High-resolution riparian vegetation mapping to prioritize conservation and restoration in an impaired desert river

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TECHNICAL ARTICLE

High-resolution riparian vegetation mapping to prioritize conservation and restoration in an impaired desert river

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In highly impaired watersheds, it is critical to identify both areas with desirable habitat as conservation zones and impaired areas with the highest likelihood of improvement as restoration zones. We present how detailed riparian vegetation mapping can be used to prioritize conservation and restoration sites within a riparian and instream habitat restoration program targeting 3 native fish species on the San Rafael River, a desert river in southeastern Utah, United States. We classified vegetation using a combination of object-based image analysis (OBIA) on high-resolution (0.5 m), multispectral, satellite imagery with oblique aerial photography and field-based data collection. The OBIA approach is objective, repeatable, and applicable to large areas. The overall accuracy of the classification was 80% (Cohen's $\kappa = 0.77$). We used this high-resolution vegetation classification alongside existing data on habitat condition and aquatic species' distributions to identify reaches' conservation value and restoration potential to guide management actions. Specifically, cottonwood (*Populus fremontii*) and tamarisk (*Tamarix ramosissima*) density layers helped to establish broad restoration and conservation reach classes. The high-resolution vegetation mapping precisely identified individual cottonwood trees and tamarisk thickets, which were used to determine specific locations for restoration activities such as beaver dam analogue structures in cottonwood restoration areas, or strategic tamarisk removal in high-density tamarisk sites. The site prioritization method presented here is effective for planning large-scale river restoration and is transferable to other desert river systems elsewhere in the world.

Key words: GIS, habitat assessment, native fish, object-based image analysis, San Rafael River, vegetation classification

Implications for Practice

- High-resolution vegetation mapping is a valuable tool for developing restoration plans that target both instream and riparian habitat.
- Quantitative measures of riparian vegetation structure can be generated at large spatial scales from high-resolution vegetation maps and used to prioritize restoration sites and actions.
- Object-based image analysis-based vegetation mapping is objective, repeatable, and applicable for both reach and site-scale planning across broad landscapes.

Introduction

Riparian zones supply streams with organic matter and nutrients that build food webs, terrestrial invertebrates that serve as important food resources for fish, and wood that aids in the formation of complex fish habitat (Minckley & Rinne 1985). Many watersheds' riparian zones across the Western United States are threatened or impaired by altered flow patterns (Poff et al. 2011), water withdrawals (Goodwin et al. 1997), and establishment of invasive, non-native plant species, such as tamarisk (*Tamarix ramosissima*; Shafroth et al. 2002; Stromberg et al. 2007). The San Rafael River, a tributary to the Green River in the upper Colorado River Basin, is one such watershed, where reduced spring flood magnitude and duration has led to less frequent floodplain inundation, limiting native riparian forest establishment, particularly cottonwood (*Populus fremontii*). This lack of tree recruitment has reduced instream wood abundance, decreasing habitat and cover for native fish (Budy et al. 2009; Keller et al. 2014). Fish habitat has been further impaired by sediment accumulation within the channel and floodplain, which has filled in backwater and pool habitats (Laub et al. 2015). Native fish are also impacted by competition and predation from non-native fish and occasional dewatering due to irrigation withdrawls in dry years. Despite degradation, the river supports populations of sensitive native fish, including seasonal use by several endangered species in the upper Colorado River Basin (Budy et al. 2009; Bottcher et al. 2013).

Author contributions: WM, CM, SG designed and carried out the vegetation mapping; WM, BL designed and carried out the restoration prioritization analysis; WM, CM, BL, SG wrote the paper.

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Due to its impaired condition and conservation importance, in 2013, the U.S. Department of Interior Bureau of Land Management (BLM) developed a large-scale restoration plan to improve riparian and fish habitat on the San Rafael River (Laub et al. 2013). The plan acknowledges that a key component in managing the river system is to identify areas with desirable aquatic and riparian habitat as conservation zones and impaired areas with the highest likelihood of improvement as restoration zones (Wissmar & Beschta 1998; Walsworth & Budy 2015). Cottonwood are a desirable native tree species that can improve instream habitat for native fishes through large wood contributions to the channel (Minckley & Rinne 1985). Thus, the restoration plan called for increased cover of native cottonwood and decreased cover of invasive tamarisk as a major restoration objective (Laub et al. 2015). The plan also addresses dewatering and competition by non-native fishes (Laub et al. 2013), although we focus on habitat restoration efforts in this article.

High-resolution vegetation maps are desirable tools for use in restoration planning because they provide sufficient resolution for targeting restoration actions at specific sites but can also guide large-scale restoration prioritization at watershed scales (e.g. Harris & Olson 1997). While manual interpretation of aerial photographs can be a precise and accurate vegetation classification method when combined with intensive field surveys (Yu et al. 2006), it tends to be time consuming and subjective rendering it impractical for large, remote areas (Blundell & Opitz 2006). Traditional remote-sensing techniques that rely on pixel-based image processing (Friedl et al. 2002) and conventional statistical approaches (Matinfar et al. 2007) are popular alternatives to manual methods.

