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Using LiDAR to assess transitions in riparian vegetation structure along a rural-to-urban land use gradient in western North America

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Abstract

Riparian forests are essential for stream ecological processes in arid and semiarid regions, however, they are often highly altered by the rapid expansion of urban areas. To maintain riparian ecosystems services, it is important to better understand the effects of urbanization on riparian forests. We quantified the three-dimensional (3D) structure and woody species composition of a riparian corridor in Utah, USA, to evaluate patterns of vegetation along stream reaches that flow through distinct hydrologic domains (with gaining and losing reaches) and through a rapid rural-to-urban gradient. By using LiDAR imaging and field observations, we explore the extent to which the riparian vegetation structure follows patterns of topography linked to energy and water subsidies and patterns of human influence along the stream. Whereas natural reaches of Red Butte Creek were characterized by native vegetation and typical riparian species (e.g., *Betula occidentalis*), urbanized reaches had higher numbers of introduced plants (e.g., *Acer platanoides*) and more upland species (e.g., *Quercus gambelii*). Urban reaches were also characterized by exceptionally high trees (>18 m) in older residential neighbourhoods. In the natural area, canopy height was negatively correlated with height above the river (HAR). Additionally, we found higher cover and taller canopies on north-facing aspects. These results show that LiDAR data, in combination with ground observations, can reveal strong influences of hydrology as well as land use in different canopy layers of riparian forests. We suggest that the decision making of individual landowners shapes vegetation beyond natural hydrological patterns, with implications for riparian forest management and restoration.

KEYWORDS

3D canopy structure, groundwater levels, land use, remote sensing, riparian forest, stream topography

1 | INTRODUCTION

Although riparian ecosystems are often relatively small in extent, they contribute greatly to regional productivity, biodiversity, and provision of ecosystem services, especially in arid and semiarid climates (Naiman & Décamps, 1997; Naiman, Décamps, & Pollock, 1993; Patten, 1998). Riparian zones are characterized by greater water availability for plants throughout the year compared to adjacent uplands, which leads to denser and more diverse forested vegetation assemblages (Naiman, Décamps, McClain, & Likens, 2005; Sabo et al., 2005).

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These riparian forests fulfil several crucial roles in riparian ecosystems (Palmer et al., 2000), including nutrient cycling and transpiration, affecting- water quality and hydrologic processes of streams (Malanson, 1993; Tabacchi et al., 2000). Riparian forests, and woody vegetation in particular, also are critically important for aquatic ecosystem structure and function, shading and thereby cooling water temperature, increasing bank stability and directly providing organic matter to the base of aquatic food webs (Brooks & Lemon, 2007; Fisher, Gray, Grimm, & Busch, 1982; Meixner et al., 2007; Stromberg, 1993).

Despite their ecological importance, many riparian ecosystems in the western United States have been degraded due to disturbances associated with human settlement. Deforestation, urbanization and other land use changes can significantly impact ecological processes in streams, with a common suite of impacts collectively referred to as 'urban stream syndrome' (Walsh et al., 2005). These impacts include high nutrient and pollutant concentrations in streams and reductions in riparian biodiversity associated with alterations to flow regimes caused by urbanization. Urban development often results in deforestation or restructuring of the vegetation in the riparian zone, leading to loss and degradation of riparian forests (Burton, Samuelson, & Pan, 2005; Walsh et al., 2005). Additionally, growing populations exert pressure on water resources, often directly lowering water tables through groundwater extraction (Allan & Flecker, 1993; Baillie, Hogan, Ekwurzel, Wahi, & Eastoe, 2007; Dynesius & Nilsson, 1994; Hall, Stuntz, & Abrams, 2008; Loáiciga, 2009). Changes in hydrologic flows commonly lead to channel incision and simplification, combined with reduced infiltration from urban surfaces that may lead to hydrologic isolation of riparian vegetation (Groffman et al., 2003; Hardison, O'Driscoll, DeLoatch, Howard, & Brinson, 2009; Sung, Li, Rogers, Volder, & Wang, 2011). This, in turn, affects many instream ecological processes such as nutrient cycling (Walsh et al., 2005).

