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What are the Conditions of Riparian Ecosystems? Identifying Impaired Floodplain Ecosystems across the Western U.S. Using the Riparian Condition Assessment (RCA) Tool

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Abstract

Environmental stressors associated with human land and water-use activities have degraded many riparian ecosystems across the western United States. These stressors include (i) the widespread expansion of invasive plant species that displace native vegetation and exacerbate streamflow and sediment regime alteration; (ii) agricultural and urban development in valley bottoms that decouple streams and rivers from their floodplains and reduce instream wood recruitment and retention; and (iii) flow modification that reduces water quantity and quality, degrading aquatic habitats. Here we apply a novel drainage network model to assess the impacts of multiple stressors on reach-scale riparian condition across two large U.S. regions. In this application, we performed a riparian condition assessment evaluating three dominant stressors: (1) riparian vegetation departure from historical condition; (2) land-use intensity within valley bottoms; and (3) floodplain fragmentation caused by infrastructure within valley bottoms, combining these stressors in a fuzzy inference system. We used freely available, geospatial data to estimate reach-scale (500 m) riparian condition for 52,800 km of perennial streams and rivers, 25,600 km in Utah, and 27,200 km in 12 watersheds of the interior Columbia River Basin (CRB). Model outputs showed that riparian condition has been at least moderately impaired across ≈70% of the streams and rivers in Utah and ≈49% in the CRB. We found 84% agreement (Cohen's $\kappa = 0.79$) between modeled reaches and field plots, indicating that modeled riparian condition reasonably approximates on-the-ground conditions. Our approach to assessing riparian condition can be used to prioritize watershed-scale floodplain conservation and restoration by providing network-scale data on the extent and severity of riparian degradation. The approach that we applied here is flexible and can be expanded to run with additional riparian stressor data and/or finer resolution input data.

Keywords Conservation planning · Riparian restoration · Watershed condition assessment · Riparian degradation · Floodplain ecology · Columbia River Basin · Utah

Introduction

Floodplain riparian ecosystems form the ecotone between streams and rivers and the terrestrial landscapes they connect, providing important ecosystem services for humans (Castellarin et al. 2011; DeLaney 1995; Lowrance et al. 1997; Mander et al. 2005) and vital habitat for numerous plant and animal species (Baron et al. 2003; Naiman and and Decamps 1997; Naiman et al. 2000). Although floodplain riparian ecosystems (herein floodplain ecosystems) represent a small portion of earth's surface area, they provide a disproportionately large amount of ecosystem services (Costanza et al. 2016; Tockner and Stanford 2002). Intact floodplains and robust riparian vegetation attenuate

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floods (Tabacchi et al. 2000; Woltemade and Potter 1994), and play vital roles in cycling nutrients and organic matter from adjacent landscapes (Lowrance 1998), improving downstream water quality. In addition to buffering streams and rivers, floodplain ecosystems also provide recreational opportunities and essential land use functions (DeFries et al. 2004; Gren et al. 1995). Similarly, these ecosystems support especially high biodiversity (Tockner and Stanford 2002; Ward et al. 1999) and are critically important for many wildlife species that are of great conservation concern (Golet et al. 2008; Kus 1998) or high cultural or economic value (Jeffres et al. 2008). However, despite their importance, riparian ecosystems, and the streams and rivers that traverse them are among the world's most heavily degraded landscapes (Dudgeon et al. 2006; Opperman et al. 2009).

Habitat degradation and biological invasions are the two leading causes of ecosystem alteration and biodiversity loss worldwide (Fahrig 2003; Pimentel et al. 2000; Vitousek et al. 1997), and these stressors' impacts are particularly evident in floodplain ecosystems (Shafroth et al. 2002; Stohlgren et al. 1998; Tockner and Stanford 2002). Removal of native riparian vegetation, replacement of floodplain habitats with impervious surfaces, and alteration of floodplain topography by transportation infrastructure (Blanton and Marcus 2013; Hall et al. 2007) alter surface water drainage patterns (May et al. 1999) and hydrologic regimes (Booth and Jackson 1997). These hydrologic impacts subsequently alter stream channel geometry (Taniguchi and Biggs 2015) and water chemistry (Carpenter et al. 1998; Liess and Schulz 1999; Schoonover et al. 2005). Riparian forest clearing for agriculture also reduces stream shading (Allan 2004; Klemas 2014), increases stream temperature (Beschta and Taylor 1988), and removes riparian sources of large woody debris (Gurnell et al. 1995).

In the western U.S., non-native riparian vegetation, like tamarisk (*Tamarix* spp.) and Russian olive (*Elaeagnus* spp. e.g., Shafroth et al. 2002; Stromberg et al. 2007), further alters riparian habitat structure, terrestrial–aquatic linkages (Roon et al. 2014, 2016), and aquatic communities (Stella et al. 2013). Additionally, habitat degradation and biological invasions occur in tandem with larger, global phenomena like climate-induced changes to rainfall, runoff, and streamflow (Galloway et al. 2004; Ormerod et al. 2010; Poff et al. 2002). Moreover, biocontrol efforts undertaken to control invasive woody vegetation can have unforeseen consequences. For example, since the tamarisk beetle (*Diorhaba* spp.) was released in 2001, it has caused widespread tamarisk defoliation and decline throughout the Colorado River Basin (Bloodworth et al. 2016). This reduction in tamarisk cover has helped restore habitat for some native shrub and tree species. However, where tamarisk has declined and hydrology has remained altered, limited woody vegetation has replaced tamarisk, reducing habitat abundance for wildlife species who rely on tamarisk for habitat (Bloodworth et al. 2016). Nevertheless, the cumulative effects of biotic and anthropogenic impacts have resulted in significantly different riparian and instream habitats than those in which many native fish and riparian fauna evolved (May et al. 1999). These alterations reduce native species abundance and diversity (Rolls and Arthington 2014; Royan et al. 2015) and decouple important linkages between biological communities and their habitats (Foley et al. 2005; Hooper et al. 2005).

Floodplain degradation associated with riparian vegetation change (Macfarlane et al. 2016a), intensive land use (Allan 2004), and transportation infrastructure (Blanton and Marcus 2013; Forman et al. 2002) is common across western North America, yet regional assessments of how these stressors align to adversely impact reach-scale riparian condition are rare. We attribute this to several factors: (1) methodological limitations of combining multiple stressors at the regional scale (Goetz 2006); (2) lack of confidence in using nationally available land cover data to assess riparian condition (Johansen and Phinn 2006); and (3) the cost prohibitive nature of using high-resolution imagery at large spatial scales (Salo et al. 2016).

Consequently, riparian ecosystem degradation studies often examine only small landscapes or isolated causes of degradation (e.g. Hough-Snee et al. 2013). This lack of comprehensive riparian condition data challenges resource managers tasked with restoring large floodplain ecosystems, often entire watersheds, leaving them with only locally available data on how and where multiple stressors have impacted these ecosystems.

In an effort to improve river and riparian management, valley bottom mapping (Gilbert et al. 2016) and reach scale vegetation change inventories have been produced for all perennial streams' valley bottoms within the state of Utah and across several interior Columbia River Basin (CRB) watersheds (Macfarlane et al. 2016a). While Macfarlane et al. (2016a) cataloged the extent to which valley bottoms have been impacted by non-native vegetation and upland encroachment, their analysis did not directly account for the impacts of land-use intensity and floodplain fragmentation on riparian ecosystems. Given the importance of functional riparian ecosystems to fish and wildlife populations, the enormous extent of riparian degradation across the western U.S. (Kauffman et al. 1997), and a general lack of riparian condition information in many regions, riparian assessments that account for these additional stressors are increasingly important for sustainable watershed management.

We developed a spatially explicit framework for assessing riparian condition that can be used for reach-level conservation and restoration planning across broad geographic areas (Harris and Olson 1997). Our objectives were to (1) develop a generic model that can use either relatively coarse *or* high-resolution land cover, transportation infrastructure, and land-use data to assess riparian condition, and (2) demonstrate the model's utility in a western U.S. context, applying the model using relatively coarse, nationally available data to assess riparian condition across a large range of physiographic settings in both the state of Utah and the CRB, USA.

Methods

Study Locations

We focused the *riparian condition assessment* (RCA) tool on perennial streams across Utah (≈25,600 km), and within 12 CRB watersheds that are of fisheries management and restoration concern (Fig. 1). Watersheds within the CRB included the John Day and Upper Grande Ronde in Oregon, the Tucannon, Entiat, Wenatchee, and Asotin in Washington, and the Upper Salmon, Yankee Fork, Lemhi, Lochsa, Lower Clearwater, and South Fork Clearwater in Idaho (totaling ≈27,200 km of streams). These watersheds occur in the Columbia Plateau Physiographic Province (Vigil et al. 2000) which includes a diverse range of mountains, plateaus, canyons, and rolling hills (Fig. 1). The CRB effort was part of the Columbia Habitat Monitoring Program (CHaMP; http://champmonitoring.org) which tracks the status and trend of anadromous salmonid habitat throughout the CRB (Bouwes et al. 2011).

Utah is a physiographically diverse landscape covering 219,808 km^2 that range from alpine meadows to desert canyons, with riparian conditions varying widely based on physical setting and management history. The state of Utah includes three primary physiographic regions, each with unique topographic, geologic, and geomorphic characteristics: the Colorado Plateau, the Basin and Range, and the Middle Rocky Mountains (Vigil et al. 2000). Utah's elevation ranges from 664 m at Beaver Dam Wash in southwestern Utah to 4123 m on King's Peak in the Uinta Mountains. Utah provided an ideal range of landscapes across which we could test the robustness of an RCA approach.

Differentiating Valley Bottom Setting

By definition, a valley bottom is composed of active and inactive stream channels and their floodplains (Fryirs et al. 2016; Wheaton et al. 2015). Fryirs and Brierley (2013) used the position of the channel on the valley bottom floor to define ranges of confinement that differentiate valley bottom settings. This includes confined, partly confined and laterally unconfined. Differentiation of these valley bottom settings reflects the position of the channel relative to the valley bottom margin, indicating how often and over what distance the channel impinges on that margin. In our classification, a confined valley settings is where the channel abuts a confining margin greater than 85% of its length, a partly confined valley setting is where the channel abuts a confining margin 10–85% of its length, and a laterally unconfined valley setting is where the channel abuts a confining margin less than 10% of its length.