Riparian zones, however, pose challenges for both manual and pixel-based vegetation mapping approaches because of their narrow width, dendritic pattern, and diverse vegetation with high variance in spectral reflectance signatures (Yu et al. 2006; Johansen et al. 2010). Due to these limitations, other approaches have emerged. Object-based image analysis (OBIA) of digital imagery is based on grouping sets of similar pixels into image objects. OBIA shows great promise to overcome the challenges of mapping riparian vegetation because it uses spectral, spatial, textural, and contextual information from image objects rather than relying on spectral information from individual pixels as the basis of categorization (Blaschke et al. 2014). In this article we describe (1) the development of a high-resolution (0.5 m) vegetation map for the lower San Rafael River corridor using an OBIA approach and (2) how vegetation classification was used to inform the San Rafael restoration plan at two scales: designating conservation and restoration reaches study area wide, and pinpointing precise locations for targeted management actions within restoration reaches.

Methods

Study Area

The lower San Rafael River is a low-gradient, 90 km, meandering river segment that alternates between wide, partly confined valley settings and narrow, canyon-bound sections that

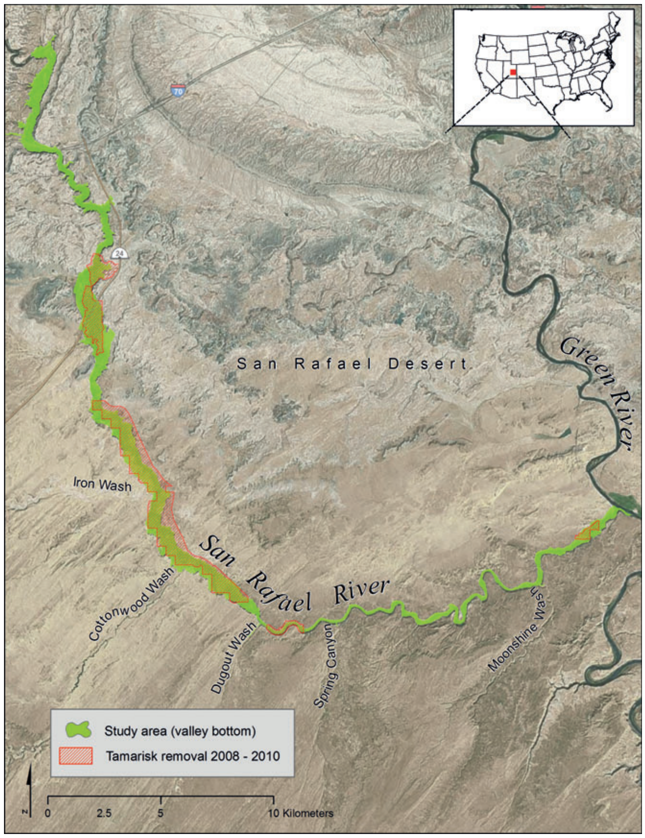

Figure 1. Study area map showing the 90 km lower San Rafael River valley bottom (green; 2,400 ha) running through the San Rafael Desert. The 2008–2010 Utah Division of Wildlife Resources and Natural Resources Conservation Service tamarisk removal areas are shaded red (425 ha). Location map (upper right) shows study area in the context of the continental United States.

flows through the San Rafael Desert (latitude 38.86700 longitude 110.233668; Fig. 1). Our study area was the river's valley bottom (2,400 ha), the dominant wetland element in an otherwise arid landscape (Fig. 1). The Utah Division of Wildlife Resources (UDWR) and Natural Resources Conservation Service (NRCS) removed virtually all tamarisk on 424.5 ha of land along 24 river kilometers within the study area during a separate restoration effort during 2008–2010 (Keller et al. 2014; Fig. 1). In addition, since 2005, tamarisk leaf beetles (*Diorhabda* spp) defoliated much of the remaining tamarisk along the lower San Rafael River (Keller et al. 2014).

Native fish that reside in the San Rafael River include the bluehead sucker (*Catostomus discobolus*), flannelmouth sucker (*Catostomus latipinnis*), and roundtail chub (*Gila robusta*), which are all considered species of management concern throughout their range, and improvement of their habitat was particularly targeted in this restoration effort. Endangered fish of the upper Colorado River Basin, including the Colorado Pikeminnow (*Ptychocheilus lucius*) and razorback sucker (*Xyrauchen texanus*), also use the San Rafael River seasonally (Bottcher et al. 2013). Bluehead sucker adults preferentially use riffle habitat with coarse substrate, roundtail chub adults

Table 1. Input data for the vegetation classification of the lower San Rafael River riparian area.

