A synthesis of dryland restoration lessons relevant to the San Joaquin Valley

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Synopsis

Scientific synthesis is a set of tools relevant to evidence-informed decision making for the drylands of California. Tools include comprehensive theory and formal scientific syntheses of the published primary literature examining restoration in drylands. Restoration lessons consistently reported in the literature provide insights into applicable theory, species-specific practices, and vegetation-driven interventions both actively and passively to support the San Joaquin Valley.

Keywords

synthesis, ecology, restoration, big picture, lessons, formal synthesis review, framework, San Joaquin Desert

Introduction

California ecosystems within the San Joaquin Valley are changing rapidly (Ramón Vallejo, et al. 2012) and are an excellent ecological representative of drylands globally (Stewart, et al. 2018). The San Joaquin Valley and Desert regions are home to unique flora and fauna that provides a profound opportunity to examine ecological processes critical to restoration (Germano, et al. 2011). Drylands include semi-arid grasslands and deserts (James Jeremy, et al. 2013). Endemic and threatened species are common in many relatively high-stress ecosystems such as these and are often coupled to vascular plants (Hobohm, et al. 2019). Shrubs in drylands can function to facilitate both animals (Lortie, et al. 2016) and other plants (Filazzola and Lortie 2014). Ecologically, changes in water stress within the San Joaquin region strongly suggest that water stress and global change require large-scale, integrated solutions (Hanak, et al. 2017). Politically, changes in land use with ownership and reductions in anthropogenic water use are forecasted for this region (Tamara, et al. 2016). There are numerous pathways to scientific, political, and social solutions to better manage the challenges, diversity, and inherent capacity for these systems to respond to change. Here, we will explore the scientific literature through the lens of scientific synthesis to seek general and consistent lessons.

Scientific synthesis is typically conceptualized as the aggregation of evidence. There are two fundamental mechanisms used to compile the scientific literature - meta-analysis and systematic reviews (Lortie 2014, Stewart 2010). Systematic reviews typically document the process of literature searching and processing the peer-reviewed publications (Gates 2002, Smith, et al. 2011). Extraction of evidence from systematic reviews in ecology and the environmental sciences focusses on the location, sample sizes, summary of methods used, and descriptions of study (Doerr, et al. 2015). A meta-analysis similarly completes these steps to define and describe the literature but also adds the step of extracting a measure of the strength of evidence from each primary study examined (Humphrey 2011). These measures generate an effect size measure that is some form of generalized contrast between the measure of key response under a treatment or intervention condition relative to that of a control or reference state (Field and Gillett 2010). However, significance testing of effect sizes and strength of evidence can vary between groups of studies due to heterogeneous methods, ecological context, or any number of factors. Syntheses in science can also include evidence maps and other tools to describe the evidence (McKinnon, et al. 2015). Consequently, a powerful outcome is the depth of understanding captured in these endeavors, and the gaps, opportunities, and reported general lessons are a general means to better inform evidence-based decision making in the disciplines of environmental science and management including restoration. Scientific syntheses can provide a rapid and comprehensive assessment of the big picture of research in a specific discipline, and to capitalize on these strengths here, we use synthesis to identify salient recommendations from the literature captured within this knowledge architecture.

Scientific synthesis is common in ecology. Restoration ecology is a relatively new discipline (Young 2000) with a focus on solution-driven conservation biology. Nonetheless, an examination of the scientific literature published to date through bibliometric searches for dryland synthesis papers returned nearly 50 publications in peer-reviewed journals. Syntheses were published beginning in 2006 up to 2020, and examined key processes for drylands. Environmental filtering in global drylands (Le Bagousse-Pinguet, et al. 2017) was proposed as a meaningful set of models to contrast functionally relevant strategies for managing diversity under changing stress. Species richness was further examined as a predictor of ecosystem function to changing climate including disturbance, grazing, and land cover change (Maestre, et al. 2016). Taken together, both these syntheses of broad research findings suggest that fundamental population and community ecology measures are useful heuristics in mitigating change in drylands through the selective management for greater species richness. Positive interactions were also examined in a synthesis to demonstrate the capacity for positive plant interactions with nurse plants such as shrubs to protect biodiversity in drylands and other extreme environments (Soliveres and Maestre 2014). This theory clearly provided scaffolding for structured mitigation of diversity loss in drylands. Local-scale management of woody structure and N deposition in drylands globally, particularly those similar to the San Joaquin Valley within a matrix of agricultural land use, also demonstrated a clear and consistent benefit to protection or management of woody species because they can drive both biodiversity patterns locally and shift systems from scrubland to grassland depending on extent and cover (Maestre, et al. 2016). Deserts, steppes, scrublands, and other drylands comprise nearly 40% of the earth surface and are sensitive to both mean annual precipitation and variation therein (Gherardi and Sala 2019, Wang, et al. 2012). In a global synthesis of 43 datasets each with at least 10 years of data, variability in precipitation had a net negative effect on primary production (Gherardi and Sala 2019). This confirms the assumption common for many dryland managers, ranchers, and agricultural experts that water limitation is a critical factor in restoration particularly for systems at the relatively depauperate end of water availability gradients regionally and locally. Water budgets, measurement of vegetation water use patterns, remote sensing, and stable isotope tracking were identified as key technological solutions to inform evidence-based decision making for drylands in a similar synthesis (Wang, et al. 2012). Land use patterns and water recharge rates have also been examined in syntheses and were identified as a powerful tools for these systems to explain local water availability in addition to climate (Scanlon, et al. 2006). Finally, syntheses on grazing were equivocal. However, these is accumulating evidence that grazing can enhance regional or beta diversity in drylands even if local reductions are sometimes associated with increasing consumer pressure (Hanke, et al. 2014). In summary, these key themes were present in all dryland syntheses published to date suggesting that plant diversity, woody species, water availability, and grazing are the key set of ideas relevant to framing decision making for the San Joaquin Valley. Consequently, the remainder of this chapter will briefly examine general restoration concepts to consider from fundamental theory, species-specific restoration evidence, and vegetation interventions beneficial to the region. The purpose remains to mine larger patterns through synthesis and not individual primary studies to ensure that the big picture is always in focus.

