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PHYSICAL AND BIOTIC DRIVERS OF CHANGE IN RIPARIAN ECOSYSTEMS

The Human Element of Restoration Success: Manager Characteristics Affect Vegetation Recovery Following Invasive *Tamarix* Control

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Abstract

We investigated the relative role of manager traits and decisions for explaining the impact of riparian restoration. To do this, we used the difference in vegetation between post-restoration and controls for 243 pairs of sites to create a success index. We then determined how much variability in success could be explained by physical variables that directly impact vegetation (environment and weed removal) versus human variables (characteristics of the people who managed those sites and their management decisions). More than 60% of the variability in vegetation change could be explained, with human variables increasing adjusted R-square values of physical-only models by an average of 47%. Restoration "success" was positively associated with an increase in the number of collaborators, the number of information sources used, and the relative priority of plant-related goals. Worse outcomes were associated with an increase in the number of roles the manager held, monitoring frequency, and with higher manager education level. These results point to the indirect impacts of the human element, and specifically supports recommendations to include multiple partners and set specific goals. To our knowledge, this is the first time the importance of human characteristics as drivers of restoration outcomes has been quantified.

Keywords Riparian restoration · Invasive species · *Tamarix* · Coupled natural-human systems · Collaboration · Monitoring

Introduction

Ecological restoration projects are inherently beholden to the people involved; outcomes will be largely affected by management decisions across a project's duration. Most studies on the ecological outcomes of restoration compare the effects of direct actions on ecosystems, such as methods used to actively remove invasive plant species (Ruiz-Jaen and Aide 2005; González et al. 2015), but a growing body of literature suggests that personal and professional traits of land managers and the specific ways they conduct restoration projects (exclusive of direct actions) may also help to predict ecological outcomes of restoration (Wortley et al. 2013; Morandi et al. 2014; Hychka and Druschke 2017; Rohal et al. 2018; Stanford et al. 2018). For example, scientists emphasize the importance of selection and prioritization of restoration goals (Shafroth et al. 2008), the type and degree of collaboration (Bernhardt et al. 2007), information sources used (Sutherland et al. 2004), and monitoring (England et al. 2008; Roni et al. 2019), but rarely if ever is the connection made from these practices to impacts on the natural systems being restored. Even characteristics of the managers themselves, such as education and experience or the number of roles they hold in the project, would be expected to influence restoration practices (Clark et al. 2019; Wallington et al. 2005). Using data from 243 restoration sites and their associated managers, we quantify for the first time (to the best of our knowledge) the role of

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manager characteristics and decisions in explaining actual ecological outcomes.

There is good reason to expect that decisions made about a project's strategy matter because of the presumed influence they have on the direct actions managers will take. For example, setting clear goals is emphasized in the Society for Ecological Restoration's principles, both for selecting management strategies and for project assessment (Gann et al. 2019). In assessing restoration outcomes, goals help to define an objective indicator of success (Prach et al. 2019). The decision to collaborate with other agencies can increase the scale of restoration projects (Oppenheimer et al. 2015), can allow managers to pool limited resources (Fliervoet et al. 2013), and can give managers the opportunity to learn from others' mistakes (Bernhardt et al. 2007). The use of multiple, evidence-based sources of information is recommended for project planning and implementation (Sutherland et al. 2004). Monitoring is also considered critical for successful outcomes (e.g., Holling and Meffet 1996; Bash and Ryan 2002; England et al. 2008), for adaptive management (Noss 1990; Moore and Rutherfurd 2017), and for managers to have a clearer interpretation of a "successful" project (Bernhardt et al. 2007). More frequent monitoring, and by multiple methods, is considered beneficial for restoration success (Sher et al. 2010). It has been found that systematic and objectively clear monitoring by managers was associated with a more realistic perspective on the success of restoration (Morandi et al. 2014), but the impact of monitoring or other project strategies on metrics of success has not been done.

The importance of characteristics of the managers themselves is even more enigmatic. Previous research has shown that attitudes held by land managers about nature or science did not significantly explain the management actions made by them, nor that education level predicted attitudes (Clark et al. 2019). However, it is reasonable to expect that education level and management experience (both total experience and experience in a given locale) should indirectly influence success of a project, by influencing decisions made and ability to carry them out. We are not aware of any attempts to study this, however.

There is also the issue of defining what is meant by "restoration success." The success of projects is frequently anecdotal (Kondolf et al. 2007) and the definition of success can be different from person to person (Hagger et al. 2017). Bernhardt et al. (2007) found that the majority of riparian managers across the US subjectively viewed their projects as "successful", however their success was not corroborated with ecological data (Jähnig et al. 2011). Ideally, success is measured as a change or difference between a reference (a control) and the conditions after restoration ("impact", sensu Smith 2001, Morandi et al. 2014, Gann et al. 2019). However, very few restoration studies employ the use of reference sites, making such determinations of change difficult (González et al. 2017a). The identification of the variables to measure is also paramount.

For the purposes of this study, we define success in those terms identified by the managers we surveyed, namely, a reduction in an invasive tree and other noxious species and an increase in native species, both in terms of total cover and also relative to noxious species. We used vegetation data from riparian restoration projects across the southwestern US where we could measure vegetation composition change between impact and control sites.

The health of riparian systems in the southwestern U.S. has been in decline in the recent past due to particularly threatening anthropogenic pressures including the introduction of invasive species such as the shrubby invasive tree *Tamarix* spp. (tamarisk, saltcedar; Sher and Quigley 2013) and its proliferation largely due to heavy regulation of river flows (Beauchamp and Stromberg 2007; Merritt and Poff 2010); a common practice in riparian restoration in the Southwest US is its removal or reduction (Briggs et al. 1994; Stromberg et al. 2007). Previous studies found that the method managers used to control *Tamarix* significantly affected the vegetation community (González et al. 2017c; Sher et al. 2018). However, there was still a great deal of unexplained variability in the success of *Tamarix* removal projects, and there are likely more human factors that directly influence the plant community than just removal method. Here, we address the following questions: 1) Does the addition of human variables (manager characteristics and decisions) improve our prediction of restoration success? And if so, 2) What is the relationship between these human variables and restoration success?

Methods

Vegetation and environmental data were compiled for 255 sites from two published studies on the effectiveness of *Tamarix* removal method (González et al. 2017c; Sher et al. 2018). Vegetation data were collected using standardized point-intercept methods by multiple researchers over time. Sites were distributed across the Upper Colorado, Lower Colorado, and Rio Grande river basins in the southwestern US and encompassed all major *Tamarix* removal projects in the region, with lands owned by a variety of public and private management agencies (Fig. 1; Clark et al. 2019). Of these, 243 were "treatment sites" where *Tamarix* removal activities had occurred, each of which we paired with a control site (i.e., still invaded, degraded) so as to measure the impact of restoration activity. For those treatment sites that were measured more than once over time, we only considered the last year of sampling. For 60 of the 243 treatment sites, the control was the same site, before *Tamarix* removal (i.e., before vs. after). The amount of time since removal varied from 1 to 23 years, but we did not find a significant effect of time on success metric (mixed model with river reach as a random effect, fixed effect of time: $F = 0.62$, $P = 0.43$), since the biggest change occurred as soon as the overstory of *Tamarix* was removed; changes over time can be extremely gradual in these systems (González et al. 2017c). The remaining 184 treatment sites used controls that were sites in locations that were sampled in the same year but did not have any restoration activities at time of sampling (i.e. control vs. impact). Of these, 50 control sites were those designated as such by the managers of the treatment sites themselves (in all cases because exotic species dominated), with the remaining 134 chosen by identifying the geographically closest reference site that was a) measured in the same year, b) was located in the same fluvial landform type (e.g., sandbar, off-channel depression, river bank, active or inactive floodplain, etc.), and similar hydrology (distance to nearest water source and whether that source was ephemeral or permanent). We prioritized controls that shared the same year because high inter-annual fluctuations in precipitation could affect herbaceous growth, and annuals are an important component of these plant communities (González et al. 2017c). Fluvial landform was prioritized because it is one of the most significant factors influencing plant community composition in riparian zones (Tabacchi et al. 1998; Cooper et al. 2003). Both types of controls (before-after and control-impact) are valuable when assessing restoration outcomes; ideally restoration research should have both (i.e., a "BACI" design; González et al. 2015, Sher et al. 2018). It should be noted that it is difficult to identify a perfect control, especially after the fact. In our case, when control sites were not in the same river reach, treatment sites were more likely to be in a drier and hotter region than the corresponding controls, with 30-year monthly average precipitation a mean of 12.3 mm less (paired t-test precipitation year sampled: $t = -6.15$, $p < 0.001$) and 1.07 °C hotter ($t = 6.4$, $P < 0.001$), thus leading to a likely underestimation of "success" in those sites; González et al. 2017b showed that for our study sites, the native plant community is positively correlated to precipitation and negatively to temperature. It should also be noted that, for the before-after pairings, mean monthly precipitation was very slightly but significantly greater (10.5 mm) the year of sampling for the sites after treatment versus before ($t = -2.20$, $p < 0.03$).For each treatment site, we compiled environmental data typically used to characterize these ecosystems and for which we had data at most or all sites, including geography/ecohydrology, climate, and management variables (Table 1). Ecohydrology is especially important in this system; the variables we were able to include for this feature included distance to water, elevation above river, and river width (which is also a measure in our system of river flow permanence),

