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Research article

Riparian vegetation as an indicator of riparian condition: Detecting departures from historic condition across the North American West

William W. Macfarlane [a,*], Jordan T. Gilbert [a], Martha L. Jensen [a], Joshua D. Gilbert [a], Nate Hough-Snee [a], Peter A. McHugh [a,b], Joseph M. Wheaton [a,c], Stephen N. Bennett [a,b,c]

[a] *Department of Watershed Sciences, Utah State University, 5210 Old Main Hill, Logan, UT 84322-5210, USA*
[b] *Eco Logical Research, Inc., Providence, UT 84332, USA*
[c] *Anabranch Solutions, LLC, Nibley, UT 84327, USA*

A R T I C L E I N F O

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A B S T R A C T

Floodplain riparian ecosystems support unique vegetation communities and high biodiversity relative to terrestrial landscapes. Accordingly, estimating riparian ecosystem health across landscapes is critical for sustainable river management. However, methods that identify local riparian vegetation condition, an effective proxy for riparian health, have not been applied across broad, regional extents. Here we present an index to assess reach-scale (500 m segment) riparian vegetation condition across entire drainage networks within large, physiographically-diverse regions. We estimated riparian vegetation condition for 53,250 km of perennial streams and rivers, 25,685 km in Utah, and 27,565 km in twelve watersheds of the interior Columbia River Basin (CRB), USA. We used nationally available, existing land cover classification derived from 30 m Landsat imagery (LANDFIRE EVT) and a modeled estimate of pre-European settlement land cover (LANDFIRE BpS). The index characterizes riparian vegetation condition as the ratio of existing native riparian vegetation cover to pre-European settlement riparian vegetation cover at a given reach. Roughly 62% of Utah and 48% of CRB watersheds showed significant (>33%) to large (>66%) departure from historic condition. Riparian vegetation change was predominantly caused by human land-use impacts (development and agriculture), or vegetation change (native riparian to invasive or upland vegetation types) that likely resulted from flow and disturbance regime alteration. Through comparisons to ground-based classification results, we estimate the existing vegetation component of the index to be 85% accurate. Our assessments yielded riparian condition maps that will help resource managers better prioritize sites and treatments for reach-scale conservation and restoration activities.

1. Introduction

In semi-arid and arid environments floodplain riparian ecosystems are often the dominant wetland elements in otherwise dry landscapes (Knopf et al., 1988), providing diverse habitats and ecosystems services. Floodplain riparian ecosystems support disproportionately diverse plant and animal communities relative to adjacent upland ecosystems, with many species occurring only at high abundance in riparian areas (Johnson et al., 1977; Knopf, 1985; Soderquist and Mac Nally, 2000). Flood dynamics and the colonization and stabilization of landforms during vegetation succession create diverse floodplain mosaics (Kleindl et al., 2015) and complex instream habitat (Hupp and Osterkamp, 1996; Kauffman et al., 1997) that support fish and other aquatic biota. Across the interior western U.S. however, many riparian areas have been altered or are threatened by human impacts that directly and indirectly impact stream hydrologic, geomorphic, and ecological processes that shape riparian vegetation (Nilsson and Berggren, 2000; Obedzinski et al., 2001).

Common impacts to riparian vegetation often include flow alteration (Poff et al., 2011) from water withdrawal, diversion or impoundment (Goodwin et al., 1997), intensive agriculture (Allan, 2004; Klemas, 2014), urbanization (Allan, 2004; Hardison et al., 2009; Paul and Meyer, 2001), fire suppression (Stone et al., 2010), invasive plant species (Shafroth et al., 2002; Stromberg et al., 2007),

* Corresponding author.
E-mail addresses: wally.macfarlane@usu.edu (W.W. Macfarlane), jtgilbert89@gmail.com (J.T. Gilbert), martaljensen@gmail.com (M.L. Jensen), joshuadgilby@gmail.com (J.D. Gilbert), nate@natehough-snee.org (N. Hough-Snee), peter.a.mchugh@gmail.com (P.A. McHugh), joe.wheaton@usu.edu (J.M. Wheaton), bennett.ecological@gmail.com (S.N. Bennett).

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beaver removal (Naiman et al., 1986), and upland species encroachment (Marlow et al., 2006). One result of human disturbance is that as flow regimes and sediment supply are altered, floodplains often become hydrologically disconnected from their channels through channel narrowing or floodplain aggradation (Pollock et al., 2014; Schumm, 1999; Simon and Rinaldi, 2006). As floodplains and channels are decoupled, riparian plant performance declines, reducing many riparian species' competitive abilities (Scott et al., 2000).

On many floodplains, the encroachment of woody invasive species (e.g. *Tamarix* spp., *Elaeagnus angustifolia*) or upland shrubs (e.g. *Juniperus* spp., *Pinus* spp.) serves as a prominent indicator of riparian habitat degradation (Harms and Hiebert, 2006; Jarnevich et al., 2011; Wang et al., 2013). Hydrologic alteration that reduces the magnitude, duration and frequency of floods, for example, often precedes the expansion of *Tamarix* along floodplains (Dean and Schmidt, 2011; Manners et al., 2014). Reduced flows and increased *Tamarisk* abundance reduce native species' physiological performance, shifting community composition further toward *Tamarisk* (Dean and Schmidt, 2011; Manners et al., 2014). When native riparian vegetation is replaced by invasive, woody species, bare, alluvial floodplain landforms can become dense thickets that rapidly accrete sediment, reducing floodplain landforms' inundation frequency and hydrologic connectivity to the channel (Dean and Schmidt, 2011; Manners et al., 2014). When mapped, these invasions manifest themselves as an increase in woody vegetation cover over historic levels (Webb and Leake, 2006). Across the interior western U.S., upland or woody invasive species' dominance is often associated with impaired flow and sediment regimes that limit native vegetation dispersal, establishment, growth and competition, reducing the amount of available native, riparian habitat (Richardson et al., 2005).

Despite widespread study of the causes and consequences of transitions from native riparian vegetation to upland or invasive species (Richardson et al., 2007), and the large number of vegetation change detection methodologies and techniques, utilizing remotely sensed data (Hussain et al., 2013), regional assessments of the magnitude and extent of riparian degradation are rare across western North America. We attribute this largely to a lack of historic data and to methodological limitations (Dunford et al., 2009; Pert et al., 2010). While researchers have used geographic information systems (GIS) to map riparian buffers (Aguiar and Ferreira, 2005; Apan et al., 2002; Pert et al., 2010), vegetation change (Piegay et al., 2009), and condition (Johansen et al., 2008), most of this research has relied on manual aerial photo interpretation or field visits at limited spatial extents (Goetz, 2006). For example, Dunford et al. (2009) mapped 174 ha of the Drone River in France, while Lawson et al. (2007) quantified vegetation change within a single Australian catchment. To understand current ecological and physical conditions and prioritize floodplains for conservation and restoration, Stella et al. (2013) noted that, "… we need to enlarge the scope of riparian studies beyond the site and reach to a true biogeographical perspective of the corridor, catchment, and regional scales."

