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METHODS, TOOLS, AND TECHNOLOGIES

A new data-driven riparian revegetation design method

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Abstract. Hydrologic and physical gradients influence vegetation zonation and can form the basis of riparian revegetation design. We present a new data-driven method to develop riparian revegetation designs by relating the ground height above river (HAR) or a low streamflow water surface as a groundwater proxy to existing vegetation cover types and applying those relationships to design conditions. Steps in the process are as follows: (1) map existing vegetation within the riparian corridor; (2) construct existing and design topographic and groundwater digital elevation models (DEMs), and then difference those DEMs to create a HAR detrended DEM (HAR dtDEM); (3) define existing vegetation habitat zones using the relationship between existing HAR dtDEM and mapped vegetation cover types; (4) apply habitat zone boundaries to detrended design topography; and (5) develop planting schematics using habitat zones and detrended design topography. We developed a revegetation design for a rehabilitation site on the Trinity River, California, using the HAR dtDEM method. We used a data-driven method to define five habitat zones in riparian areas: aquatic, emergent margin, mesic, mesic–xeric transition, and xeric zones. Zonal boundaries were identified using four criteria: (1) capillary fringe elevation above the low flow water surface, (2) shifts from herbaceous to woody-dominated cover types, (3) a difference equal to or >0.5 m between two adjacent ranked cover types, and (4) locations where a linear trendline intersected median HAR values or where a group of regression residuals changed from positive to negative or vice versa. The capillary fringe height was the most effective method when determining vegetation zones near the channel. The shift between herbaceous and woody-dominated cover types defined the boundary between the emergent margin and mesic zone. Elevation increases >0.5 m between adjacent ranked cover types defined the upper and lower mesic–xeric transition zone boundaries best. Comparing linear residuals was most useful for separating drier cover types occurring on higher ground surfaces. Existing habitat zone boundaries were applied to detrended design topography to direct which selected native plant species could be arranged within habitat zones to improve planting survival and increase ecological function following rehabilitation.

Key words: cover type; detrended DEM; habitat zones; height above river; revegetation; riparian restoration; riparian revegetation; vegetation patterns; zonation.

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Introduction

River restoration has become an important modern discipline to ameliorate human impacts to riparian landscapes around the world. Some restoration projects are small and performed by hand crews and volunteers. Others involve entire watersheds, civil design teams, and a support network composed of public and private sector experts. Large-scale earthworks may create new floodplains, point bars, side channels, ponds, and alcoves, which can restore fluvial geomorphic processes and create instream habitat but also severely impact riparian vegetation in the process. Revegetation is thus a critical component to river restoration, and design of successful riparian revegetation projects can affect overall project success or failure.

Over the last two decades, advancements in remote sensing technologies and photogrammetric methods, along with cost reductions for these methods, have enabled environmental spatial data (e.g., vegetation maps, LiDAR), hydraulic modeling, hydrology, and ground topography to be commonly developed as part of almost all watershed planning or physical river restoration efforts. Revegetation designs are often integral components of long-term post-project recovery and should be designed to take advantage of restored function. However, developing revegetation designs that identify and place the appropriate plant species in locations where they will grow and thrive under future conditions remains a challenge that is hampered by putting concepts into practice (Jensen and Platts 1990).

Revegetation designs should seek to mimic natural distribution and arrangement of native species in locations where they would thrive, but currently there are no data-driven methods for how to successfully identify these locations without significant professional experience in the watershed. The diversity and dynamism of the riparian zone itself contributes to the difficulty in deriving a single method for revegetation design. Riparian areas have been extensively studied and described, though they manifest differently depending on their local context. The regional expression of riparian zones in response to environmental conditions often leads to development of watershed expertise (Griggs 2009, Yochum 2018) that may or may not be applicable in other watersheds.

Riparian areas are influenced by local hydrology and geology, distance to (i.e., depth of) shallow groundwater, soil texture and depth, disturbance regime, plant life histories, and in the case of rivers, flood magnitude, timing, frequency, inundation duration, and the rate of streamflow change (Warner and Hendrix 1984, Gregory et al. 1991, Hupp and Osterkamp 1996, Naiman and Décamps 1997, Brinson et al. 2002, National Research Council 2002, Corenblit et al. 2009, Johnson et al. 2018, Politti et al. 2018). Riparian plant diversity is controlled by individual species' life-history tactics and the environment in which they establish (Gregory et al. 1991, Braatne et al. 1996, Naiman and Décamps 1997, Shafroth et al. 1998, Bendix and Hupp 2000, National Research Council 2002, Tron et al. 2015), which can be found generally within a soil's capillary fringe above shallow groundwater. The capillary fringe is a complex region between saturated groundwater and dry soil at the ground surface. The capillary fringe height varies with soil texture, which influences the functional distance hydrophytic plants must grow to reach available soil moisture. This functional distance can be estimated, and while it is common practice to plant cuttings in holes dug down to groundwater (Swenson and Mullins 1985, Dreesen and Fenchel 2008), it is not common to use the anticipated future ground surface height above groundwater to develop revegetation designs that ensure plantings are placed in favorable locations.

Vegetation growing in riparian areas may be a combination of aquatic, emergent, mesic, and xeric plants that grow where there are physical and hydrologic conditions favorable to their establishment and long-term survival. Emergent and mesic plant species typically persist in locations where groundwater is consistently shallow, whether created by drainage into the groundwater from the valley wall, or due to low-lying surfaces adjacent to water (i.e., supplied by the stream). Emergent plants are associated with soils that are saturated throughout the growing season. Mesic plants are associated with substrates that are moist for most of the growing season. Many mesic plants are phreatophytes and establish within a short distance from (i.e., height above) the shallow groundwater elevation. Given suitable hydrology and soils, mesic plants dominate vegetation types in riparian areas.

Emergent and mesic plant species have life-history strategies that facilitate initiation, establishment, and long-term growth in physically dynamic and hydrologically variable environments (Vannote et al. 1980, Walker et al. 1986, Cronk and Fennessy 2001, Capon 2003, Francis et al. 2006, Stromber et al. 2008, Bornette and Puijalon 2011, Tron et al. 2015). Planted vegetation can die for a wide variety of reasons, including desiccation (Briggs et al. 1994, Stillwater Sciences 2007), inappropriate species selection (Webb and Erskine 2003), poor condition and/or inadequate size of planting stock (Stillwater Sciences 2007), and competition with exotic species (Sweeney et al. 2002). Additionally, the dynamic and somewhat unpredictable patterns of deposition and scour can change habitat conditions for planted vegetation at time scales that vary from within the year of planting to years or even decades after planting. Despite the importance of riparian revegetation recovery, there is not a standard method to follow when designing revegetation plans based on civil restoration designs. Existing environmental data (e.g., hydrology, groundwater measurements, soil maps, and test pits) collected as part of river restoration projects can identify the conditions that support various species, which can be incorporated into revegetation designs for future conditions.

Currently, there are few tools available to evaluate how existing vegetation patterns in riparian corridors relate to physical and hydrologic conditions, and how those relationships could then be used to specifically create revegetation designs that take advantage of future restored river form and function. Vegetation planting zones created by hydrologic and physical gradients have been variously defined based on streambank location (Fig. 1) (Hoag and Landis 2001, 2002) and have included the toe, overbank, riparian, transitional, upland, and other zones (Hoag and Landis