Each of the treatment sites was then paired with human data obtained from managers' survey results associated with these sites (Clark et al. 2019). "Managers" were defined as individuals who made management decisions for that site, including job titles such as restoration ecologist, wildlife biologist, hydrologist, program manager, planner, or superintendent. These data were collected from an online survey administered through Qualtrics to the land managers (Clark et al. 2019, University of Denver Institutional Review Board #816375–5). The survey covered two main topics: manager characteristics and management decisions (Table 2). Manager characteristics included education and experience (overall and local). These manager traits were those for which there was enough replication within response categories to do statistical analysis. Management decisions were site-specific for the treatment sites and included goal-setting, monitoring, information sources (including partners), and project organization.

Monitoring We recorded the types of monitoring methods used by managers (i.e., visual, biological, physical, or chemical) as a count to represent the number of methods. In the survey, managers also selected monitoring frequency for each type of monitoring used but because of small sample sizes for the physical (e.g., channel cross-sections or pebble counts) and chemical (e.g., water temperature or dissolved oxygen) methods, we created an ordinal variable for monitoring frequency using the highest frequency for any method.

Information This category refers to contextual, i.e. external to the project, information sources. We recorded the count of the number of influential sources rated "somewhat influential" or higher by managers. We also developed a categorical variable for the type of information source: informal (e.g., face-to-face interactions, networking), formal (e.g., published sources, conference presentations), or a mixture. This variable was based on the qualitative assessment made by research assistants of open-ended questions and interview responses where available (following methods in Saldaña 2014) and double-checked for accuracy and consistency.

Organization Collaboration was recorded as a count of the number of groups managers worked with on that specific restoration project (e.g., personnel within their agency, university scientists, local managers, etc.). We also recorded the organization or agency that employed the manager, and how many distinct roles the manager held in the project. These included: Directly make land/resource management decisions, responsible for implementing management decisions, oversee restoration projects with input from a team or partnership, collect data on management actions, and "other" (were asked to specify).

Goal-Setting Managers selected and ranked goals for each project among 14 goals to choose from, including an "other" option where managers could write in additional goals (Appendix 1). We simplified the goal variable into five groups based on similarity (Table 3) and assigned a mean rank for that group based on tercile (i.e., ranked in the bottom, middle, or upper third for priority in the list of goals for that site). Higher values indicated greater importance.

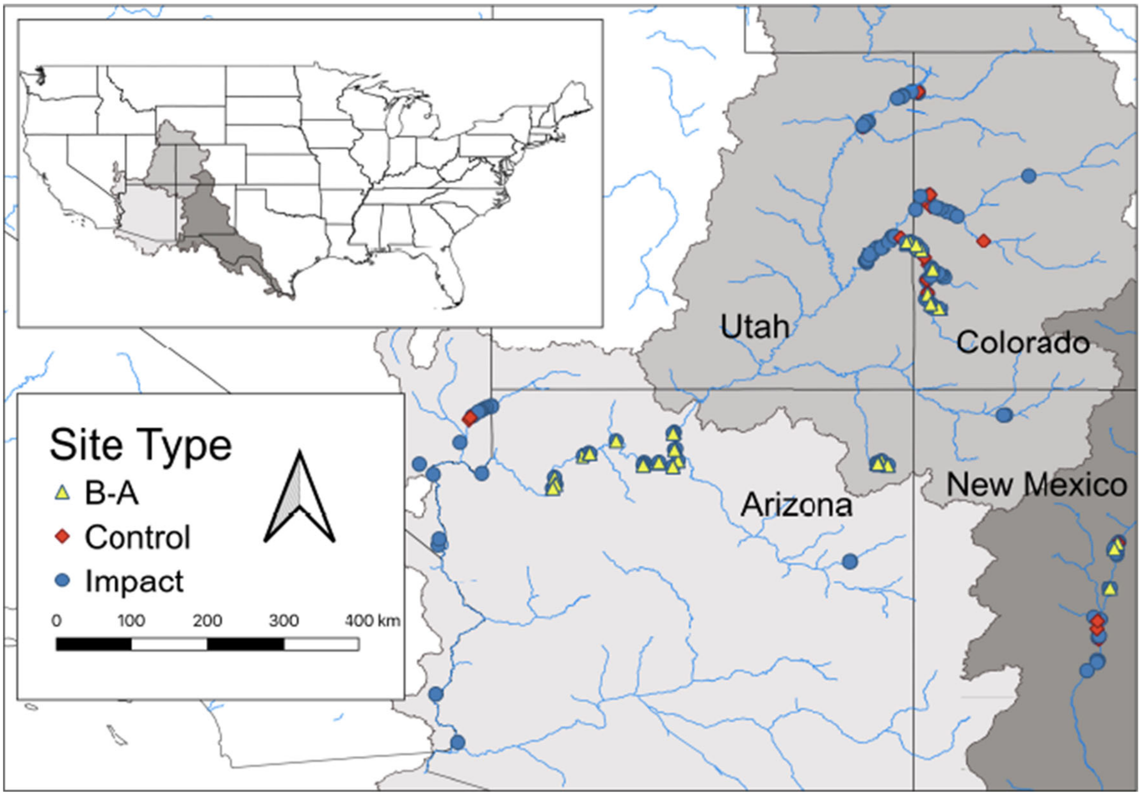


Fig. 1 Map of study area and sites included in this study, spanning the Lower Colorado River Basin (light grey), Upper Colorado River Basin (medium grey), and Rio Grande River Basin (dark grey). "B-A" sites represent one location where data were available before as well as after *Tamarix* removal. "Control" sites represent an experimental control where *Tamarix* was present, but not treated. "Impact" sites were sites where restoration occurred, primarily *Tamarix* removal, but for which no pre-*Tamarix* data were available. These sites were paired with a "Control" site sampled in the same year. The nearest "Control" site in geographical proximity within the same fluvial landform type (e.g., sand bar, off-channel depression, river bank, active or inactive floodplain, etc.) was chosen for each "Impact" site

Table 1 Environmental variables by category used in the analysis. All variables are continuous except where indicated