Recent advancements in image analysis software, imagery resolution, and the availability of accurate, free GIS data, now provide opportunities to map changes in riparian vegetation composition, structure, and spatial extent at unprecedented scales (Dufour et al., 2012). These geospatial tools have evolved in parallel with similar tools for mapping geomorphic change (Wheaton et al., 2010) and mapping landforms (Gilvear and Bryant, 2016), allowing for network scale evaluation and characterization of entire stream networks, including their valley bottoms (Gilbert et al., 2016; Roux et al., 2015). These technical advances allow for unprecedented evaluation of hydrologic, geomorphic, and ecological change of entire river systems. Here, we take advantage of these advances to expand the scope of riparian condition studies to large landscapes where human land- and water-use have altered the hydrologic, physical, and ecological processes that historically supported native riparian vegetation communities. We ask two questions:

(1) *How does current riparian vegetation composition differ from historic riparian vegetation composition across the western United States?*
(2) *Where riparian vegetation has changed from its historic composition, what are the causes of this transition?*

We address these questions by assessing riparian vegetation change (departure from historic condition) across the state of Utah and within twelve watersheds of the interior Columbia River Basin (CRB). We estimate the causes of vegetation change within discrete reaches, mapped to entire drainage networks, and validate current vegetation condition using field observations. These maps of vegetation change, and its probable causes, are presented at a spatial resolution that can support both reach-level assessments of current condition and watershed-scale restoration planning.

2. Methods

2.1. Riparian vegetation departure index

The *riparian vegetation departure index* (RVD) is a ratio that is similar to the 'observed' to 'expected' ('O/E') type metrics used in environmental condition assessments (e.g., Hawkins et al., 2010). RVD characterizes riparian vegetation condition for a given stream reach as the ratio of existing vegetation to an estimation of pre-European settlement vegetation coverage (Fig. 1). To numerically calculate condition, native riparian vegetation is coded as '1' and invasive and upland classes are coded as '0' in both the existing, and pre-European settlement vegetation rasters (see supplementary materials Table S1) and condition is calculated as the ratio of current to historic native riparian coverage for a given reach.

To support reach-level assessments, we bound the lateral extent of our analysis by generating analysis polygons within the valley bottom. By definition, a valley bottom is comprised of the stream or river channel and the associated low-lying, contemporary floodplain (Fryirs et al., 2015; Wheaton et al., 2015). The valley bottom is used because it roughly represents the maximum possible extent of riparian vegetation (Ilhardt et al., 2000). Analysis polygons are generated in three steps. First, each valley bottom unit is split into a series of Thiessen polygons, with centroids located at the midpoint of each stream segment (Fig. 1). Thiessen polygons were chosen for this process because their geometric properties guarantee that all points within a polygon are closer to its centroid than to any other polygons (Esri, 2016). This ensures that vegetation adjacent to the reach is applied to the correct segment, even when working with irregular planform geometries and valley bottoms. This is similar to the concept of Notebaert and Piegay (2013) of breaking up the valley bottom into *discrete geographic objects* (DGOs) using the Fluvial Corridor Tool (Roux et al., 2015). Second, the valley bottom is buffered by the pixel resolution of the vegetation data (i.e., 30-m vegetation data is buffered by 30 m) to ensure that the relevant vegetation data is completely contained within the valley bottom in headwater reaches (Fig. 1). Finally, we clip the Thiessen polygon layer to the buffered valley bottom. The resulting polygons become the analysis features for which the RVD tool calculations are summarized (Fig. 1 and see supplementary materials Fig. S1).

Within each polygon, the mean of the values (i.e. the 1s and 0s) is calculated for both the existing and historic vegetation layers, resulting in values that represent the proportion of each polygon

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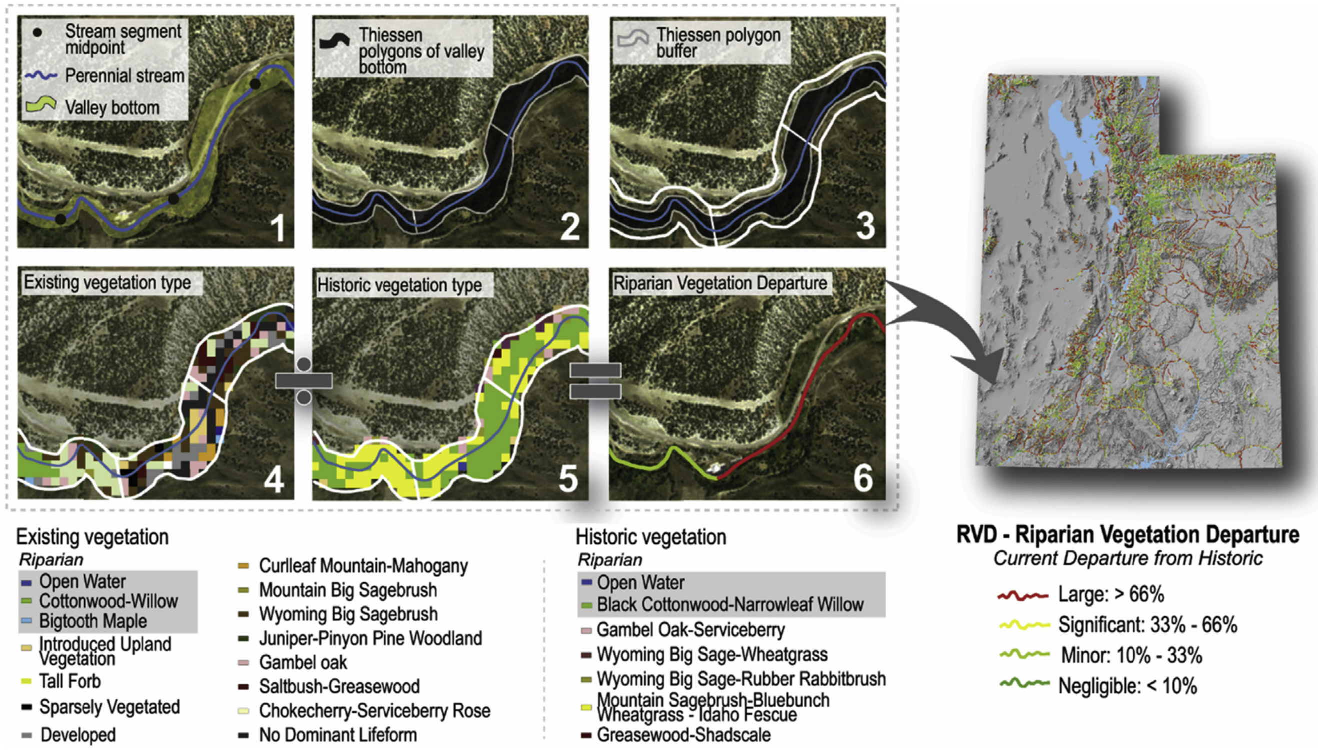

Fig. 1. A conceptual diagram of the *riparian vegetation departure index* showing how mid points of the drainage network (1) are used to generate Thiessen polygons (2) and how these polygons are buffered by the resolution of the vegetation data to ensure that vegetation data is completely contained within the valley bottom in headwater reaches (3). Riparian vegetation departure is calculated using the ratio of existing area of native riparian vegetation (4) to historic area of native riparian vegetation (5) and the output is a segmented drainage network containing riparian departure from historic condition scores (6).

with native riparian cover (Eqn. (1); Fig. 1 and see supplementary materials Fig. S1). The final processing step is to apply the RVD calculation from the analysis polygons to reach segments and divide the historic proportion by the existing proportion (Eqn. (2); Fig. 1 and see supplementary materials Fig. S1). Low values (closer to 0) signify large departures from historic riparian coverage whereas high values (i.e., approaching or exceeding 1.0) denote that riparian communities are relatively intact (or even increasing). To facilitate output display we symbolize each reach based on departure from historic cover, defined as the calculated ratio subtracted from one, which results in a percent departure (Eqn. (3)). We categorize 'negligible departure' as less than 10%, 'minor departure' 10%–33%, 'significant departure' 33%–66% and 'large departure' > 66%. The quality of this ratio depends both on the accuracy of the vegetation coverage datasets, and the appropriateness of the spatial scale (i.e., reach) at which calculations are made, relative to input data resolution.

