the dryland phase because of belowground competition for water resources. This competition further stabilizes the natural surface from degradation. Surface soil moisture is higher because of surface shading by woody and grassland taxa. AE is lower than PE in the dryland phase, but likely greater than in the degraded phase because of transpiration from vegetated surfaces and hydrologic lift associated with both the woody and grassland vegetation.

Wetland Phase—The wetland phase is the natural reference state that occurs when groundwater levels are at or above the vegetated surface resulting in standing water and saturated soils within and adjacent to a ciénega (fig. 5a). Most woody taxa are excluded from the ciénega surface because of the saturated soils. The combination of surface flow and groundwater flow through the system results in rapid and consistent aggradation of plant biomass and capture and burial of fine sediments from upstream sources (Heffernan and Fisher 2010). Pollen preservation is good during the wetland phase due to the

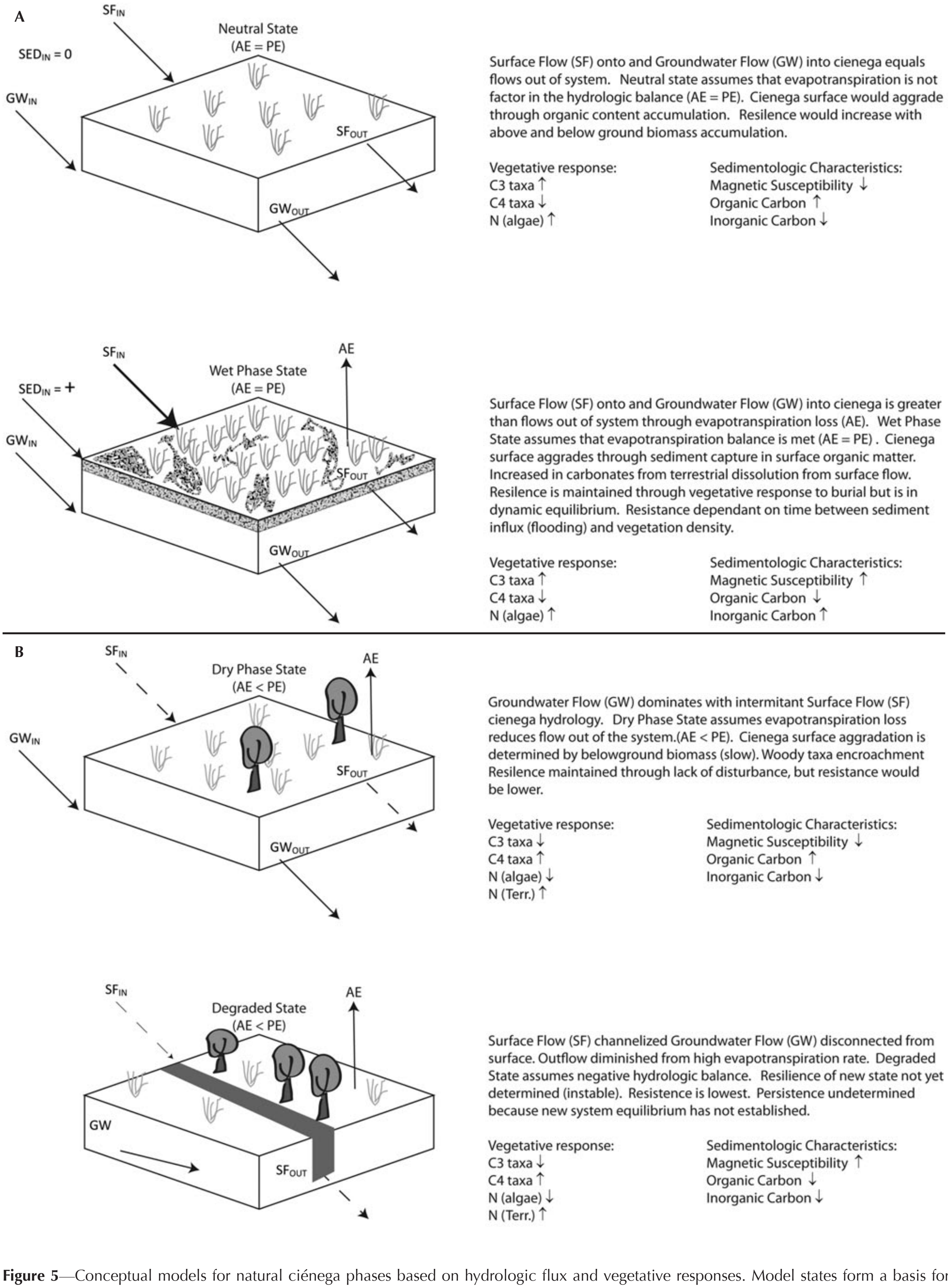

Figure 5—Conceptual models for natural ciénega phases based on hydrologic flux and vegetative responses. Model states form a basis for interpreting paleoenvironmental records from ciénega environments as well as provide management and restoration goals for present and future stable states. The neutral state forms a null hypothesis for comparing the three observed conditions for ciénegas in the American Desert.