Geography and ecohydrology	Basin: Upper Colorado (UCRB), Lower Colorado (LCRB), Rio Grande (Grande)
	Reach (26 sections of rivers)
	River width (m)
	Distance from water's edge (m)
	Slope of river channel (% change in elevation)
	Elevation above sea level (m)
	Elevation above river (m)
	Distance from nearest paved road or railway (m)
	Distance from nearest road of any type (m)
Climate	Precipitation year of sampling (mm)
	Max. temperature year surveyed (°C)
	Min. temperature year surveyed (°C)
	Avg. precipitation* (mm)
	Avg. maximum monthly temperature* (°C)
	Avg. minimum monthly temperature* (°C)
Management	Method of removing *Tamarix* (biocontrol only, chain saw, heavy machinery)
	Use of herbicides to control *Tamarix* resprouts or other weeds (yes/no)

*Averages of precipitation, maximum temperature and minimum temperature are monthly means for growing season (April to September) over 30 years

Analysis

We created a "success index" variable from the difference in vegetative cover between treatment sites and their corresponding control for the following variables: *Tamarix* cover (ΔTARA), noxious understory species cover (ΔNox), total native species cover (ΔNat), and relative native understory cover (i.e., (native understory)/(total understory); ΔRNU). Total understory includes both native and exotic cover, thus ΔRNU can also be considered a metric of relative exotic cover. We defined a non-native species as noxious if that was its legal status in at least one of the six states where our study sites were located (USDA-NRCS 2014). These variables reflecting vegetation change were selected based on restoration goals stated by managers (Clark et al. 2019) and individually have been used in other publications (González et al. c, d and Sher et al. 2018). The data for these four variables differed very little from normality (Appendix 2 Fig. 5). We then used Principal Components Analysis (PCA) to collapse these four variables into a single index (corresponding to site scores along the first PCA axis, PC1) to reflect change in the plant community.

We tested the multicollinearity among all physical and human variables to be used as independent variables with a correlation matrix (Appendix 3 Table 4). All independent variables were scaled with the function "scale" in R (values minus means divided by standard deviation), so as to be able to compare the regression estimates of variables that were originally in different units or orders of magnitude. All analyses were performed using JMP Pro v. 14 (SAS Institute Inc.) and R 3.6.1 with RStudio 1.1.463 (R Core Team 2019) and the following packages: vegan (Oksanen et al. 2019), MASS (Venables and Ripley 2002), nlme (Pinheiro et al. 2019), MuMIn (Bartón 2019). To address our first question as to whether the addition of human variables improved prediction of success, we used the success index calculated from the vegetation response (PC1) as the dependent variable in linear mixed effects models with river reach as a random variable and the three categories of potentially explanatory variables as fixed effects (physical, including environment and removal method; and human, including management decisions, and manager characteristics). River reach refers to the location on a stretch of river; including it allowed us to account both for variability purely due to geographic location, as well as to avoid pseudo-replication, given that restoration projects tend to be clustered in space. Physical variables were first selected using a backward selection based on adjusted-R^2; all physical variables increasing the explained variation in success index (from the most informative to the least) were selected for inclusion. Highly correlated variables (i.e., any with a correlation coefficient > 0.7) were alternatively accounted for in this selection process (e.g., since distance to the nearest paved road was highly correlated with distance to the nearest road of any type, separate models were created using each variable),

Table 2 Human variables obtained via survey, as described in Clark et al. (2019). All variables reflect the rank managers placed on each category of roles, with higher values meaning a rank of higher importance

Manager Characteristics	
Manager's highest level of formal education	High school, Bachelor's, Master's, PhD
Overall experience	<11 years, 11–20 years, >20 years
Local experience	<11 years, 11–20 years, >20 years
Management Decisions	
Monitoring	
Number of monitoring methods used	Discrete
Frequency of monitoring	annually or greater, every 1–2 years, every 4 years or less
Information	
Level of formality of information used by managers	informal, formal, both
Number of information sources used	Discrete
Organization	
Number of agency collaborators on restoration project	Discrete
Employing agency	16 different federal, private, local, state and non-profit
Number of management roles	Number of distinct roles held by manager (up to 5)
Goal-setting	
Plant related goals	Discrete
People related goals	Discrete
Water related goals	Discrete
Wildlife related goals	Discrete
Other types of goals	Discrete

Table 3 Specific restoration goals as presented in the survey by category

Goal group	Specific goals
Plants	Improve native plant diversity, exotic plant removal, ecosystem resilience
People	Recreation, aesthetics, wildfire mitigation
Water	Channel maintenance, restore over-bank flooding, water quality
Wildlife	Endangered species, habitat improvement
Other	Livestock, water conservation, salinity, research, none, unknown

thereby creating variations by including different sets of competing variables. This method resulted in eight distinct physical-only models, as there were four correlated climate variables and two correlated road variables. To create the final physical-only models, we conducted backward stepwise selections on the eight starting models, using maximum adjusted-R2 as the criterion for inclusion; this resulted in six distinct physical-only models. To these six models, human variables were added using a forward selection also aiming to maximize adjusted-R^2. Any improvement in adjusted-R^2 from a considered variable resulted in inclusion in the model. None of the human variables were highly correlated. Finally, we removed the physical variables from each full model (keeping human variables exactly the same) in order to construct the human-only models. The explained variation of restoration success could then be partitioned into physical, human, and shared components. We chose this method as it allowed us to determine the additional explanation provided by each human variable individually, starting from an environmental-only model. Adjusted-R^2 was used as the criterion as our goal was to maximize explanatory power, with less emphasis on parsimony.

To address our second question about the relationship between human variables and restoration outcomes, we used the sign of the parameter estimates from the full models and, as a complementary analysis, ran separate linear mixed effect models for each individual human variable using river reach as a random variable.

Results

Both within and among categories of variables (Physical and Human Characteristics) there was remarkably low multicollinearity, with the exception of high correlations (>0.7) among elevation and climate variables (i.e., 30-year monthly averages of precipitation, minimum temperature and maximum temperature) and between landscape variables (distance to nearest road, slope, and river width). Thus, for each model, only one climate variable and one landscape variable were alternatively selected to be included in the subsequent models.

The PCA on the difference in vegetation cover between treatment sites and their controls yielded a first PC vector that explained 44% of the variability of the entire plant community

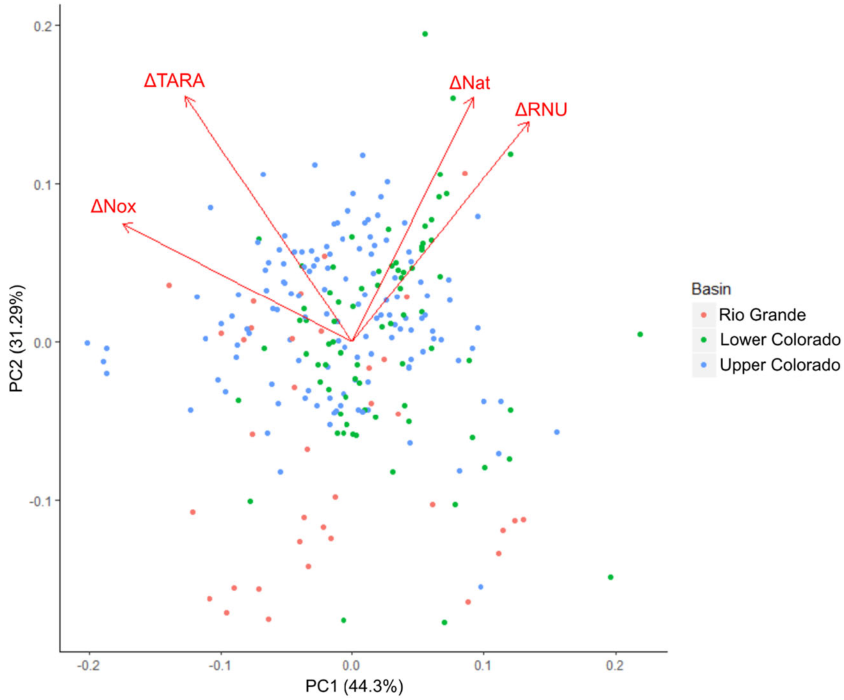
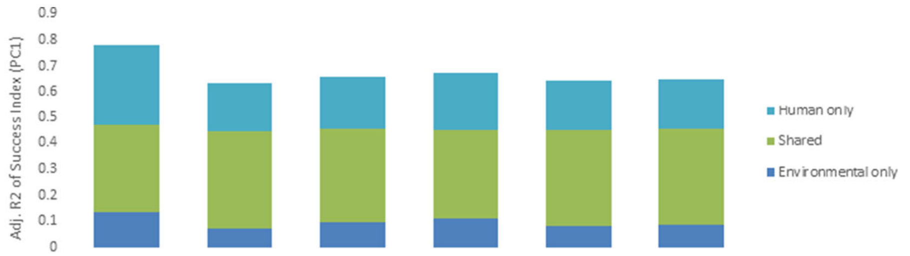