Restoration lessons from restoration ecology theory

Restoration ecology is changing. Scope, inference, connections with other disciplines, and urgency depending on local context and global stressors are increasing. This is both a grand challenge and an opportunity. Reinventing the wheel can lead to novel and heretowith new discoveries (Bornmann, et al. 2010), but existing theory can serve as a launchpad for restoration research and for management. The value of basic theory versus applied research is false dichotomy because we always use ideas and concepts to structure research and practice. All models are wrong but some are useful (Stouffer 2019). Theory and restoration can be used in many ways to inform practice and build meaningful and relevant narratives (Otto and Rosales 2019, Paschke, et al. 2019). Regional restoration within the San Joaquin Valley is no exception and can leverage syntheses of theory to frame the key concepts and ideas germane to successful outcomes. Using the Web of Science bibliometric resource, we searched for peer-reviewed publications in ecology and the environmental sciences that explicitly examined restoration, synthesis, and theory in parallel (Table 1). This process highlighted efforts within the field of restoration ecology to describe a plan of attack and lessons for future efforts. Here, we summarize both the findings and the derived lessons so as to elucidate approaches directly relevant to this region in research, planning, and strategy.

Theory development in restoration ecology embraces a holistic vision of restoration. Restoration ecology includes repair and conservation of systems and is proposed to be best implemented through process-based thinking and across multiple scales (Cairns and Heckman 1996, Holl and Crone 2004). Several key lessons were evident and consistent beginning with the formal development of concepts in this field (Table 1, items 1-2). First, every challenge within a region will differ, and there are end-goal and process-based objectives - both must be defined. Process-based criteria are the stepping-stones to restoring a region (repair and conservation) whilst goals can include definitions of function, diversity, or sustainable endpoints. The other major lesson common in the relatively early development of theory was that landscape-level processes cannot be overlooked even when the focus or goal is local. Island biogeography, scale, and patch-size considerations are cornerstones of applied ecology and can similarly inform restoration. The theme of biogeography was echoed in another lesson (Table 1, item 3) specific to agri-environment subsidy planning (Donald and Evans 2006). Two critical lessons from this synthesis apply to the San Joaquin region. Firstly, soften agricultural lands by providing non-agricultural habitat within them that benefits wildlife movement. Secondly, use connectivity theory from ecology to inform decision making for wildlife. These ideas can include meta-population theories and connectivity analyses. This is intuitive, but process-based restoration for wildlife does not necessary entirely overlap with vegetation or habitat-based restoration because of dispersal and connectivity issues for animals. Finally, in the early theory development work directly relevant to the San Joaquin region, obstacles were discussed (Weiher 2007). Again, there were at least two key lessons. Move beyond demonstration or single study science to inform decisions for a region. Seek principles generally and specifically for a region because restoring the best places locally is not always an option. This is applicable to any region in California particularly the San Joaquin Valley. Collectively, these critical syntheses of theory to application suggest that keeping the big picture in mind for any restoration agendas that are at scales larger than a single focal site is a best practice.