$$M_{rip} = \frac{(0 \times 0_{tot}) + (1 \times 1_{tot})}{C_{tot}} \tag{1}$$

$$Prop = \frac{M_{ex}}{M_{hist}} \tag{2}$$

$$Dep = 1 - Prop \tag{3}$$

2.2. Riparian vegetation conversion type classification

While RVD provides a score of vegetation's departure from historic condition, it provides no information regarding the potential causes of the departure, nor does it necessarily provide a realistic target for restoration (e.g., given contemporary constraints on the system; Dufour and Piégay, 2009). The *riparian vegetation conversion type classification* (RVCT) compares existing land cover types to historic land cover types for the same location, which can provide insights into potential causes of the departure from its historic condition. Specifically, land cover classifications for the historic and existing vegetation layers are compared on a pixel-by-pixel basis to determine whether a conversion has occurred (e.g., a pixel classified as riparian in the historic layer is now depicted as agriculture in the existing layer) (see supplementary materials Fig. S1). The output network is attributed with fields containing proportions for each type of conversion (which consist of conifer encroachment, conversion to agriculture, conversion to grass/shrubland, conversion to invasive, devegetation, development and no change) for a given reach, and can be symbolized accordingly for displaying this information. Additionally, a raster output depicting change on a cell by cell basis is produced.

To determine the RVCT the existing and historic riparian vegetation rasters were coded with unique integer scores based on vegetation type; the values were assigned based on general land cover types such as riparian, conifer, and upland (see supplementary materials Fig. S2, Tables S2 and S3). For land cover classes that exist in both the existing and historic vegetation rasters, we assigned identical values (i.e. riparian vegetation types are coded as 100 in both the existing and historic land cover). Unique values were assigned to land cover types within the existing vegetation raster that did not exist in the historic (e.g. agriculture, urban, invasive vegetation). The values from the existing vegetation raster were then subtracted from the values of the historic vegetation raster, resulting in new, unique values representing specific conversion types (see supplementary materials Table S4). Within

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each Thiessen polygon, the relative proportion of each conversion type was calculated, and these values were attributed to the drainage network output with a unique field for each conversion type. For symbolization, if the proportion of "no change" for a reach was 0.85 or greater, the reach was symbolized as "no change." Otherwise, it was symbolized by the next most dominant conversion type. When symbolized with a conversion type, a reach was sub-categorized into minor, moderate or significant conversions (e.g., 'minor conifer encroachment) based on the proportion associated with the conversion. If the dominant conversion's proportion was less than or equal to 0.25, it was categorized as minor. If the proportion was between 0.25 and 0.5, it was categorized as moderate, and if it was greater than 0.5, it was categorized as significant (see supplementary materials Fig. S2). We have packaged the RVD and RVCT indexes into the RVD tool and the supplement materials to this paper provides RVD tool documentation.

2.3. Case study application and validation

2.3.1. Study locations

Our assessment of vegetation condition focused on perennial drainage networks across Utah ($\approx$25,600 km of streams), as well as twelve watersheds within the CRB. Collectively, these two regions are the focus of ongoing riparian restoration efforts that aim to improve the status of imperiled riparian and aquatic species. Focal watersheds within the CRB include the John Day and Upper Grand Ronde Oregon, the Tucannon, Entiat, Wenatchee, and Asotin in Washington, and the Upper Salmon, Yankee Fork, Lemhi, Lochsa, Lower Clearwater, and South Fork Clearwater, Idaho (totaling $\approx$27,565 km of streams). 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 and support a wide range of riparian conditions. 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 (USGS, 2016c). Elevations in Utah range from 664 m at Beaver Dam Wash in the southwestern corner of the state to 4123 m high King's Peak in the Uinta Mountains. Utah provides an ideal range of landscapes across which the robustness of a riparian vegetation departure analysis can be tested. Similarly, the CRB is comprised of the Columbia Plateau Physiographic Province (USGS, 2016c) which includes a diverse range of landscapes including mountains, plateaus, canyons, and the rolling hills and deep soils of Washington and Oregon's Palouse region (Fig. 2).

2.3.2. Case study data inputs

The segmented drainage network. We used the US Geological Survey (USGS) National Hydrography Dataset (NHD), a cartographically derived 1:24,000 drainage network (USGS, 2016b) that we reduced to perennial streams and rivers (Table 1). We segmented the drainage network longitudinally into 500 m long segments because this was a reasonable length along which to sample 30 m LANDFIRE vegetation data within the valley bottom to get a representative sample of vegetation condition. The choice of reach length here also reflects a resolution useful for conservation and restoration planning.

The valley bottom polygon. We used the Valley Bottom Extraction Tool (V-BET) with manual editing to delineate valley bottoms (Gilbert et al., 2016) (Table 1). V-BET is an ArcGIS Toolbox and the source code is downloadable at https://bitbucket.org/jtgilbert/riparian-condition-assessment-tools/wiki/Home. V-BET requires two inputs: a DEM and a polyline drainage network. For this regional application, only nationally available USGS National Elevation Data (NED) 10 m DEMs (USGS, 2016a) provided the required coverage. We used NHD cartographic 1:24,000 scale dataset (USGS, 2016b), subset to perennial streams and rivers as the drainage network.

Vegetation layers. For the existing vegetation layer we used LANDFIRE EVT 2012 Version LF_1.3.0 (the latest version available), a nationwide 30 m Landsat satellite imagery-based land cover classification (LANDFIRE, 2016a) (Table 1). For the historical vegetation layer, we used the LANDFIRE Biophysical Settings (BpS) layer (Table 1). The BpS layer is an estimation of the vegetation that may have been dominant on the landscape prior to Euro-American settlement. BpS is based on both the biophysical environment and an approximation of the historical disturbance regime (LANDFIRE, 2016b). LANDFIRE uses the Landscape Succession Model (LANDSUM) a spatially explicit vegetation dynamics simulation program where succession is regarded as a deterministic process and disturbances (e.g. fire, insects, and disease) are treated as stochastic processes (Rollins, 2009).

Zhu et al. (2006) used a cross-validation technique to determine that LANDFIRE EVT data layer accuracies were between 60 and 89% and that LANDFIRE BpS accuracies were between 64 and 67%. A study in Utah that reconstructed reference conditions for 11 forested sites based on trees present in 1880 using tree-ring data found that LANDFIRE BpS data were 58% accurate compared with the tree-ring data for each plot (Swetnam and Brown, 2010). It is important to note that this accuracy assessment was conducted for many more classes, (i.e., individual forest tree species) hence, a lower classification accuracy would be expected compared to aggregating to relevant classes (native riparian, nonnative riparian, and upland) like we have done in this study.

A large river polygon. In some cases, there are raster cells falling within valley bottoms that are not classified as vegetation, either under existing (EVT) or historic (BpS) conditions, and must be treated differently in RVD/RVCT calculations. The open water class falls into this category and, accordingly, was coded as 'No Data' in large rivers whereas it was coded as '1' outside of large rivers. This coding was determined through test runs and comparisons to field data that revealed that if all open water was classified as a '1' it overestimated departure from historic condition, but that if all open water was classified as 'No Data' it underestimated departure from historic condition. Open water cells outside of large rivers are generally single isolated cells among various vegetation classes so they do not have a large impact on the departure calculations.

2.4. Accuracy assessment analysis

We assessed the accuracy of existing vegetation layer input data by estimating how well the LANDFIRE EVT classification compared to field observations of both vegetation extent and composition (i.e., % of floodplain occupied and % native riparian vegetation). We performed field assessments in randomly selected analysis polygons in the Weber watershed of northern Utah, and systematically stratified analysis polygons in the Tucannon watershed of southeastern Washington. The surveys were stratified based on access, quality of the vantage point, and USEPA Level IV Ecoregions (EPA, 2016). The field data collection consisted of estimating native riparian cover within analysis polygons from viewpoints above the valley bottom. We surveyed 91 analysis polygons, 31 within the Weber watershed (see supplementary materials Fig. S4) and 60 within the Tucannon watershed (see supplementary materials Fig. S5).