Although vegetation structure and composition of riparian forests are commonly quantified (Dufour, Rodríguez-González, & Laslier, 2019), few studies have included information about the three-dimensional (3D) structure of the canopy. Structural components of riparian forests such as canopy density and the vertical distribution of the vegetation play a key role in forest function and productivity by affecting water, nutrient and carbon cycling (Shugart, Saatchi, & Hall, 2010). Three-dimensional features of riparian vegetation also influence the structure and diversity of higher trophic levels, as different faunal species inhabit different canopy layers (Patten, 1998; Webb, Leake, & Turner, 2007; McGrath & van Riper III, 2005). This is especially true in arid systems where forested canopies are usually only present close to streams. In recent decades, the 3D distribution of plant canopies has been increasingly studied using remote sensing techniques. Originally mostly used in forestry, airborne LiDAR is now proving to be a cost-effective tool to study ecological structure and function in forests (Davies, Tambling, Kerley, & Asner, 2016; Evans, Davies, Goossens, & Asner, 2017; Jung, Kaiser, Böhm, Nieschulze, & Kalko, 2012; Miller, Budy, & Schmidt, 2010; Seavy, Viers, & Wood, 2009; Szaro & Belfit, 1987).

Most riparian plants are obligate or facultative phreatophytic species that require water sources other than local rainfall to sustain growth (Patten, 1998). Many riparian species use stream water and/or rely on (deeper) groundwater sources for transpiration (Bowling, Schulze, & Hall, 2017; Brooks, Barnard, Coulombe, & McDonnell, 2010; Dawson & Ehleringer, 1991; Thorburn & Walker, 1994). A typical riparian zone has a lateral stream-to-upland vegetational gradient with a transition from hydric to xeric species that may occur within 10 to 100 m from the stream in hot and dry environments (Patten, 1998; Webb, Leake, & Turner, 2007). Because water table depth generally varies with stream topographic variables such as bank steepness, channel width, floodplain curvature and height above the river (HAR), these topographic variables are commonly associated with plant community structure (Cadol & Wine, 2017; Dilts, Yang, & Weisberg, 2010; Hardison, O'Driscoll, DeLoatch, Howard, & Brinson, 2009; Stromberg, Tiller, & Richter, 1996; White, Carreiro, & Zipperer, 2014). Additionally, observed patterns of stream discharge may be associated with riparian vegetation structure and composition due to the influence of surface water–groundwater interactions on plant water availability. Stream reaches fed by groundwater ('gaining reaches') and reaches that lose water to groundwater ('losing reaches') may differ in distance to the water table and therefore affect water availability for riparian vegetation (Winter, Harvey, Franke, & Alley, 1998). These spatial patterns in gaining and losing reaches strongly influence surface water chemistry (Brooks & Lemon, 2007; Dent, Grimm, & Fisher, 2001; Lohse, Brooks, McIntosh, Meixner, & Huxman, 2009), plant productivity (Harner & Stanford, 2003), community composition (Harvey & Skelton, 1978) and resilience to drought (Tai et al., 2018). However, the extent to which gaining and losing reaches interact with urbanization to influence the structure and composition of riparian forests is uncertain.

In this study, we utilized a dense dataset of 3D vegetation distribution provided by airborne LiDAR paired with ground-based measurements of woody species composition to assess riparian forest structure along a strong land use gradient from highly protected natural areas to highly urbanized stream reaches in Salt Lake City, Utah, USA. We addressed the question: Are transitions in land use and/or gaining and losing stream reaches associated with changes in riparian forest structure and composition? We hypothesized that water subsidy (from stream and alluvial groundwater) should influence vegetation, and this availability of water will differ based on whether a reach is losing or gaining, and with height above the stream. Furthermore, we hypothesized that riparian vegetation structure (height, canopy density andcomposition) would be correlated with land use gradients along the stream. The dense datasets provided by LiDAR measurements can provide a means of disaggregating the complex effects of stream geometry, water availability and land management on riparian forest structure. Adding ground-based measurements helps us identify patterns of change in the woody species assembly. By analysing canopy structure and composition along a stream urban-to-rural gradient, as well as based on distance from the stream and HAR, we can assess the relative importance of topography, groundwater flows and