Broader and more inclusive thinking on the ideas relevant to restoration was also a common theme in the proposed lessons from theory synthesis papers in this field. Testing simple combinations of ecological principles was proposed as a key lesson from restoration syntheses (Huth and Possingham 2011, Wortley, et al. 2013). Investment in small patches of low quality is not recommended, and inclusive thinking should not only include economics but socioeconomics (Table 1, item 6). Tools to facilitate this dimension within the region can include assessments of the economics of different techniques, contingent values, opportunity costing (particularly relevant to this region), and cost-benefit analyses for social measures (Wortley, et al. 2013). A critical lesson was that without social outcomes, restoration practices will not become policy. Ecological complexity in experiments was also proposed as an important principle for an integrated regional restoration plan (Table 1, items 7-9). Complexity but not complicated restoration lessons included testing all three community assembly filters for a region such as biotic, abiotic, and dispersal factors (Hulvey and Aigner 2014). This perfectly aligns with process-based objective planning for a region. The key filters limiting ecological processes for repair and recovery need to be identified. This thinking extends to triage approaches wherein we plan locally, regionally, and at multiple scales whilst accepting that there will be trade-offs in that extent that we can restore process-based and goal-oriented objectives for a region depending on spatial extents and the timeframes available to practitioners (Rappaport, et al. 2015). One solution proposed was to prioritize planning through habitat rankings within a region. A component of this approach must also recognize that habitat quality is not always a direct predictor of restoration outcomes because animals have preference and cognition biases that can lead to ecological traps (Hale and Swearer 2017). This is a critical trade-off associated with habitat restoration targets without concomitant work with the local species-specific wildlife conservation targets. Finally, theory (and cost with trade-offs) naturally leads to different classes of restoration strategy - namely passive versus active interventions (Wainwright, et al. 2018). A key lesson from synthesis is that a flexible strategy that incorporates both passive and active approaches to restoration within a region is not only likely to be more cost effective but ecologically effective as well because some processes operate over longer-time scales and are thus best examined through passive strategies. Goals associated with diversity, ecological and evolutionary timescales of responsiveness, and benchmarks that are accessible to practitioners are best practices from these syntheses. Theory clearly plays a role in strategic thinking and guides decision makers through evidence-informed inquiry by providing landmarks in the categories of concepts applicable to a given challenge.

Restoration lessons from species-specific efforts in the San Joaquin Valley

The San Joaquin Desert is home to many species that are unique and endemic regionally. Some of these species are endangered with declines in habitat over 90% (Germano, et al. 2011). These species include the San Joaquin kit fox (Vulpes macrotis ssp. mutica), three species of kangaroo rats (Dipodomys ingens, D. parvus, D. nitratoides), the blunt-nosed leopard lizard (Gambelia sila), and the San Joaquin antelope squirrel (Ammospermophilus nelsoni) in addition to others. Restoring the San Joaquin Desert requires managing the land to create habitat for these species. However, research on the best habitat for these species is limited because declines occurred early in the century, and remaining habitat can be low quality (Williams, et al. 1998). An informed decision on management practices for these species can nonetheless be provided using existing evidence on species habitat preferences.

There are habitat characteristics that are shared amongst these endangered species. There is a need to improve habitat size and connectivity. Lands are a major limitation in the San Joaquin Desert with only relatively small parcels remaining of habitat embedded in an agricultural matrix. These small patch sizes can negatively impact the species that are found within them (Flagship 5). For example, the blunt-nosed leopard lizard benefits from at least a 2 km buffer from human development because of roadkill risks (Germano, et al. 2016). The area of their habitat should also be at least 500 hectares to support a sustainable population (Germano, et al. 2016, Germano 2007). While the largest population of blunt-nosed leopard lizards are in the Carrizo Plain, protected by the National Park Service, there are other small and scattered populations throughout the San Joaquin Valley. For larger vertebrate animals, the area required increases significantly such as the San Joaquin kit fox which requires 600 hectares of habitat with high suitability for a single-family group. Increasing the habitat area that is protected from development or agriculture is a critical first step in the restoration process for these species. Additionally, connectivity between habitat patches can significantly benefit at-risk species (Flagship 3). Populations can be separated by agriculture, utility corridors, or roads, and this can prevent the resilience of small populations to disturbance or climate extremes, such as drought. However, these features can be modified to improve connectivity. For instance, agriculture can be managed to provide movement corridors for some species (Flagship 3), and there can be wildlife underpasses that allow movement around linear human features in deserts (Murphy-Mariscal, et al. 2015). An effective restoration program for at-risk species within the San Joaquin Desert requires improving habitat area and connectivity.

Improving the quality of habitat for species is another critical component of successful restoration. However, the features needed for high quality habitat can be species specific (Flagship 9). For instance, blunt-nosed leopard lizards require burrows created by rodents to nest. Some agricultural practices damage these burrows and threatened the lizard populations (Cypher, et al. 2013). Creating artificial burrows can be a viable restoration practice. Alternatively, using an integrated restoration plan that promotes both the blunt-nosed leopard lizards and the rodents that construct burrows such as the giant kangaroo rat is also viable and are an important restoration lesson - i.e. consider multiple species and their interactions both positive and negative. Kangaroo rats have been identified as ecosystem engineers that promote the abundance and diversity of other desert species in the areas they occupy (Prugh and Brashares 2012). Improving the habitat for the at-risk species of kangaroo rats can will thus extend to other sensitive species. Foundational shrubs are another example of using interactions among species to promote restoration within the San Joaquin Desert. For example, kangaroo rats utilize burrows more frequently that are close to shrubs (Striplin 2004). Dominant shrubs in the San Joaquin Desert, such as Ephedra californica or Atriplex spp. can be planted in degraded habitats or abandoned agricultural lands to promote vertebrate species restoration through preferred habitat in addition to other direct restoration benefits. In summary, species-specific needs restoration does not have to focus only one species at a time sequentially and can incorporate interactions between them species and consider the needs of multiple species for key habitat attributes ecologically.