Fig. 2 Principal components analysis of change in vegetative cover for 243 treatment sites. Site scores correspond to treatment sites, with circles of different colors for the three river basins studied. PC1 was used as our success index as desirable vegetation (total native cover [ΔNat] and understory relative native cover [(ΔRNU]) correspond to more positive values for PC1, with undesirable vegetation (*Tamarix* cover [ΔTARA] and other noxious cover [ΔNox]) corresponding to more negative values. The contribution of each vegetation variable to PC1 (species scores) is denoted in the figure (with red arrows indicating direction and magnitude).

(Fig. 2). Negative values were associated with an increase in undesirable species and positive values indicated an increase in desirable species. PC1, a single measure of the composition of the entire plant community, was thus used as our metric of ecological outcome, the "success index". PC2 (31% explained) reflected an increase in overall vegetative cover, both desirable and undesirable, and thus was not as useful for our purposes of distinguishing between better and worse outcomes.

A linear mixed effect model with river reach as random variable did not find that basins differed in PC1 as a measure of restoration success (F2,241 = 0.13, $P > 0.05$), despite basins significantly differing in every physical measurement (Appendix 4 Table 5). Thus, we concluded that our random variable (river reach) sufficiently accounted for regional effects.

The six physical (geography, climate, and weed management) variable models showed similar performance in explaining retained success according to adjusted R^2 values (0.44–0.47). Adding human variables yielded six distinct models that improved adjusted R^2 values by 47% on average (full model adj. $R^2 = 0.63–0.78$) (Fig. 3). For all models, $p < 0.001$. Model parameters are shown in detail in Appendix 5 Table 6. Managing agency category and monitoring frequency were present in all models, with all three manager characteristics and five management decisions contributing to one to four models. The only variables tested that were not present in any stepwise model were number of monitoring methods used, ranks of plant, people, water or "other" goals, and level of formality of information sources. When considered in univariate tests, restoration success increased with number of information sources used and when the manager had a management (vs. science) degree, whereas more frequent monitoring was associated with decreasing restoration success (Fig. 4). Several variables contributed to one of the full models while not significant in a univariate mixed model, meaning that they increased explained variance only in conjunction with other variables. These included both managing and employing agency categories (i.e., what agency managed or employed the manager, respectively), wildlife goal rank (positive trend), number of collaborating groups (positive trend), education level (negative trend), local experience (negative trend), and overall experience (negative trend). An increased priority of plant-related goals and goals in the category of "other" (i.e., not water-, people-, or wildlife-related goals) were both associated with increases in success in the univariate models. A high proportion of



HUMAN VARIABLES						
Managing agency category	■	■	■	■	■	■
Monitoring frequency	■	■	■	■	■	■
Number of sources used	■	■	■	■		
Employing agency category		■	■	■		
Number of collaborating groups	■			■		
Degree field		■	■			
Number of management roles		■				
Goals: "wildlife"	■					
Total experierce	■					
Local experience	■					
ENVIRONMENTAL VARIABLES						
Herbicide used	■	■	■	■	■	■
Precipitation year sampling	■	■	■	■	■	■
Longitudinal slope	■	■	■	■	■	■
Minimum temp year sampling					■	■
Normal precipitation	■				■	
Distance to nearest paved road			■			■
Maximum normal temp				■		
Minimum normal temp						■

Fig. 3 Six models to explain the success index (PC1) constructed from both physical variables (environmental and removal methods) and human variables (manager characteristics and management decisions). Variables included in each model are indicated. Height of bars indicates the adjusted R2 to explain the success index (PC1), with colors showing proportion of variability explained by only human variables (manager decisions + manager characteristics), only physical variables, and the proportion of the variability explained that overlapped between the two (shared)

the variability was explained by both physical and human variables in all three models ("Shared" in Fig. 3). An increase in cover of desirable species were generally associated with warmer sites with less precipitation, at greater slopes, farther from roads, and where herbicide was used (on *Tamarix* or other species). It is important to note that the absence of an environmental or management variable in these models should not be taken as evidence that they do not matter, since the random variable of reach may have partially accounted for them. For this reason, and because physical effects for these sites have been explored elsewhere (González et al. 2017a), our interpretations will focus on the human variables.

Discussion

This is the first time the relationships between human factors (i.e., manager characteristics and indirect management decisions) and restoration success have been quantified. There is