land use in relation to vegetation patterns. This rich dataset can contribute to an improving understanding of the interactions between ecohydrologic processes and land management practices in urbanizing regions, which are increasingly affected by urbanization in many regions of the world.

2 | METHODS

2.1 | Study site

This study focused on riparian forests along Red Butte Creek, Utah, USA, which flows from Red Butte Canyon in the Wasatch Range westward into the Salt Lake Valley (Figure 1). The creek's drainage basin covers ~20.9 km^2 (Ehleringer, Arnow, Arnow, McNulty, & Negus, 1992) and flows along an elevation gradient of 2,020 to 1,330 m. The semiarid climate of the study area is characterized by long cold winters and hot dry summers. Peak flows occur in Red Butte Creek during spring snowmelt in May, and after snowmelt, stream discharge originates primarily from groundwater inputs (Ehleringer, Arnow, Arnow, McNulty, & Negus, 1992).

2.1.1 | Land use history

In the late 19th and early 20th century, Red Butte Creek was used as a water supply for a US military base (Fort Douglas) at the mouth of the canyon. A dam was built in the canyon in 1930, creating a reservoir that currently covers about 5.2 ha (Andersen et al., 2007). After the military left Fort Douglas in 1969, land ownership of the canyon was transferred to the US Forest Service and designated a Research Natural Area, which is closed to the public. Kept free from cattle grazing and recreational use, the upper reach of Red Butte Creek is located in a highly protected area. Red Butte Canyon is one of the few remaining undisturbed watersheds in the Great Basin, the high elevation desert region located between the Sierra Nevada and the Rocky Mountains (Ehleringer, Arnow, Arnow, McNulty, & Negus, 1992). After flowing through ~8 km of protected area in the Red Butte Canyon, the stream enters the University of Utah campus and then flows through densely built residential neighbourhoods in Salt Lake City, where after ~12 km, it is channelized underground.

2.1.2 | Land use transitions and hydrologic domains

Three major transitions in land use along Red Butte Creek form a strong rural-to-urban gradient, starting with the headwaters in the montane Red Butte Canyon Research Natural Area, then the University of Utah Campus and finally the residential neighbourhoods in the Salt Lake Valley. Within this gradient of urbanization, several stream reaches can be described. Abrupt changes in land use ownership and differences in past and current land use mark the transitions between these sections of the stream riparian habitat. We delineated three separate reaches in the natural montane Red Butte Canyon (0–7.7 km): 'Upper Canyon', 'Reservoir' and 'Lower Canyon'; three separate reaches in the University of Utah Campus (7.7–10.1 km): 'Campus Research Park', 'Campus VA' and 'Campus Sunnyside Park'; and three separate reaches embedded in the Salt Lake Valley residential neighbourhood (10.1–11.9 km): 'Residential Miller Park',