Input Data/Process	*Spatial Resolution*	*Source*
Satellite imagery/Object-Based Image Analysis (OBIA)	0.5 m	Digital Globe Foundation http://www.geoeyefoundation.org/Imagery_Grants.html
Aerial photography/georectification and Russian olive classification	1 m	National Agriculture Imagery Program (NAIP) www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-programs/naip-imagery/
Land use/agriculture and developed land classification	1:24,000	Utah Water Related Land Use http://gis.utah.gov/data/planning/water-related-land/
Oblique aerial photography/vegetation classification	300–500 m above ground	Utah State University Department of Watershed Sciences https://usu.box.com/AerialObliquePhotos
Photosynths/effectiveness monitoring	12 megapixel	Utah State University Department of Watershed Sciences https://usu.box.com/Photosynths

use deeper pools with cover, flannelmouth sucker adults use diverse habitats, and juvenile life stages of each species use shallow, slow-velocity, backwater habitats (Bezzerides & Bestgen 2002). In the San Rafael River, the distribution of these native fish is correlated with the availability of complex habitat, comprised of riffles, pools, and backwaters (Budy et al. 2009; Walsworth & Budy 2015).

Large instream wood plays an important role in generating complex habitat the San Rafael River by providing cover and collecting in piles that force bank erosion and scouring of deep pools (Keller et al. 2014). Research on undeveloped streams in Arizona also found that large wood provides unique pool habitat not otherwise available (Minckley & Rinne 1985). Beaver activity is ongoing in the San Rafael River and dam-building often forms wood jams that provide important fish habitat (Keller et al. 2014). Greater beaver dam-building activity may be restricted by lack of large wood sources, flash floods, and sandy substrate in the riparian zone.

Riparian Vegetation Classification

Development of the high-resolution riparian vegetation map combined (1) high-resolution satellite imagery, (2) oblique aerial photography, (3) field-based training data collection, and (4) OBIA to delineate and classify riparian vegetation (Table 1) (as detailed in Macfarlane & McGinty 2013).

We obtained GeoEye-1 multispectral imagery acquired during August–November 2012. GeoEye-1 imagery consists of blue (450–520 nm), green (520–600 nm), red (625–695 nm), and near infrared (NIR; 760–900 nm) bands supplied at 1.65-m pixel resolution at nadir (vertical), and a panchromatic band (pan; 450–900 nm) at 0.5-m pixel resolution. We performed image point-to-point matching to improve the relative spatial accuracy of the imagery. This georectification procedure required the identification of identical, recognizable points such as road centerlines on both the reference 2011 National Agriculture Imagery Program (NAIP) imagery and the GeoEye-1 imagery. We used a second-order polynomial model to spatially adjust the imagery. The resulting georectified imagery matched the valley bottom extent polygon mapped from the NAIP imagery within ±4 pixels (2 m). To further enhance the spatial resolution of the GeoEye-1 imagery, we used the 0.5-m panchromatic band within Edras Imagine 13 (Intergraph 2013) to pan-sharpen the multispectral imagery, a technique used to increase the spatial resolution of imagery by using a single-band image to improve the resolution of a multispectral image. The resulting data were 0.5-m, four-band multispectral imagery with enhanced detail for vegetation classification (Fig. 2).

Oblique aerial photography was collected 5 November 2012 during low-flying (300–500 m above ground level) airplane overflights by EcoFlight (http://ecoflight.org), a nongovernmental organization that facilitates conservation aviation. The Landscape Assessment System (Macfarlane et al. 2013) was used to capture and process oblique angle photos taken during the overflight. We chose to collect oblique photographs because: (1) given a constant altitude, oblique aerial photos can cover a much larger area than vertical aerial photos; and (2) an oblique view of a riparian corridor, when used in conjunction with a vertical view, provide the interpreter with complementary views of vegetation structure, and height, allowing for effective visualization of various land cover classes. To generate an additional visual reference of the riparian vegetation, we created a Google Earth 3-D "tour" of the overflight.

The oblique aerial photos and virtual 3-D "tour" of the overflight were used as references for discriminating land cover classes and establishing potential vegetation plots (https://usu.box.com/AerialObliquePhotos). Using this visualization method, we were able to identify 400 potential ground-based classification plots representing multiple examples of each of the 10 land cover classes described in the results section. In the field, 384 of the 400 potential plots were accessible and were sampled as training sites for the vegetation classification. At each circular 0.04-ha plot, we assigned a landcover class, estimated percent species cover, collected GPS point data, digital photographs, and Photosynths (http://photosynth.net/) 360-degree panoramic images of the plots which provided detailed information on vegetation species composition.