One shared requirement for many San Joaquin species is the management of invasive grasses. At-risk kangaroo rats have been identified to be negatively associated with high grass densities and instead prefer bare, sandy soil (Chock, et al. 2020). High densities of exotic grasses can also inhibit movement of desert animal species, which can increase predation (Vásquez, et al. 2002). Grazing has been recommended as a tool to combat high densities of invasive grasses, but the effects remain controversial. Grazing can also have negative impacts on animals such as damaging burrows or trampling. Seeding native plant species could be an effective strategy to reduce exotics (Flagship 7). However, native plants in the San Joaquin Desert have also declined significantly (Borders, et al. 2011). Securing sufficient seed for the restoration of rangelands or abandoned agricultural areas can be difficult because remnant habitat often has low native diversity to collect from and/or it may not be appropriate to collect (Borders, et al. 2011). Collections from these remaining populations can be commercially grown at high volumes but would likely require multiple years to be used for restoration projects. Giant kangaroo rats have been identified to prefer native seeds over exotics, suggesting that promoting native plants could benefit the endangered animals. However, this can complicate restoration efforts as the kangaroo rats are removing native seeds from native seeding projects (Gurney, et al. 2015). Seeding projects may need to adjust for granivory by either excluding rodents from seeded plots or compensating with higher seed densities. Supporting the native animals in the San Joaquin Desert requires managing the vegetation composition to increase the native species, which can be challenging both to reduce exotics and increase natives.

Monitoring populations of these at-risk species is necessary in restoration projects. However, monitoring can be challenging because these species are rare and unlikely to be found at high densities. Survey technique depends both on the animal being monitored and the goal of the monitoring. Detection dogs have been used to find the scat of blunt-nosed leopard lizards and San Joaquin kit fox. Using scat can be informative because DNA can be extracted to estimate the size of population size from where the scat was collected (Smith, et al. 2006). Unfortunately, scat can be costly both in the deployment of the dog-handlers and DNA work afterwards. Camera traps can be a more affordable method to track animal populations and has been effective for even small animals, such as the blunt-nosed leopard lizard. Camera traps also allow for recording video to infer animal behavior in addition to estimates of population abundance. More traditional approaches include walking along a transect and identifying individuals. Although transect surveys tend to be low-cost, there is a risk of missing desert species that are typically cryptic. Using telemetry to monitor animal survival and movement has been successful for San Joaquin kit fox and blunt-nosed leopard lizard but can have a high initial set-up cost. Proxy measures for animal abundance can be an effective way to monitor populations during restoration efforts. For example, the burrows of giant kangaroo rats can be rapidly and effectively assessed using aerial surveys (Bean, et al. 2012). There are many tools available for proper monitoring of at-risk species within the San Joaquin desert that can fit the resources of the land manager.

Restoration efforts for at-risk species within the San Joaquin Desert requires consideration of land development and climate change. A significant portion of the San Joaquin Desert has been developed in the last century and remaining habitat has recently been threatened by solar farm development. However, there are also considerable agricultural lands being retired that if done strategically and properly restored can benefit native species (Lortie, et al. 2018). Increasing the area and connectivity of habitat throughout the San Joaquin Desert will assist in the recovery of these endangered species or provide resiliency with climate change. Predictions of climate change suggest that climate in California will become more variable particularly for precipitation (Pierce, et al. 2013). The changing climate will likely change the behavior of these animals. For example, the Balinville's horned lizard (Phrynosoma blainvilli) has declined significantly in the San Joaquin Desert and has a narrow temperature window for activity (Hult and Germano 2015). Higher temperatures may result in more time spent thermoregulating and less time outside of its burrow (Hult and Germano 2015). Other animals may temporarily migrate during periods of drought or consecutive heat extremes, highlighting the need for greater habitat connectivity and area. Restoration strategies to promote at-risk species in the San Joaquin Desert should explore changing land practices and incorporate a changing climate into habitat identification.

Restoration lessons from vegetation-specific efforts in California drylands

Restoration efforts typically include the native vegetation in degraded ecosystems. Conventional agricultural practices impact abiotic and biotic conditions of environments through water (Bommarco, et al. 2013, Tilman 1999) and changes in native habitat for plants and animals (Bommarco, et al. 2013). These practices and generate risks to soil microorganisms, pollinators, and wildlife (Garibaldi, et al. 2019). Therefore, restoration of native vegetation including for instance cover, richness and diversity following agricultural retirement is a necessary action to protect from soil erosion (Li, et al. 2007) and more severe habitat degradation (Yang, et al. 2006). Synthesis was used to identify different interventions that have been applied to restore vegetation in California drylands and to summarize the big-picture evidence (Lortie 2014, Stewart 2010). Restoration interventions comprised those of minimal human assistance (i.e. passive restoration) and others that involved direct manipulation of ecosystems (i.e. active restoration) (Holl and Aide 2011). The evidence is summarized here by describing the most compelling studies pertinent to the San Joaquin region of California.