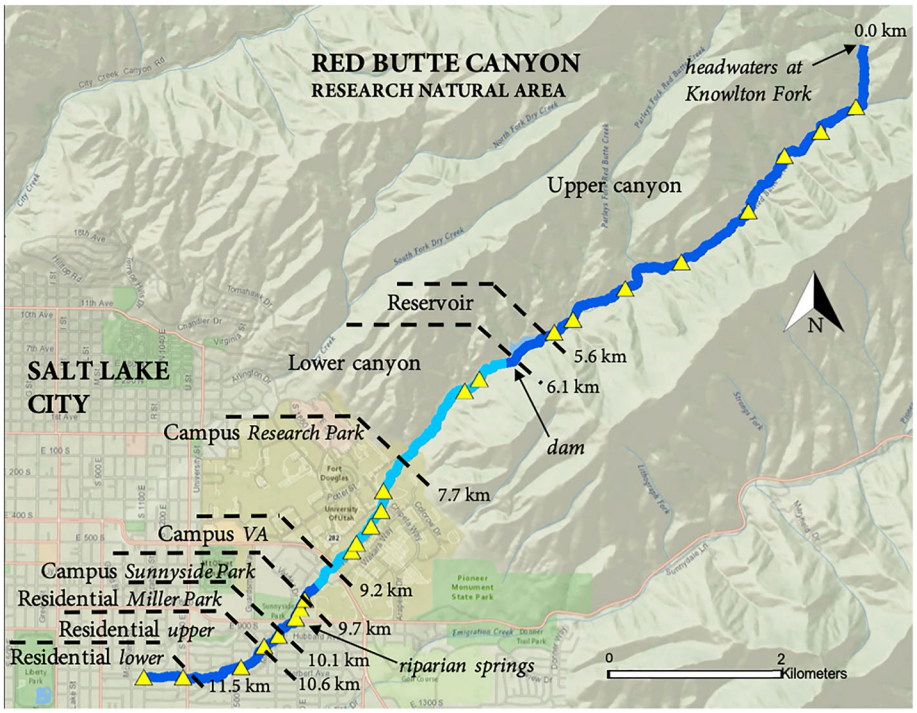

FIGURE 1 Map of the Red Butte Creek with transitions in land use (black dotted lines), hydrologic states: always gaining (dark blue) and transitional/summer losing (light blue), and transect locations for woody species plant survey (yellow triangles). Different land use types that the creek flows through are Upper Canyon; Reservoir; Lower Canyon; Campus Research Park; Campus VA; Campus Sunnyside Park; Residential Miller Park; Residential Upper; and Residential Lower (Table 1). Markers show distance in km from the headwaters at Knowlton Fork (GPS coordinates in decimal degrees: −111.765427, 40.808954). After ~12 km, the Red Butte Creek largely flows underground until it flows into Liberty Park and eventually joins the Jordan River (not shown in map). The Red Butte Dam and the location where riparian seeps and springs start occurring are indicated with arrows

'Residential Upper' and 'Residential Lower' (Figure 1). A land use description and the location of each reach is provided in Table 1.

Gabor et al. (2017) identified three distinct hydrologic domains along Red Butte Creek based on discharge and water chemistry measurements. The upper 0–6 km gains year-round ('upper gaining'); the middle 6–9.5 km gains during winter and loses during summer ('transitional'); and the lower 9.5–12 km also gains year-round ('lower gaining') (Figure 1). The upper and lower gaining reaches exhibit minimal discharge variability throughout years and between seasons. Urban inputs are clearly visible in the water chemistry of the lower gaining reach (Gabor et al., 2017). Discharge from the middle transitional reach varies highly in space and time. This middle reach is losing throughout most of the year, except during snowmelt conditions. Since these hydrologic domains are based on long-term averages, we expect these zones to capture trends on time scales pertinent to tree establishment and growth.

Along with our variables of interest (land use and hydrology), there are several confounding factors that may contribute to observed patterns of vegetation structure along the stream. We included the elevational change and slope aspect in our analysis for this reason. The stream undergoes a change in elevation of approximately 700 m from the headwaters to the lower residential neighbourhood. Each small section of the stream has a different slope aspect due to the meandering nature of the stream. However, to capture the broad-scale effects of increased energy availability on vegetation patterns along the stream, we categorized the right bank of the stream (largely SE facing) into a 'south-facing' category and the left side of the stream (largely NW facing) into a 'north-facing' category.