Our OBIA approach applied the multiresolution image segmentation algorithm in eCognition software (Trimble 2013) which groups pixels into image objects based on a homogeneity criteria. Image layer weight, scale parameter, shape, and compactness were the four segmentation algorithm input variables that helped determine the boundaries of the image objects. We also merged neighboring image objects based on similarities in

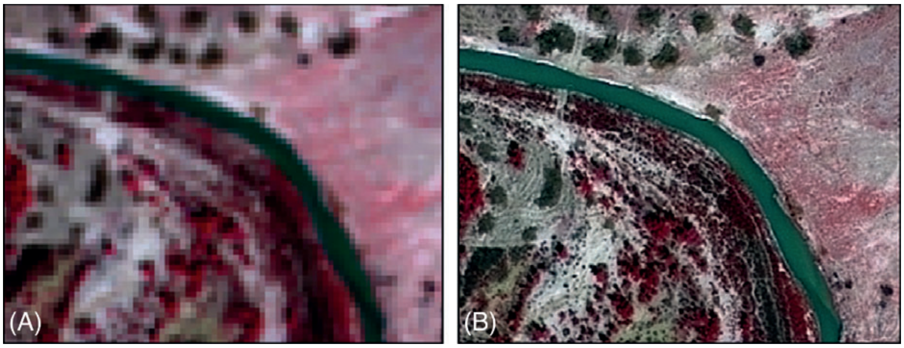

Figure 2. (A) Native multispectral GeoEye-1 imagery (1.65-m pixel resolution) of the lower San Rafael River. (B) The same image enhanced with pan-sharpening to a resolution of 0.5 m.

the image layer intensity and spectral difference values using the spectral difference segmentation algorithm. Once the imagery was segmented into meaningful image objects, we developed a set of knowledge-based classification rules to assign image objects to a specified vegetation class based on object properties, such as spectral reflectance, shape, size, and neighbor relations.

Accuracy Assessment Analysis

Ninety-six of the 384 ground-based classification points (25%) were randomly withheld for accuracy assessment. Agreement between the vegetation classification and field-observed vegetation was evaluated using an error matrix (Foody 2002). We calculated overall accuracy as the proportion of points correctly classified and Cohen's κ (K) statistic as a measure of ground and map agreement adjusted for the agreement expected due to chance alone (Aronoff 2005). Additionally, for each vegetation class, we calculated consumer accuracy (% of a modeled class that mirrored the ground truth class) and producer accuracy (% of a ground truth class that the model correctly identified), as well as errors of omission (% of a ground truth class that the model classified incorrectly) and commission (% of a modeled class that was placed into the wrong ground truth class).

Use of Vegetation Classification for Conservation and Restoration Planning

Our aim was to inform restoration actions at two scales: identifying conservation and restoration reaches, and pinpointing precise locations for tamarisk removal and beaver dam analogue (BDA) structures. BDAs are man-made structures intended to mimic the geomorphic and hydrologic functions of beaver dams and are described by Pollock et al. (2014). River reaches with existing cottonwood stands that currently met restoration criteria could be identified as conservation areas while reaches dominated by non-native tamarisk will require restoration to achieve objectives. We created cottonwood and tamarisk density layers by converting all 0.5-m raster vegetation classification cells identified as tamarisk or cottonwood to points. We calculated the relative density of these points using the Point Density Function in Esri ArcGIS 10.1 (Esri 2013) with a 100-m neighborhood window.

We used the resulting tamarisk and cottonwood density layers along with existing reach-scale data on instream habitat complexity, channel bed material, and fish species distributions (Laub et al. 2015) to identify the conservation and restoration potential of river reaches. We assigned a ranking of low, medium, or high cottonwood density to each 300-m segment, based on visual estimation of the relative cottonwood density surrounding each 300-m segment. Segments with high cottonwood density, coarse substrate, and high instream habitat complexity were ranked as priority conservation areas, whereas segments with low cottonwood density, fine substrate, and low habitat complexity were ranked as high priority restoration sites, provided they were also close to existing native fish populations.

High-resolution vegetation maps along with cottonwood and tamarisk density maps were used to determine specific locations for tamarisk removal and installation of BDAs. Areas of relatively dense cottonwood and willow stands were selected for BDA placement, because the availabilities of food and dam-building material are strong predictors of beaver dam density in western rivers (Macfarlane et al. 2015). High-density tamarisk stands downstream of relatively high-density cottonwood stands were identified as ideal locations for tamarisk removal, as the upstream cottonwood stands could provide a seed source for recruitment once tamarisk was removed. In addition, removal of dense stands of tamarisk in the vicinity of cottonwoods will reduce fuel loads and the potential that native fire intolerant riparian plant species will be damaged by wildfire (Busch 1995; Smith et al. 2009). We used cottonwood and tamarisk density maps to visually identify areas where high-density tamarisk stands occurred near and downstream of relatively high-density stands of cottonwoods, and designated these locations as priority restoration areas.

Results

Riparian Vegetation Classification

Our OBIA approach delineated the seven land cover classes identified by resource management agencies (BLM, UDWR) and the research team as important to riparian conservation and restoration: (1) bare ground/sparsely vegetated, (2) cottonwood, (3) desert shrub, (4) grassland/invasive annual, (5)

Table 2. Accuracy assessment error matrix. Agriculture, developed and Russian olive land classes were excluded from the accuracy assessment because they were not generated using the OBIA approach. B, bare ground/sparsely vegetated; C, cottonwood; D, desert shrub; G, grassland/invasive annual; T, tamarisk; Wa, water; Wi, willow/phragmites. The diagonal in bold text shows correctly classified ground plots.