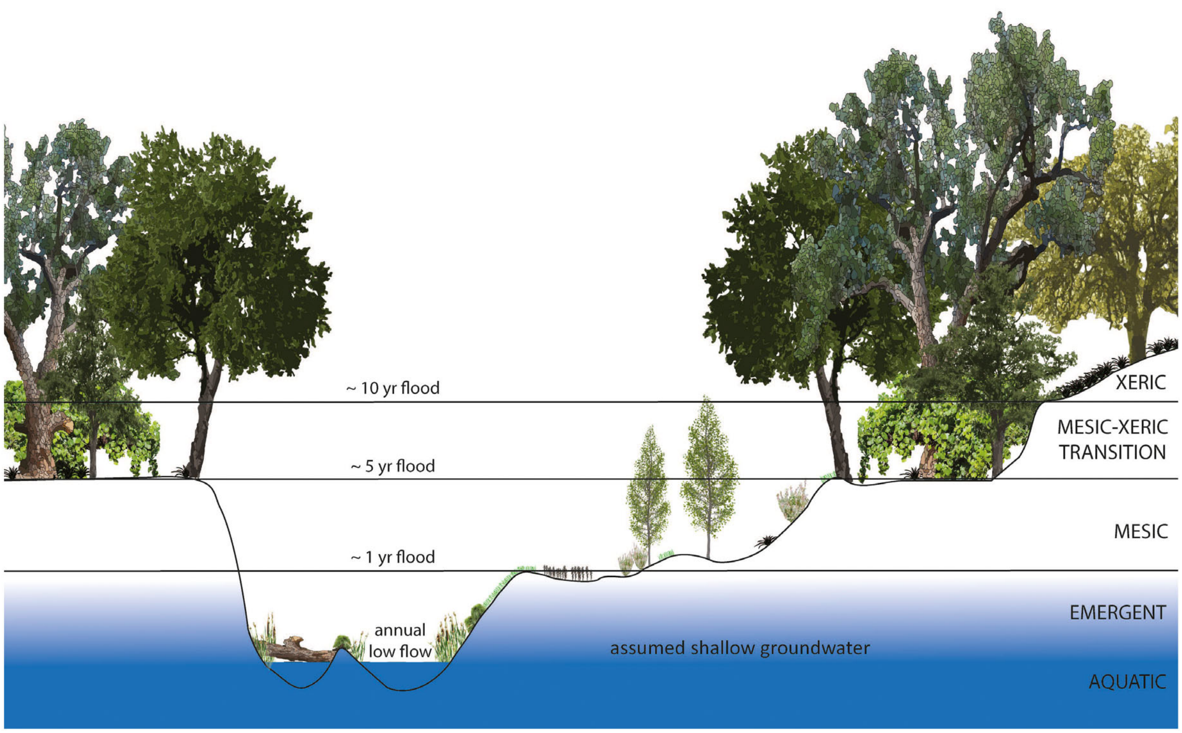

Fig. 1. Planting zones in riparian areas, defined variously by approximate flood recurrence interval, geomorphic surface, height above the fall water surface, and changes in vegetation (based on concepts in Hoag and Landis 2001).

2002). While planting zones have been defined using empirical data, such as changes in topography and/or vegetation for use during revegetation (Hoag and Landis 2002, National Resources Conservation Service 2011), they usually rely on professional judgment and personal knowledge of a site or region for definition. Professional judgment can be subjective, and there has been no published empirical and repeatable method to apply planting zones based on existing vegetation patterns within riparian corridors to future design topography and groundwater or some proxy for riparian function.

This paper presents an approach to developing revegetation designs using data routinely gathered for river restoration projects to evaluate existing vegetation patterns as a basis for riparian revegetation designs (Hoag and Landis 2001, 2002, Bair et al. 2003, Sullivan and Bair 2004, Hoopa Valley Tribal Fisheries Department and McBain and Trush Inc. 2006, Hoopa Valley Tribal Fisheries Department et al. 2011, Hoopa Valley Tribal Fisheries Department et al. 2015). The method described here is less subjective, can be broadly applied, and uses a data-driven analysis of existing vegetation as a basis for evaluating how design topography would change the location and extent of existing habitat zones and directing the placement of plants in locations where they would thrive. Final zone boundary determination is based on data-guided user interpretation. We demonstrate how to define the site-specific elevation breaks between common habitat zones in riparian areas: the aquatic, emergent channel margin (emergent margin), mesic, mesic–xeric transition, and xeric zones; and present a method for standardizing the ground surface height above groundwater across a site to tailor revegetation designs to future site conditions. We apply the method to a stream restoration site on the Trinity River, California, to demonstrate the method using real data. The type of analysis presented in this paper can be used in most watersheds with highly permeable (i.e., sandy) soils where appropriate data are available.

Presenting a New Data-driven Method for Developing Revegetation Designs

River restoration is a rapidly developing field with many physical and hydrologic data available to quantify existing system condition and develop restoration plans that restore form and function. Aerial photographs can provide historical and contemporary comparisons of conditions at a site. Vegetation mapping enumerates the amounts and types of vegetation in the project area. Remote sensing (e.g., LiDAR), topographical surveys, and geographic information systems (GIS) can be combined to create detailed digital elevation models (DEMs). DEMs are used to illustrate existing topography and can be manipulated to create design topography. GIS tools can also be used to describe detailed vegetation metrics characterizing reference conditions. Hydrologic monitoring via stream gages and groundwater wells can establish current flow regimes and groundwater dynamics at a site. The suite of existing conditions data is used to guide restoration projects by providing benchmarks for creating successful future conditions based on what is known to support existing vegetation patterns.

There are several steps to identify relationships we use to develop revegetation designs within a riparian corridor (Fig. 2):

1. Map existing vegetation within the riparian corridor,
2. Construct existing and design topographic and groundwater digital elevation models (DEMs),
3. Difference the topographic and groundwater DEMs to create a height above groundwater/river detrended DEM (HAR dtDEM),
4. Define existing habitat zones using the relationship between existing HAR dtDEM and mapped vegetation cover types,
5. Apply habitat zone boundaries to detrended design topography, and
6. Develop planting schematics using habitat zones and detrended design topography.

To briefly illustrate the benefits of the HAR dtDEM method, we describe its application within a northern California watershed where multiple restoration projects have been designed and implemented over the past 15 yr. The study area is a 64-km reach of the Trinity River in northern California, between Lewiston Dam and the North Fork Trinity River (Fig. 3). The Trinity River is a National Wild and Scenic River and is

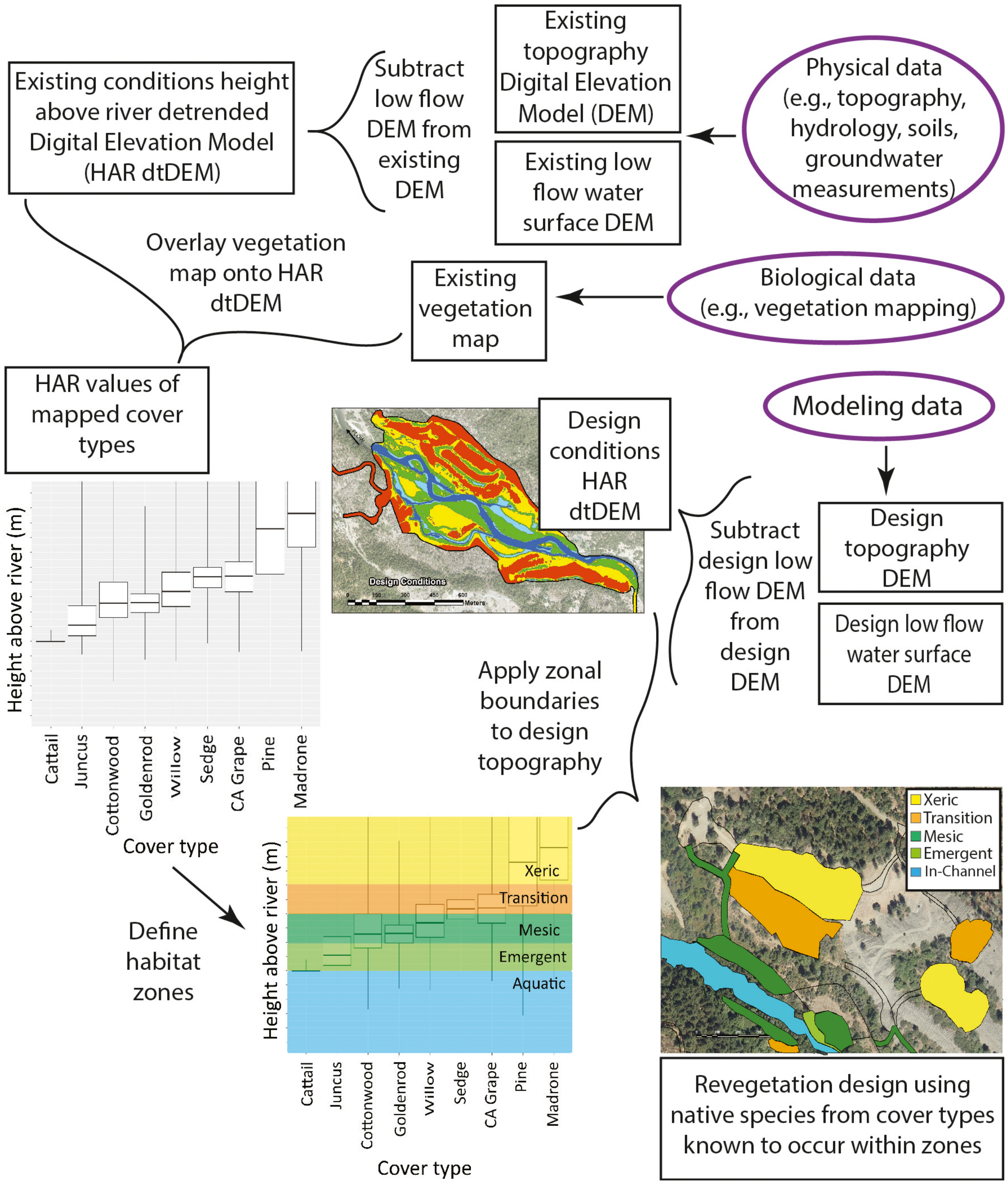

Fig. 2. Conceptual flow chart showing steps to produce a data-driven riparian revegetation design using height above river as a benchmark.