Similar to most stream systems (Allan, 2004), the natural and anthropogenic gradients in our study system covary. The confounding character of land use, hydrology and elevation in this study limits the possible inference. However, by using multiple approaches and data sources, we can begin to disentangle some of this covariation by identifying where observed vegetation structure diverges from expected patterns based on energy and water availability. For example, a gradual increase in air temperature moving downstream should increase water demand, reducing either the amount or size of vegetation. Similarly, differences between north- and south-facing banks should become greater downstream due to increased energy availability and resultant higher water demand. We speculate that there is a continued divergence between north- and south-facing aspects as water becomes more limiting in the losing reaches, as the water table subsides.

TABLE 1 Description of land use along Red Butte Creek stream reaches, their abbreviation, distance from the headwaters and altitude

Reach name	Code	Distance[a] (km)	Altitude (m)	Land use description
Upper Canyon	CAN1	0–5.6	1,986–1,634	Montane section with undisturbed flow, starts at Knowlton Fork in the canyon, ends just before the reservoir. Designated Research Natural Area. Most of the canyon is public land managed by the USDA Forest Service.
Reservoir	R	5.6–6.1	1,634–1,601	Red Butte reservoir and dam.
Lower Canyon	CAN2	6.1–7.7	1,601–1,520	Regulated flow, starts below the reservoir and dam. Undisturbed montane area and botanical garden. Most of the lower canyon is managed by the Red Butte Garden (www.redbuttegarden.org).
Campus Research Park	UC1	7.7–9.2	1,520–1,454	University of Utah campus. Urban developed area in valley, widely spaced buildings and lawns.
Campus VA	UC2	9.2–9.7	1,454–1,430	Veteran Affairs property within the University of Utah campus. Urban developed area in valley, widely spaced buildings and lawns.
Campus Sunnyside Park	UC3	9.7–10.1	1,430–1,419	Park located within the University of Utah campus. Public recreational park managed by Salt Lake City parks division (www.slc.gov). Sports fields, mostly turfgrass.
Residential Miller Park	RES1	10.1–10.6	1,419–1,397	Urban developed area in valley. Public recreational park managed by Salt Lake City parks division (www.slc.gov). Miller Park bird refuge is nestled within densely built residential houses and yards.
Residential Upper	RES2	10.6–11.5	1,397–1,356	Urban developed area in valley. Most of the riparian habitat part of residential yards, privately owned by residents. Residential homes generally >20 m from the stream channel.
Residential Lower	RES3	11.5–11.9	1,356–1,332	Urban developed area in valley. Most of the riparian habitat part of residential yards, privately owned by residents. Residential homes generally close to the stream channel (<10 m).

[a]Distance from headwaters at Knowlton Fork (GPS coordinates in decimal degrees: −111.765427, 40.808954).

2.2 | Data collection

We used two different data sets to evaluate the different aspects of vegetation structure. We obtained freely available airborne LiDAR to map the vertical distribution of the vegetation. To evaluate changes in the species composition along the creek, we identified woody species along line transects in the field. The emphasis for this study was on woody vegetation; however, some information on herbaceous vegetation is included in the LiDAR analysis, as this layer of vegetation is inherently present in the LiDAR point cloud. We focused on woody vegetation as these species are easier to identify in the field, contribute the most to the aboveground 3D structure of the forest and because the classification of the LiDAR point cloud is typically inaccurate for vegetation <0.4 m. Additionally, woody species are more responsive to long-term changes in water level fluctuations (with deeper rooting depths; Stromberg, 2013), so we expected woody vegetation to be more informative in evaluating vegetation patterns along the three hydrologic domains.

2.2.1 | LiDAR—Vegetation height distribution

Raw data processing

We obtained raw airborne LiDAR data through OpenTopography (www.opentopography.org) for the Salt Lake City area, collected in 2013–2014 with eight returns per m^2 and horizontal and vertical accuracy of approximately 7 cm (StateOfUtah, 2015). We classified the raw point cloud into ground, buildings, water and vegetation points using the *lasclassify* tool in the LAStools software package (LAStools, 2014). To create a digital terrain model (DTM), we usedonly ground points, and to create a spike-free canopy height model (CHM), we used height-normalized ground and vegetation points (Khosravipour, Skidmore, & Isenburg, 2016). To evaluate LiDAR estimates (ground-truthing), we sampled tree height in 2016 in 12 areas along the stream. Field measurements were 2.6 ± 2.0 m higher, which can be attributed to tree growth between LiDAR data collection (2013–2014) and data collection for ground-truthing (2016).