Ground Data	*Vegetation Classification*									
	B	*C*	*D*	*G*	*T*	*Wa*	*Wi*	*Row Total*	*Producer Accuracy*	*Omission Error*
B	**10**			1				11	91%	9%
C		**14**			1			15	93%	7%
D	3		**7**	1				11	64%	36%
G	5			**16**	1			22	73%	27%
T	1			3	**8**		1	13	62%	38%
Wa						**12**		12	100%	0%
Wi				1	1		**10**	12	83%	17%
Column total	19	14	7	22	11	12	11	**96**		
Consumer accuracy	53%	100%	100%	73%	73%	100%	91%			
Commission error	47%	0%	0%	27%	27%	0%	9%			
Overall accuracy 80%	80%									
Cohen's *K*	0.77									

tamarisk, (6) water, and (7) willow/phragmites (Table S1, Supporting Information). Three additional classes were relevant as context: agriculture, developed, and Russian olive (Elaeagnus angustifolia). The agriculture and developed classes were digitized using the State of Utah Water Related Land Use dataset that depicts the type and extent of irrigated crops (http://gis.utah.gov/data/planning/water-related-land/) and Russian olive was mapped as point data using aerial photo interpretation. The distinctive silver-gray color of Russian olive foliage and the small number of Russian olive trees made this an accurate and efficient method. A total of 19 individual Russian olive trees were mapped in the study area.

The error matrix of field-observed vegetation and classified vegetation indicate a high overall level of agreement. Overall map accuracy was 80% and the Cohen's *K* statistic (0–1) was 0.77 (Table 2). A *K* statistic from 0.61 to 0.8 indicates substantial agreement (Landis & Koch 1977). The consumer accuracy of water (100%), cottonwood (100%), and desert shrub (100%) and williow/phragmites (91%) showed very high to perfect agreement. The tamarisk (73%) and grassland/invasive annual class (73%) both showed adequate agreement. Tamarisk was most commonly included within grassland/invasive annual class. Tamarisk was also included within the bare ground/sparsely vegetated class, likely because defoliated tamarisk and bare ground/sparsely vegetated and grassland/invasive have similar low normalized difference vegetation index (NDVI) values. Similarly, the grassland/invasive class was most commonly misclassified as bare ground/sparsely vegetated. Bare ground/sparsely vegetated showed the lowest consumer accuracy at only 53% and was often misclassified as grassland. Agriculture, developed, and Russian olive classes were not included in the accuracy assessment because they were not generated using the OBIA methods used for the majority of the vegetation classification.

The vegetation classification captured vegetation patterns throughout the riparian zone of the lower San Rafael River (Fig. 3). The vegetation patterns included a narrow band (2–15 m) of willow and phragmites that dominates the riparian berm that has formed along the river banks. Dense stands of tamarisk defoliated by tamarisk leaf beetles dominate the floodplain outside the berm and are intermixed with grasslands, invasive annuals, and bare ground that occur along abandoned channels, meander bends, and oxbows. Cottonwood forest patches are also associated with these historic features and are concentrated at tributary junctions. Swaths of desert shrub occupy drier sites. To illustrate the resolution of the vegetation classification, it was displayed in detail in a map atlas (1:3,000; 199 pages; https://usu.box.com/SanRafaelMapBook). The riparian land cover classification indicates that grassland/invasive annual (34%), bare ground/sparsely vegetated (25%), and tamarisk (25%) are the dominant land cover classes found throughout the study area (Fig. 4). The remaining seven land cover classes are far less prevalent across the study area (Fig. 4).

Cottonwood and tamarisk density mapping proved to be an important spatial representation of the relative prevalence of these species across the study area (Figs. 5 & 6). Cottonwood density was moderate to high only in isolated patches with the highest densities generally in wider valley settings and in the vicinity of tributary junctions (Fig. 5). In contrast, moderate to high densities of defoliated tamarisk were found throughout the entire study area *except* where tamarisk removal had taken place (Fig. 6).

Use of Vegetation Classification for Conservation and Restoration Planning

Two reaches (Iron Wash and Spring Canyon) with high densities of cottonwood and existing complex habitat and native fish occurrence were identified as conservation reaches requiring no restoration action. Two reaches (Below SH 24 and Canyon 3) ranging from 5 to 10 river kilometers in length were identified as high-priority for restoration based on lack of existing habitat complexity and native cottonwood stands but close proximity