In our RCA we treated streams with *confined* valley bottom settings differently than streams with partly confined and unconfined valley bottom settings (hereafter both referred to as unconfined) because confined streams lack a floodplain (Wheaton et al. 2015), have limited space to grow riparian vegetation, and are difficult to detect from medium-resolution satellite imagery (Macfarlane et al. 2016a). Consequently, confined reaches were assigned to one of two categories: *confined-impacted* or *confined-unimpacted*. A reach was considered *impacted* if there was a *detectible* reduction in vegetation or conversion of land or transportation infrastructure within the valley bottom.

To separate confined from unconfined streams within the model's automated workflow, we used valley bottom width as a proxy for confinement, defining an adjustable valley bottom-width threshold parameter that represents valley bottom width in meters (which was calculated automatically for each reach). To calibrate the valley bottom-width threshold, we calculated valley bottom confinement using the approach outlined in Fryirs et al. (2016) and the *confinement tool* developed in O'Brien et al. (In Revision). For each watershed, the total length of confined streams was calculated using the *confinement tool*. These length values were used to calibrate the valley bottom-width threshold. Specifically, for each watershed within the study area, the valley bottom-width threshold was adjusted until the resulting stream lengths matched the confined streams lengths as calculated by the *confinement tool*.

Riparian Condition Assessment

The RCA tool identifies riparian condition across valley bottoms. We split valley bottoms into a series of Thiessen polygons with centroids located at the midpoint of each 500-m stream segment (Fig. 2). Thiessen polygons were chosen for this process because their geometric properties guarantee that all points within a polygon are closer to that polygon's centroid than to any other polygon (Esri 2016b). This ensures that land cover and land use adjacent to the reach are attributed to the correct stream segment, even when working with irregular planform geometries and valley bottoms.

Riparian condition was summarized in the resulting analysis polygons (Fig. 2) using an algorithm based on lines of evidence that include: (1) riparian vegetation departure

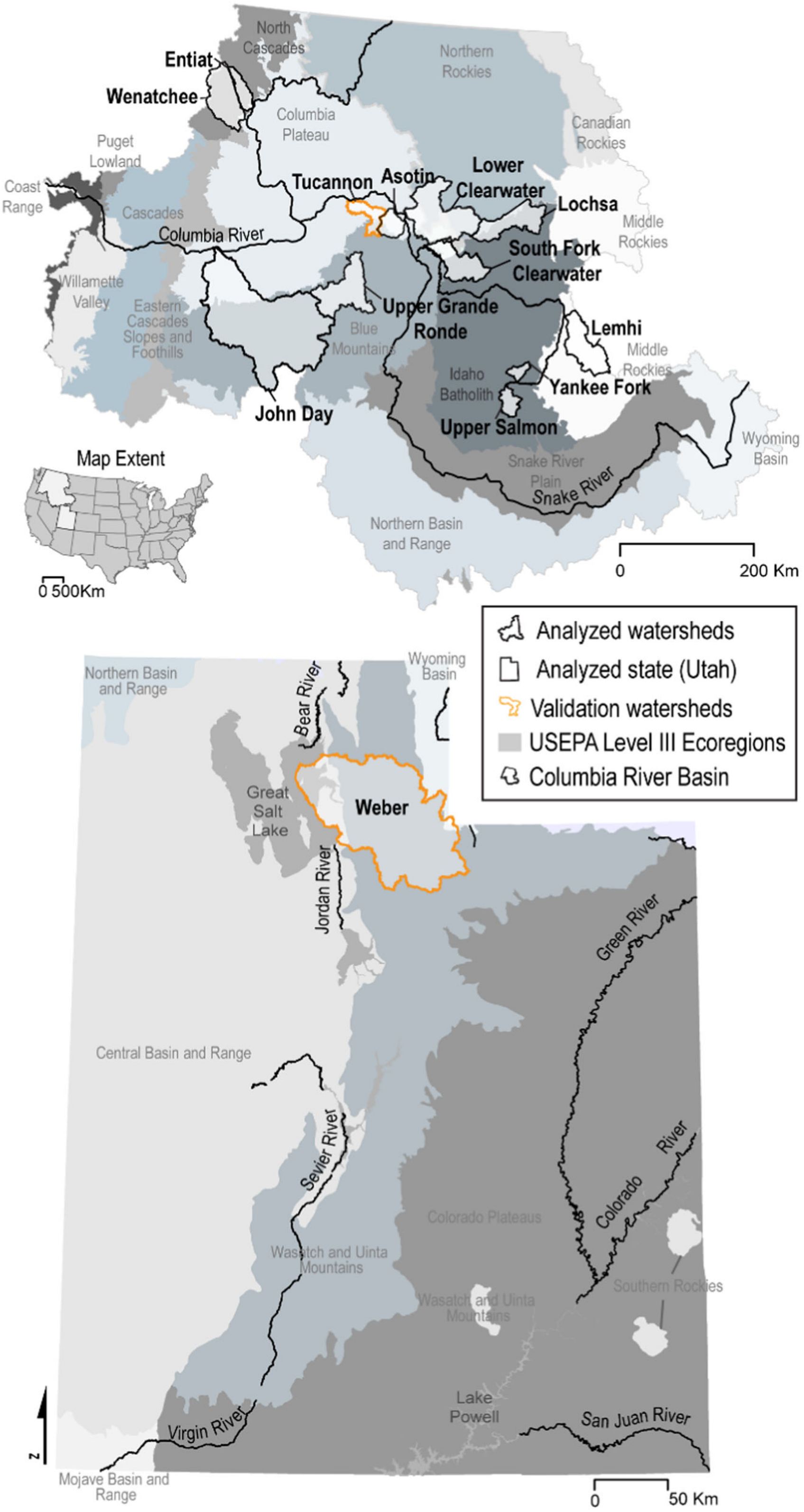

Fig. 1 Study locations within the state of Utah and 12 interior Columbia River Basin watersheds of fisheries management concern. These are mapped over US Environmental Protection Agency Level III Ecoregions for additional context

(RVD) from historic condition, (2) land-use intensity, and (3) impediments to floodplain accessibility caused by transportation infrastructure (e.g., raised grades; Blanton and Marcus 2013). Each drainage network segment was attributed with continuous values for each line of evidence. The lines of evidence were combined using an FIS to

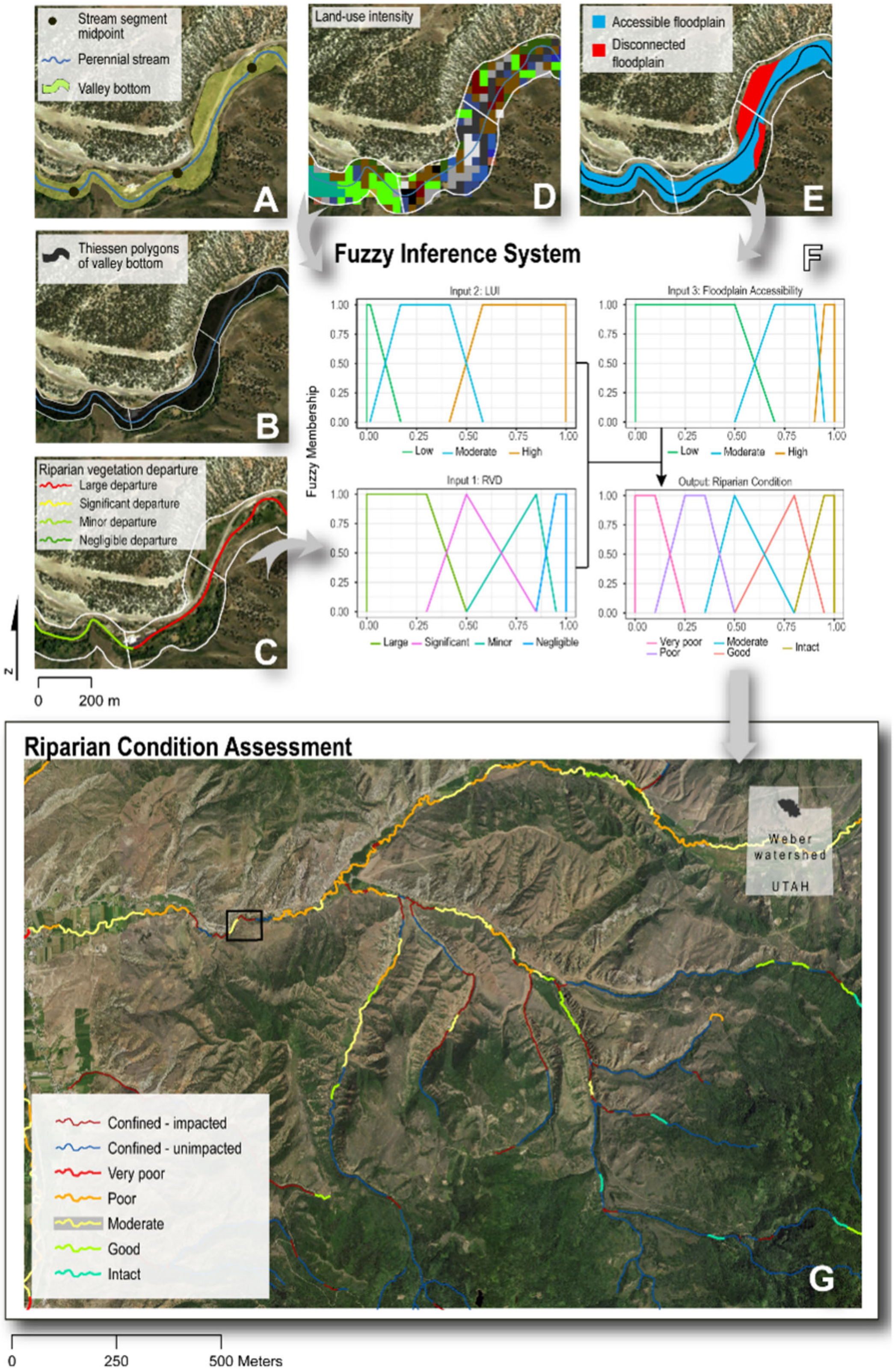

Fig. 2 Conceptual diagram of *riparian condition assessment* (RCA) tool showing how midpoints of a drainage network (**a**) are used to generate Thiessen polygons (**b**). Riparian vegetation departure index outputs (**c**) are combined with land-use intensity (**d**) and floodplain accessibility outputs (**e**) within a Fuzzy Inference System (**f**) to produce a segmented drainage network containing riparian condition assessment scores (**g**)

collectively estimate riparian condition based on a linguistic, expert-based rule system (Fig. 2).