Plot delineation

We defined nominal 50 × 50 m and nominal 10 × 50 m sample plots using ArcGIS (ESRI, Redlands CA, v.10.3.1) to analyse changes in vegetation structure from headwaters to downstream and along the stream-to-upland gradient (Figure 2). Plot sizes were chosen to encompass the complete riparian forest zone, as determined through visual inspection of aerial images (Google Earth). Starting from a smoothed stream centerline (Dilts, Yang, & Weisberg, 2010), we delineated the plots longitudinally via transects running perpendicular to the centerline at 50 m increments and laterally by offsetting the centerline on both sides by 10, 20, 30, 40 and 50 m. Then, the original channel line and perpendicular transects were used to delineate sampling plots on either side of the stream (the plots on the right bank are referred to as generally 'south-facing' and the left bank as generally 'north-facing').

Vegetation metrics

We quantified vegetation structure for every 50 × 50 m (along the stream channel) and 10 × 50 m (along the stream at five distances from the stream channel) plot. We used the *lasheight* and *lascanopy* tools (LAStools, 2014) to compute three different metrics: cover, canopy height and canopy density. Vegetation cover (%) is calculated from the raw point cloud and represents the percentage of ground that is covered by vegetation higher than 0.4 m within a plot. We calculated cover by dividing the number of *first* returns classified as 'vegetation' by the total number of *first* returns (vegetation + ground points) in each plot using the *lascanopy* tool (LAStools, 2014). Average canopy height (m) was calculated from the pit-free CHM, which provides better estimates of canopy height than the raw point cloud (Khosravipour, Skidmore, & Isenburg, 2016). Canopies in the CHM are derived from the height (in m) of all *first* returns of vegetation. The threshold for vegetation height was set to 0.4 m to minimize errors from variation in land surface height. We calculated canopy density

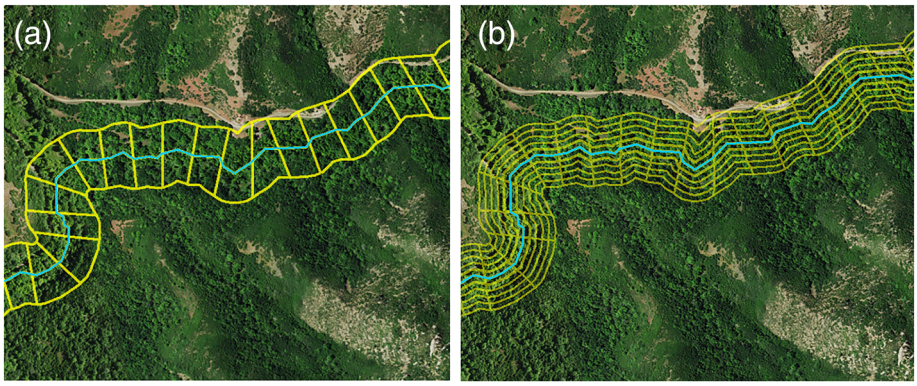

FIGURE 2 Example of plot delineation (yellow lines) along both sides of the Red Butte Creek channel line (light blue). (a) Plots of approximately 50 × 50 m were created for longitudinal analysis of the stream vegetation by taking 50-m segments of the stream centerline and buffering to either side by 50 m. (b) Plots of 50 m in length and 10 m in width were created for additional lateral analysis of the stream vegetation by taking the same stream centerline segments and buffering by five 10-m increments