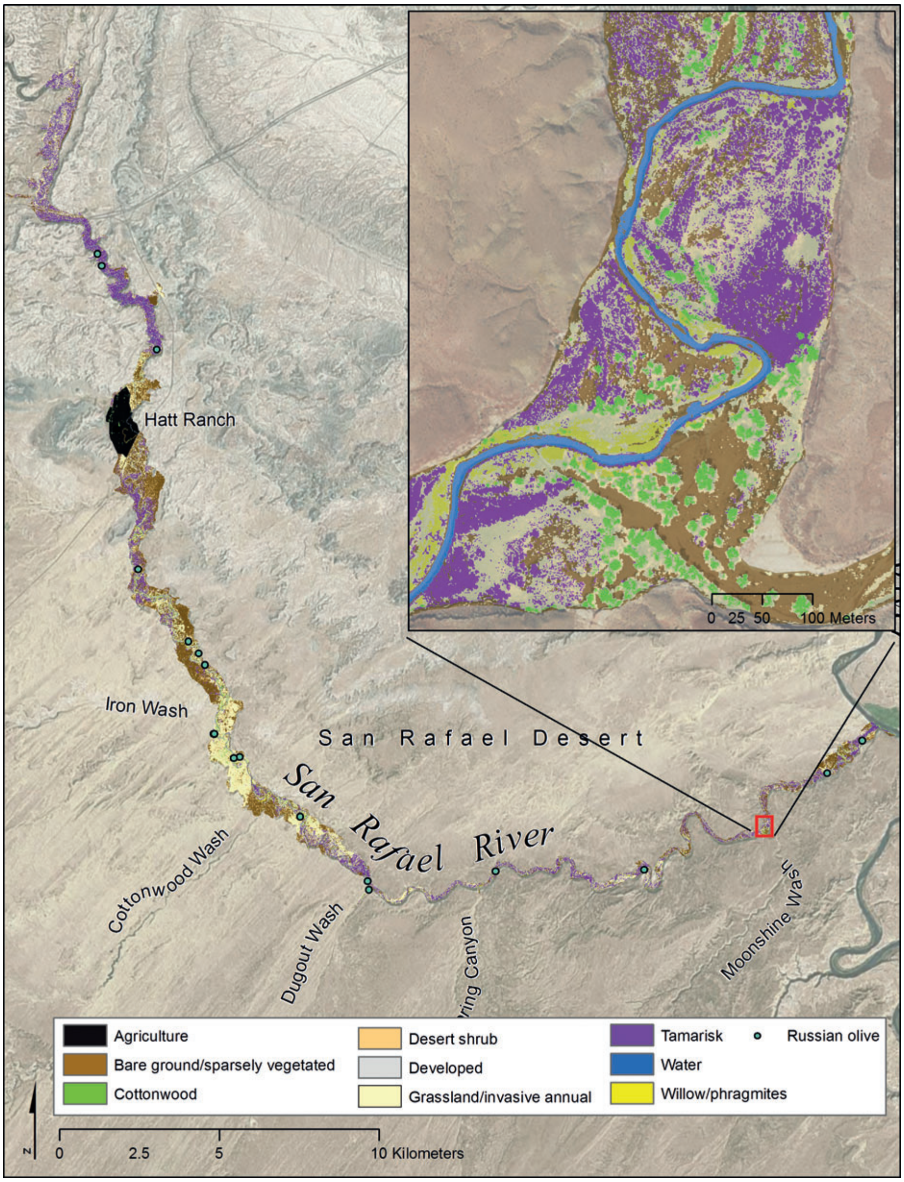

Figure 3. High-resolution (0.5 m) land cover classification of the lower San Rafael riparian zone. The classification consisted of 10 land cover classes: (1) agriculture, (2) bare ground/sparsely vegetated, (3) cottonwood, (4) desert shrub, (5) developed, (6) grassland/invasive annual, (7) tamarisk, (8) water, (9) willow/phragmites, and (10) Russian olive. The inset map illustrates the fine scale resolution of the riparian vegetation mapping that delineates, e.g. individual cottonwood canopies.

to native vegetation and fish colonization sources (Laub et al. 2015; Fig. 7). Restoration treatments in high-priority reaches were implemented in spring 2015 and consisted of installation of BDA structures and tamarisk removal. Remaining reaches not identified as conservation reaches or high-priority restoration reaches were set aside for later phases of restoration under the BLM large-scale restoration plan (Laub et al. 2013).

Discussion

Joint restoration planning for multiple taxa, like native fish and native riparian vegetation, is rare. For example, tamarisk removal efforts along desert rivers have rarely considered the potential for riparian restoration (e.g. cottonwood planting) to benefit fish habitat, even though dense invasive vegetation (Shafroth et al. 2002), native riparian vegetation (Sankey et al. 2015) and its large wood contributions (Minckley & Rinne 1985) often interact with climate to shape geomorphic and aquatic habitat change (Manners et al. 2014). In desert rivers, strategic tamarisk removal has been shown to aid recovery of river processes that generate complex fish habitat (Keller et al. 2014). Without a high-resolution vegetation map generated using the methods we describe here or using another proven method, the development of a systematic site prioritization to