the largest tributary to the Klamath River. The Trinity River has been anthropogenically managed for resource extraction since the mid-1800s. Historic gold mining operations eroded entire hillsides and reworked the stream channel from bank to bank, resulting in elevated sediment loads, enormous piles of dredger mine tailings (i.e., barren cobbles), and negative impacts to

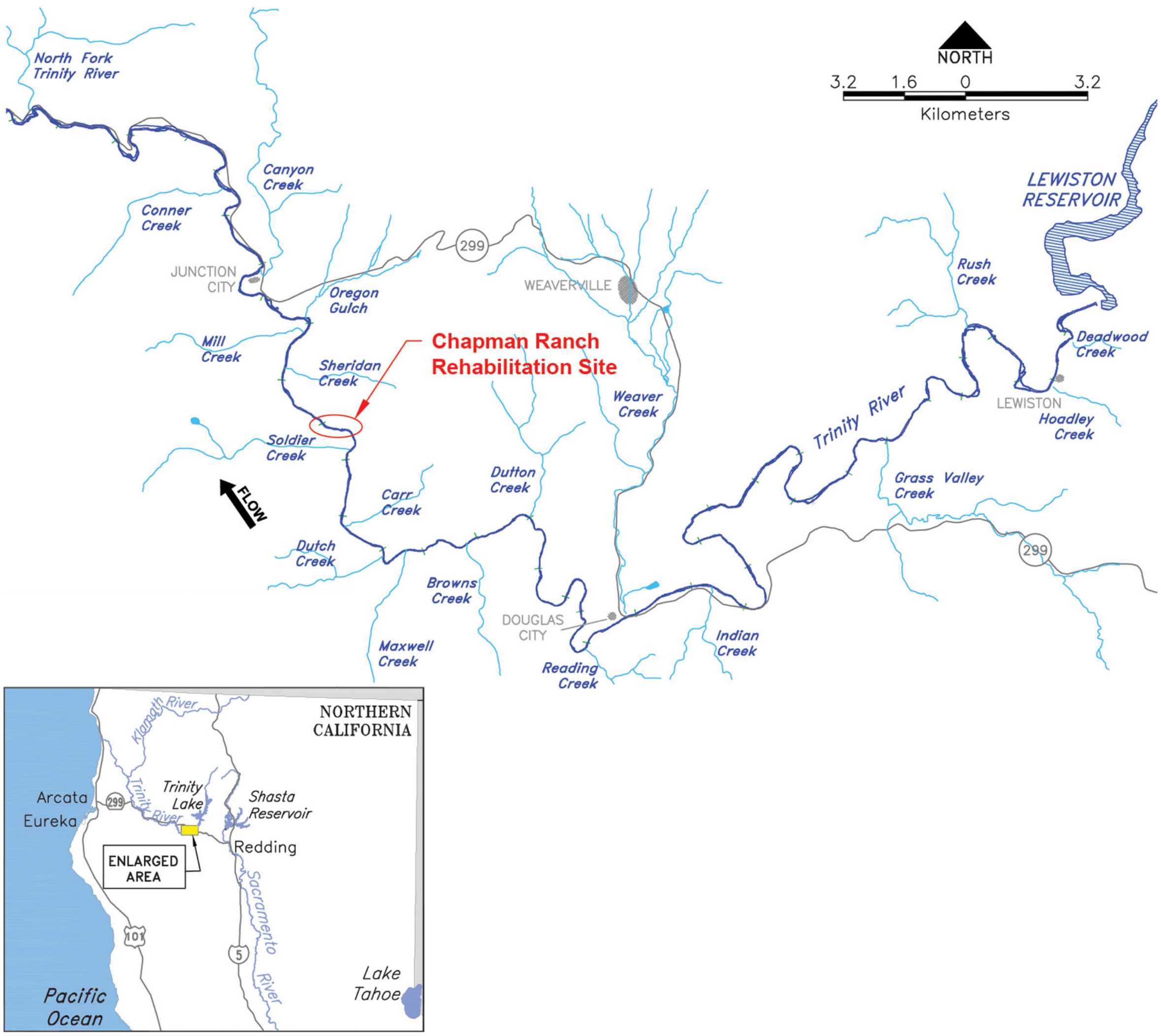

Fig. 3. Location map of Trinity River in northern California. The 64-km study area extends from Lewiston Dam down to the confluence of the Trinity River and North Fork Trinity River (from Bair et al. 2018).

both aquatic and riparian environments. The construction of Trinity Dam and Lewiston Dam in the early 1960s led to water diversions into the Sacramento River basin, which kept streamflows in the study area at a constant flow, reduced by 80–90% of pre-dam conditions, for several decades. Urbanization within the watershed led to constraints to the amount of water that could be released from the dams at one time; houses and other infrastructure were threatened at flows above 340 cubic meters per second (cms), the historical 1.5-yr flood. In response to reduced flows, riparian hardwoods (e.g., alders and willows) were able to grow along the perennially wetted channel edge for decades, creating a dense, linear band of vegetation along both riverbanks through most of the study area. The river channel became a simplified, rectangular shape with encroached streambanks. The floodplains were no longer inundated because of the greatly reduced flow regime. Salmon populations collapsed, and it did not take long for land managers to recognize the need for a different river management strategy. Three decades of flow experiments, scientific studies, and monitoring led to the Trinity River Record of Decision in 2000 (USDI 2000), which outlined a plan to restore the Trinity River and its fish and wildlife populations. The Trinity River Restoration Program (TRRP) was created to restore the Trinity River using a combination of mechanical channel rehabilitation, sediment augmentation, and flow management under an adaptive management approach.

Trinity River rehabilitation projects often involve removing vegetation encroaching into the summer flow wetted area along the stream channel, by creating a gently sloping streambank that simulates alluvial bar morphology, building side channels, lowering floodplains, and other large earthwork activities within and adjacent to the river. Revegetation is necessary from a regulatory standpoint to replace removed riparian vegetation, but it also improves the successful outcome of rehabilitation projects by providing immediate cover, species richness and structure, and beneficial effects of selecting the desired dominant species. Revegetation is an integral part of linking physical channel rehabilitation to aquatic and terrestrial riparian habitats and involves selecting the appropriate plant species and placing them in locations where they can establish and thrive into the future.

In the following sections, we describe the process to develop revegetation designs using a HAR analysis specific to the Trinity River study area. The HAR dtDEM method described in this paper was developed for the entire 64-km study area and applied to an individual rehabilitation site (Chapman Ranch) within the study area. The method was used for: (1) generating HAR elevation values associated with existing vegetation cover types in the study area, (2) describing and illustrating the variation of HAR elevation values associated with each vegetation cover type in the study area, (3) analyzing median HAR elevation values associated with each cover type to define habitat zones reflective of existing topographic and hydrologic conditions for the study area, and (4) applying HAR habitat zone boundaries to design conditions at the Chapman Ranch rehabilitation site. The application of habitat zone boundaries to design topography ensures that dominant or ecologically important plant species currently at the site can be planted in similar HAR elevations based on proposed design conditions. Vegetation–HAR dtDEM relationships can be used to evaluate vegetation differences between proposed alternative topographic and hydrologic conditions that may exist after construction.

Vegetation mapping

Developing relationships between topography and vegetation relies on existing biological and physical data that describe the site and the surrounding area to the extent possible. Biological data are summarized in a digital vegetation map, which includes cover types and supplemental notes about species composition and areas of high-quality habitat (i.e., reference conditions). Existing data should include at least some areas of high-quality riparian vegetation to use as a reference condition upon which to base the revegetation designs (Griggs 2009). The existing vegetation map contains a spatially explicit inventory of native cover types within the study area. There are many methods and standards for vegetation mapping (The Nature Conservancy 1998, Brohman and Bryant 2005, U.S. National Vegetation Classification 2019, California Department of Fish and Wildlife 2020), but most involve the use of recognizable and defensible vegetation cover types that are defined based on visible physical characteristics or dominant plant species in the canopy.

Vegetation within the 64-km study area was mapped in 2014 as part of ongoing riparian vegetation recovery monitoring (Hoopa Valley Tribe and McBain Associates 2015) using the alliance-based Manual of California Vegetation classification (Sawyer et al. 2009). Over 2080 hectares of vegetated and unvegetated areas and 130 cover types were mapped. Each cover type was assigned a wetland rating based on the dominant or codominant plants that define that cover type (Lichvar et al. 2016). The five wetland ratings (obligate, facultative wetland, facultative, facultative upland, and upland) indicate a species' propensity to grow in permanently saturated soils (i.e., wetlands) and thus provide some indication of how likely a cover type is to grow closer to groundwater (Stromberg et al. 1996, Lichvar et al. 2016). Obligate plants always occur in wetlands, whereas upland plants rarely do. Assigning wetland ratings to cover types was another way to characterize the assemblage of plants recognized as a group, and wetland ratings were used in a later step to determine habitat zones.