by dividing the number of *all* returns classified as 'vegetation' by the total number of returns (vegetation + ground points) in each plot using *lascanopy*. We additionally used *lascanopy* to compute five relative height density rasters, to count the points whose heights fall into the following intervals: 0.4–1.5 m ('low'), 1.5–5 m ('low/mid'), 5–9 m ('mid'), 9–18 m ('high') and >18 m ('very high'). To compute this metric of density representing the 3D distribution of the canopy, the vegetation returns within each height interval were divided by *all* returns (vegetation + ground points) in a plot and scaled to a percentage. From hereon, we will refer to these counts as 'canopy density' for specific vegetation layers. The chosen canopy height intervals were based on plant groups that were previously described in the Red Butte Canyon by Ehleringer, Arnow, Arnow, McNulty, and Negus (1992): herbs/low shrubs (<1.5 m); tall shrubs/small trees (1.5–5 m); small trees (5–9 m); tall trees (9–18 m); and very tall trees (>18 m; see Appendix SA, Table SA1 for typical species in each group). See Lefsky, Cohen, Parker, and Harding (2002) for a review of lidar data collection and uses in ecological studies.

2.2.2 | Field observations—Woody vegetation species composition

Field data collection

We collected field data on the composition of woody species along 23 transects in the summer of 2016 with line transects in the riparian zone perpendicular to the stream. Rather than matching the 50 × 50 m plot size used for LiDAR analysis, we chose to record woody species 0–10 m from the stream channel to avoid interruptions by steep slopes and built structures. The 20-m transects consisted of a 10-m transect on each side of the stream channel. We placed transects approximately equidistant (~500 m) to create a profile of the woody species composition along the stream that was visually comparable to the LiDAR profiles. We adjusted or removed transects locations that were inaccessible due to steep slopes or private property (Red Butte Garden in the Lower Canyon; Campus VA; residential homes). We determined woody species composition with a step-point technique, developed by Coulloudon et al. (1996) and Elzinga, Salzer, and Willoughby (1998) to obtain a 3D view of the forest community. We recorded the number of 'hits' for each woody species at 1-m intervals on each transect. A 'hit' was recorded for each plant that was intercepted by a straight line running from the ground to the sky. This technique closely relates to the way that our density metric was created with the LiDAR point cloud, where 'hits' would resemble laser returns. For each transect, we divided the number of *hits per species* by the *total number of hits* along that transect, to estimate the relative abundance or density of each species in 3D space. Woody plants were identified to species or genus level.

Native status and WIS

We categorized species by native status ('native' vs. 'introduced') and wetland indicator status (WIS) according to the USDA PLANTS database (USDA, NRCS, 2016). The WIS classifies plants in five groups: (1) 'obligate': almost always a hydrophyte, rarely found in uplands; (2) 'facultative wetland': usually a hydrophyte but occasionally found in uplands; (3) 'facultative': commonly occurs as either a hydrophyte or nonhydrophyte; (4) 'facultative upland': occasionally is a hydrophyte but usually occurs in uplands; and (5) 'upland': rarely is a hydrophyte, almost always in uplands. The wetland indicator was developed by Reed (1988) to help identify hydrologic habitat in wetland systems, based on a species-typical occurrence in saturated soil conditions. In this study, the application of the wetland indicator status was extended to indicate riparian hydrologic habitat, following Auble, Scott, Friedman, and Collins (2005); Castelli, Chambers, and Tausch (2000); Coles-Ritchie, Roberts, Kershner, and Henderson (2007); Riefner and Boyd (2007); Stromberg et al. (2006); Stromberg (2013); McCoy-Sulentic et al. (2017); and Solins and Cadenasso (2020).

2.2.3 | LiDAR—Stream topography

To calculate HAR, we used the Riparian Topography Tools extension (Dilts, 2015) in ArcMap. Conceptually, HAR is the elevation difference between an upland location and the stream location it flows into. In practice, the tool models stream grid cell elevation as a distance-weighted average of river elevations near the focal stream cell, using a kernel density function (Dilts, Yang, & Weisberg, 2010). We used the DTM and a flow accumulation model as inputs for the HAR tool. To create an accurate flow accumulation model, the stream was burned into the DTM in areas where the stream was redirected through culverts. We compared the average HAR of our 50 × 50 m plots to the vegetation structure within the same 50 × 50 m plots.