Agreement between index-based and field-based assessments of native riparian coverage was evaluated using an error matrix

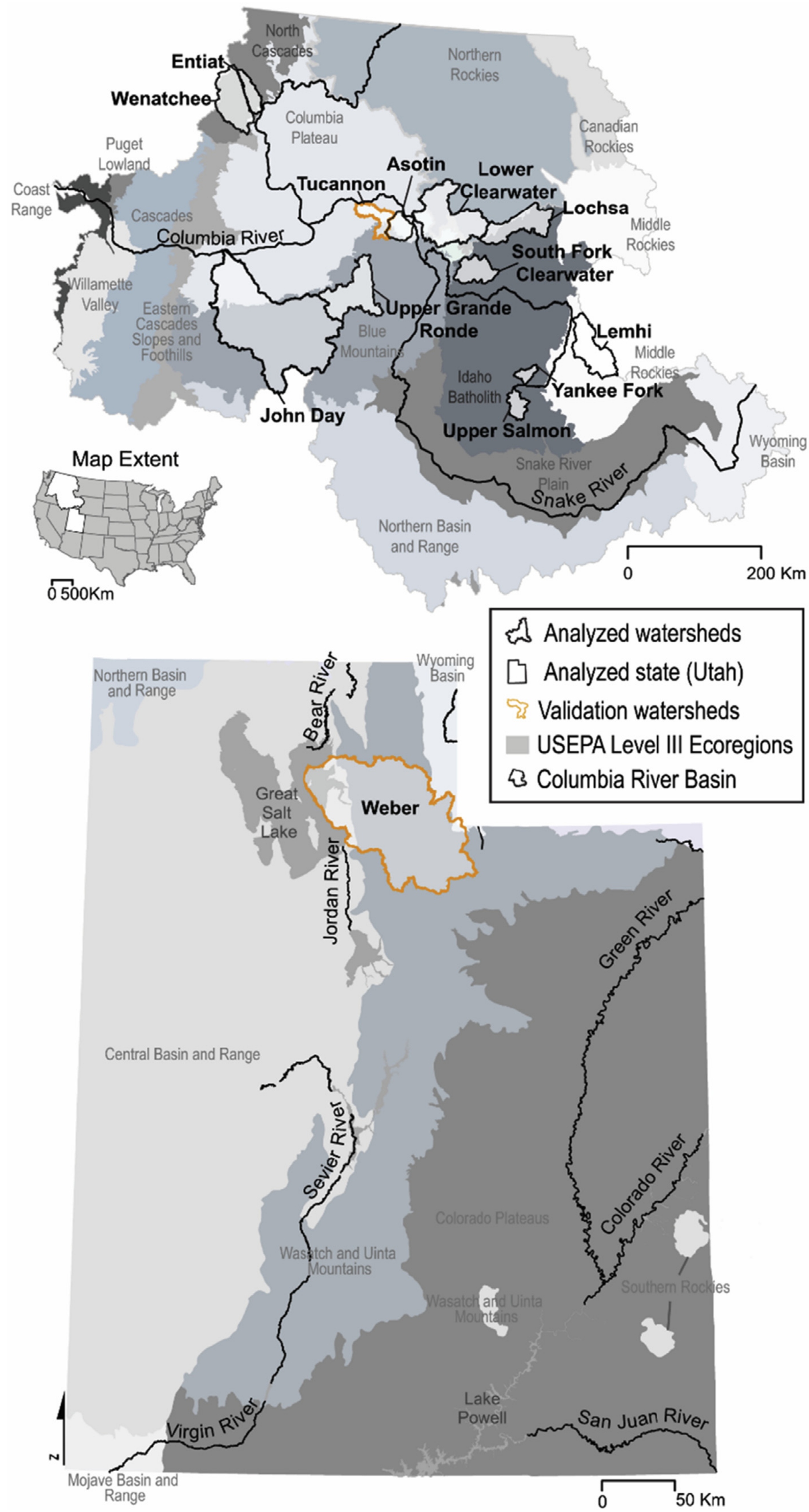

Fig. 2. Study locations map showing the state of Utah and the twelve watersheds within the interior Columbia River Basin that were assessed using the *riparian vegetation depature index* and *riparian vegetation conversion type classification*. U.S. Environmental Protection Agency Level III Ecoregions are also displayed for physiographic context.

Table 1
Input data used in the *riparian vegetation departure index*.

Input data	Criteria	Source
Segmented drainage network	Perennial streams and rivers	USGS National Hydrography Dataset Cartographic 1:24,000 scale http://nhd.usgs.gov/
Digital Elevation Model	Terrain model for delineating valley bottom	USGS National Elevation Dataset 10 m Digital Elevation Model http://ned.usgs.gov/
Valley bottom polygon	Maximum riparian extent	Valley Bottom Extraction Tool (V-BET) https://bitbucket.org/jtgilbert/riparian-condition-assessment-tools/wiki/Home
Existing vegetation LANDFIRE version LF_1.3.0 2012 (EVT)	Existing vegetation	LANDFIRE Existing Vegetation Type (EVT) data http://www.landfire.gov/NationalProductDescriptions21.php
Historic vegetation: LANDFIRE version LF_1.3.0 2012 (BPS)	Historic vegetation	LANDFIRE Biophysical Setting (BpS) depicted reference condition http://www.landfire.gov/NationalProductDescriptions20.php

(Foody, 2002). Overall accuracy was calculated as the proportion of points correctly classified by LANDFIRE EVT and Cohen's Kappa (K) statistic as a measure of ground and map agreement, adjusted for the agreement expected due to chance alone (Aronoff, 2005). Additionally, for each vegetation class consumer accuracy (% of a modeled class that mirrored the ground truth class) and producer accuracy (% of a ground truth class that the index correctly identified), as well as errors of omission (% of a ground truth class the index classified incorrectly) and commission (% of an index class that was placed into the wrong ground truth class), were calculated.

3. Results

3.1. Region wide results

3.1.1. Statewide Utah application

Across Utah, the RVD tool revealed spatially variable patterns of riparian vegetation departure from historic condition. Significant to large departures were evident for the large alluvial rivers, where agricultural and urban land uses are common (Fig. 3). Minor to negligible departures were common for the headwater streams located on public lands (Fig. 3). Roughly 38% of the drainage network throughout the state showed negligible to minor departures from historic condition while roughly 62% showed significant to large departures from historic condition (Fig. 4A and Table 2), indicating that riparian vegetation along 15,736 km of Utah's drainage network have been significantly altered since Euro-American settlement. These departure patterns are highlighted in ecoregion-level summaries, where the less populated and less intensively farmed regions showed lower departure scores. Our RVD analysis thus suggests that a majority of Utah's riparian areas are in an altered or degraded condition relative to historic conditions.

The RVCT output for Utah shows similarly variable spatial patterns of riparian vegetation conversion across the state (see supplementary materials Fig. S6) to the RVD (Fig. 3). The tool identified conversion to agriculture and developed land within the most populated portions of the state (see supplementary materials Fig. S6). Eight percent of the state's riparian areas have been converted to agriculture and 13% have been converted to ‘developed’ lands. Seven percent of the network shows conversion to invasive species, predominantly in the southern and southeastern parts of the state where tamarisk invasion is common (Fig. 4 and see supplementary materials Fig. S6). The ‘not converted’ balance (39% of all perennial riparian areas) were generally distributed throughout mountainous, headwater portions of the state's drainage network.