Constructing digital elevation models

Physical data were used to create a series of digital elevation models (DEMs). First, topographic and bathymetric surveys and bare earth LiDAR data were combined to create an existing topography DEM. A bare earth digital terrain model (DTM) was derived from LiDAR data and bathymetric surveys conducted between 2016 and 2017 (Pryor 2017). Ground surface elevations within the study area were imported to ArcGIS as points and breaklines to create a triangulated irregular network (TIN) surface. The DTM was exported as a 0.3-m existing ground DEM raster file to define habitat zone boundaries for the study area.

Next, a groundwater/streamflow DEM was constructed. Groundwater elevation may be measured at single points (e.g., using piezometers) but can be difficult to characterize across a floodplain consisting of a gravel, sand, and cobble mosaic. On rivers with highly permeable substrates (i.e., sandy soils) adjacent to the river, the depth to groundwater can be approximated using the low flow stream water surface elevation when groundwater data are unavailable. For use in revegetation designs, the lowest flow representing the driest conditions experienced by plants at the site should be selected. The elevation of the low flow water surface can be simply extended in a flat plane across the site topography, although a better "hydro-planar" surface can be created using a combination of surveyed water surface elevations, groundwater data if available, modeled water surface elevations at HEC-RAS 1-dimensional cross sections, and two-dimensional flow modeling output, such as HEC-RAS 2-D, SRH-2-D, or ArcGIS Spatial Analyst (Dilts et al. 2010). The groundwater DEM for the study area used the LiDAR point data obtained in July 2016 when flows at Lewiston was 12.7 cms, approximating late season baseflows. For the remainder of this paper, we use the term groundwater DEM, though in reality it was the low flow water surface elevation.

Once the existing topography and groundwater DEMs were constructed, they were used to create a detrended DEM (dtDEM) to portray the ground surface relative to the groundwater surface. This common type of dtDEM is known as the "height above river" (HAR), where the elevation of the groundwater surface is differenced from the existing ground DEM using ArcGIS (Fig. 2). The HAR dtDEM represents the height above the groundwater surface and standardizes elevations across a large site or study area (Coe 2016). The Trinity River 12.7 cms hydro-planar DEM points were differenced from individual existing ground surface points to construct the HAR dtDEM at a 0.3-m pixel resolution (Graham Matthews and Associates 2017). Elevation values were negative for the riverbed bathymetry below the 12.7 cms water surface (i.e., under water) and positive for the riverbank above the water surface (i.e., dry, height above river).

The process of creating a dtDEM for existing conditions was repeated using physical design topography (i.e., the project grading plan) and design groundwater surface elevation (Fig. 2). Physical design DEMs are usually a combination of existing ground surfaces and modified ground surfaces. To build the design conditions HAR dtDEM, the same groundwater elevation or streamflow should be used as for existing conditions, which is usually obtained from hydraulic model output, such as HEC-RAS or SRH-2-D.

The design topography at Chapman Ranch was developed in AutoCAD. The design topography was integrated into the existing ground DEM to create the design DEM. The 12.7 cm water surface under future designed conditions was obtained from a HEC-RAS hydraulic model. The modeled stream water surface elevations were laterally extended to construct a 12.7 cm hydro-planar terrain design surface DEM (TRRP and GMA 2017). A design dtDEM was constructed by differencing the 12.7 cm hydro-planar design DEM from the individual design ground surface points (TRRP and GMA 2017).

Relating height above river to vegetation

The next steps related HAR elevations to vegetation map polygons to identify patterns between cover type distribution and height above river. Using ArcGIS, the existing 2014 vegetation cover map was overlaid onto the 2016 existing conditions 12.7 cm HAR dtDEM (Fig. 2) and summary statistics calculated for each vegetation cover type. The center point of each HAR dtDEM pixel that falls within the polygon boundaries of a given cover type was summarized together with all other center points of that cover type as a multipart polygon (i.e., all mapped pixels of a given cover type were analyzed at the same time) and the following summary statistics for each cover type were calculated: elevation range; minimum, maximum, and median elevation; and first and third quartiles (25th and 75th percentiles). To simplify the data and reduce noise, cover types with areas <5% of the total mapped area were omitted from further analysis, resulting in 65 cover types included in the final HAR analysis for the study area. Unvegetated cover types (i.e., tailings piles, boulders, bedrock, and roads, etc.) were also omitted. Non-native plant-dominated cover types should be included if they comprise more than 5% of the total mapped area, as they may inform potential threats to revegetation success (e.g., invasive aquatic species that may colonize newly rehabilitated sites).

Using the summary statistics, box plots were constructed for each vegetation cover type and ranked from lowest median elevation (i.e., closest to the groundwater) to highest median elevation (farthest from the groundwater). A simplified version is shown in Fig. 4 for illustrative purposes. Because riparian revegetation designs focus on mesic and hydrophytic plants, cover types with a median elevation higher than a certain distance (e.g., 10–15 m) above the groundwater surface can be excluded from further analyses. The actual distance above the groundwater surface will vary from site to site depending on channel morphology, site topography, and hydrology.

A second box plot analysis was constructed in the same way using the wetland ratings associated with the dominant plant species in each cover type. The cover types were recoded using the wetland rating code and the same summary statistics. Plots were constructed for each wetland rating code assignment and ranked from lowest median elevation to highest median elevation.

Defining habitat zones

Once the median HAR of each cover type was determined and ranked, habitat planting zones were defined based on the distribution of existing vegetation in the study area. The number of habitat zones depends on the river morphology, since meandering rivers likely have vegetation close to the channel margins in some locations while incised rivers may have steep streambanks that lack vegetation near the water surface. However, all rivers have a mesic zone and a xeric zone, with a zone of transition between them (Table 1). Approximate flow ranges can be assigned to the habitat zones if they are known, though the specific flow range for each vegetation zone on a river will vary depending on river morphology, annual hydrology, and the results of the box plot analyses (Table 2).

Four criteria were used to identify the potential elevation of the boundaries between habitat zones (Fig. 4). The criteria used quantitative data to identify the height above river that may separate one habitat zone from another. The data-derived preliminary criteria were combined with user judgment to define habitat zone boundaries.

The first criterion to identify habitat zone boundaries relied on the elevation of the capillary fringe associated with common riparian soils in the study area (Fig. 4). Capillary fringe height above river will be higher in finer substrates such as fine sand than in coarser substrates such as medium sand (Fetter 1980, Reid et al. 1987, Mausbach 1992, Bair 2001) and is not usually higher than 1 m above permanent groundwater (Mausbach 1992). The capillary fringe height was used as a preliminary habitat zone boundary identifier because it represents a constant source of available soil moisture, which is critical for the survival of hydrophytic and phreatophytic plant species (Robinson 1958). It also inherently reflects soil texture, since the capillary fringe will be greater in finer textured soils (Reid et al. 1987). The height of the capillary fringe was marked on the cover type and wetland rating box plot charts (green hatching in Fig. 4).

The second method to identify habitat zone boundaries used the physical habit of the dominant species in each cover type. Specifically, the change from herbaceous-dominated cover types to woody plant-dominated cover types was identified and the corresponding height above river was marked on the cover type and wetland rating box plot charts (green line in Fig. 4). The change between herbaceous-dominated and woody-dominated cover types was selected as a preliminary habitat zone boundary identifier for wetter habitat zones because often, herbaceous