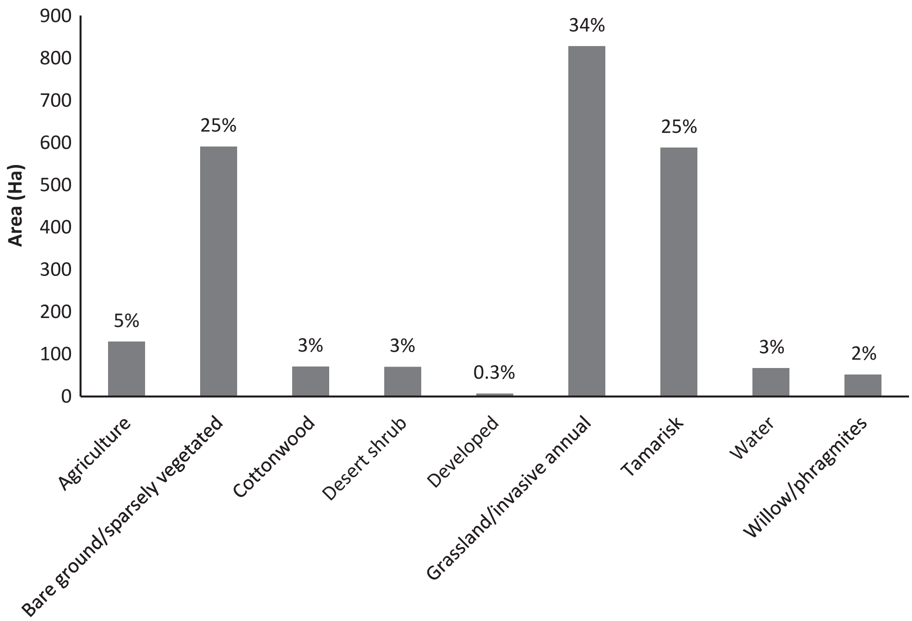

Figure 4. Absolute and proportional cover of land cover classes within the study area (2,400 ha). The Russian olive class was captured as point data without associated areal extents (Fig. 3) and therefore was not represented here.

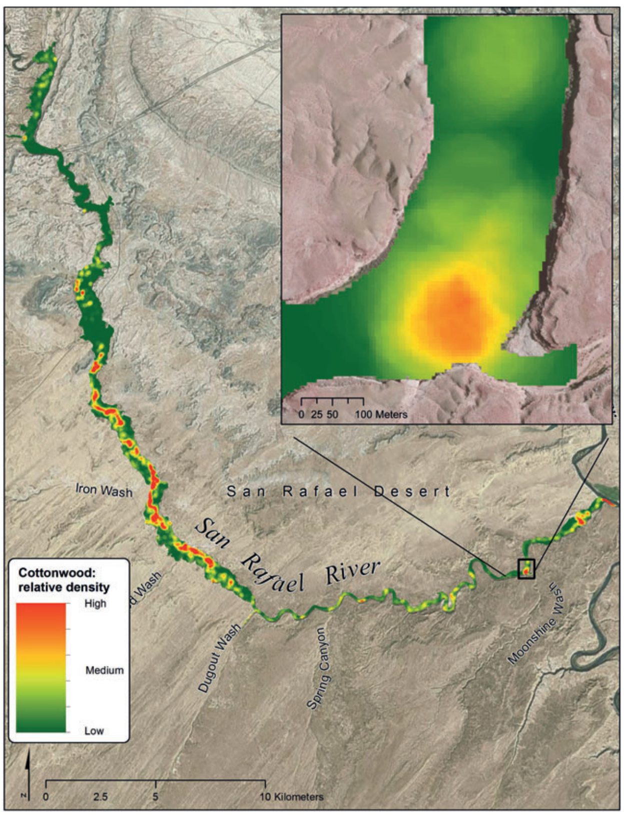

Figure 5. Relative cottonwood density in the lower San Rafael riparian zone with zoom-in showing the detailed mapping within one of the priority restoration reaches (Canyon 3). Generally, relatively higher cottonwood densities are found in wider valley settings and in the vicinity of tributary junctions.

aid riparian and river channel management would not have been possible because existing 30-m spatial resolution land cover classifications such as LANDFIRE (LANDFIRE 2015) are too coarse to consistently provide sufficient detail in narrow desert riparian corridors. Additionally, our high-resolution vegetation map helped guide restoration activities within high priority reaches, including identifying tamarisk removal areas and BDA structure locations, both of which are predicted to benefit both native fish and riparian vegetation.

While the mapping approach presented here is applicable to many landscapes, it requires image processing skill and may not be applicable to all landscapes, or optimal for all restoration planning projects. In particular, the San Rafael River's riparian flora is relatively species poor and the identified vegetation classes were distinct on aerial imagery, a situation that may not be consistent in regions beyond the arid southwest. For example, in small streams of the Columbia River Basin, multiple riparian communities have been identified, many of which occur below dense conifer canopies (Hough-Snee et al. 2014) and cannot be accurately described from aerial imagery or remote sensing alone (Congalton et al. 2002). In complex landscapes with heterogeneous vegetation, increased density of classification observation points may be required alongside remote-sensing methods to identify riparian vegetation composition, and assess site condition. High-resolution mapping may not be necessary in situations in which vegetation does not control habitat-forming physical processes, such as in bedrock confined canyons. However, we anticipate that in many cases, high-resolution riparian mapping will improve aquatic and riparian restoration planning efforts by aiding in large-scale reach prioritization as well as aiding in the identification of specific locations for restoration activities.