RVD Index

To assess riparian vegetation condition, we used the RVD index (Macfarlane et al. 2016a). The RVD index calculates riparian vegetation's departure from its historic condition as the ratio of current vegetation cover to estimated historic riparian vegetation cover. Both existing and historic vegetation that occurred as native riparian vegetation were coded as '1' while invasive and upland classes were coded as '0.' For each polygon, the mean vegetation value was calculated which represents the proportion of native riparian cover within each polygon. The area of native riparian cells, within the analysis polygons, modeled in the historic vegetation input was used as the denominator in the RVD ratio, and the area of native riparian cells modeled in the existing vegetation input was used as the numerator. Low values (closer to 0) signify larger departures from historic riparian vegetation condition whereas high values (closer to 1) signify small departures.

Assessment of Land-Use Intensity

We classified land-use intensity along a continuum from zero to one where one is highly altered and zero is unaltered using 2012 LANDFIRE EVT data (Table S1). Urbanization, a land use that often dramatically and permanently alters riparian ecosystems by covering floodplains with impervious surfaces, corresponds to a land-use intensity score of one (highly altered). Agriculture, which modifies floodplain vegetation and disturbance regimes, corresponds to a land-use intensity score of 0.33 to 0.66, depending on the intensity (0.33 for pastoral use; 0.66 for row crop). Areas that have no defined land-use were scored as zero (unaltered). To attribute input network segments with a land-use intensity value, we calculated the mean of land-use intensity values for all cells within each analysis polygon, resulting in a continuous value between zero and one that was attributed to the corresponding drainage network segment.

Assessment of Floodplain Accessibility

The RCA tool is designed to characterize floodplain accessibility similar to Blanton and Marcus (2013), using a transportation network layer that includes roads and railroads as line features. We overlaid the transportation network on the valley bottom polygon and split the polygon at each location where a road or railroad occurred. These splits separated the valley bottom into portions where the river has the potential to inundate the floodplain at flood stages and portions where the river's access to the floodplain has been eliminated or severely reduced by elevated railroad and road grades. It is possible to extend the inputs for this analysis with other infrastructure like levees, but we excluded these from our analysis due to lack of nationally consistent data. We generated the floodplain accessibility analysis automatically using a geoprocessing method and visually inspected results to ensure that all disconnected areas were identified. We made additional manual splits where lateral connectivity was misclassified by automated geospatial analyses (Figure S2). For each analysis polygon, we calculated the proportion of floodplain that is accessible by the river channel as a ratio from zero (completely disconnected) to one (completely connected), and the corresponding drainage network segment was attributed with that value. The specific geoprocessing steps are described in Appendix A.

Fuzzy Inference Systems to Score Riparian Condition

We used an FIS to combine the three lines of evidence to estimate riparian condition over our study areas' drainage networks (Fig. 3). The FIS provided a consistent and repeatable framework for combining continuous variable inputs to produce a continuous output. Categorical ambiguity and uncertainty among categories were explicitly accounted for using fuzzy logic and by representing all inputs and outputs as continuous variables with overlapping membership functions for each category (Openshaw 1996; Zadeh 1996). The FIS also allowed for 'computing with words,' whereby the three lines of evidence were mathematically combined based on an expert-based rule system (Table 1) using continuous numeric inputs that provided continuous numeric outputs (Adriaenssens et al. 2003; Klir and Yuan 1995). The FIS framework is also flexible and expandable and can easily accommodate additional lines of evidence for evaluating floodplain condition if such data are available.

Within the FIS RVD, land-use intensity, and floodplain accessibility scores were divided into categories. RVD scores were split into four categories: *large, significant, minor*, and *negligible* departure, under the framework of (Macfarlane et al. 2016a). Both land-use intensity and floodplain accessibility scores were split into three categories: low, moderate, and high. For each combination of input category scores, a corresponding rule was created to determine the output value range and associated categories (Table 1). The range of output values was split into five different categories of riparian condition: very poor, poor, moderate, good, and intact (Fig. 3). For each input stream segment, membership in each output category was calculated, and a final value attributed to the segment, using the centroid defuzzification method (Mathworks 2017).

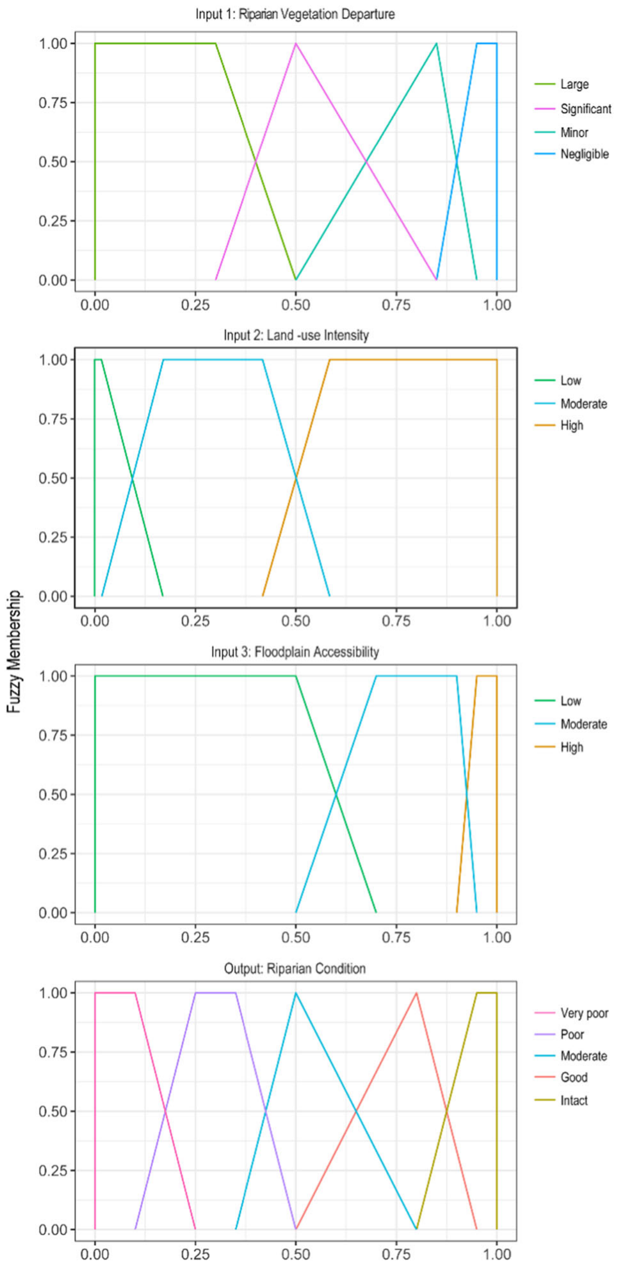

Fig. 3 Fuzzy Inference System for *riparian condition assessment* (RCA) tool. This shows the specification of fuzzy membership functions with overlapping values for categorical descriptors in inputs and outputs

Case Study Application and Validation

Case study data inputs

Segmented drainage network For our analyses we trimmed the U.S. Geological Survey (USGS) National Hydrography Dataset (NHD), a cartographically derived 1:24,000 drainage network (USGS 2016), to perennial streams and rivers (Table 2). We segmented the resulting perennial drainage network longitudinally into 500 m long segments. This was a reasonable length along which to sample 30 m LANDFIRE land cover and land-use data and floodplain accessibility. The 500 m reach length used here is also an ideal resolution for conservation and restoration planning at large spatial scales (Wheaton et al. 2017).

Valley bottom polygon We used the Valley Bottom Extraction Tool (V-BET; Gilbert et al. 2016) with additional manual editing to delineate valley bottoms across the study areas. V-BET requires three inputs: a digital elevation model (DEM), a drainage network, and a flow accumulation raster in which the value for each cell represents the upstream drainage area (in km^2). For this regional application, we used USGS National Elevation Data (NED) 10 m DEMs (Gesch et al. 2009) and NHD 1:24,000 scale dataset (USGS 2016) as the drainage network. V-BET is based on the assumptions that: (1) valley bottom width is a function of upstream drainage area, with wider valley bottoms corresponding, crudely, to larger upstream drainage area (Montgomery 2002; Nardi et al. 2006); (2) the average slope of a valley bottom is related to upstream drainage area; the larger the drainage area, the flatter the valley bottom (McNamara et al. 2006; Montgomery 2001; Schorghofer and Rothman 2002; Tucker and Bras 1998; Willgoose et al. 1991); and (3) valley bottoms are relatively flat areas with margins often defined by abrupt changes in slope (Gallant and Dowling 2003).

In our application areas, streams with drainage area of less than 25 km^2 were generally confined headwater streams, those streams with drainage area in the 25–250 km^2 range were in a transition zone where valleys widened and slopes decreased and those with drainage area greater than 250 km^2 were generally larger rivers or tributaries in alluvial valleys. Following the aforementioned assumptions, V-BET delineates valley bottoms for these different types of river reaches distinguished by drainage area using varying thresholds for valley width and slope. The larger rivers in alluvial valleys are delineated using higher maximum valley width and lower slope thresholds, whereas the valley bottoms of confined headwater reaches are delineated using narrow maximum width and relatively higher slope thresholds.