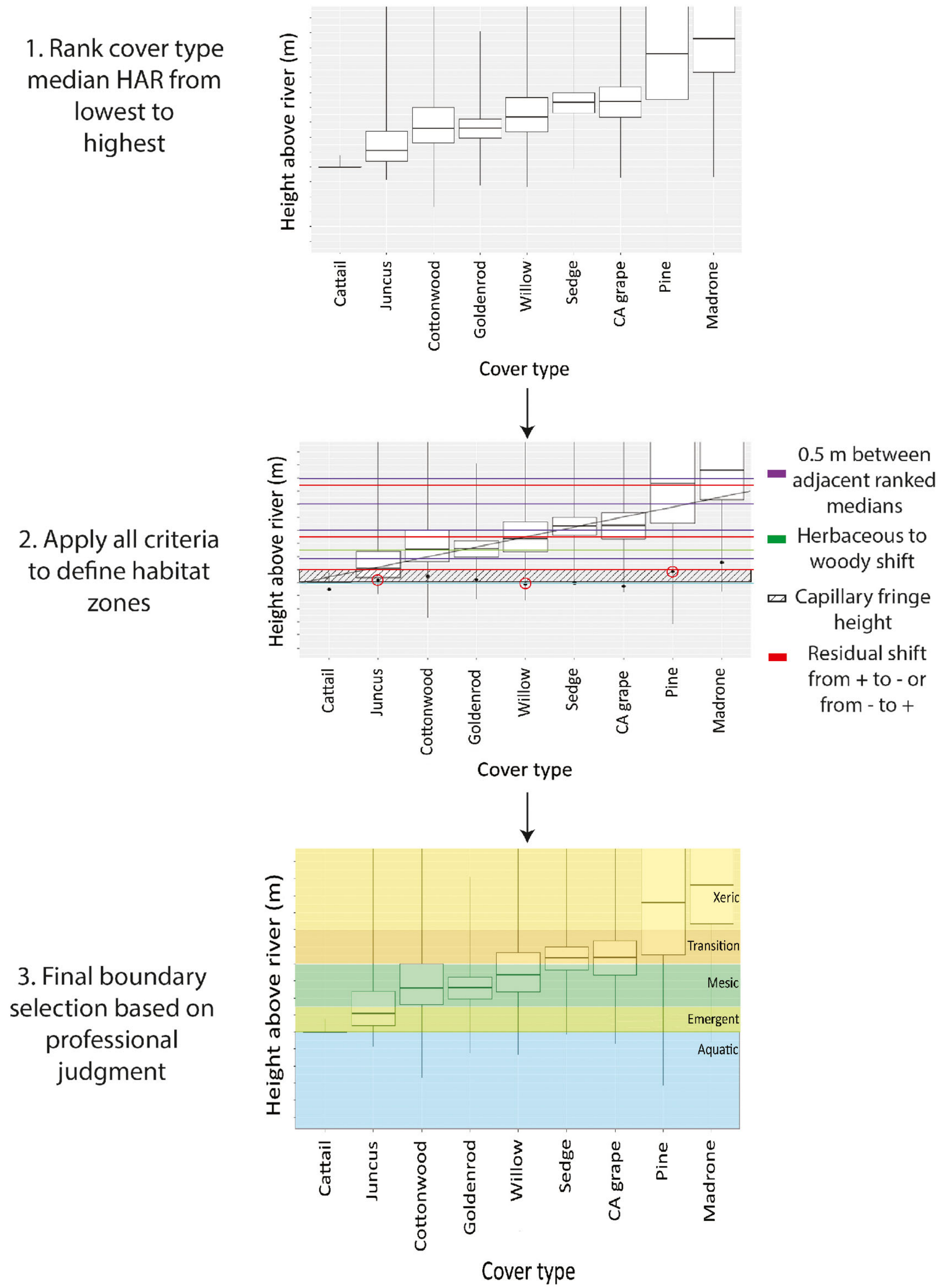

Fig. 4. Sample box plot analysis showing cover types ranked from lowest median HAR elevation to highest

(Fig. 4. *Continued*)
median HAR elevation. The box plot was truncated at 10 m; additional cover types could occur above 10 m but are not likely to be included in riparian revegetation designs. The same process was used to create a box plot analysis using wetland ratings.

Table 1. Possible habitat zones that can be defined relative to the groundwater surface, depending on river conditions and morphology.

Habitat zone	Height above groundwater surface	Annual inundation duration	Flow range	Description
Aquatic	Determined by zonal analysis	All year	<Low flow water surface	Inundated all year. This zone represents the water within the channel and is unvegetated
Aquatic vegetated	Determined by zonal analysis	All year	<Low flow water surface	Inundated all year. This zone occurs close to the channel edge and represents the part of -the channel vegetated with aquatic and -submerged plants. Not always present
Emergent margin	Determined by zonal analysis	All year or multiple months	Low flow water surface to ˜1 ft above water surface	Inundated frequently and occurs entirely within the substrate's capillary fringe next to water. The soil is saturated or at field capacity the entire year. Herbaceous plants are most abundant in this zone. Not always present
Mesic	Determined by zonal analysis	Multiple months to many weeks	Low flow water surface to ˜5-yr flood	Inundated at least once annually, and the substrate is saturated or at field capacity for most of the growing season. Woody plants are most abundant in this zone
Mesic–xeric transition	Determined by zonal analysis	Many weeks per year to once a century	Approx. 5-yr flood to 100-yr flood	May be inundated every other year to once a century. Prolonged soil moisture at or above field capacity is infrequent. Woody plants are most abundant in this zone
Xeric	Determined by zonal analysis	Never	>>100-yr flood	Not inundated. Soil moisture is recharged through precipitation alone. Woody plants are most abundant in this zone

cover types occur closest to the channel (Dixon and Johnson 1999, Lyons et al. 2007).

The third criterion to identify habitat zone boundaries compared the relative difference in median elevation between adjacent ranked vegetation cover types and wetland ratings (purple lines in Fig. 4). Ground elevations in riparian areas often reflect the flood return intervals they experience (Friedman et al. 2006), and inundation frequency influences the distribution of riparian vegetation cover types (Auble et al. 1994, Hupp and Osterkamp 1996, Bendix and Hupp 2000). Ranked vegetation cover types with similar median elevations are presumably more alike and found in the same habitat zone, whereas adjacent cover types with larger differences in median elevations may occur in different habitat zones. Differences between vegetated cover type median HAR elevations (i.e., disjunct HAR elevations) are important indicators of rapid changes in environmental condition and a species' affinity to a certain zone. Often, the box plot charts will show at least a few natural "breaks" between some adjacent cover types. The criterion for what constitutes "different" will vary between sites depending on channel morphology, substrate, hydrology, disturbance regime and intensity, and vegetation heterogeneity across the site, but a difference of >0.5 m between adjacent medians is a good starting point. Once the breaks were identified, they were marked on the cover type and wetland rating box plot charts (Fig. 4).

The fourth criterion to identify habitat zone boundaries used a linear relationship between median HAR and assigned rank. Each rank was assigned a value from 1 to x, with x being the number of cover types in the analysis. A linear trend of median HAR elevation by cover type was developed and used to extract residuals

Table 2. Five habitat zones defined in the study area relative to the 12.7 cm water surface.

Habitat zone	Height above groundwater surface elevation (m)	Annual inundation duration	Flow range (cms)
Aquatic	<0	All year	<12.7
Emergent margin	0–1.0	All year or multiple months	12.7–105
Mesic	1.0–3.0	Multiple months to many weeks	105–530
Mesic–xeric transition	3.0–6.0	Many weeks per year to once a century	>530
Xeric	>6.0	Never	>>530

Table 3. Total area of habitat zones at the Chapman Ranch rehabilitation site for existing conditions and design conditions.

Habitat zone	Existing conditions (ha)	Design conditions (ha)	Percent change
Aquatic	4.0	5.6	+40
Emergent margin	0.9	3.6	+300
Mesic	8.5	10.9	+28
Mesic–xeric transition	20.1	13.5	–33
Xeric	26.7	26.6	–0.4
Total	60.2	60.2	

between the calculated median HAR values and the predicted HAR values. Heights where the line exactly intersected the median elevation were marked on the box plot charts. Locations where the residuals changed from positive to negative or from negative to positive were also noted and marked on the box plot charts (red circles corresponding to red lines in Fig. 4). The linear residual comparison was conducted for the cover type box plots and the wetland rating box plots.

Once potential quantitative habitat zone boundaries were drawn onto the cover type and wetland rating box plot charts, each box plot chart was assessed. Assessment of the box plot chart involved user judgment to "fine-tune" placement of the habitat zone boundaries, and final boundary selection was guided by professional judgment and obvious groupings based on the HAR analysis results (Fig. 4). It is likely that several of the quantitative boundaries occur close to each other and that only a single boundary is necessary. For example, the capillary fringe height and linear residual comparison in the study area both placed a boundary at 1 m above the groundwater surface (Fig. 4), and the difference in ranked height above groundwater places a boundary at 1.5 m above the groundwater surface. These three marks are close to one another, suggesting that a single boundary could be appropriate. Using the median height of cover types, the final boundary was assigned at 1.5 m so that cattail–bulrush and Juncus cover types are included in the same "Emergent Margin" habitat zone (Fig. 4). Final elevation boundaries should be ecologically relevant for the vegetation cover types within a defined habitat zone; for instance, a boundary separating cover types such as cattail and bulrush would be inappropriate because they are both obligate wetland herbaceous cover types occurring within the active channel and therefore should be grouped in the same habitat zone.