anaerobic depositional environment. Flood pulse attenuation occurs in the wetland phase, because of surface characteristics and protection of soft sediments by the structure of dense above- and below-ground biomass (Heffernan 2008; Heffernan and others 2008). Seasonal flood pulses are slowed and sheet flooding across the entire surfaces results in increased inputs of sands, silts and clays (T. Minckley and others 2011). The moisture surplus results in a local balance of AE and PE.

Degraded Phase—Based on this conceptual model, the generic degraded state of ciénegas can be characterized as incised, having no surface water, poor groundwater connection for shallow rooted taxa, and experiencing woody taxa encroachment. Flood pulses are not attenuated in the degraded phase because of channelization concentrates flow and reduces sheet-flooding. AE is much lower than PE because of surface drying and low vegetation densities reduce near surface soil moistures (fig. 5b). The reconfiguration of the degraded state, relative to the natural states, may be extremely resilient to movement from this state, since flood power will be increased by concentrated flows within the channels and the incised channels maintain water levels well below the rooting zone of the adjacent terraces. Returning to one of the natural states, whether dryland or wetland, may be difficult based on present water availability, sediment flux, and vegetated surface-stability (DeBano and Schmidt 1990; Heffernan, 2008; Heffernan and others 2008), but is clearly possible as the state-change in Sycamore Canyon, Arizona, has demonstrated (Heffernan 2008). Natural re-establishment of ciénegas from the degraded state may occur primarily within recently formed (last 100 years) and much narrower active channels, while re-establishment of ciénegas to their former extents across entire valley channel widths may require active intervention that both redistributes surface flow and raises groundwater levels (i.e., check-dams placed within incised channels) (Heffernan 2008).

Management for the Paleoecological Perspective

State-changes in desert wetlands occur on multiple temporal scales; however, the current conditions of ciénegas in the American deserts are an artifact of the last 100-125 years of EuroAmerican settlement. Early research in changes in vegetation associated with lowered groundwater table (Bryan 1928) was the first indication of change in the region that favored deep rooted plant species. That changes in vegetation and hydrology are recent and upon the release of grazing pressure ciénegas can naturally reform (Heffernan 2008), suggests the natural resilience of these systems remains. Stromberg and others (2008) put forth that the responsiveness of vegetation in riparian corridors to changes in water availability reflected the constant renewal of the seed bank from both upland and riparian taxa. The constant double-sourcing of the seed bank would provide a mechanism for observed rapid vegetation changes in ciénega systems or state-changes over the long-term in both modern and paleoenvironmental studies. The rapid response may be based simply on changing precipitation timing and amount, and the consequent groundwater recharge, as the depth to water table is likely the ultimate control on natural ciénega states (Stromberg and others 1996).

Setting restoration targets for the management of ciénegas requires using the best information available. Unfortunately, reference conditions are poorly known as the degradation of ciénegas in the American Deserts was a post-hoc observation of a region changed by settlement, grazing, and land-use (Bryan 1925, 1928; Leopold 1949; Turner 2007; Turner and others 2003). The paleoecological record does provide insight into how ciénegas behaved under different climate regimes providing achievable restoration and management targets, based on current climate conditions and water availability, both natural and legal based on water rights. Based on the hydrologic flow and evidence of two potential natural states, ciénega management and restoration can target the dryland or wetland state as equally viable and within the natural range of variability for these environments (Millar and Woolfenden 1999).

Management could be focused on restoration of surface stability as either a grassland or wetland phase as a first order goal. In either state, the potential ecosystem services of ciénegas and the potential for natural state changes are restored. Passive management could follow allowing the natural seeding of the system to adjust the vegetation composition based on short and long-term climate variability (Stromberg and others 2008). Ciénegas have the potential to represent a great success story in conservation given that the degradation of these systems is relatively recent and we observe a great resilience in ciénega vegetation released from disturbance pressure (Garnett and Lindenmayer 2011; Heffernan and Fisher 2012; Heffernan 2008; Heffernan and others 2008). Optimistically, our expanding understanding of the mechanisms controlling ciénega form and function in the Madrean Archipelago can serve as a model for management of these resources in arid regions around the world (T. Minckley and others, *in review*).

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