3.1.2. Columbia River Basin application. Across eleven of the twelve watersheds assessed within the interior CRB, the RVD tool revealed coherent patterns of riparian vegetation departure from historic condition (Fig. 5). The notable exception was the Lemhi watershed, where LANDFIRE EVT appears to model significantly less riparian vegetation than exists on the ground. As in Utah, significant to large departure was evident for the large alluvial rivers where bigger valley bottoms allow for the most intensive land uses (Fig. 5). Minor to negligible departure was common for headwater streams (Fig. 5). Roughly half (52%) of the drainage networks in assessed watersheds showed negligible to minor departure from historic condition, while roughly half (48%) showed significant to large departure from historic condition (Fig. 6A and Table 3.), indicating that riparian vegetation along 13,101 km in assessed CRB watersheds have been significantly altered since Euro-American settlement.

Across watersheds, RVD suggests riparian vegetation within the Lemhi watershed is in the poorest condition, with over 85% of assessed kilometers having a large departure from historic condition (Fig. 6A). The Tucannon showed the next largest departure with over 58% with a large departure, which likely stems from the sub-basin's location, southeast Washington's Palouse country, an intensively farmed wheat-growing region, At the low end of the impact spectrum, the John Day watershed showed the least degradation in vegetation with only 22% of assessed km showing large departure from historic condition. This may be due to the high proportion of the drainage network occupying public lands, where historic logging practices have greatly diminished and riparian areas likely show some recovery. As in other watersheds, low condition segments tend to occur predominantly along mainstem reaches within broad alluvial valleys within the John Day Basin.

The RVCT outputs highlight logical spatial patterns of riparian vegetation conversion across the CRB watersheds that largely track contemporary land uses and the degree to which the imprint of past land uses still persist (see supplementary materials Fig. S7). The tool identified conversion to agriculture and developed land along the most populated portions of the watersheds (Fig. 6B). Twenty-seven percent of the rivers throughout the assessment watersheds showed conifer encroachment. Across all watersheds, over 6% of stream segments showed conversion to agriculture, 5% showed conversion to developed and less than one percent showed conversion to invasive vegetation (Fig. 6B and see supplementary materials Fig. S6). Nearly half (46%) of the riparian areas showed no detectable conversion of vegetation type.

3.2. Accuracy assessments

Error matrices of field-observed riparian cover and LANDFIRE EVT riparian cover for the Weber (Table 4 and see supplementary materials Fig. S4) and Tucannon watersheds (Table 5 and see supplementary materials Fig. S5) indicate a high overall level of agreement. For the Weber watershed, overall exiting vegetation classification accuracy was 84%. The Cohen's Kappa (K) statistic, which ranges from 0 (no agreement) to 1 (perfect agreement) was 0.77. A K between 0.61 and 0.80 is generally taken as evidence of

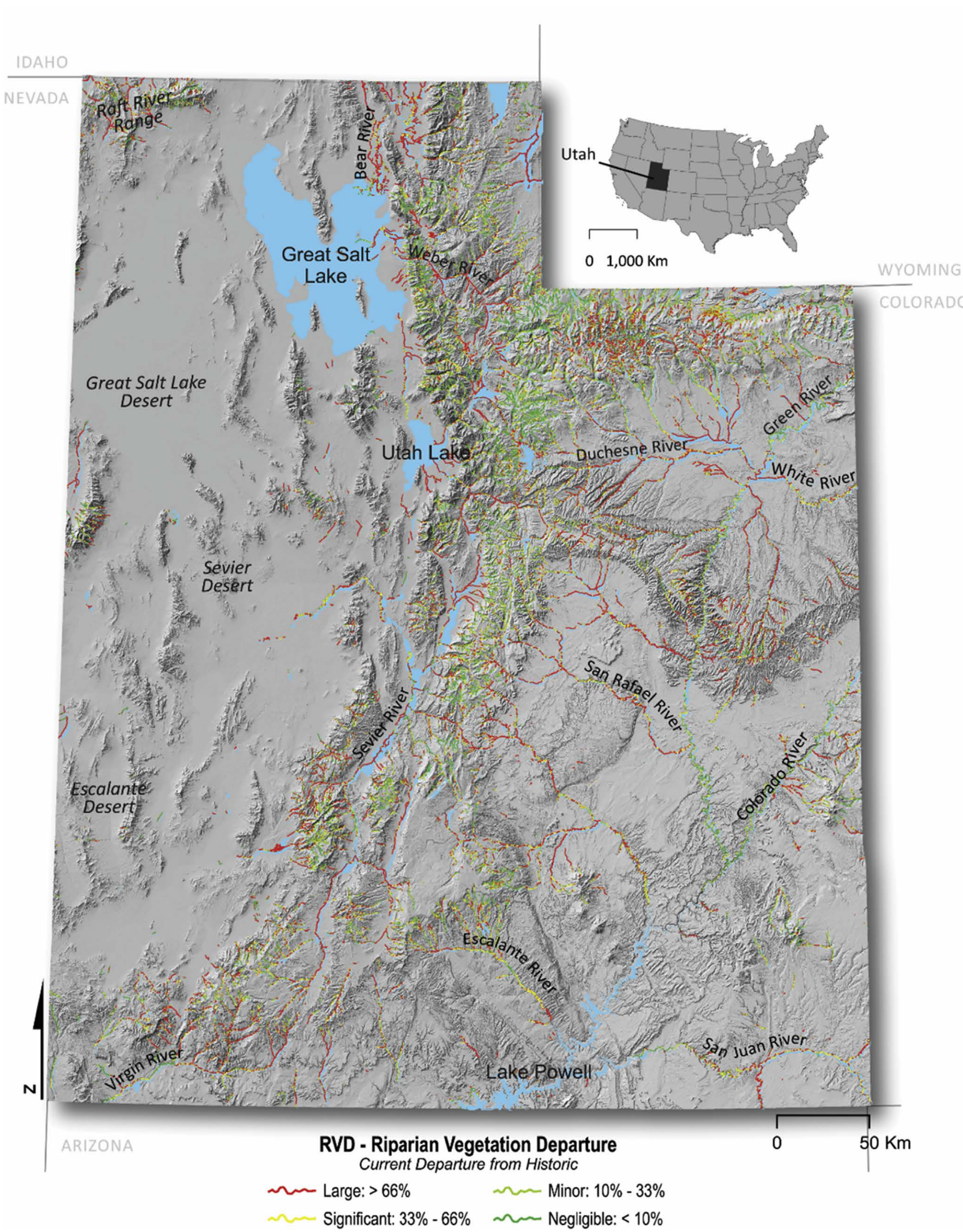

Fig. 3. Map showing the *riparian vegetation departure index* across the perennial drainage network of Utah.