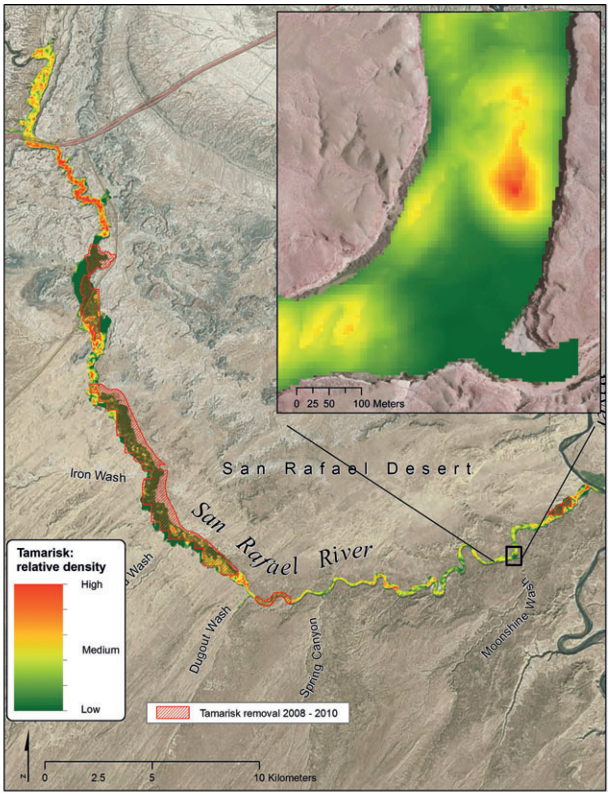

Figure 6. Relative tamarisk density in the lower San Rafael riparian zone with zoom-in showing the detailed mapping within one of the priority restoration reaches (Canyon 3). As expected, low-density areas coincide with tamarisk removal areas. The inset map shows a reach that has areas of high, medium, and low tamarisk densities.

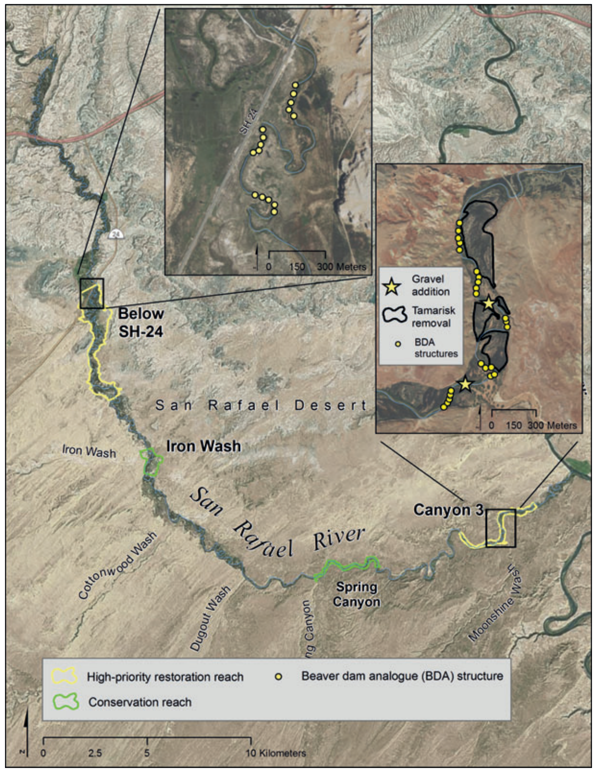

Figure 7. The lower San Rafael River valley bottom, with the two conservation reaches (green), Iron Wash and Spring Canyon, and two priority restoration reaches (red), Canyon 3 and Below SH 24. Inset maps of Canyon 3 and Below SH 24 show the locations of the restoration treatments.

Watershed-scale riparian conservation and restoration are crucial for management of biodiversity in dryland ecosystems because these wetland areas provide essential habitat for numerous terrestrial and aquatic species (Kingsford et al. 2006; Stromberg et al. 2013). However, limited restoration funding often dictates that watershed-scale restoration must be effectively prioritized, so limited resources can be applied where they are likely to have the greatest benefit (Bernhardt et al. 2005). We have illustrated how high-resolution vegetation mapping can be used to identify conservation and priority restoration zones, as well as finer-scale placement of specific restoration activities on the lower San Rafael River. The San Rafael riparian zone is representative of many impaired desert rivers due to altered flow regime, fish passage barriers, habitat loss, and non-native fish and vegetation encroachment (Olden & Poff 2005; Poff et al. 2011). As such, the framework of the BLM large-scale restoration plan (Laub et al. 2013) and high-resolution vegetation mapping can be used to develop restoration plans that target the ecological conditions of other impaired desert rivers. In the future, it may be appropriate to apply the method at broader scales (e.g. the Colorado Plateau Ecoregion). Application of this methodology at broad scales would provide critical riparian vegetation information and improve landscape management efforts for the restoration and conservation of riparian habitats.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Plant species identified during training site field visits per land cover classification based on USDA Plants Database (www.plants.usda.gov).

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