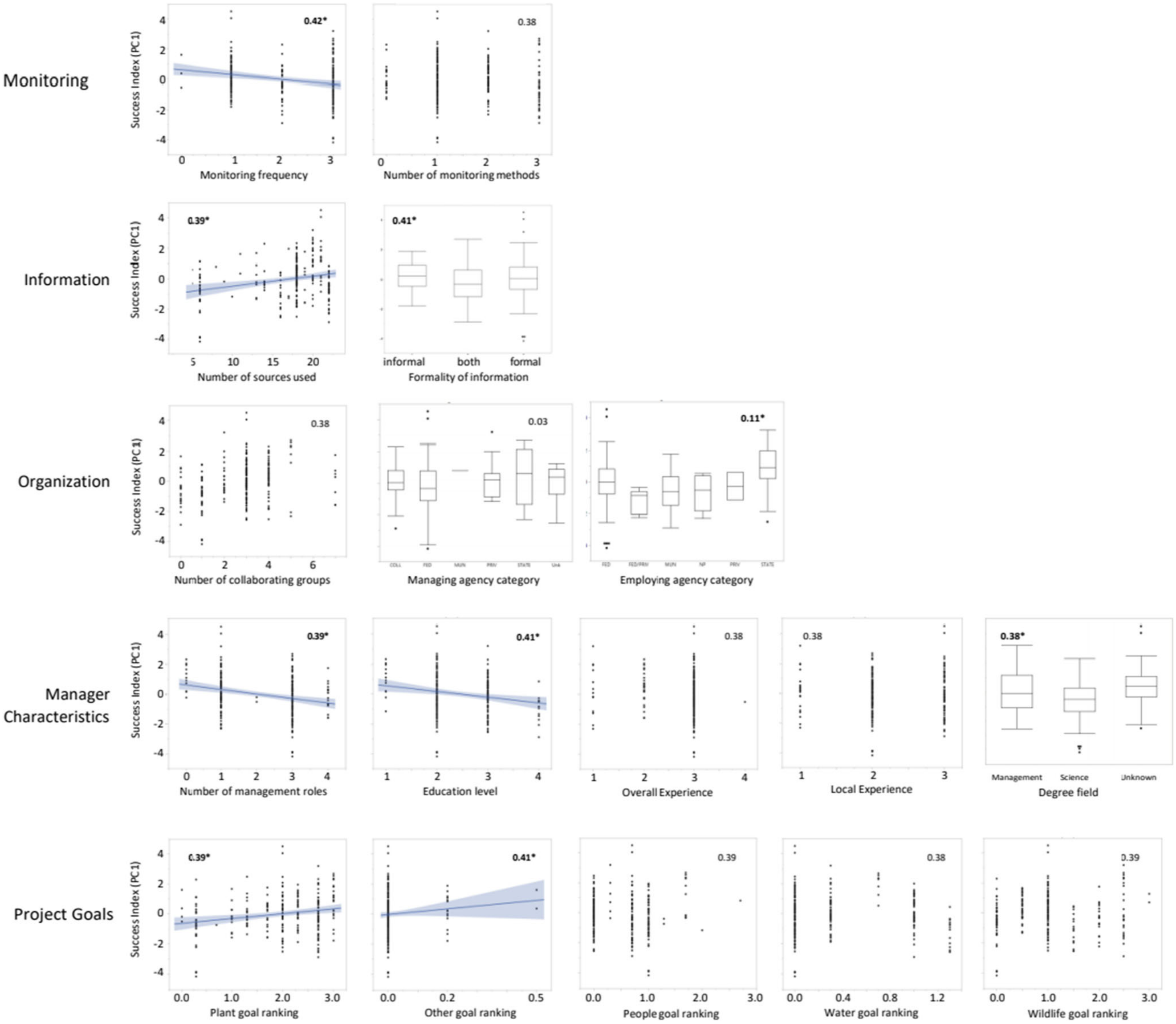


Fig. 4 Linear regressions of human variables against the restoration success index (PC1). Adjusted R-square values are from univariate mixed models with reach as random variable. Significant models have R-square in bold and show trend lines with 95% confidence intervals. Agency categories are, in order: college (Managing only), federal, municipal, non-profit (Employing only), private, state, and unknown (Managing only). Some agency categories did not include both managing and employing agencies and are thus only shown in one plot. See Table 2 for descriptions of ordinal variable axes

always an element of stochasticity in response to management, making predictions of ecological outcomes difficult, especially in a system with so many sources of variability. For example, White et al. (2019) found in their species management experiments that even in the highly controlled conditions of a flour beetle microcosm, the same removal rates had highly variable success. However, our study has demonstrated that even with such difficulties for prediction, as much as 78% of the variability in restoration outcomes could be explained if we included both physical and human factors.

Human factors as defined here have necessarily indirect effects, but may point to mechanisms whereby a restoration project will be more likely to succeed or fail as a result of individual manager characteristics as well as the agencies they represent. These may indirectly influence aspects of management that we did not directly measure in our study, including frequency a site is visited, types and dosage of herbicides used, methods and care of application, and implementation of adaptive management (adjustments in response to findings). The large degree of overlap between variability explained by human and environmental variables illustrates that such elements are closely related as a group, even if individual variables are not highly correlated. What seems clear is that common environmental measurements have predictive limitations that may be overcome by considering aspects of human involvement.

In particular, features relating to the organization and planning of a project were highly influential in our models. It is intuitive that overloading a manager with too many responsibilities could lead to poorer outcomes, because important details may be missed or the capacity of the manager to respond to issues may be more limited. That the categories of both managing agency and employing agency were explanatory variables suggests that there are characteristics of an agency beyond the assignment of roles that are important. Certainly, funding of an agency could have cascading impacts on such things as the quality and size of work crews for labor-intensive tasks (as are often used in *Tamarix* control projects), the quality of equipment and supplies, and type of training for both the manager and work crews. Unfortunately, this information was not available. There are also important differences in how federal versus more local agencies operate, as well as the size of the lands they own, which can have important implications. For example, we expect that smaller agencies and organizations will generally be able to respond and adapt more quickly and can operate at a finer scale than larger ones. Furthermore, previous findings from this population have shown that stakeholders with a vested interest in restoration outcomes have different project motivations from each other (Clark 2018), suggesting that the mission of each managing agency (which also has a vested interest) likely also impacts how projects are managed through the prioritization of goals. For example, people-related goals were found to be a high priority for local agencies relative to state or federal agencies; local agencies tend to be more focused on public use, recreation, and safety, all of which align with the people-related goals of aesthetics, recreation, and wildfire mitigation.

The importance and relevance of goal-setting is also illustrated here; when plant goals and/or wildlife goals were prioritized higher, our vegetation-based metric of success increased. It is reassuring that prioritizing goals such as invasive plant removal or increasing native plant diversity does, in fact seem to lead to these outcomes. Prioritization of water goals was not found to increase success, which may result from the tradeoff between evapotranspiration reduction and native vegetation increase (Cleverly 2013). To our knowledge, this is the first time the impact of goal-setting has been quantified in actual vegetation change.

Perhaps most importantly, our results point to the value of having various inputs of information for success, both in terms of number of sources used and number of organizations collaborating. Instead of "too many cooks spoil the stew," we are seeing that the input of many voices is clearly positive. Although collaborations of multiple agencies are sometimes difficult for the participants (Clark 2018), at least in this system they can be associated with significantly improved outcomes on the ground. We believe that this is because broad collaboration makes the inclusion of scientific information more likely, as well as the input of more experienced persons (Clark et al. 2019). This may be consistent with our finding that projects with informal sources of information, that is, from talking to partners rather than from reading papers or taking workshops, had slightly better outcomes. That complexity of human organizational structure was positive is also consistent with the observation that ecological complexity is often considered to be beneficial for restoration (e.g., Palmer et al. 2005; Nilsson et al. 2016; Fernandez et al. 2017).

It is likely that both the high degree of collaboration we are seeing in these projects and the paramount importance of the agency/organization is the reason why experience level of the manager did not seem to matter, and education actually had a negative association. This also may explain a previous finding that that attitudes of managers toward science and nature had no predictive power to explain management decisions (Clark et al. 2019). It seems likely that the influence of both information sources and collaborators trumps such aspects of the manager him or herself. Conversely, the negative relationship between restoration success and the characteristics of education level, experience level, and a science (vs. management) degree of the manager may be caused by an increasing reluctance to follow others' ideas. Scientists can show a tendency toward arrogance and isolation which may interfere with the good of collaborations and diverse information sources (Choi et al. 2005). It may also be true that when the primary manager has more education and experience, others may perceive him/her as more inaccessible and be more reluctant to share their ideas, thus impeding the benefits of collaboration. Additionally, the training associated with most master's and Ph.D. programs, particularly for a science degree, is not to do this type of work; such individuals may have less appropriate education for their jobs than those with only a high school or bachelor's degree, and certainly less than those with a management-related degree. Clearly, the manager does not need to be (and perhaps should not be) a scientist, but rather just open to implementing scientists' ideas (Choi et al. 2005). Previous research in this system has shown that not only are managers listening to scientists, but scientists' work is also influenced by managers (Clark et al. 2019).

A perhaps surprising finding was the negative relationship between restoration success and monitoring frequency. Although variability was high, this undeniable trend may point to a reversal in the causal factor; if a site is not doing well or is in a more challenging site, it may prompt more frequent monitoring. Alternatively, more frequent monitoring may mean less resources for other aspects of a project such as weed control. The importance of monitoring is widely mentioned, although much less frequently implemented (Bernhardt et al. 2007). Our sites are hardly representative of restoration sites generally, as all were included in the study because at some point a detailed vegetative survey was conducted. In a few cases this was done by outside researchers, but typically monitoring was already a feature of the project. To assess the impact of monitoring on restoration itself, it would be necessary to obtain a random sample of sites, also including sites that have no monitoring whatsoever. What is plain from our results is that type of monitoring was not a predictor, and that there was no improvement associated with higher frequency of monitoring.