Using the four criteria described above, we identified five habitat zones in the study area (Table 3). The 65 mapped vegetation cover types and their wetland ratings were ranked along the height above river gradient (Fig. 5, Fig. 6). The boundary between the emergent margin zone and mesic zone was identified using a combination of the capillary fringe height, the shift between herbaceous- and woody-dominated cover types, and the relative difference in median elevation between adjacent ranked vegetation cover types and wetland ratings. The box plot chart showed a 0.3-m "break" between adjacent cover types above the height of fine sand capillary fringe (~100 cm) and after the beginning of the woody cover types. Changes >0.3 m between the median elevation of two cover types in the study area were used to place boundaries between the aquatic and emergent margin zones and the emergent margin and mesic zones. The disjunct adjacent elevation method was most effective in determining the boundary between the xeric zone and the mesic–xeric transition zone. The linear residual method was most useful for drier cover types occurring on higher ground surfaces.

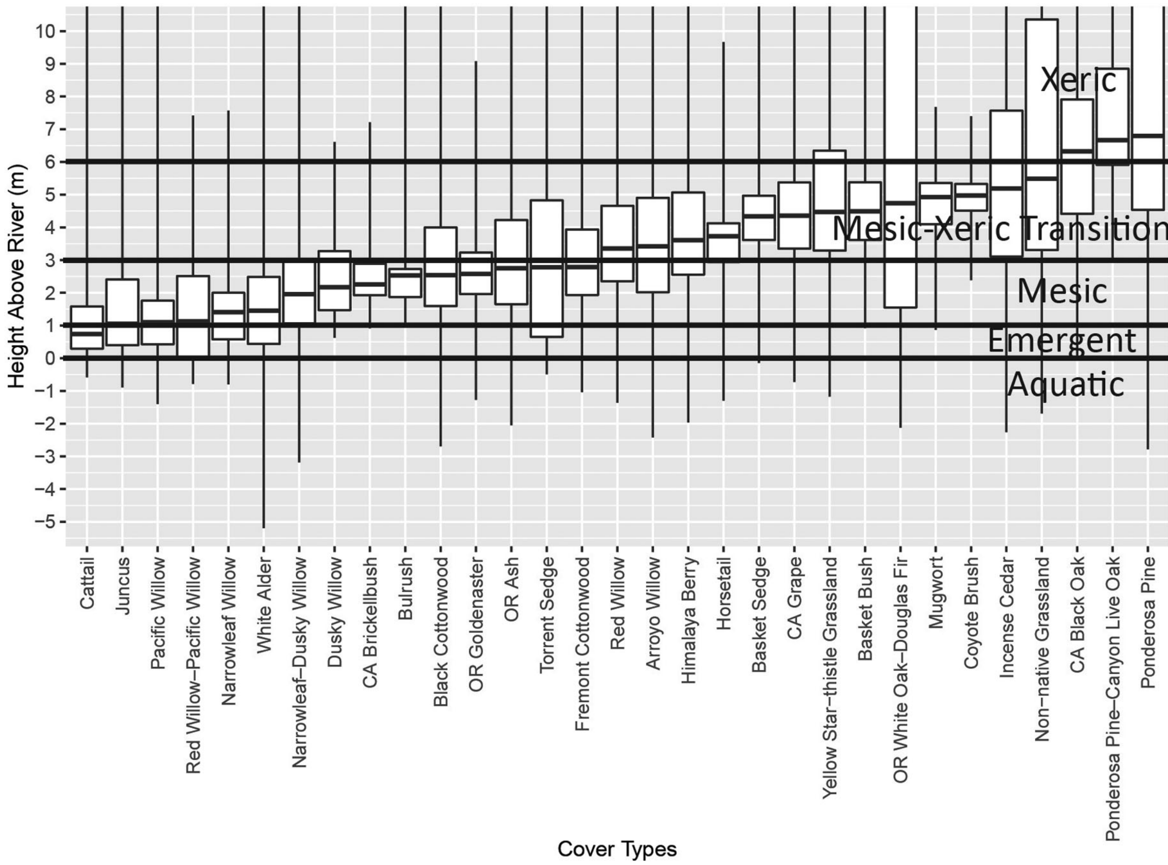

Fig. 5. Box plots illustrating the median and quartiles of 2014 mapped cover types' heights above the 12.7 cm hydro-planar surface in the Trinity River study area. The box is bounded by the first and third quartiles with the median shown as a black bar, and the gray lines show the range of data between minimum and maximum. The height in the chart is truncated to 10 m. Modified from Bair et al. (2018).

Developing revegetation designs specific to design topography

Once the habitat zone elevations were defined, they were applied to the physical design dtDEM developed for the Chapman Ranch rehabilitation site. Design dtDEM elevations were classified into habitat zones based on the HAR boundaries defined for existing conditions. The habitat zones were used to develop revegetation designs at Trinity River rehabilitation sites. The Chapman Ranch rehabilitation site is 60.2 ha and includes approximately 1.3 river kilometers of channel, associated banks, gold mining tailings piles, and pre-dam floodplain. Revegetation designs had to meet the goals of the physical designs, which were intended to perform both ecological and geomorphic functions. Aside from fish-related goals, additional project goals were to promote the establishment and growth of a more diverse assemblage of deciduous riparian hardwoods with varying ages so that the size and frequency distribution of large wood naturally recruited into the river will increase in the future, and to increase total cover (abundance) of mesic vegetation cover types and create vegetation patches with a more polygonal shape (i.e., less linear) after the project was completed. Trees, shrubs, forbs, and herbs were proposed for planting on constructed topographic features and islands of remnant riparian vegetation to improve the complexity of aquatic and riparian habitats across a range of streamflow magnitudes.

Next, we compared zonal area between existing conditions and design conditions to

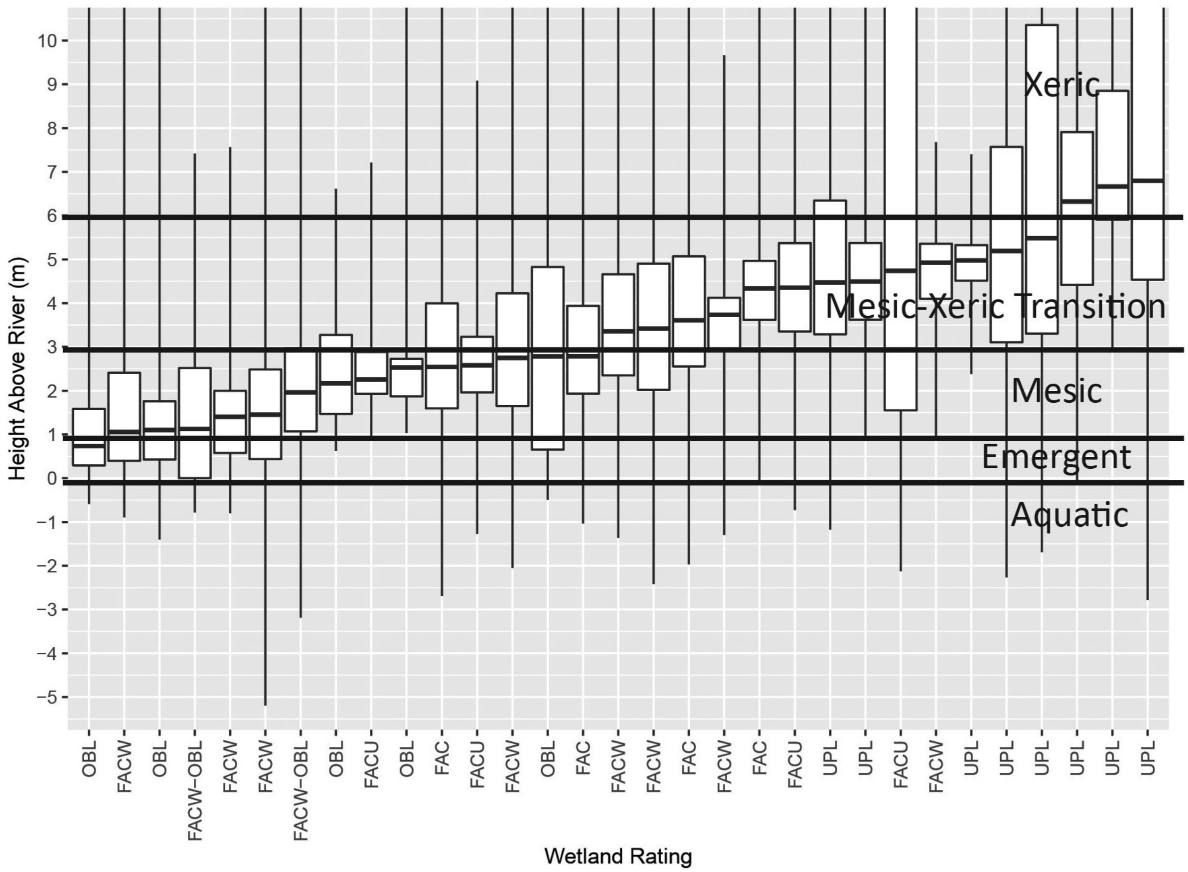

Fig. 6. Box plots illustrating the median heights above the 12.7 cm hydro-planar surface and quartiles of 2014 mapped cover types defined by wetland rating. The box is bounded by the first and third quartiles with the median shown as a black bar, and the gray lines show the range of data between minimum and maximum. The height in the chart is truncated to 10 m. Wetland ratings are abbreviated (OBL = obligate, FACW = facultative wetland, FAC = facultative, FACU = facultative upland, UPL = upland).

determine the area within each habitat zone to be revegetated (Table 3, Fig. 7). Habitat zone boundaries developed for the 64-km study area were applied to the existing ground DEM, and total area within each zone under existing conditions was summarized (Table 3).