Plants are key components in terrestrial ecosystems. Plants provide key ecosystem services and functions such as energy input, soil fixation, water infiltration, and habitats for other species (Díaz, et al. 2015, Filazzola, et al. 2017). One of the main biodiversity threats in California drylands is the invasion by exotic annual grasses and the competitive exclusion of native perennial species (Lucero, et al. 2019, Seabloom, et al. 2003). Restoration practices have been done to ameliorate the impact of exotics. Seeding native annual species with similar resource requirements of exotic grasses has shown a competitive decrease in exotic species recruitment, seedling growth, and seed production (Table 3, item 3). In addition to the direct exclusion of native perennial grasses, invasive annual grasses serve as fuel of problematic fires for native shrub communities that severely affect the recruitment of desert shrubs and benefit the dominance of exotic plants (Table 3, item 6). Therefore, restoration actions after the occurrence of fire are required to limit exotics invasion. Herbicides and mechanical removal of exotic grasses were successful in reducing invasive grass and forb species after fire (Table 3, item 6). However, these interventions must be applied with caution because they can also have negative impacts on native plants including but not limited to mortality and soil disturbance. Contrast of the resource requirements for native and exotic plants is another source of evidence for restoration projects. Carbon addition to decrease N availability to plants is a restoration intervention conducted to reduce exotics (Suding, et al. 2004), and it is successful only when exotics and native species differ in their N requirements. In desert environments, carbon amendment is not always an optimal tool for invasive annual species control

(Table 3, item 4). The addition of water accelerated the timing of exotic annual species germination compared to natives. However, the exotic grasses germination resulting from water supplementation can also induce herbivory by rodents, and therefore, increased exotic seedling mortality providing an added benefit (Table 3, item 9). Managing resources relevant to the plant community is thus a viable set of tools for restoration in the region provided non-native plants are considered.

Interactions between plants is also an important lesson for restoration ecology practitioners. Positive plant-plant interactions (i.e. facilitation) has been used a restoration tool in degraded ecosystems. In drylands, shrubs act as foundational species (Angelini, et al. 2011) promoting the germination and establishment of other plant species under their canopy (Table 3, item 1). Furthermore, native shrubs offer shelter and refuge to endangered endemic animal species in drylands (Filazzola, et al. 2017). However, it broader scale effects of different desert shrub species in facilitating other (native) plants needed to be examined. Some shrubs species in drylands can recover from physical damage (Table, item 1) but not all. Understanding interactions and identifying foundation plant species can be key to conserve intact populations and at times also likely accelerate the restoration of degraded scrublands.

Revegetation of degraded drylands is mainly constrained by water availability (Elliott, et al. 2014). The addition of water and nutrients to adults of a shrub species produced an increase in the number of seeds produced and in seed weights (Table 3, item 6). Nonetheless, identifying ideal microsites and safe sites for seedling establishment and growth it is also a key consideration for restoration in drylands. Lessons from research on suitable sites for shrub transplants in particular suggest that a method to protect seedling against herbivores can be critical. Therefore, some authors suggested seeding as a faster and more economical method than transplanting (Table 3, item 7). Supplementing water to seeded shrub species produced different species-specific effects on germination and a monoculture of a species (Table 3, item 10). Irrigation is not always a good strategy because non-focal species resident in the system can also respond to a release from limitation. Seed and seedling provenance sources is another lesson from the research for revegetation projects. Provenance studies suggest that local is best but one must also incorporate seed from a broad range of environmental variables includes genetic variability to increase the likelihood of plant establishment to a given site (Table 3, item 2). Revegetation is thus viable for this region but managing resources, provenance, and site selection are the three criteria to consider.

Native revegetation has been well studied in the drylands of California. To control the invasion of exotic annual grasses and forb species, one of the main threats for native species revegetation, restoration interventions include the use of chemicals (addition of nutrients and application of herbicides), mechanical control, and water addition. The outcomes were highly species-specific and depend also on the functional group of the plant species tested (i.e., grasses or forbs) evaluated. These lessons apply to both natives and exotics. Species interactions such as facilitation, competition, and herbivory (Table 3, items 3, 8 and 9) were also evaluated and suggested as important processes relevant to restoration. All the restoration efforts to combat exotic plants involved first some form of active human intervention, and results from species interactions were variable and typically influenced by water availability. Adding water to shrub species also depended on the life stage when water was added (adults or seed), the specific native shrub species, and the extent of exotic plant invasion at the specific site. Restoration is certainly about the positive, i.e. addition of native and foundation species, but we cannot neglect the negative either, i.e. control and management of non-native plants.