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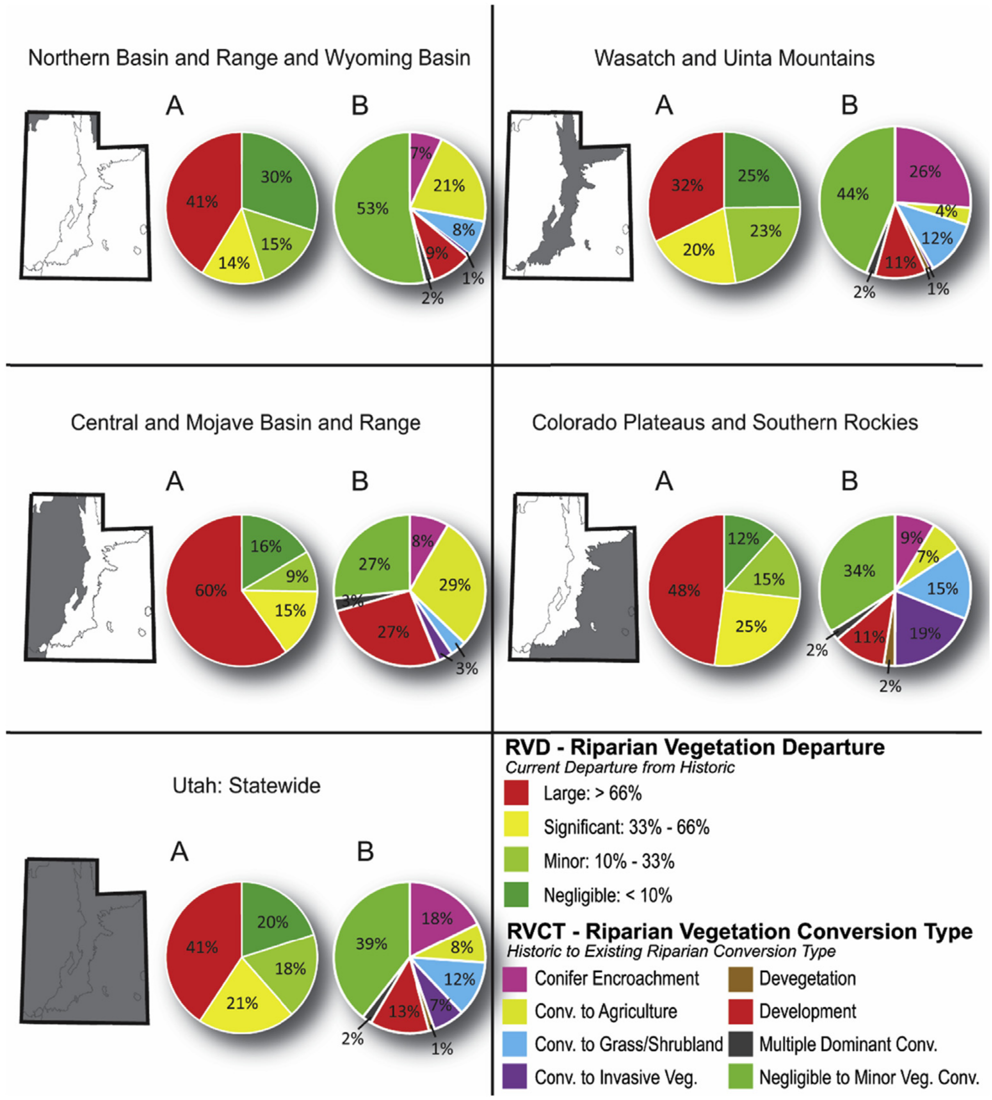

Fig. 4. Pie chart showing (A) the *riparian vegetation departure index* and (B) *riparian vegetation conversion type classification* by U.S. Environmental Protection Agency Level III Ecoregions across the perennial drainage network of Utah.

‘substantial’ agreement (Landis and Koch, 1977). Classification accuracy in the Tucannon watershed was similarly favorable, with an overall accuracy of 86% and *K* of 0.81; *K* between 0.81 and 1.00 indicates ‘almost perfect’ agreement (Landis and Koch, 1977). Thus, the RVD tool's input for characterizing contemporary native riparian vegetation coverage appears to accurately capture what on-the-ground assessments revealed in these two watersheds.

4. Discussion

4.1. Extent of riparian vegetation change, causes, and future applications

Floodplain riparian ecosystems are highly dynamic mosaics of distinct landforms with different fluvial and upland disturbance regimes (Kleindl et al., 2015; Whited et al., 2007), environmental stressors, and high rates of species turnover (Decocq, 2002).

Table 2
Summary of the *riparian vegetation departure index* categories for the perennial drainage network of Utah.

Departure from historic condition	Stream length (km)	% of drainage network
Large	10,416	41
Significant	5320	21
Minor	4697	18
Negligible	5144	20
Total	**25,577**	

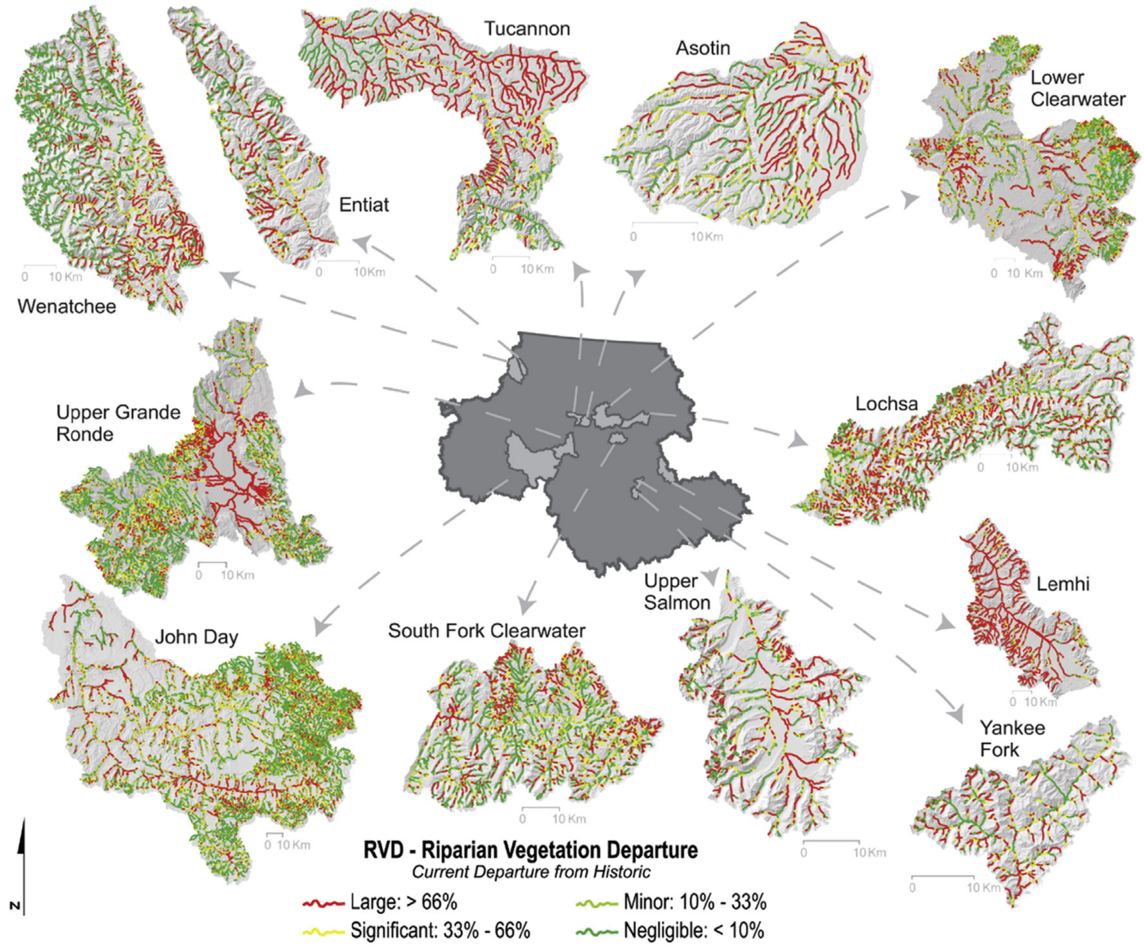

Fig. 5. Map showing the *riparian vegetation departure index* output across the perennial drainage network of the twelve watersheds of fisheries management concern of the interior Columbia River Basin.

Riparian vegetation change reflects successional processes that are either cyclical, such as valley bottoms being reshaped by floods at a given recurrence interval (Naiman et al., 2000), or directional such as when water is withdrawn from a channel and effectively eliminates flood-mediated disturbance, propagule transport, and soil moisture that support riparian forest establishment and growth (Souchon et al., 2008).