RVD index layer We calculated RVD from historic condition using the RVD index (Macfarlane et al. 2016a). In this application, Landsat imagery classification of existing land cover (LANDFIRE EVT; LANDFIRE 2016a) and a modeled estimate of pre-European settlement land cover (LANDFIRE BpS; LANDFIRE 2016b) were used to characterize riparian vegetation condition at a given 500 m reach. LANDFIRE EVT vegetation map units are a mixture of the following: ecological systems (defined as “groups of vegetative associations that tend to co-occur within

Table 1 Rule table for three input fuzzy inference system that models riparian condition using riparian vegetation departure, land-use intensity within the valley bottom, and floodplain accessibility due to transportation infrastructure

	If	Inputs						Output
		Riparian vegetation departure		Land-use intensity		Floodplain accessibility		Riparian condition
Rules	1	Large	&	Low	&	Low	, then	Poor
	2	Large	&	Low	&	Moderate	, then	Poor
	3	Large	&	Low	&	High	, then	Moderate
	4	Large	&	Moderate	&	Low	, then	Poor
	5	Large	&	Moderate	&	High	, then	Poor
	6	Large	&	High	&	Low	, then	Very Poor
	7	Significant	&	Low	&	Low	, then	Moderate
	8	Significant	&	Low	&	Moderate	, then	Moderate
	9	Significant	&	Low	&	High	, then	Good
	10	Significant	&	Moderate	&	Low	, then	Poor
	11	Significant	&	Moderate	&	High	, then	Moderate
	12	Significant	&	High	&	Low	, then	Poor
	13	Minor	&	Low	&	Low	, then	Moderate
	14	Minor	&	Low	&	Moderate	, then	Good
	15	Minor	&	Low	&	High	, then	Intact
	16	Minor	&	Moderate	&	Low	, then	Moderate
	17	Minor	&	Moderate	&	High	, then	Moderate
	18	Minor	&	High	&	Low	, then	Poor
	19	Negligible	&	Low	&	Low	, then	Moderate
	20	Negligible	&	Low	&	Moderate	, then	Good
	21	Negligible	&	Low	&	High	, then	Intact
	22	Negligible	&	Moderate	&	Low	, then	Moderate
	23	Negligible	&	Moderate	&	High	, then	Good
	24	Negligible	&	High	&	Low	, then	Poor
	25	Any value	&	Moderate	&	Moderate	, then	Moderate
	26	Any value	&	High	&	Moderate	, then	Poor
	27	Any value	&	High	&	High	, then	Moderate

landscapes with similar ecological processes, substrates, and environmental gradients" (Comer et al. 2003)), aggregations of ecological systems for LANDFIRE purposes (e.g. riparian systems or sparsely vegetated systems) (Rollins 2009), and US National Vegetation Classification alliances (Grossman et al. 1998). For example, the Rocky Mountain Subalpine-Montane Riparian Shrubland class consists of montane to subalpine riparian shrublands occurring as narrow bands of shrubs lining streambanks and alluvial terraces in narrow to wide, low-gradient valley bottoms. The dominant shrubs include *Alnus incana, Betula glandulosa, Betula occidentalis, Cornus sericea, Salix bebbiana, Salix boothii, Salix brachycarpa, Salix drummondiana, Salix eriocephala, Salix geyeriana, Salix monticola, Salix planifolia,* and *Salix wolfii* (http://explorer.natureserve.org/servlet/NatureServe?searchSystemUid=ELEMENT_GLOBAL.2.722841). Although used primarily for wildland fire behavior mapping, LANDFIRE map units were also designed to be useful for applications such as habitat analysis and sustainable natural resource planning (Rollins 2009). We chose LANDFIRE data because of the thorough national coverage, consistent collection methods and accessible documentation.

Land-use layer We used the 2012 LANDFIRE EVT layer to derive a land-use intensity layer (see above).

Manually created floodplain connectivity layer Transportation layers from the TIGER dataset (US Census Bureau 2016) were used to fragment the associated floodplains of the valley bottoms within our study areas.

Accuracy assessment analysis

A critical component of any geospatial modeling exercise is a rigorous, ground-based accuracy assessment. Because RCA outputs are summarized in an ordinal-scale that is based on a composite score, we chose to validate the

Table 2 Input data used to represent the lines of evidence of *riparian condition assessment* (RCA) tool

Input data	Criteria	Source
Riparian Vegetation Departure (RVD) index output	Riparian vegetation condition	http://www.sciencedirect.com/science/article/pii/S0301479716308489
LANDFIRE 2012 (EVT)	Land-use intensity	LANDFIRE land cover data http://www.landfire.gov/
Roads	Transportation infrastructure	TIGER https://www.census.gov/geo/maps-data/data/tiger.html
Railroads	Transportation infrastructure	TIGER https://www.census.gov/geo/maps-data/data/tiger.html
Valley Bottom Extraction Tool (V-BET) output	Valley bottom delineation	http://www.sciencedirect.com/science/article/pii/S0098300416301935

component model inputs (RVD index values, land-use intensity scores, and floodplain fragmentation percentage) rather than the composite output scores. We validated our model using a field accuracy assessment of: (1) existing vegetation, (2) land-use type and intensity within the valley bottom, (3) percentage of floodplain accessible to the river, and (4) types of transportation infrastructure present in the valley bottom. We validated RCA inputs in the Weber River (Utah) and Tucannon River (Washington) watersheds. We selected validation sites within the Weber River watershed using a stratified sampling approach, constrained by public access and quality of vantage point. In the Tucannon watershed, validation sites were selected using a systematic survey, stratified by USEPA Level 4 Ecoregions and whether a polygon occurred in the mainstem river or tributary streams. We conducted systematic, road-based surveys assessing road access and how well riparian extent and composition could be assessed from each potential vantage point every 1-km along roadways that traversed rivers and streams of the watershed.

To validate condition, the framework and rule table of RCA was used, but with the collected field data informing input values rather than the remotely sensed data used in the analyses. We validated floodplain accessibility and land-use intensity using field data to determine input categories. For example, if field data showed that the valley bottom was used as a pasture for livestock grazing, the segment was attributed with *moderate* land-use intensity, whereas if there was no land-use observed in the valley bottom, the segment was attributed with *low* land-use intensity. The RVD outputs were validated independently (Macfarlane et al. 2016a), and as such modeled RVD values were used in lieu of field data. After we attributed every segment with modeled values for RVD and field values for land-use intensity and floodplain accessibility, we then applied the rule set used in the automated model to determine field data based riparian condition for each segment. Finally, we directly compared condition based on field validation data to condition based on remotely sensed information. Cohen's kappa statistic (Cohen's κ) was used to measure agreement between modeled condition and field-based observations because it accounts for chance agreement and is more robust and conservative than an overall error rate (Congalton 1991).

Results

Confined Valley Settings

In Utah, nearly half (45%) of the states' perennial drainage network was classified as *confined* valley settings (i.e., those lacking floodplains), consisting predominantly of headwater streams concentrated in mountainous portions of the state (Figs. 4 and 5 and Table 3). Of the *confined* streams across the state, 26% (4,104 of 15,539 km) were classified as *impacted* vs. 74% (11,436 of 15,539 km) classified as *unimpacted* (Table 3). Similarly, the majority (64%) of the CRB watersheds perennial drainage network was classified as *confined* consisting of mostly headwater streams concentrated in the mountainous portions of the region (Figs. 6 and 7 and Table 4). Of the *confined* streams across the CRB, 17% (2891 of 17,319 km) were classified as *impacted* vs. 83% (14,428 of 17,319 km) were classified as *unimpacted* (Table 4).

Region-Wide Results

Utah-Wide Application

Across Utah, the RCA tool showed that roughly 70% of unconfined valley bottoms were in *moderate* to *very poor* riparian condition (Fig. 4 and Table 5). Floodplains of large alluvial rivers where agricultural and urban land uses are common were frequently in *poor* to *very poor* condition (Fig. 4). In contrast, *intact* and *good* condition were common in floodplain ecosystems along large to medium-sized, rivers in more remote areas of the state such as the Colorado and Green Rivers, where transportation infrastructure and intensive land uses are not common. *Moderate* condition (41%) floodplains occurred throughout the state, often corresponding to rural land use common along these river corridors.

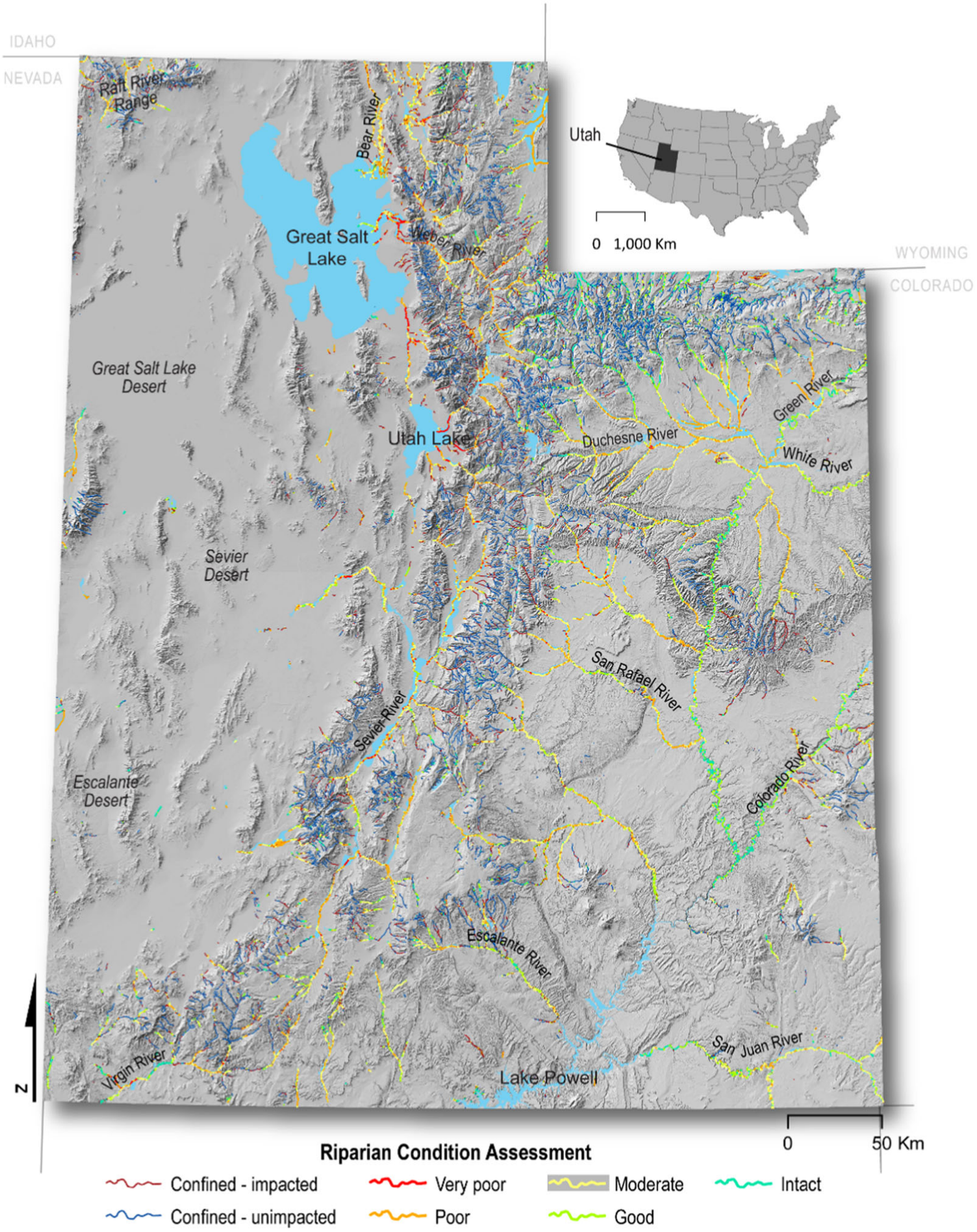

Fig. 4 Map showing *riparian condition assessment* (RCA) tool outputs across the state of Utah

Modeled riparian condition was slightly worse in Utah's western portion, including the Northern Basin and Range/Wyoming Basin and Central/Mojave Basin and Range Ecoregions compared to Utah's central (the Wasatch and Uinta Maintains) and eastern portions (the Colorado Plateaus/Southern Rockies; Fig. 8). The Central/Mojave Basin and Range Ecoregion, which has experienced widespread urbanization along the Wasatch Front, exhibited the highest proportion of *very poor* condition floodplains (8%; Fig. 8). The Northern Basin and Range/Wyoming Basin had the largest percentage of *poor* condition floodplains (42%), coinciding with high intensity agriculture. The Wasatch and Uinta Mountains and Colorado Plateaus/Sothern Rockies Ecoregions had similar riparian conditions overall, but degradation in each ecoregion was driven by different factors. In the Wasatch and Uinta Mountains, agriculture, roads, and urbanization had the greatest impacts. In contrast, in the Colorado Plateau/Southern Rockies, invasive riparian vegetation had the largest impact on riparian condition.