Conclusions

Restoration ecology is an exciting and contemporary field of interdisciplinary research and practice. This birds-eye view of syntheses for drylands, theory, species-specific patterns for the San Joaquin region, and vegetation-specific interventions illuminated a set of best practices for restoration here. Synthesis is the big picture, and this framework is always needed for restoration at all scales. Diversity was a consistent and critical end goal or objective in dryland syntheses. Scale should never be ignored. Single studies can demonstrate an idea, but principles are needed for policy and reproducible restoration within a region. Policy will advance through principles but only when social costing for a region is also incorporated. Trade-offs, triage, and rankings are a reality for restoration in the San Joaquin region, and ecological theory even in simple combinations can inform decision making. Benchmarks are needed and should include ecology with flexible, realistic definitions of space and time for restoration. Biogeography and multi-factorial thinking were persistent lessons from the general synthesis literature of theory. There is an opportunity within the San Joaquin region to restore remnant habitat and retired lands to support endangered species. Restoration of the San Joaquin Desert requires a whole community approach that targets many plants and animal groups because the interactions amongst these species can maintain a stable ecosystem. To support at-risk species, there should be a focus on increasing habitat area, improving connectivity, increasing the ratio of native plants to exotics, and consistent monitoring to evaluate restoration efficacy. Finally, we also have the opportunity to restore and conserve natural habitats to provided ecosystem services for resident human populations. The restoration of native vegetation in degraded drylands including revegetation of native perennial plants supports these benefits directly and indirectly. Collectively, the lessons from this scientific synthesis highlights numerous key criteria that enable a vision of restoration that is both specific and generalizable depending on the challenge.

Table 1

A summary of synthesis papers examining restoration theory in ecology and the environmental sciences. This list was populated from a search of Web of Science (January 2020) using the keywords restoration, synthesis, and theory.

item	year	title	journal	key findings	lessons
1	1996	Restoration ecology: The state of an emerging field	ANNUAL REVIEW OF ENERGY AND THE ENVIRONMENT	clear definition that restoration ecology is about repair, cannot also ignore protection, and is a holistic discipline; restoration ecology is both goal-oriented and process-oriented	in every challenge, goal and process-oriented restoration will differ and clear objective and criteria must be defined; the most successful interventions should consider linkages to ecosystem services or key ecological theories
2	2004	Applicability of landscape and island biogeography theory to restoration of riparian understorey plants	JOURNAL OF APPLIED ECOLOGY	patch size and scale including island biogeography can be useful theories for restoration ecology	consider landscape-level processes when doing restoration locally; community dynamics operate at multiple scales
3	2006	Habitat connectivity and matrix restoration: the wider implications of agri-environment schemes	JOURNAL OF APPLIED ECOLOGY	agri-environment payments to farmers protect biodiversity but can also can larger-scale matrix effects to habitat	consider island biogeography and meta-population theories for land allocations; soften agricultural lands by providing non-ag habitat within them; higher trophic levels such as wildlife can benefit significantly from connectivity theories for restoration
4	2007	On the status of restoration science: Obstacles and opportunities	RESTORATION ECOLOGY	terrestrial restoration ecology is too simple; synthesis and links to theory need to be more explicit	we need to move beyond demonstration science showing that an intervention works only once; we need to replicate interventions more extensively; use conceptual ideas and explore principles otherwise we always only end up restoring the best places and that is not always an option

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item	year	title	journal	key findings	lessons
5	2011	Basic ecological theory can inform habitat restoration for woodland birds	JOURNAL OF APPLIED ECOLOGY	small patches of low quality are not viable investment strategies for bird restoration; patch size is a key predictor for birds at large, continental scales	simple combinations of ecological principles such as patch size, structure, and species richness is a general lesson for strategy development; ecological models can inform marginal returns on investment when choosing between size and quality
6	2013	Evaluating Ecological Restoration Success: A Review of the Literature	RESTORATION ECOLOGY	empirical review of literature shows that key attributes of restoration outcomes are increasingly reported; ecology is well reported at 95 percent as an outcome but socioeconomic outcomes of restoration are not at only 1-2.5 percent of all studies; the number and duration of restoration studies is increasing; controls and restoration targets are used in restoration	include socioeconomic outcomes in restoration studies; cost of restoration can be included in many forms including the economics of techniques, contingent values methods, opportunity costing, and cost-benefit analyses; social outcomes are needed to ensure restoration practices become policy
7	2014	Using filter-based community assembly models to improve restoration outcomes	JOURNAL OF APPLIED ECOLOGY	native seed combinations and increased native seed densities increase resistance to invasion by exotics; litter must be removed; plant traits need to be considered	experiments that include all three assembly filters for restoration including biotic, abiotic, and dispersal are most likely to succeed; management actions include overcome dispersal limitations for natives, manipulate sites by prepping soils, and choose natives with desirable local traits