By mapping riparian vegetation departure from historic condition, we have shown that directional change away from dominant, historic vegetation communities is a common phenomenon for riparian areas in the western U.S. Although our analysis was largely descriptive, the conversion type (RVCT) component, combined with past work (e.g. Manners et al., 2014), provides insight on the mechanisms that are driving and maintaining this directional shift across otherwise dynamic floodplains. In many cases, human land and water use have fundamentally changed disturbance regimes and streamflow dynamics (Poff et al., 2007). These changes have pushed riparian succession toward upland species, including conifers (Greene and Knox, 2014) and invasive woody species (Stromberg et al., 2007). This vegetation transition can further “lock” landforms into place and alter underlying hydrologic and geomorphic processes that drive cyclical succession and maintain diverse floodplain vegetation composition and structure (Dean and Schmidt, 2011; Greene and Knox, 2014; Scott et al., 2000).

Cyclical succession was historically common along free-flowing rivers of the western U.S., as bank erosion, floods, droughts and fire (Kleindl et al., 2015) created floodplain mosaics of distinct landforms and riparian communities that vary with flood inundation frequency and duration (Nakamura et al., 2007). This led to the development of species-diverse floodplain mosaics that were captured within the LANDFIRE potential vegetation dataset that was used to determine historic condition. As floodplain modification occurred at many reaches, succession was no longer based on fluvial disturbance (e.g. Mouw et al., 2013), and competition between species, but instead upland disturbance, and direct conversion of floodplains to other land uses became the dominant factors shaping riparian vegetation dynamics.

Our assessment showed that conifer encroachment represents the largest vegetation conversion type in both Utah (18%) and the CRB (26%) suggesting that our assessment is effectively capturing this pervasive form of land cover change. Increased wildfire suppression since European settlement, paired with groundwater pumping and flow alteration, may allow conifer encroachment to occur more rapidly than in areas where flow alteration has occurred alone (Pettit and Naiman, 2007). Natural disturbance regimes (fire, hydrology) have been dramatically altered throughout the western U.S. (Carlisle et al., 2011), fostering upland encroachment throughout our study region and much of the western U.S. (Theobald et al., 2010).

In the higher elevation forests, considerable research has shown that grassland and shrublands are being replaced by forest (Zier and Baker, 2006) and aspen stands are declining due to changes

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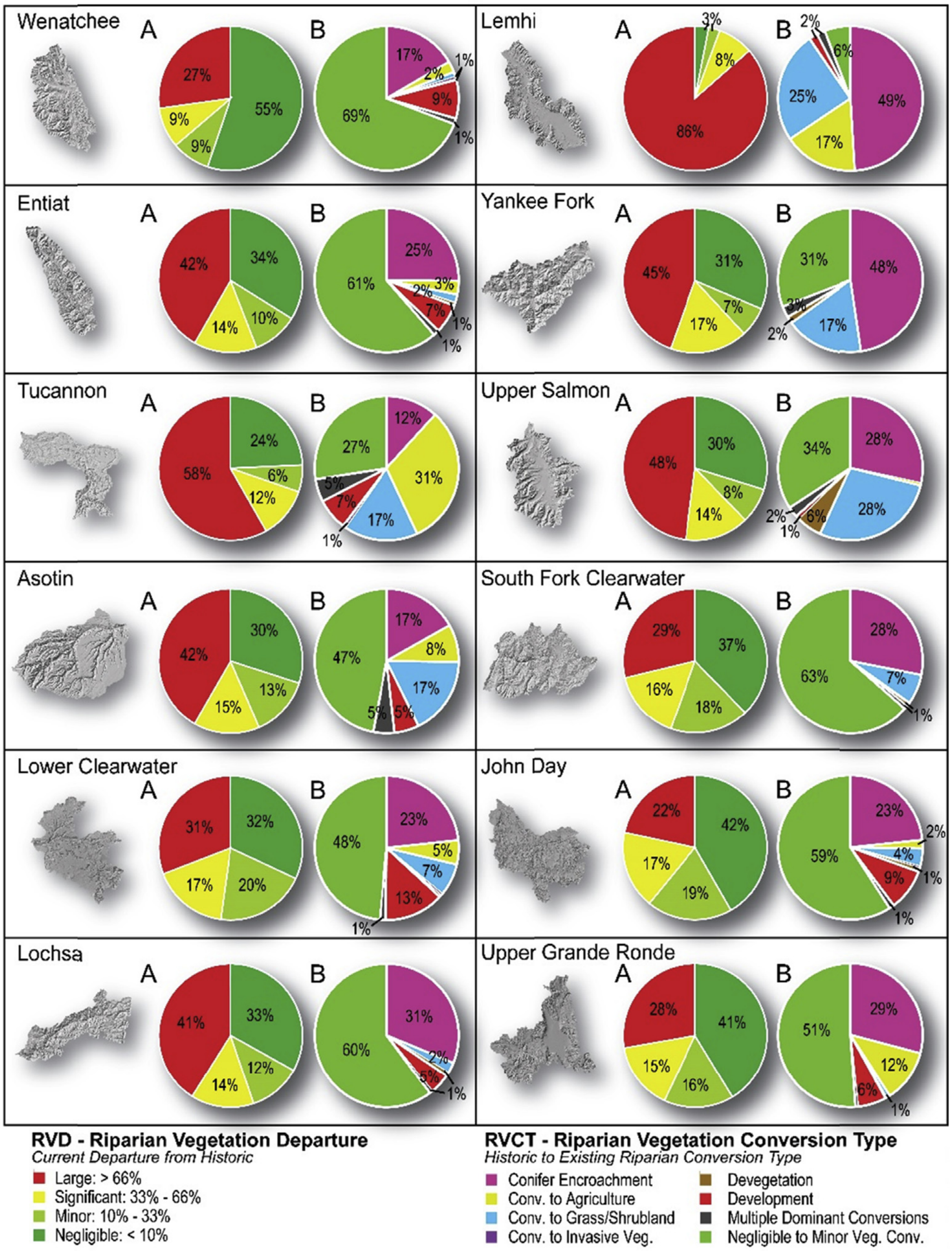

Fig. 6. Pie chart showing (A) the *riparian vegetation departure index* and (B) the *riparian vegetation conversion type classification* across the perennial drainage network of the twelve watersheds of fisheries management concern of the interior Columbia River Basin.

Table 3
Summary of the *riparian vegetation departure index* by category across the perennial drainage network of the twelve watersheds of fisheries management concern of the interior Columbia River Basin.

Departure from historic condition	Stream length (km)	% of drainage network
Large	8984	33
Significant	4117	15
Minor	4140	15
Negligible	10,324	37
Total	**27,565**	

in disturbance regimes (Rogers, 2002). In the mid-elevations of the Great Basin the encroachment of upland shrubs (e.g. *Juniperus* spp., *Pinus* spp.) is widespread and pervasive (Van Auken, 2000). Our riparian condition index and conversion type assessment show that this encroachment extends to wetter landforms— particularly where flow-mediated fluvial disturbance and the water necessary

Table 4
Field-based Weber watershed error matrix and Cohen's K score illustrating the agreement of ground based existing vegetation with LANDFIRE EVT classification. The diagonal in bold text shows the correctly classified ground plots.

Field data	Large	Significant	Minor	Negligible	Total	Producer Accuracy (%)	Omission Error (%)
Large	**14**				14	100	0
Significant		**3**			3	100	0
Minor		2	**4**		6	67	33
Negligible		1	2	**5**	8	63	38
Column total	14	6	6	5	31		
Consumer aAccuracy (%)	100	50	67	100			
Commission Error (%)	0	50	33	0			
Overall accuracy (%)	84						
Cohen's K		0.77					

Table 5
Field-based Tucannon watershed error matrix and Cohen's K score illustrating the agreement of ground based existing vegetation with LANDFIRE EVT classification. The diagonal in bold text shows the correctly classified ground plots.