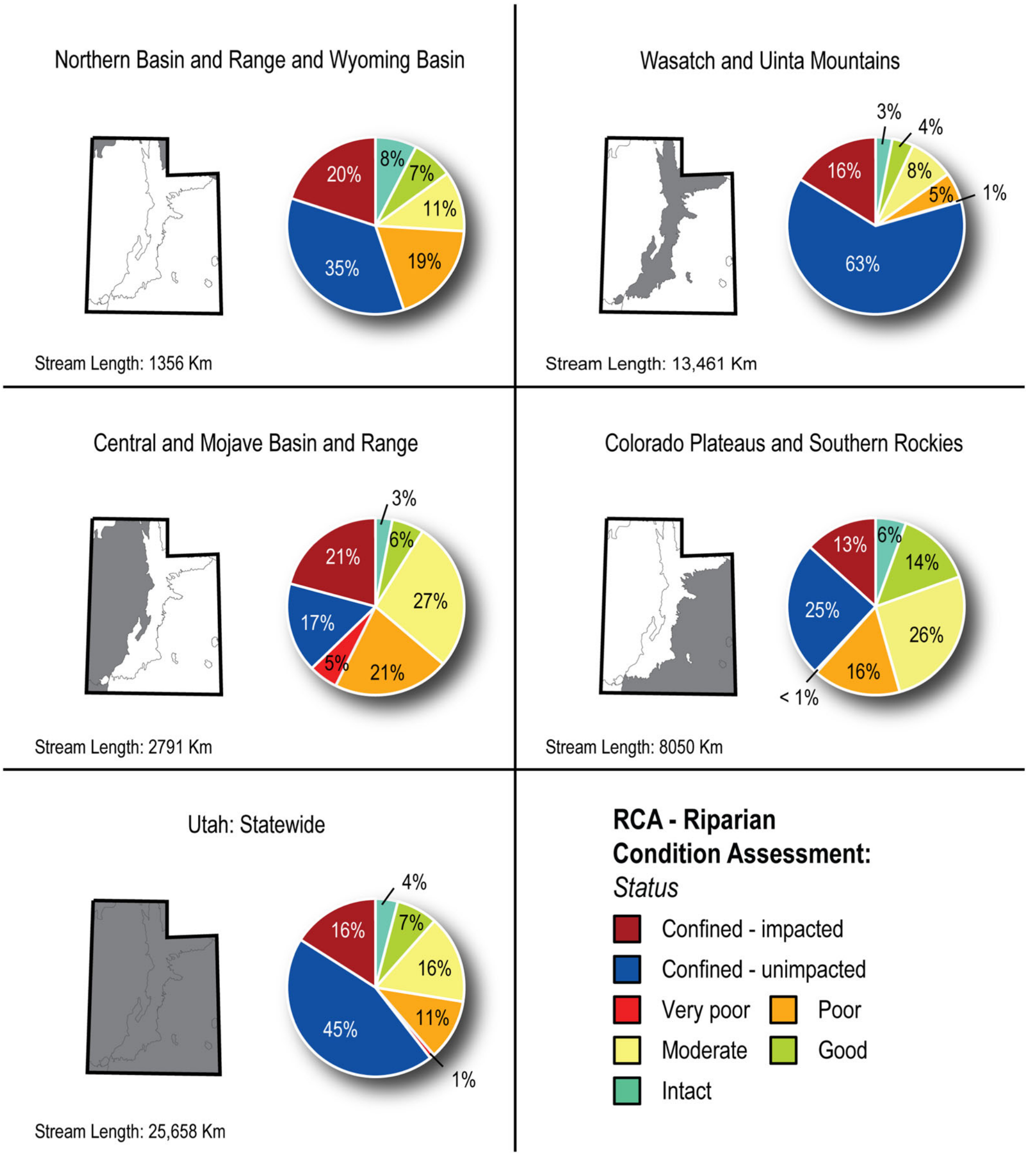

Fig. 5 Pie chart showing *riparian condition assessment* (RCA) tool outputs for *all streams* by US Environmental Protection Agency Level III Ecoregions in Utah

Table 3 Summary of the Utah statewide *riparian condition assessment* (RCA) tool for *all* streams by category

Riparian condition assessment	Stream length (km)	% of drainage network
Confined-impacted	4103.8	16
Confined-unimpacted	11,436.2	45
Very poor	211.7	1
Poor	2839.4	11
Moderate	4108.4	16
Good	1917.9	7
Intact	1040.6	4
Total	25,658	

CRB Watershed Application

Across the 12 CRB watersheds, the RCA model suggests that just under half (49%) of riparian ecosystems are in *moderate* to *very poor* condition (Fig. 6; Table 6). As in Utah, the RCA tool illustrated spatially variable patterns of riparian condition within CRB watersheds. Floodplains in *very poor* condition were rare (only 1%) and isolated to only the most developed urban areas (Fig. 6). *Poor* condition floodplains were uncommon (14%), and were evident only along large alluvial rivers where agricultural and urban land uses are common (Fig. 6). *Moderate* condition floodplains (34%) were the most widespread category in the CRB, and were found interspersed

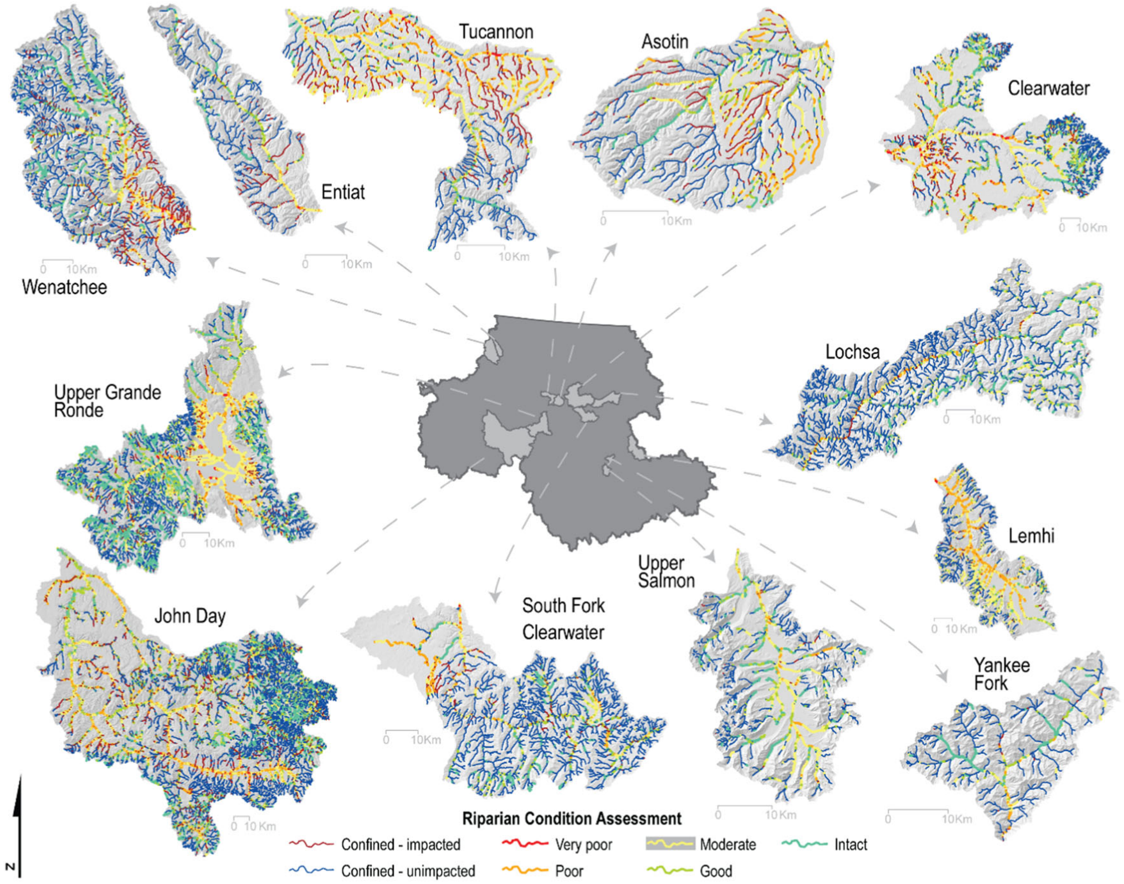

Fig. 6 Map showing *riparian condition assessment* (RCA) tool outputs across the select watersheds of the Columbia River Basin

throughout the watersheds (Fig. 6). About half (51%) of the floodplains were found to be either *intact* (31%) or in *good* (20%) condition (Fig. 9 and Table 6). Watersheds with the best condition were the Lochsa, Entiat, and Yankee Fork (Fig. 9), all relatively remote watersheds that lack urban and intensive agriculture land use and have only limited roads. The Lemhi and Tucannon were the most impacted watersheds (Fig. 9). The Tucannon watershed is dominated by intensive agriculture, which has heavily impacted riparian areas. The current riparian corridor consists primarily of only narrow streamside bands of cottonwood (*Populus trichocarpa*) and alder (*Alnus* spp.).

Validation

For ground truthing we surveyed 31 analysis polygons in the Weber watershed (Figure S4) and 61 analysis polygons in the Tucannon watershed (Figure S5). Error matrices were constructed from field assessments of riparian condition, derived from observations of transportation infrastructure and land-use intensity. Our model estimates of condition indicated a high overall level of agreement between data sources. For all streams we identified an overall map accuracy of 87% based on the 92 analysis polygons (Table 7). The calculated Cohen's κ was 0.87. Using Cohen's κ, *one* indicates full agreement and *zero* indicates complete disagreement between modeled and measured values. Thus, a 0.87 indicates an *almost perfect* agreement (Landis and Koch 1977) between modeled and field-based data.