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item	year	title	journal	key findings	lessons
8	2015	A landscape triage approach: combining spatial and temporal dynamics to prioritize restoration and conservation	JOURNAL OF APPLIED ECOLOGY	if the restoration outcomes are focussed on biodiversity optimization, consider spatiotemporal dynamics at more than one scale; nearly 400 wooded landscapes benefitted from models that considered resilience, cover loss, and cover gain over time; urgency, feasibility, and regional importance ranking were effective planning factors	do not ignore landscape-level trajectories of change and restore based only on contemporary landscape; plan locally, regionally, and consider multi-scale tradeoffs; decision making can leverage rankings of habitat value through time and in space to prioritize planning
9	2017	When good animals love bad restored habitats: how maladaptive habitat selection can constrain restoration	JOURNAL OF APPLIED ECOLOGY	perceptual and ecological traps can undermine restoration interventions to enhance animal biodiversity; 5 key criteria include structural habitats, animals local to recolonize, measure underlying processes, restored sites must provide resources, and restored sites must increase reproductive rate	habitat quality and preference must be linked in restoration planning; resource-based restoration is a viable strategy and functional planning of habitats can augment outcomes; use cognitive theory for animals to plan restoration
10	2018	Links between community ecology theory and ecological restoration are on the rise	JOURNAL OF APPLIED ECOLOGY	over 1000 restoration ecology experiments surveyed in synthesis show that use of community ecology concepts increasing over time; community assembly and succession theories	theory and practice in restoration can look to community ecology for insights and levers for strategy; passive versus active restoration interventions need to be flexibly applied depending on the restoration outcome and theory; consider ecological timescales in addition to evolutionary frameworks; in nothing else, use community ecology to define benchmarks for practitioners

Table 2

Flagship studies for species-specific restoration efforts within the San Joaquin Desert, California. Studies populated from the Web of Science using species name and restoration are key search terms.

item	year	title	journal	key findings	lessons
1	1996	Restoration ecology: The state of an emerging field	ANNUAL REVIEW OF ENERGY AND THE ENVIRONMENT	clear definition that restoration ecology is about repair, cannot also ignore protection, and is a holistic discipline; restoration ecology is both goal-oriented and process-oriented	in every challenge, goal and process-oriented restoration will differ and clear objective and criteria must be defined; the most successful interventions should consider linkages to ecosystem services or key ecological theories
2	2004	Applicability of landscape and island biogeography theory to restoration of riparian understorey plants	JOURNAL OF APPLIED ECOLOGY	patch size and scale including island biogeography can be useful theories for restoration ecology	consider landscape-level processes when doing restoration locally; community dynamics operate at multiple scales
3	2006	Habitat connectivity and matrix restoration: the wider implications of agri-environment schemes	JOURNAL OF APPLIED ECOLOGY	agri-environment payments to farmers protect biodiversity but can also can larger-scale matrix effects to habitat	consider island biogeography and meta-population theories for land allocations; soften agricultural lands by providing non-ag habitat within them; higher trophic levels such as wildlife can benefit significantly from connectivity theories for restoration
4	2007	On the status of restoration science: Obstacles and opportunities	RESTORATION ECOLOGY	terrestrial restoration ecology is too simple; synthesis and links to theory need to be more explicit	we need to move beyond demonstration science showing that an intervention works only once; we need to replicate interventions more extensively; use conceptual ideas and explore principles otherwise we always only end up restoring the best places and that is not always an option

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item	year	title	journal	key findings	lessons
5	2011	Basic ecological theory can inform habitat restoration for woodland birds	JOURNAL OF APPLIED ECOLOGY	small patches of low quality are not viable investment strategies for bird restoration; patch size is a key predictor for birds at large, continental scales	simple combinations of ecological principles such as patch size, structure, and species richness is a general lesson for strategy development; ecological models can inform marginal returns on investment when choosing between size and quality
6	2013	Evaluating Ecological Restoration Success: A Review of the Literature	RESTORATION ECOLOGY	empirical review of literature shows that key attributes of restoration outcomes are increasingly reported; ecology is well reported at 95 percent as an outcome but socioeconomic outcomes of restoration are not at only 1-2.5 percent of all studies; the number and duration of restoration studies is increasing; controls and restoration targets are used in restoration	include socioeconomic outcomes in restoration studies; cost of restoration can be included in many forms including the economics of techniques, contingent values methods, opportunity costing, and cost-benefit analyses; social outcomes are needed to ensure restoration practices become policy
7	2014	Using filter-based community assembly models to improve restoration outcomes	JOURNAL OF APPLIED ECOLOGY	native seed combinations and increased native seed densities increase resistance to invasion by exotics; litter must be removed; plant traits need to be considered	experiments that include all three assembly filters for restoration including biotic, abiotic, and dispersal are most likely to succeed; management actions include overcome dispersal limitations for natives, manipulate sites by prepping soils, and choose natives with desirable local traits

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item	year	title	journal	key findings	lessons
8	2015	A landscape triage approach: combining spatial and temporal dynamics to prioritize restoration and conservation	JOURNAL OF APPLIED ECOLOGY	if the restoration outcomes are focussed on biodiversity optimization, consider spatiotemporal dynamics at more than one scale; nearly 400 wooded landscapes benefitted from models that considered resilience, cover loss, and cover gain over time; urgency, feasibility, and regional importance ranking were effective planning factors	do not ignore landscape-level trajectories of change and restore based only on contemporary landscape; plan locally, regionally, and consider multi-scale tradeoffs; decision making can leverage rankings of habitat value through time and in space to prioritize planning
9	2017	When good animals love bad restored habitats: how maladaptive habitat selection can constrain restoration	JOURNAL OF APPLIED ECOLOGY	perceptual and ecological traps can undermine restoration interventions to enhance animal biodiversity; 5 key criteria include structural habitats, animals local to recolonize, measure underlying processes, restored sites must provide resources, and restored sites must increase reproductive rate	habitat quality and preference must be linked in restoration planning; resource-based restoration is a viable strategy and functional planning of habitats can augment outcomes; use cognitive theory for animals to plan restoration
10	2018	Links between community ecology theory and ecological restoration are on the rise	JOURNAL OF APPLIED ECOLOGY	over 1000 restoration ecology experiments surveyed in synthesis show that use of community ecology concepts increasing over time; community assembly and succession theories	theory and practice in restoration can look to community ecology for insights and levers for strategy; passive versus active restoration interventions need to be flexibly applied depending on the restoration outcome and theory; consider ecological timescales in addition to evolutionary frameworks; in nothing else, use community ecology to define benchmarks for practitioners