It is our hope that these results are encouraging to practitioners by demonstrating that limitations imposed by the environment may be overcome to some degree through human aspects over which we have more control. Importantly, this includes the positive benefit of setting goals, collaboration, and use of diverse sources. It has been previously demonstrated that riparian restoration projects in the southwestern U.S. may have an unusually high degree of information exchange between scientists and practitioners (Clark et al. 2019). These results provide the first quantitative physical evidence that implementation of recommendations made by scientists (such as use of diverse sources of information) have real, positive impacts on the ground. We also think that incorporating the human component into restoration evaluation may be seen as one more step towards restoring ecosystem complexity, a necessary condition to attain the highest level of ecosystem recovery (Gann et al. 2019). According to information theory, a more complex system requires more information –including human- to be described (e.g., trophic linkages, Moreno-Mateos et al. 2020). This new perspective in the evaluation of river restoration aligns with recognizing rivers as social-ecological systems and will be key to conserve rivers in the Anthropocene (Poff 2014).

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Author Contributions AAS, EG and LC conceived of the study and obtained funding. LC was responsible for the collection, entry, and organization of all human data. AH constructed the dataset, and she and LC performed extensive preliminary analyses. BB contributed the R scripts, while AG did most of the final data analyses; EG and BB advised on all data analysis methods, and EG did significant work on the writing of the methods and the revision. AT and IS conducted exploratory analyses and created many of the manuscript elements. AAS led the data analysis and writing effort, with significant contributions to these by all authors.

Appendix 1

Survey given to all managers associated with 234 sites included in this study, administered with Qualtrics (Clark et al. 2019)

1. Which describes your role? Select all that apply:
    a. Directly make land/resource management decisions
    b. Responsible for implementing management decisions made by someone else (e.g., a supervisor)
    c. Oversee restoration projects with input from a team or partnership
    d. Collect data on management actions
    e. Other (specify)
2. How long have you been a land/resource manager?

    a. Less than 2 years
    b. 2–5 years
    c. 6–10 years
    d. 11–20 years
    e. More than 20 years
    f. I am not a land/resource manager.

3. Is the ownership consistent across all land you work with?

    a. Yes
    b. No

4. (If yes) Which best describes your land's ownership?

    a. Federal (e.g., BLM, USFS, etc.)
    b. State (e.g., State Forest Service)
    c. Non-profit (e.g., land trust)
    d. Private
    e. Other (specify)

5. (If a selected for question 4) Which federal agency owns the land you manage?

    a. Bureau of Land Management
    b. US Fish and Wildlife Service
    c. National Park Service
    d. US Forest Service
    e. Other (specify)

6. (If b selected for question 4) Which state agency owns the land you manage?

    a. State Fish and Wildlife Service
    b. State Forest Service
    c. State Park Service
    d. Other (specify)

7. Is the managing agency consistent across all land you manage?

    a. Yes
    b. No

8. (If yes) Who makes management decisions on your land? Select all that apply.

    a. Federal agency personnel
    b. State agency personnel
    c. County personnel
    d. Private individuals
    e. Other (specify)

9. How many codes were you given? [minimum of 1, maximum of 8]

________ codes

10. Enter the first (or only) code here.

11. Please list the location/name of the sites this code refers to.

12. (If no to question 3) Which best describes the ownership of these sites?

    a. Federal (e.g., BLM, USFS, etc.)
    b. State (e.g., State Forest Service)
    c. Non-profit (e.g., land trust)
    d. Private
    e. Other (specify)

13. (If a selected for question 12) Which federal agency owns the land you manage, corresponding to this code?

    a. Bureau of Land Management
    b. US Fish and Wildlife Service
    c. National Park Service
    d. US Forest Service
    e. Other (specify)

14. (If b selected for question 12) Which state agency owns the land you manage, corresponding to this code?

    a. State Fish and Wildlife Service
    b. State Forest Service
    c. State Park Service
    d. Other (specify)

15. (If no to question 7) Who makes management decisions for these sites? Select all that apply.

    a. Federal agency personnel
    b. State agency personnel
    c. County personnel
    d. Private individuals
    e. Other (specify)

16. How long have you been working in this specific area?

    a. Less than 2 years
    b. 2–5 years
    c. 6–10 years
    d. 11–20 years
    e. More than 20 years

17. What were your specific restoration goals for these sites? Select all that apply.

    a. Improve native plant diversity
    b. Aesthetics
    c. Forage supply for livestock
    d. Water access for livestock
    e. Recreational access to water
    f. Ecosystem resilience (i.e., ability to recover from disturbance)
    g. Removal of exotic plants

- h. Wildfire mitigation
- i. Channel maintenance
- j. Restore natural flows/over-bank flooding
- k. Habitat improvement
- l. Water quality
- m. Endangered species
- n. Other (specify)

18. Please rank your selected restoration goals in importance with 1 as the most important by dragging and dropping them.
19. What was your biggest concern in managing these sites?

Repeat questions 10–19 for each code

20. How much do these information sources influence your decisions? (1 = Not influential at all, 2 = Not very influential, 3 = Somewhat influential, 4 = Very influential, 5 = Extremely influential, Do not use)

- a. Bureau of Land Management (BLM)
- b. US Forest Service (USFS)
- c. US Fish and Wildlife Service (USFWS)
- d. State Weed Coordinator
- e. County weed coordinator (or other county officials)
- f. NRCS
- g. Extension service
- h. State Forest Service
- i. Water Conservation Districts
- j. USDA-ARS (Agricultural Research Service)
- k. The Nature Conservancy
- l. Tamarisk Coalition
- m. US Geological Survey (USGS)
- n. Personal communication with neighbors/peers
- o. Scientific articles
- p. Private consultants (e.g., Habitat Management Inc., Rim to Rim Restoration, etc.)
- q. Newspaper/magazine articles
- r. Supervisor/employer
- s. Workshops/Conferences
- t. Short-courses
- u. Email/listserv communications
- v. Personal past experience in the area

21. (For every agency selected 3, 4, or 5 in question 20) List specific resources (if any) from these agencies/information sources that you find particularly helpful.
22. Are there any other information sources that you use?

- a. Yes
- b. No

23. (If yes) Please list any other information sources and where they come from.
24. Is there ongoing monitoring of restoration projects on your land?

- a. Yes
- b. No

25. (If no) Why is monitoring not being done?
26. (If yes to question 24) Who performs/performed the monitoring? Select all that apply.

- a. Yourself
- b. Other personnel in your agency
- c. Collaborators
- d. University scientists
- e. Private consultants
- f. Other (specify)

27. (If yes to question 24) Which monitoring methods do you use? Select all that apply.

- a. Visual (e.g., repeat photographs from a particular point)
- b. Biological (e.g., fish populations or riparian vegetation)
- c. Physical (e.g., channel cross-sections or pebble counts)
- d. Chemical (e.g., dissolved oxygen or water temperature)

28. (If a selected for question 27) How often do you use visual methods?

- a. More than once a year
- b. Once a year
- c. Once every other year
- d. Every 5 years
- e. Less than every 5 years
- f. Other (specify)

29. (If a selected for question 27) In one sentence, how do you visually monitor?
30. (If b selected for question 27) How often do you use biological methods?

- a. More than once a year
- b. Once a year
- c. Once every other year
- d. Every 5 years
- e. Less than every 5 years
- f. Other (specify)

31. (If b selected for question 27) In one sentence, how do you biologically monitor?
32. (If c selected for question 27) How often do you use physical methods?