The high accuracy when considering all streams may result from the simplicity of the binary categorization as *confined-unimpacted* or *confined-impacted* of confined streams. Therefore, we evaluated the accuracy of polygons containing only unconfined stream segments with floodplains ($n = 71$). For this subset, the overall map accuracy was 84%, and Cohen's κ was 0.79 (Table 8), indicating a 'substantial' agreement (Landis and Koch 1977). A Cohen's κ of 0.79 suggests that the RCA tool accurately estimates riparian condition for medium-sized rivers where the validation occurred (Weber and Tucannon). However, small streams with narrow bands of riparian vegetation and small patches of land use may not have the spatial extent to be resolved in 30 m datasets. In such settings, the RCA tool's accuracy is likely to be lower.

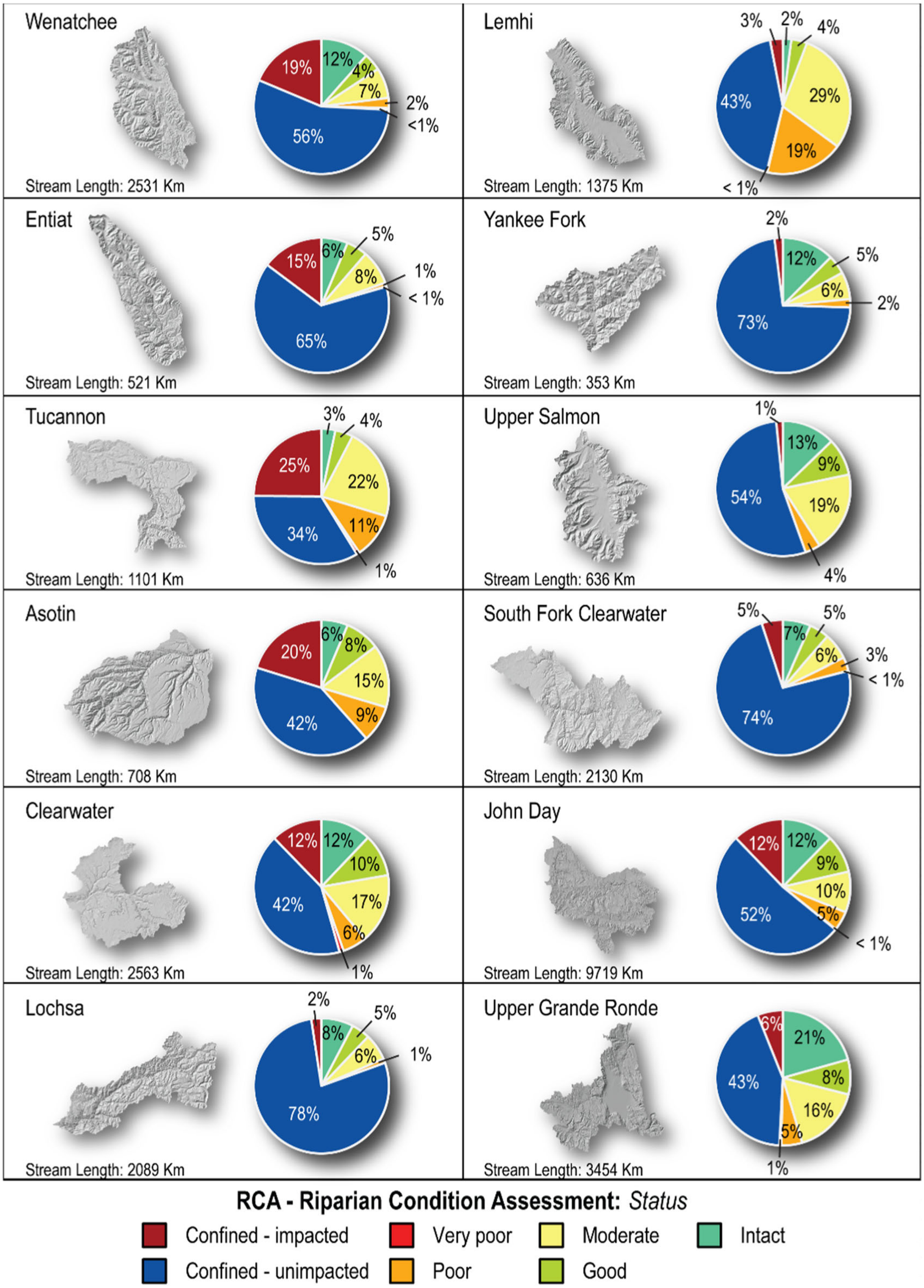

Fig. 7 Pie chart showing *riparian condition assessment* (RCA) tool outputs for *all streams* by select watersheds in the Columbia River Basin

Table 4 Summary of *riparian condition assessment* (RCA) tool outputs for *all* streams by category in the Columbia River Basin watersheds

Riparian condition assessment	Stream length (km)	% of drainage network
Confined-impacted	2891	11
Confined-unimpacted	14,428	53
Very poor	71.5	<1
Poor	1390	5
Moderate	3332	12
Good	1986	7
Intact	3080	11
Total	27,179	

Table 5 Summary of Utah statewide *riparian condition assessment* (RCA) tool for *partly confined* and *unconfined* streams by category

Riparian condition assessment	Stream length (km)	% of drainage network
Very poor	211.7	2
Poor	2839.4	28
Moderate	4108.4	41
Good	1917.9	19
Intact	1040.6	10
Total	10,118	

Discussion

Interpreting and Comparing Riparian Conditions Between Regions

One should exercise caution when interpreting and comparing riparian condition results between Utah and the CRB watersheds. The CRB watersheds of this study were not randomly selected and therefore are not an accurate representation of the larger CRB. In fact, the selected watersheds represent some of the least developed portions of the CRB, skewing the riparian condition assessment to reflect more intact conditions than likely exist elsewhere in the basin. To emphasize this point, if a Washington statewide analysis were performed, including watersheds near densely populated Puget Sound, where many watersheds have been converted to urban land uses and dense transportation infrastructures, it is highly likely that the analysis would have similar overall riparian condition to Utah. Consequently, it is not surprising that 30% of the riparian areas in Utah were classified as poor or very poor condition compared to only 15% in the watersheds analyzed in the CRB, which includes no major metropolitan areas, and that only 10% of the riparian areas in Utah compared to 31% in the CRB were classified as intact.

Land Ownership Implications for Riparian Management

Riparian management in the western U.S. is complicated by the fact that most riparian acreage is privately controlled or intermingled with other ownerships (Leonard et al. 1997). For instance, while only 21% of the state of Utah is private, 66% of the unconfined valley bottoms are privately owned. Similarly, in the CRB watersheds 41% of the total land is private while 69% of the unconfined valley bottoms are private (Fig. 10). Because of this disproportionate private ownership of riparian areas, the involvement and cooperation of private landowners, ranchers, and local, state, and federal resource managers is critical to the success of riparian management programs (Leonard et al. 1997). Moreover, riparian areas under private ownership were found to be in much poorer condition than publicly administered land (Fig. 10). Specifically, in Utah 40% of privately owned riparian areas were in poor condition vs. publicly administered lands that had only 14% of their riparian areas in poor condition. In the CRB privately owned riparian areas were found to have 21% poor vs. publicly administered land with 4% poor condition. The higher rates of degradation on private lands underscores the need to engage with private landowners through agencies such as the Natural Resources Conservation Service (NRCS) and state fish and wildlife agencies (e.g. State Departments of Natural Resources). These agencies can provide landowners with financial and technical assistance to help improve the condition of riparian areas on many working range, forest, and farmlands.

Uses, Limitations, and Future Work

While higher resolution imagery (e.g., Macfarlane et al. 2016b) and LiDAR (e.g., Johansen et al. 2010) have been successfully used to drive riparian vegetation classifications, it is often prohibitively expensive to classify large watersheds at high resolutions (Salo et al. 2016). Moreover, such inputs are not uniformly available across many parts of the U.S. Consequently, our interest was in testing the model's capacity to produce accurate results using nationwide publicly available, moderate resolution datasets. We found that even when run with these moderate resolution datasets, the RCA model produced riparian conditions that reasonably approximated actual conditions, especially in areas where transportation infrastructure, land-use intensity, and riparian vegetation conversion are important factors. This finding is similar to Lisenby and Fryirs (2017) who found that moderate resolution data were appropriate for assessing sediment connectivity at the watershed scale.

We attribute our successful model outputs using medium-resolution inputs, at least in part, to processing