For each zone, a list of appropriate plant species to use in revegetation designs was created based on the existing vegetation cover types associated with each zone. Common and abundant plant species associated with cover types occurring within habitat zones should be selected for use in revegetation to increase successful establishment of plantings and improve ecological function following rehabilitation. High-quality areas observed during vegetation mapping should serve as templates for determining the desired plant species, vegetation structure, and/or habitat conditions for terrestrial and aquatic fauna to guide revegetation designs. Species with wide ecological amplitude (i.e., occurring across a range of elevations) can be selected to improve planting outcomes by increasing the resilience of planted vegetation to dynamic stream processes and site evolution following design implementation.

By way of example, design areas located within 1.0 m above the 12.7 cm water surface occurred within the emergent margin habitat zone. Native species suitable for the emergent margin planting zone included small-fruited bulrush (*Scirpus microcarpus*) and cattail (*Typha*

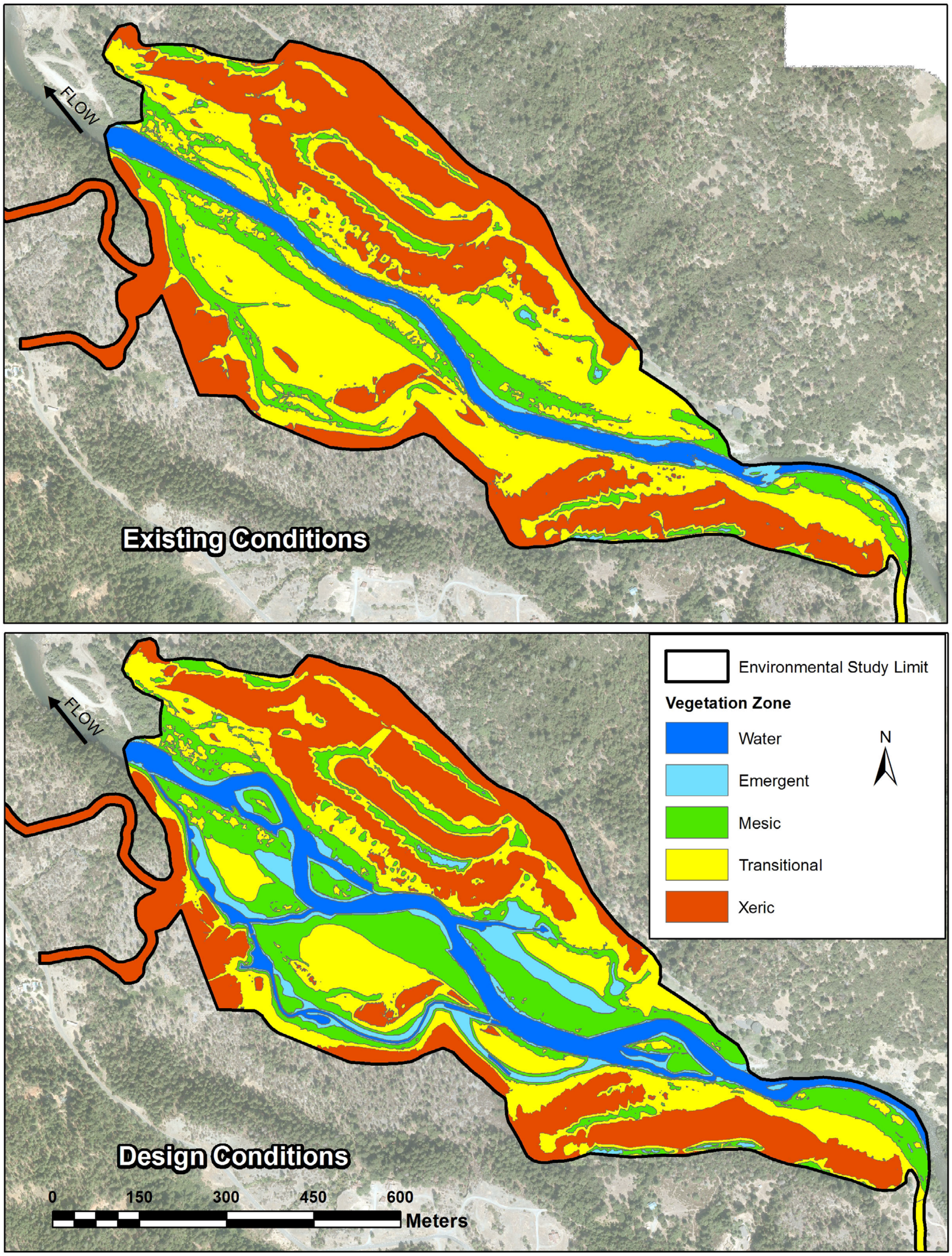

Fig. 7. Example existing (top) and design (bottom) detrended digital elevation model (dtDEM) habitat zonation comparison, showing an increase in aquatic, emergent, and mesic habitat zones under design conditions. Modified from Bair et al. (2018).

latifolia). It would not be appropriate to plant a species characteristic of the mesic–xeric transition zone, such as Pacific dogwood (*Cornus nuttallii*), in the emergent margin habitat zone, even though dogwood is native to the study area and occurs within the riparian corridor (Fig. 5). Known rooting elevations and soil depth and texture requirements for native species within the study area should be incorporated into revegetation designs whenever they are available (Stella et al. 2003, Griggs 2009).

Some cover types have extensive overlap with more than one habitat zone in their upper or lower elevation ranges (the gray bars in Fig. 5), for example, red willow–shiny willow. The ecological amplitude of some vegetation cover types suggests that using dominant species from these cover types for revegetation within habitat zones where they have been documented will result in successful outcomes because the species are adapted to conditions within those zones. Once the dominant or common codominant plants were identified for each zone, they were arranged to reflect cover types targeted for rehabilitation.

Discussion

We present a new data-driven approach to identify habitat zone elevations for use in designing riparian revegetation projects during river restoration work. To our knowledge, this is the first data-driven approach to determine site-specific planting zone elevation boundaries published and we believe it will increase the effectiveness of riparian revegetation work by: (1) providing a consistent, objective methodology to achieve successful revegetation, and (2) opening a discussion for refinement of the methods based on additional, as yet unpublished, professional experience and expertise from the public and private sectors. Many technical guides to species selection and general planting locations occur in the gray literature published by government and non-profit agencies (e.g., Hoag and Landis 2001, 2002, Griggs 2009, many others). However, specific details of how to apply planting zones in real-world settings are vague and open to interpretation. Where exactly does the emergent zone end and the riparian zone begin? Additionally, peer-reviewed methods for placing species in appropriate locations following restoration are generally unavailable. An extensive database of practical rules to achieve successful riparian revegetation certainly exists within the public and private sectors via the professional restoration experts who have learned through trial and error (Stillwater Sciences 2007, Griggs 2009). However, funding of restoration projects rarely, if ever, includes publication of case studies that demonstrate successes and failures or the description of quantitative design methods. We hope our contribution provides a starting point that leads to collaborative improvement of an accepted industry standard for determining habitat zone boundary locations for use in riparian revegetation design.

The four methods used to develop preliminary habitat zone boundaries were useful for identifying different zones in sandy soils. The capillary fringe height was the most effective method when determining habitat zones near the channel, where soils were saturated or at field capacity at the water surface or a short distance above it. Many types of emergent and wetland plants can only successfully establish and thrive in the zone just above the water surface where soils are constantly saturated. A shift in herbaceous and woody plant types often occurs at the interface between saturated soils and those that may gradually dry throughout the growing season (Fig. 5). Herbaceous plants typically dominate wetland and emergent habitats while woody plants may grow and dominate in more mesic locations that are moist but farther above the groundwater surface. Identifying the shift between principally herbaceous plant-dominated and woody plant-dominated cover types as a boundary between the emergent margin zone and the mesic zone was straightforward, although in our example it was not the final boundary selected. This criterion would not be appropriate for woody plant-dominated wetlands and swamps. The difference between adjacent cover type median HAR was most effective in determining the boundaries, both upper and lower, of the mesic–xeric transition zone. The regression method was most useful for drier cover types occurring on higher ground surfaces where water availability was likely a less important driver of vegetation cover type distribution.