- a. More than once a year
- b. Once a year
- c. Once every other year
- d. Every 5 years
- e. Less than every 5 years

   f. Other (specify)

33. (If c selected for question 27) In one sentence, how do you physically monitor?
34. (If d selected for question 27) How often do you use chemical methods?

    a. More than once a year
    b. Once a year
    c. Once every other year
    d. Every 5 years
    e. Less than every 5 years
    f. Other (specify)

35. (If d selected for question 27) In one sentence, how do you chemically monitor?
36. Who do you work in partnership with on a regular basis as a land manager? Select all that apply.

    a. Federal agency personnel
    b. State agency personnel
    c. Private consultants
    d. Scientists
    e. Neighbors/Peers
    f. Other (specify)

37. (If d is selected for question 36) Which agency or agencies do the scientists you collaborate with work for? Select all that apply.

    a. Federal
    b. State
    c. County
    d. Private consultants
    e. Non-profit agency
    f. Universities
    g. Other (specify)

38. Who is responsible for research on your land? Select all that apply.

    a. Yourself
    b. University scientists
    c. Other scientists (specify)

39. What is your highest level of formal education?

    a. Less than high school
    b. High School diploma/GED
    c. Some college/technical school
    d. Associate's degree
    e. Bachelor's degree
    f. Master's degree
    g. Doctorate
    h. Prefer not to answer

40. Any additional comments or information you'd like to share?

The following is the template of possible interview questions.

1. Please talk me through any experience with restoration or conservation you had before taking this job.
2. What did you get your degree in?

    a. Do you find that it helps you do your job?

3. You said you have worked as a land manager here for ___ years. What kind of changes have you seen since you started, in terms of the riparian areas?
4. How did this particular project come about?
5. How involved were you?
6. Are you still doing restoration on these sites?
7. What are the positives and negatives of having multiple managing agencies here?

a. (If not covered in response to the previous question) How does it affect decision making?

8. Tell me about the individual collaborations (give specific examples taken from survey) you are a part of. Do they work? How have they impacted this project?
9. Which of the people involved in this project are scientists?
10. What differences, if any, do you see in working with agency scientists rather than university scientists?
11. What information sources do you use the most?

    a. Why are they the most useful for you?
    b. Ask about USFWS and Tamarisk Coalition if they don't come up on their own.

12. You said that _____ was not influential at all. Why not?
13. Are there kinds of information or other sources you wish you had access to?
14. Why is removal of exotic plants not one of your selected goals?
15. How were the overall goals for this project generated?

    a. If not addressed: were there differences among the multiple agencies involved in managing the site?
    b. If so, how were those differences reconciled?

16. How do you determine if these goals have been met?
17. Who decides what monitoring methods you use?
18. What do you do with the data?
19. Do you consider this project to be successful? Why/why not?
20. Is there anything else I didn't ask about that you think I should know?
21. Is there anyone you recommend I interview?

Appendix 2

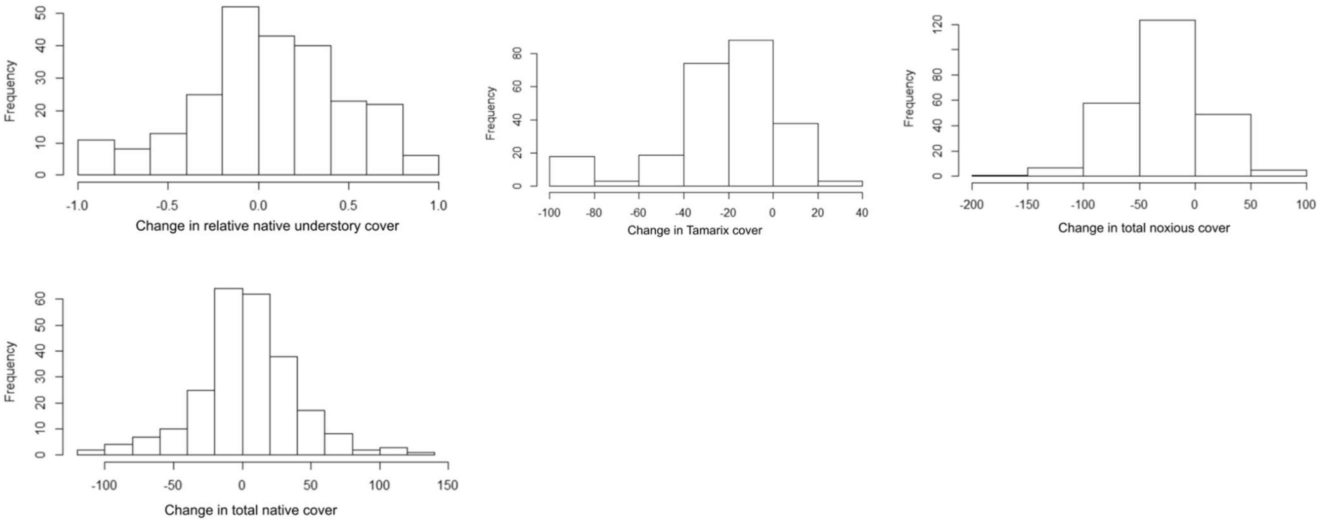

Fig. 5 Histograms of vegetation measures used in Principal Components Analysis (PCA) to create success index

Appendix 3

Table 4 Correlation matrix of all independent variables used in analysis, using Spearman's rho. Variables are summarized in table on following page. Cells showing correlation <0.7 are highlighted in light blue, and cells showing correlation <−0.7 are highlighted in light pink

V1	-																										
V2	0.52*	-																									
V3	-0.72*	-0.58*	-																								
V4	0.20*	0.21*	-0.40*	-																							
V5	-0.23*	-0.43*	0.35*	-0.74*	-																						
V6	-0.26*	-0.35*	0.42*	-0.73*	0.91*	-																					
V7	-0.01	-0.07	-0.16*	0.77*	-0.48*	-0.53*	-																				
V8	-0.08	-0.21*	0.22*	-0.73*	0.79*	0.74*	-0.68*	-																			
V9	-0.1	-0.25*	0.31*	-0.74*	0.84*	0.93*	-0.66*	0.79*	-																		
V10	0.25*	0.47*	-0.37*	0.69*	-0.94*	-0.88*	0.44*	-0.74*	-0.80*	-																	
V11	-0.05	0.04	0.03	-0.11	0.04	0.02	-0.08	0	-0.01	-0.09	-																
V12	-0.59*	-0.53*	0.60*	-0.23*	0.31*	0.29*	-0.04	0.24*	0.20*	-0.34*	-0.14*	-															
V13	-0.70*	-0.57*	0.66*	-0.37*	0.35*	0.39*	-0.20*	0.24*	0.32*	-0.38*	-0.13	0.70*	-														
V14	-0.36*	-0.14*	0.18*	0.04	0.01	0.17*	-0.01	-0.01	0.13*	-0.04	0.05	0.12	0.29*	-													
V15	0.57*	0.39*	-0.53*	0.25*	-0.21*	-0.13*	0.19*	-0.16*	-0.08	0.24*	-0.06	-0.46*	-0.49*	-0.17*	-												
V16	-0.22*	-0.22*	0.20*	-0.12	0.12	0.19*	-0.14*	0.15*	0.18*	-0.12	0.01	0.27*	0.33*	0.46*	-0.32*	-											
V17	0.15*	0.35*	-0.26*	0.12	-0.1	0	-0.12	0.01	0.07	0.14*	-0.05	-0.27*	-0.09	0.54*	0.02	0.37*	-										
V18	0.02	0.03	-0.12	0.28*	-0.14*	-0.08	0.31*	-0.16*	-0.15*	0.14*	-0.01	-0.08	-0.11	0.33*	0.26*	-0.25*	-0.01	-									
V19	-0.03	0.14*	-0.03	0.13*	-0.07	0.06	-0.13*	0.07	0.09	0.11	-0.31*	-0.1	0.06	0.38*	-0.09	0.11	0.38*	0.15*	-								
V20	-0.30*	-0.29*	0.22*	0.01	0.11	0.19*	-0.14*	0.14*	0.19*	-0.18*	-0.03	0.20*	0.26*	0.50*	-0.45*	0.55*	0.35*	-0.18*	0.21*	-							
V21	0.39*	0.52*	-0.47*	0.36*	-0.43*	-0.45*	0.26*	-0.42*	-0.44*	0.45*	0.24*	-0.46*	-0.53*	-0.26*	0.37*	-0.09	0.24*	-0.31*	-0.35*	-0.20*	-						
V22	-0.32*	0.03	0.05	0.12	-0.15*	-0.06	0.1	-0.18*	-0.13*	0.14*	0	-0.01	0.23*	0.43*	0.05	-0.15*	0.20*	0.26*	0.19*	-0.12	0.04	-					
V23	0.35*	0.27*	-0.43*	0.56*	-0.43*	-0.43*	0.31*	-0.32*	-0.36*	0.43*	-0.11	-0.33*	-0.48*	-0.26*	0.35*	-0.34*	0.02	0.21*	0.01	0.11	0.29*	-0.14*	-				
V24	-0.17*	-0.28*	0.14*	-0.06	0.19*	0.20*	0.02	0.25*	0.17*	-0.29*	-0.12	0.31*	0.18*	0	-0.01	0.13*	-0.16*	0.02	0.02	0.33*	-0.25*	-0.27*	0.18*	-			
V25	0.02	0.14*	-0.14*	0.14*	-0.11	-0.01	0.06	-0.1	-0.02	0.04	-0.22*	-0.12	0.01	0.34*	-0.01	0.05	0.32*	0.27*	0.27*	0.18*	-0.05	0.1	0.03	0.31*	-		
V26	-0.14*	-0.46*	0.21*	-0.08	0.21*	0.21*	0	0.12	0.26*	-0.21*	-0.21*	0.22*	0.35*	0.26*	-0.31*	0.53*	0.20*	-0.16*	0.02	0.56*	-0.31*	-0.19*	-0.14*	0.16*	-0.1	-	
V27	0.08	-0.16	0.34	-0.05	0.21	0.23	0.03	0.10	0.24	-0.21	-0.21	0.30	0.35	0.24	-0.19	0.48	0.27	-0.08	0.19	0.17	0.54	-0.30	-0.23	-0.04	0.13	-0.08	-
	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16	V17	V18	V19	V20	V21	V22	V23	V24	V25	V26	V27