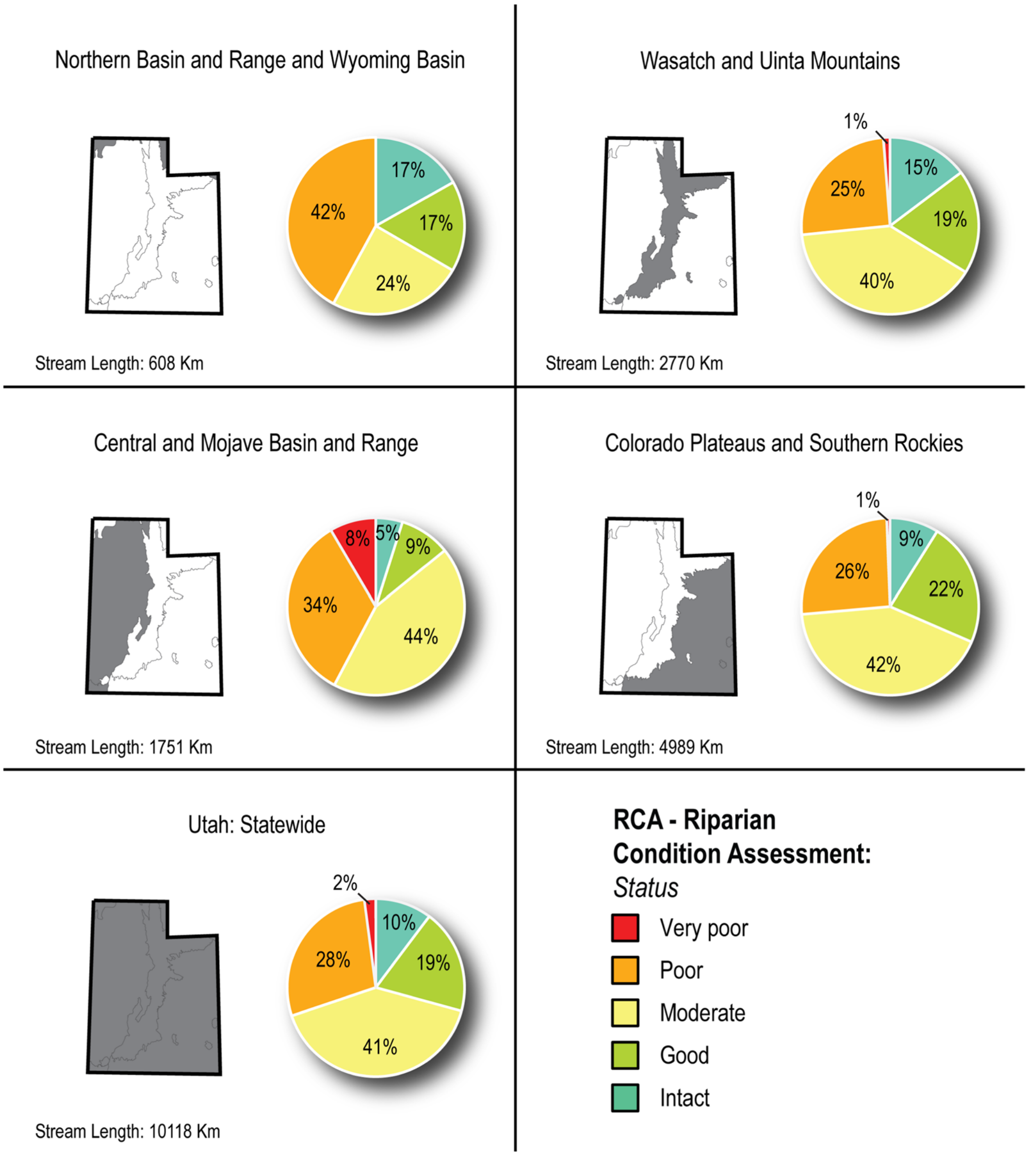

Fig. 8 Pie chart showing *riparian condition assessment* (RCA) tool outputs for *partly confined* and *unconfined* streams by US Environmental Protection Agency Level III Ecoregions in Utah

Table 6 Summary of the *riparian condition assessment* (RCA) tool outputs for *partly confined* and *unconfined* streams by category in the Columbia River Basin watersheds

Riparian condition assessment	Stream length (km)	% of drainage network
Very poor	71.5	1
Poor	1390.5	14
Moderate	3332	34
Good	1986	20
Intact	3080	31
Total	9860	

steps within our workflow that (1) aggregated land cover classes into two broad categories (native and non-native/upland) and (2) averaged condition values over 500 m reaches. Studies show that classification accuracy greatly increases when vegetation classes are lumped together (e.g., Driese et al. 2004). Nevertheless, the coarseness of the input data resulted in output data limitations. There are at least three limitations that are worth discussing: (1) 30 m land cover classifications may be too coarse to consistently capture narrow riparian areas, (2) 30 m land cover classifications may often misclassify invasive vegetation, and (3) there is uncertainty in what historic vegetation existed and at what levels of coverage.

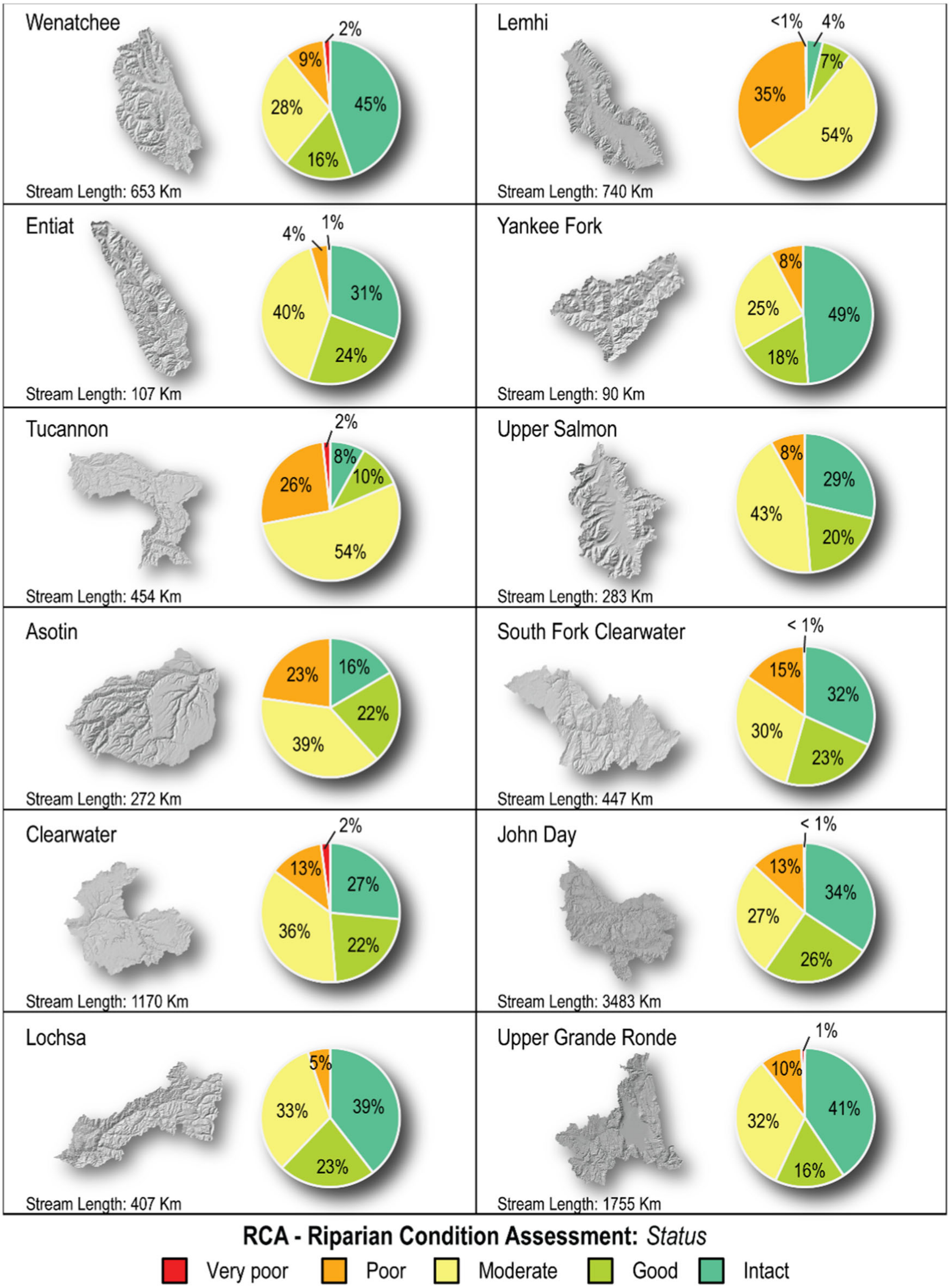

Fig. 9 Pie chart showing *riparian condition assessment* (RCA) tool outputs for *partly confined* and *unconfined* streams by select watersheds in the Columbia River Basin

In narrow, riparian corridors, 30 m spatial resolution data appear to be too coarse to adequately capture riparian condition (e.g., Congalton et al. 2002; Muller 1997). Further, because riparian areas have steep environmental gradients that produce many plant species within a short distance, a given 30 m pixel may contain a mixture of

Table 7 Error matrix and Cohen's Kappa score for *all* assessed stream reaches illustrating the agreement of ground based to modeled floodplain and riparian condition assessment

Field data	RCA model output									
	Impacted	Unimpacted	Very poor	Poor	Moderate	Good	Intact	Row total	Producer accuracy	Omission error
Impacted	**11**							11	100%	0%
Unimpacted	1	**9**						10	90%	10%
Very poor			**2**	1				3	67%	33%
Poor				**18**	2			20	90%	10%
Moderate					**21**			21	100%	0%
Good					6	**12**		18	67%	33%
Intact						2	**7**	9	78%	22%
Column total	12	9	2	19	29	14	7	92		
Consumer accuracy	92%	100%	100%	95%	72%	86%	100%			
Commission error	8%	0%	0%	5%	28%	14%	0%			
Overall accuracy	87%									
Cohen's κ	0.87									

The diagonal in bold text shows correctly modeled riparian condition

Table 8 Error matrix and Cohen's Kappa score illustrating the agreement of ground based to modeled floodplain and riparian condition assessment for *partly confined* and *unconfined* reaches

Field data	RCA model output							
	Very poor	Poor	Moderate	Good	Intact	Row total	Producer accuracy	Omission error
Very poor	**2**	1				3	67%	33%
Poor		**18**	2			20	90%	10%
Moderate			**21**			21	100%	0%
Good			6	**12**		18	67%	33%
Intact				2	**7**	9	78%	22%
Column total	2	19	29	14	7	71		
Consumer accuracy	100%	95%	72%	86%	100%			
Commission error	0%	5%	28%	14%	0%			
Overall accuracy	84%							
Cohen's κ	0.79							

The diagonal in bold text shows correctly modeled riparian condition

several plant species in various proportions producing "mixed pixels" (Zomer et al. 2009). As such, RCA outputs created using 30 m data are more reliable in wider floodplain riparian ecosystems with larger homogeneous patches of vegetation. In narrower riparian areas, higher resolution inputs may be more appropriate (e.g., Macfarlane et al. 2016b), or an on-the-ground assessment may be necessary. Fortunately, with minor modifications, the RCA tool can be run with higher resolution input data. Higher spatial resolution increases the number of "pure pixels", thus removing a large source of error (Zomer et al. 2009), allowing for finer resolution outputs. Future work will focus on running the RCA tool with higher resolution inputs where available.