Field data	Large	Significant	Minor	Negligible	Total	Producer Accuracy (%)	Omission Error (%)
Large	**21**				21	100	0
Significant	2	**13**			15	87	13
Minor	1	2	**9**	2	14	64	36
Negligible		1		**9**	10	90	10
Column Total	24	16	9	11	60		
Consumer Accuracy (%)	88	87	100	82			
Commission Error (%)	12	13	0	18			
Overall Accuracy (%)	87						
Cohen's K		0.81					

to support hydrophytic vegetation have been removed. For example, we found that within the Lemhi and Asotin watersheds forest succession has shifted toward conifer, invasive, or other upland vegetation types. These converted reaches are likely to become locked into place if hydrogeomorphic disturbance and upland disturbance regimes remained altered, making it difficult to reinitiate cyclical succession that supports diverse plant communities like those historically found along floodplains within the study area.

A limitation of our conversion type assessment index is that it qualifies all non-conformity to historic condition as a degradation, even though there are situations where conversion is not necessarily a degradation. For example, a characteristic aspect of rivers is the natural rejuvenation of valley bottoms by bank erosion, followed by vegetation succession (Geerling et al., 2006). As such, the conversion classes' *devegetation* and *conversion to grass/shrubland* may have a natural cause: rejuvenation by a meandering river. However, further investigation indicates that non-degradation conversion is limited across our study areas. Using aerial photo interpretation in Google Earth, we interrogated the *devegetated* and *conversion to grassland/shrubland* outputs within a representative watershed: Weber watershed, Utah. We examined the conversions and attributed them to either (a) degradation resulting directly (e.g., gravel mining or the construction of transportation infrastructure) or indirectly (e.g., upland encroachment) from anthropogenic disturbance, or (b) natural rejuvenation manifest as bare or vegetating floodplain surfaces. The vast majority of *devegetated* (~75%) and *conversion to grassland/shrubland* (~85%) conversions were identified as degradation. The conversions identified as natural rejuvenation were limited in size and mainly restricted to larger mainstem rivers. By excluding the active (bankfull) channel from computations (i.e., lying within a *large river polygon*), our analysis framework inherently minimizes the potential for mischaracterizing rejuvenation. In practice, the consequences of this limitation are minimal given that our tools are meant primarily for human-affected landscapes, in which conversion due to degradation rather than natural succession is the likely case; and that restoration practitioners are likely to make on-the-ground site visits before allocating resources to specific actions.

While our effort describes historic and current vegetation types, future research could pair vegetation change with historic, recent, or projected (future) stream flow records to inform hypotheses on how flow alteration may be driving unidirectional succession away from hydrophytic riparian vegetation. By linking our riparian vegetation departure index with past and future models of floodplain hydrology and climate in specific terms, riparian vegetation change from historic riparian habitat mosaics (Whited et al., 2007) can be used to infer trajectories of future floodplain succession and homogenization that shape species composition and habitat quality. Currently, our index maps the most obvious symptom of riparian degradation—vegetation change at the aggregate composition level. There are other, perhaps more subtle, changes preceding these shifts that offer insight on mechanisms that foster dynamic, healthy riparian ecosystems. Across the interior Pacific Northwest and Utah, our index informs more specific, basin-level research agendas to effectively answer these fundamental questions.

4.2. Watershed and riparian management implications

We applied the RVD tool to two heavily altered, U.S. riverscapes that are the focus of watershed planning and restoration campaigns. To our knowledge, this is the first region-wide effort to map riparian vegetation on drainage networks as it departs from historic condition while also identifying the causes of vegetation conversion. Similar regional instream habitat and geomorphic network analyses have been undertaken (Benda et al., 2007), as have analyses assessing riverscapes' capacity to support beaver dam building activity (Macfarlane et al., 2015), yet similar assessments of adjacent riparian vegetation communities were largely lacking.

Our approach contrasts with intensive reach-scale studies that identify vegetation change following known hydrologic or geomorphic alteration (Merritt and Cooper, 2000; Scott et al., 2000) or space-for-time studies that consider multiple field-monitored reaches to understand relationships between riparian vegetation community types and their environmental correlates (Hough-Snee et al., 2015). While reach-scale studies elucidate many processes that shape vegetation communities, they do not provide sufficient spatial coverage to inform landscape-scale riparian conservation. In contrast, our analyses complement these fine-scale studies by offering simple metrics (i.e., a departure index and conversion type details) that can be rapidly quantified across entire watersheds. This framework provides baseline data for detailed studies of current vegetation composition, and future riparian vegetation trends, and informs watershed planning, conservation, and restoration.

Output from RVD enables planners to identify conservation areas that are intact and should be protected, and areas that have been altered from their historic condition and potential candidates for intervention. RVCT results, which characterize how current vegetation differs from historic vegetation, provide further restoration planning insight by narrowing candidate reaches to those with reasonable recovery potential. For example, with two reaches characterized by low but similar RVD values, yet different dominant conversion types (e.g., to agricultural vs. developed use), restoration resources may be preferentially allocated to the site with a greater restoration potential. Despite clear utility for identifying candidate sites for restoration, our tools *do not* prescribe restoration treatments, nor do they spell out what the goals of a given restoration should be. Riparian restoration potential is tied to the remaining ecological, hydrological, and geomorphic processes along a given stream and floodplain. Accordingly, historic reference points such as past vegetation composition and structure, are impractical restoration goals, and most conservation organizations now identify realistic, process-based restoration targets rather than compositional goals based on historic vegetation types.

Prior to this study, spatially explicit riparian vegetation data did not exist for most of Utah. Resource managers within Utah now have a consistent baseline assessment of riparian habitat condition that is useful for planning restoration and conservation activities for species listed, or considered for listing, under the U.S. Endangered Species Act (ESA; e.g. greater sage grouse; NRCS, 2015). Riparian areas are critical for sage grouse rearing, for example, and the RVD tool can help managers identify high priority areas for conservation and/or restoration that facilitates their life cycle (Donnelly et al., 2016). Similarly, in our Columbia River Basin study area, the RVD tool can provide managers with a consistent assessment of riparian condition across several watersheds containing ESA-listed salmon and steelhead populations. Although salmon and steelhead recovery planning processes are in place (e.g. Snake River Salmon Recovery Board, 2011), many restoration decisions are still made at the sub-basin level and informed by the best available data, which can often be limited to ‘expert opinion’ (Booth et al., 2016). Our work provides freely available and consistently interpretable data that can inform future basin-wide assessments of riparian condition and ultimately streamline aquatic and floodplain habitat recovery planning.

5. Conclusions

The index-derived riparian vegetation departure from historic condition data provides important baseline information on how riparian vegetation has changed across Utah and the interior Columbia River Basin. This approach was appropriate for coarse-scale evaluations of riparian vegetation condition across regional drainage networks and is flexible and can be easily updated with higher resolution or better quality inputs as they become available. High-resolution riparian vegetation imagery may be necessary in areas with narrow riparian corridors that cannot be effectively captured with 30 m resolution data. The index provides information that can guide watershed- and reach-scale riparian conservation and restoration planning.

Data availability

The outputs of this work are published in both a shapefile format useable in any GIS program and as KML files for exploring and visualizing outputs in Google Earth. The outputs are publicly available at: http://etal.joewheaton.org/rcat and the source code of the Riparian Condition Assessment Tool (R-CAT) is available at: https://bitbucket.org/jtgilbert/riparian-condition-assessment-tools/wiki/Tool_Documentation/RVD. Data in KML format is also available online in Appendix A.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2016.10.054.

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