	Variable	Description
Environmental variables	V1	River width
	V2	Distance to river water's edge
	V3	Longitudinal slope
	V4	Average precipitation
	V5	Average monthly maximum temperature
	V6	Average monthly minimum temperature
	V7	Precipitation year surveyed
	V8	Monthly maximum temperature year surveyed
	V9	Monthly minimum temperature year surveyed
	V10	Elevation above sea level
	V11	Relative elevation
	V12	Distance to nearest paved road or railway
	V13	Distance to nearest road
Manager variables	V14	Goals: "plants"
	V15	Goals: "people"
	V16	Goals: "water"
	V17	Goals: "wildlife"
	V18	Goals: "other"
	V19	Information type
	V20	Number of sources used
	V21	Number of monitoring methods used
	V22	Monitoring frequency
	V23	Number of collaborators
	V24	Number of roles held by manager
	V25	Overall experience
	V26	Local experience
	V27	Education level

Significant values ($p < 0.05$) are denoted with asterisks

Appendix 4

Table 5 Environmental differences between river basins: Rio Grande, Lower Colorado River Basin (LCRB), and Upper Colorado River Basin (UCRB)

	Rio Grande $N = 36$	LCRB $N = 77$	UCRB $N = 130$	F-ratio
River width (m)*	84.9 (9.0)a	15.5 (3.2) b	54.8 (5.3) c	66.5
Distance from river water's edge* (m)	164.2 (29.4) a	27.9 (7.8) b	71.8 (13.4) c	82.6
Slope of river channel* (%)	0.8 (0.2) a	45.4 (3.4) b	2.5 (0.2) c	189.7
Precipitation year sampled (mm)	101.2 (3.8) a	80.0 (3.8) a	165.6 (5.0) b	90.0
Max. temperature year surveyed (°C)	36.1 (0.3) a	39.1 (0.3) b	34.1 (0.2) c	130.7
Min. temperature year surveyed (°C)	4.2 (0.3) a	7.6 (0.3) b	1.8 (0.2) c	202.1
Elevation above sea level (m)	1453.8 (9.7) a	700.5 (35.2) b	1442.1 (16.0) a	300.6
Elevation above river (m)	201.1 (10.6) a	229.5 (5.2) a	269.1 (9.0) b	11.8
Dist. from paved road or railway (m)*	740.1 (178.9) a	13,877.7 (1370.8) b	2079.8 (309.3) a	58.9
Dist. from any road (m)*	114.7 (16.2) a	13,414.4 (1389.0) b	383.4 (61.2) a	162.7
Method of removing *Tamarix*	4.9 (0.1) a	4.3 (0.07) b	4.5 (0.06) c	11.2
Avg. precipitation (mm)	149.1 (1.1) a	83.2 (3.3) b	146.9 (2.2) a	180.1
Avg. maximum temperature (°C)	34.6 (0.1) a	40.2 (0.2) b	34.6 (0.2) a	288.6
Avg. minimum temperature (°C)	3.2 (0.04) a	9.1 (0.2) b	2.2 (0.1) c	495.2

For each environmental variable tested, mean value (1 standard error) and ANOVA results shown. Where needed for normality, ANOVA was performed on log transformed data, as indicated. Superscripts indicate Tukey post hoc differences. All F-ratios are significant at the $p < 0.0001$ level

Appendix 5

Table 6 Model details showing individual *p* value of each variable included. Variables are listed in order of increasing p

Model 1		Model 4			
Variable	p	Variable	p	Variable	p
Monitoring frequency	0.0025	Monitoring frequency	0.0001	Monitoring frequency	0.00011
Managing agency category	0.00357	Employing agency category	0.00082	Employing agency category	0.00076
Normal precipitation	0.01047	Managing agency category	0.01535	Managing agency category	0.0045
Total experience	0.03998	Longitudinal slope	0.07468	Distance to nearest paved road or railway	0.14282
Goals: wildlife	0.04329	Any herbicide applied	0.19505	Any herbicide applied	0.14461
Longitudinal slope	0.05632	Number of sources	0.23494	Longitudinal slope	0.15829
Any herbicide applied	0.1157	Number of roles	0.9051	Number of sources	0.23686
Local experience	0.17468	Degree field	0.94085	Degree field	0.75123
Number of collaborators	0.23548	Precipitation year sampling	0.96483	Precipitation year sampling	0.7858
Number of sources	0.34783				
Precipitation year sampling	0.45931				

Model 1	Model 4		Model 6			
Variable	Variable	p	Variable	p	Variable	p
Monitoring frequency	Monitoring frequency	0.00011	Monitoring frequency	0.00131	Monitoring frequency	0.00443
Managing agency category	Employing agency category	0.00043	Normal precipitation	0.00236	Managing agency category	0.00818
Normal precipitation	Managing agency category	0.00151	Managing agency category	0.00437	Minimum temperature year sampling	0.03517
Total experience	Longitudinal slope	0.07482	Minimum temperature year sampling	0.0241	Minimum normal temperature	0.06146
Goals: wildlife	Number of sources	0.13667	Any herbicide applied	0.10732	Any herbicide applied	0.08965
Longitudinal slope	Any herbicide applied	0.22376	Longitudinal slope	0.1326	Precipitation year sampling	0.17884
Any herbicide applied	Number of collaborators	0.29337	Precipitation year sampling	0.85756	Distance to nearest paved road or railway	0.34233
Local experience	Minimum normal temperature	0.50335			Longitudinal slope	0.49012
Number of collaborators	Precipitation year sampling	0.90942				
Number of sources						
Precipitation year sampling						

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