In the Colorado Plateau ecoregion of Utah, where tamarisk is the dominant floodplain species (Nagler et al. 2011) land cover classifications derived from 30 m data often fail to capture the full extent of tamarisk invasions. This is especially true in narrow valley bottoms or gorges where vegetation can be hard to accurately detect in 30 m resolution satellite imagery due to shadows. We also attribute this classification failure, at least in part, to large swaths of tamarisk defoliated by the tamarisk leaf beetles. The tamarisk beetle was released as a biological control agent by the U.S. Department of Agriculture and since 2001 tamarisk leaf beetle have defoliated much of tamarisk in this area (Bloodworth et al. 2016). In the LANDFIRE's EVT classification defoliated tamarisk are often misclassified as upland classes, likely because these classes have low NDVI (greenness) values similar to those of defoliated tamarisk (Macfarlane et al. 2016b). As such, the RCA results indicate *intact* and *good* condition for some of these rivers, yet these

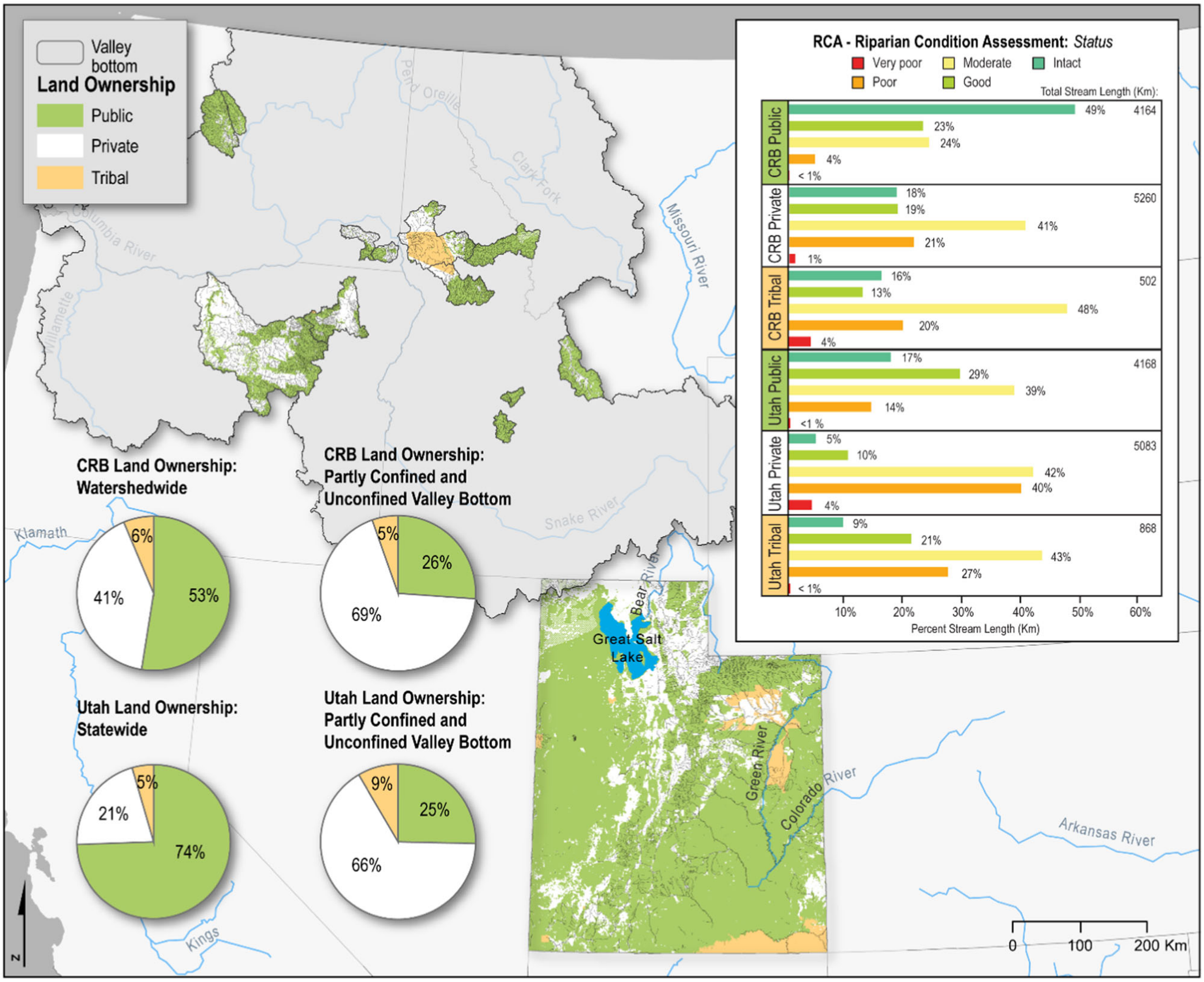

Fig. 10 Land ownership map showing percent ownership of the entire regions and for *partly confined* and *unconfined* valley bottoms along with *riparian condition assessment* (RCA) tool outputs values by ownership type

areas are dominated by tamarisk (see for example Colorado and Green Rivers Fig. 4).

RVD scores, an important input to the RCA tool, depend on how well the historic vegetation layer captures the historic coverage of native riparian communities. The LANDFIRE BpS, which we used in this study, uses a predictive modeling approach based on plot data and biophysical gradient data layers, but does not incorporate imagery (LANDFIRE 2016a). As such, historic vegetation data are inherently coarser than existing vegetation data, which is based on Landsat satellite imagery (LANDFIRE 2016a). Despite this, the RCA model outputs still provide a reliable indicator of riparian modification because the location and extent of riparian vegetation are highly predictable (i.e. adjacent to perennial waterways and in floodplains) and the level of classification needed for model application is relatively coarse (i.e. native vs. non-native riparian vegetation).

Despite precision and accuracy issues associated with running the RCA tool using medium-resolution inputs, the RCA tool outputs can be effectively applied to various river and floodplain restoration and conservation planning efforts. At the regional scale, RCA outputs can provide meaningful contextual analyses of riparian condition between watersheds. By revealing patterns of degradation, such analyses provide critical information to resources managers for prioritizing watershed conservation and restoration efforts (e.g., Corsair et al. 2009). Specifically, RCA outputs can be used to cost effectively identify areas where restoration may be ineffective owing to high floodplain fragmentation (potential sacrifice areas), areas in need of restoration that have the potential to transition toward improved condition (O'Brien et al. 2017), or to prioritize urban growth management and prevent encroachment on relatively unimpacted floodplains. Once priority restoration and conservation areas have been identified, targeted collections of higher resolution land cover and land use classifications can be utilized in these priority areas if so desired. This approach maximizes limited restoration resources by limiting the collection of costly high-resolution classifications to only where you are likely to "get the greatest return on investment".

Independent of watershed conservation and restoration planning, RCA outputs can be used for modeling and evaluating relationships between species that rely on riparian habitats for portions of their life cycles, and the condition of those riparian habitats (e.g., Decker et al. 2017). The RCA tool maps how floodplains have been altered onto drainage networks. Independently, each vegetation change, human land use, and transportation infrastructure input used in the RCA tool directly impacts riparian and aquatic species life cycles and community structure. For example, riparian birds and amphibians, as well as many fish species, are negatively affected by transportation infrastructure (Ficetola et al. 2009; Hennings and Edge 2003; Kaufmann and Hughes 2006; Rieman et al. 1997), non-native riparian vegetation (Kennedy et al. 2005; Miller et al. 2003), and riparian land use (Blair 1996; Kauffman and Krueger 1984; Martin and McIntyre 2007). Additionally, future work could include pairing predictions of riparian condition with data on hydrology (e.g., Lane et al. 2017; Wenger et al. 2010), water temperature (e.g., Isaak et al. 2016; McNyset et al. 2015), and geomorphic setting and context (Beechie et al. 2013; Kasprak et al. 2016; Wheaton et al. 2015) to conceptually understand factors that impact biological communities across river networks.

In this application, our primary intent was to develop a consistent regional analysis of riparian floodplain condition. Our selected indicators of riparian floodplain health, RVD, land use intensity, and floodplain fragmentation were well suited for this application because they could be consistently "mapped" using freely available, region-wide data. Hydrologic alterations are another important riparian condition stressor. For instance, in the Colorado River basin water withdrawals from dams and diversions reduce the magnitude, duration, and frequency of floods, which often leads to dense thickets of tamarisk along floodplains followed by rapid accretion of sediment on floodplains, resulting in channel narrowing (Dean and Schmidt 2011; Manners et al. 2014). Yet, hydrologic alteration stressors were not assessed in this analysis because dam and diversion data are difficult to use and are not regionally consistency and/or available. Nevertheless, this does not preclude the use of such data in future applications of the RCA tool because the FIS framework is expandable and can be modified to include additional inputs when and where available. In priority watersheds, where funding has allowed us to collect and analyze a suite of additional stressor data, we have developed more comprehensive watershed scale condition assessments (O'Brien et al. 2017). We plan to continue to expand the RCA tool to produce more comprehensive riparian condition assessments by including additional riparian stressors in watersheds where funding and data are available.

In an effort to examine riparian condition change over even broader spatial and temporal scales, we plan to run the RCA tool as a time-varying dynamical model over large areas such as the entire western U.S. To accomplish this, we will use Google Earth Engine in a similar fashion to Donnelly et al. (2016) and vary vegetation and land use inputs through time using historic Landsat imagery derivatives. If the model were to be run in this manner, the outputs might help measure the effectiveness of restoration actions or natural flow and climatic variability. Ideally, a time-step version of the RCA will elucidate informative patterns associated with urban development, agriculture, vegetation community shifts due to disturbance (e.g. timber harvest, fire, etc.) and impacts like browse pressure (e.g. from beaver, cattle, elk, etc.).

Conclusions

Effectively managing stream and river ecosystems requires comprehensive and accurate riparian condition data on how multiple stressors can affect floodplains. The results of the newly developed drainage network-based model that we present here provides one of the first major riparian conditions assessments across large areas of the interior western U.S. We found that the watersheds of Utah and the interior CRB were ideal settings within which to develop and test our floodplain condition assessment tool due to the diverse climate, disturbance regimes and land use histories of these regions. We also found that across our study watersheds, riparian condition is highly variable, and is often impacted by a combination of the multiple stressors we examined.

Even when using relatively coarse input data, our condition assessment provides critical information regarding the extent to which riparian areas remain intact or have been degraded. As such, these data can enhance river and floodplain restoration and conservation planning by allowing resource managers to identify the causes of riparian degradation, prioritize watersheds for conservation, target areas in need of restoration, and identify areas where restoration and conservation may be ineffective due to land use constraints. Although we were able to identify how land-use intensity, vegetation change, and valley bottom infrastructure impact floodplains across Utah and the CRB, spatially explicit, multi-stressor assessments simply do not exist for much of the world. Fortunately, the framework on which the model is built provides a foundation for broad applications elsewhere in the world where sufficient input data exist or can be collected. Moreover, the techniques are scalable to entire regions and/or could be run in smaller regions with higher resolution inputs.

Data Availability

We generated spatial data layers to enable resource management agencies, restoration practitioners, and other interested parties to access and use RCA data to inform their management decisions. The outputs of this work are publicly available at: http://rcat.riverscapes.xyz and the source code of the Riparian Condition Assessment Toolbox (R-CAT) is available at: https://github.com/Riverscapes/RCAT.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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