Table 3

A summary of synthesis papers examining restoration lessons from vegetation efforts.

item	year	title	journal	key findings	lessons
1	2017	The Groot Effect: Plant facilitation and desert shrub regrowth following extensive damage	ECOLOGY AND EVOLUTION	benefactor shrub species recover from physical damage; ecological effects of a foundational shrub species were not related to canopy size	include fundation species recovery from physical damage in facilitation studies; important to understand species specificity of foundational plant species
2	2017	Landscape genetic approaches to guide native plant restoration in the Mojave Desert	ECOLOGICAL APPLICATIONS	temperature may predict patterns of adaptive divergence across plant functional types within the Mojave Desert	link landscape genetics with ecological restoration; model local adaptation through molecular markers
3	2014	Can native annual forbs reduce Bromus tectorum biomass and indirectly facilitate establishment of a native perennial grass?	JOURNAL OF ARID ENVIRONMENTS	native annual forb species from the Great Basin were highly effective at suppressing growth and seed production of an exotic annual species	seeding native annual forbs after disturbance may decrease exotics seed production and reduce their competition
4	2011	Can resource-use traits predict native vs. exotic plant success in carbon amended soils?	ECOLOGICAL APPLICATIONS	carbon amendments will not impact invasive annuals since they do not have higher N requirements from natives	the most effective restoration strategy for native grasslands may be to manipulate water availability; when invasive species differ in N-use from desired species, carbon amendments may be successful to control invasive grasses

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item	year	title	journal	key findings	lessons
5	2010	Post-Fire Control of Invasive Plants Promotes Native Recovery in a Burned Desert Shrubland	RESTORATION ECOLOGY	fire increase invasive annuals and reduce the abundance and cover of native shrubs; fusilade II (herbicide) reduce invasive forb and grasses	non-specific treatments such as raking could be useful when invasive plants are vulnerable and desired plants are not; removal of invasive grasses and forbs is a logical first step in desert restoration
6	2008	Irrigation and fertilization effects on seed number, size, germination and seedling growth: implications for desert shrub establishment	OECOLOGIA	seed production and weight of a native shrub species increase with water and nutrient addition; improvements in seed quality were not large enough to influence the growth of seedlings	increasing seed production, combined with treatments to improve the quality of seedling micro-environments, should increase seedling recruitment with lower management intensity than other active practices
7	1998	Transplanting Native Plants to Revegetate Abandoned Farmland in the Western Mojave Desert	JOURNAL OF ENVIRONMENTAL QUALITY	planting into augered holes with plastic cone to herbivory protection yielded more vigorous plants; high plant mortality due to water limitation	planting methods and type of herbivory protection are important factors to consider, but, plant survival and vigor are limited by water availability; seeding is faster and more economical method than transplanting native shrubs
8	2011	Seasonal priority effects: implications for invasion and restoration in a semi-arid system	JOURNAL OF APPLIED ECOLOGY	exotic annual grasses and forbs germinated quickly and reached a higher abundance than native species; high mortality by herbivory of exotic seedlings	priority effects via exotic germination plasticity confer competitive superiority to exotics; pre-growing season irrigation pulses may be a viable restoration technique in systems with early stages of exotic grass invasion and herbivores to constrain survival of exotics seedlings

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item	year	title	journal	key findings	lessons
9	2011	The roles of exotic grasses and forbs when restoring native species to highly invaded southern California annual grassland	PLANT ECOLOGY	if exotic grasses are removed, exotic forbs expand and prevent native forbs from occupying the vacant habitat; seeding native species is not effective at increasing native species cover, although density of seeded species may increase when all exotic species are removed	removal of exotic forbs could increase the dominance of exotic grasses (and vice versa) resulting in lower abundance of native forbs; if increasing the density and cover of native species is desired, it may be necessary to control exotic grasses and forbs
10	2000	The Effects of Irrigation on Revegetation of Semi-Arid Coastal Sage Scrub in Southern California	ENVIRONMENTAL MANAGEMENT	irrigation resulted in differences in the timing of germination among seeded species; earlier germination did not appear to enhance survival; irrigation resulted in a near monoculture of a species	increasing water availability and stimulation of earlier germination does not promote a more rapid long-term restoration; where diversity of plant species is an objective, irrigation is not necessary and beneficial.

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