We used the quantitatively defined habitat zones to guide the revegetation design at the

Chapman Ranch rehabilitation site. The method we developed applied the relationship between vegetated cover types and the environmental locations where they locally grow to physical designs to numerically quantify differences between design alternatives and evaluate changes compared with existing conditions. Our HAR analysis used data commonly collected as part of a broad project area and applied them in the site-specific rehabilitation civil design process. The HAR analysis can be conducted at a site or watershed scale and applied to specific rehabilitation site designs. For watersheds with multiple rehabilitation projects, this approach represents a significant cost savings over developing individual revegetation designs on a site-by-site basis within a single watershed and offers greater integration between different site designs and better long-term results by tying ecological function to revegetation designs.

Vegetation mapped on an aerial photograph represents a moment in time but reflects both current and historical environmental conditions leading up to the date of mapping. Existing vegetation may include relict stands that initiated under different conditions (e.g., prior to flow regulation) that no longer exist in the riparian zone. Vegetation growing within the riparian area in the Trinity River study area has been influenced by placer and hydraulic mining, urbanization, and streamflow regulation, including streamflow restrictions following dam construction as well as flows intended to restore ecological function of the regulated river channel. Locations along the river where cottonwoods and willows established before flow regulation may reflect streamflow patterns and cycles representative of pre-regulation conditions that are no longer present. It is possible that cover types associated with plants that established prior to flow regulation in 1965 could cause median elevations above groundwater to be higher than they would be under current regulated conditions.

Along similar lines, riparian restoration designs often seek to change the ecological function of impaired river reaches, thus creating significantly different future conditions compared with existing conditions. The use of a static "snapshot" evaluation of current vegetation as the basis for developing revegetation designs in a dynamic landscape such as the riparian zone may seem counterintuitive, but we believe it still provides a useful guide to the locations and ground surface elevations where certain plants can survive and grow. This is especially true for the first few years following project implementation, when revegetation is often intended to meet regulatory requirements and has the added benefit of front-loading a suite of desirable species on newly constructed floodplains.

The question of how long revegetation is expected to persist following project implementation is valid given the widespread damage caused during implementation and the high cost of revegetation. Applying quantified height above river preferences of selected or preferred cover types to future ground surface elevations ensures that initial survival of plantings will be high. However, it is important to consider that riparian zones are naturally dynamic and the plants that specialize in this area have adapted over millennia to unpredictability. As stream restoration projects evolve over time, new surfaces will be created for natural riparian regeneration while other surfaces and the vegetation on them will be scoured away. While natural systemwide responses such as channel migration cannot be controlled, selecting species with wide ecological amplitude can mitigate some of the effects of disturbance, whether it is from flow-induced deposition or a landscape-level wildfire, by building resilience into riparian revegetation designs.

The relationship described here between vegetation and the ground height above river oversimplifies the influence and complexities of soils and shallow groundwater that create the physical conditions supporting riparian vegetation. The height above the low flow water surface used in the 64-km study area was a simple flat plane projection of the wetted edge and may not have portrayed the actual groundwater conditions at a given location. Installing and monitoring piezometers within a project site could improve the estimate of the distance to groundwater by providing empirical measurements of groundwater within a site, which could be combined with low water surface elevations if necessary. However, depending on the scale of the study area, approximations of groundwater elevation via low water surface elevation may be necessary. Late summer or fall streamflows typically occur at the driest times of the year when the maximum depth to groundwater is achieved. Plants that require constant access to water are stressed during the late summer and fall, and if conditions are too dry, they may not persist.

This method was developed in sandy soils in an area with a Mediterranean climate and is most appropriate for similar climates where seasonal moisture availability limits plant growth and where groundwater supplies moisture that precipitation does not. However, the method is flexible in that the user selects the reference water surface that represents the driest conditions at the site and the capillary fringe height that best describes soil conditions. Selecting the water surface representative of the driest conditions during the year will produce a revegetation design that places plants closer to groundwater in a configuration where they are known to grow successfully under existing conditions and therefore can be expected to grow successfully under (improved) design conditions. Additionally, the method has been successfully applied in both unregulated and regulated watersheds.

Our HAR method for developing successful revegetation designs is specific to sandy soils. Other soil types are implicitly accommodated through the capillary fringe height criterion, but additional soil dynamics such as stratified soils and root use of available moisture are not. The HAR method could be improved by either (1) including detailed soil information (e.g., soils maps) during the definition of existing conditions by constructing a box plot sorted by soil preferences or (2) adding soil-specific criteria during the definition of habitat zones, or both. We have successfully applied the method in silty soils on coastal tributaries to Humboldt Bay, California (Elk River, Fay/Freshwater Slough), without detailed consideration of soil moisture dynamics. However, the method could likely benefit from inclusion of soil characteristics.

The HAR analysis presents the median height above assumed perennially available groundwater where a vegetation cover type currently grows but may not necessarily represent a place where the species can grow from a seed and survive under current or future hydrological conditions. To improve long-term design and revegetation function, the mechanisms of natural vegetation recruitment should be incorporated into revegetation efforts, such as planting early colonizers that require bare substrate for germination near dynamic geomorphic features (i.e., gravel bars, depositional floodplains) or co-planting species such that a fast-growing tree or shrub can provide shade for another species that requires shade to become established (Griggs 2009). The ability of planted vegetation to regenerate in situ will improve the long-term success of planted areas on rehabilitated sites if the species are able to naturally replace themselves in the future.

It is difficult to predict how plant species and communities (e.g., cover types) will respond to future environmental changes resulting from climate change. Developing revegetation designs based on existing vegetation patterns will likely be able to account for future changes from the rehabilitation designs, but it is unclear how climate change will be accommodated. There is a general expectation that increasing temperatures and aridity will lead to a significant reduction or even extinction of many species throughout a portion or the entirety of their ranges (Walther et al. 2002, Parmesan and Yohe 2003, Thomas et al. 2004, Thuiller et al. 2005, Urban 2015). However, climate modeling has predicted an increase in available favorable habitat for Fremont cottonwood in the western United States in response to climate-induced temperature increases (Ikeda et al. 2014). “Over restoration” in biological hot spots, where large areas are planted with native species to anticipate increasing temperatures, has been one proposed strategy for anticipating climate change (Davies 2010). But rarely in restoration projects is there enough capital for modest revegetation, let alone “over restoration.” Restoring function (i.e., improving hydrology, sediment supply and routing, and reconnecting floodplains) to an impaired river system can go a long way toward buffering the presumed negative effects of climate change. Selecting adaptable species for revegetation can further buffer the long-term successful outcome of physical rehabilitation projects. The box plots show cover types ranked by their median height above low flows, but most cover types showed a large range within the data. Some cover types were documented in three habitat zones, indicating their adaptability within the riparian zone. This ecological amplitude may reflect phenotypic plasticity and/or genetic diversity that could allow species to respond favorably to changes in climate (Harris et al. 2006, Valladares et al. 2014). Selecting native species from these presumably adaptable cover types for revegetation can increase the resilience of revegetated areas in response to environmental shifts resulting from changing climate.

Riparian areas represent a gradient between the upland and aquatic environment and riparian vegetation patterns occur according to location along the gradient. Qualitative methods are commonly applied in riparian areas to portray the environmental gradients that occur with the riparian area (e.g., zonation), and in this paper, we propose a new data-driven stepwise method to aggregate cover types using box plots, the hydric code evaluation, the regression line, and some generalization of the capillary fringe. The proposed method to define habitat zone boundaries still requires user interpretation, but the user interpretation is guided by data and analysis. Coarsely aggregating cover types into functional groups (i.e., habitat zones) that represent the environmental affinities of the dominant species within a cover type is a useful way of illustrating broad vegetation patterns and indicating specific types of environmental conditions (e.g., wetlands). Cover types aggregate in a predictable way (i.e., zones) along the environmental gradient that occurs in riparian areas.

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Data Availability

Data sets for this research are available as follows:

Digital terrain model: GMA 2017. http://www.trrp.net/library/data?id=99.

Hydraulic model: TRRP and USBR 2018. http://www.trrp.net/library/data?id=104.

Vegetation map: Hoopa Valley Tribe and McBain Associates 2015. https://www.trrp.net/DataPort/data.php?id=74.

Chapman Ranch 100% Civil restoration designs: Hoopa Valley Tribe and McBain Associates 2019. http://trrp.net/perm/ma/Chapman_A_Design_Features_20190723.zip and http://trrp.net/perm/ma/Chapmpan_B_Design_Features_20210301.zip.