2.3 | Data analysis

2.3.1 | Sampling design

Our sampling design consists of continuous 50 m increments, which in effect creates a census of the LiDAR data on stream vegetation. We chose a sample size of 50 × 50 m, based on the width of the riparian zone in the natural canyon. To deal with the nonindependence and spatial autocorrelation of individual plots, we used several different approaches to evaluate and disentangle some of the effects on vegetation structure. Sample plots where the stream has been piped and diverted underground and plots around the managed reservoir, which represents a littoral rather than a riparian system, were omitted from statistical analyses. All statistical analyses were performed in R (R Core Team, 2018).

2.3.2 | Profiles of vegetation structure and floristics along the stream

First, we created profiles of the vegetation along the stream and made descriptive comparisons of change in vegetation structure

along the stream. We visually compared changes in vegetation structure between stream reaches in each land use and hydrologic domain. Then, we described the vegetation structure moving away from the stream channel, in increments of 10 m. In addition, we visually compared the LiDAR vegetation structure metrics to change in the floristic composition of the vegetation close to the stream channel (<10 m).

2.3.3 | Multiple regression analysis

We carried out multiple linear regression to disentangle the relative importance of HAR, bank orientation and elevation in influencing the three LiDAR vegetation structure metrics (cover, canopy height and canopy density). We fit separate models for each response variable, as well as for each hydrodomain (upper gaining, middle transitional and lower gaining), because of the a priori differences in hydrology we expected between these reaches. We decided to apply a mixed-effects modelling approach using generalized least squares (GLS). This approach allowed us to model complex residual structures that include heteroscedasticity and spatial correlation (Zuur, Ieno, Walker, Saveliev, & Smith, 2009). Our model selection procedure consisted of three steps: (1) data exploration, (2) random effect structure selection and (3) fixed effect structure selection. In Step 1, we visually checked for outliers following the approach recommended by Zuur, Ieno, Walker, Saveliev, and Smith (2009; Appendix SA). We also checked for correlation among covariates based on the variance inflation factor (VIF) (in R package 'car'; Fox & Weisberg, 2011), using VIF > 3 as a cutoff. In Step 2, we selected the optimal random structure in our model. We started with a simple model using the 'gls' function ('nlme' package; Pinheiro, Bates, DebRoy, Sarkar, & R Core Team, 2018) containing the main fixed effects (elevation, HAR, bank orientation) and no interactions. We evaluated spatial autocorrelation for each model with a variogram ('gstat' package; Gräler, Pebesma, & Heuvelink, 2016; Pebesma, 2004), a bubble plot ('sp' package; Bivand, Pebesma, & Gomez-Rubio, 2013; Pebesma & Bivand, 2005) and Moran's I ('ape' package, Paradis & Schliep, 2019). If Moran's I was significant ($p < 0.05$), we proceeded to choose an optimal spatial covariance structure (exponential or spherical) based on Akaike's information criterion (AIC), with a cutoff of dAIC > 3 to determine the significant change in AIC from the null model ('stats' package; R Core Team, 2018). The statistical assumption of normality and equal variances were evaluated by inspecting model residuals (with residual–fitted plot and histogram of residual distribution). When necessary, we also included a VarIdent variance structure (Zuur et al., 2009, p. 75) to allow for different variances between land use categories (i.e., heteroscedasticity). In Step 3, we started with the optimal random structure and continued with a backwards selection procedure to choose the optimal fixed effect structure. For the full model, we started with the main effects elevation, HAR and bank orientation and interaction terms for HAR:elevation and HAR:bank. We applied backwards selection using a likelihood ratio test with ML estimation, as per the approach laid out by Zuur, Ieno, Walker, Saveliev, and Smith (2009). This method is based on several rounds of model selection, comparing the AIC of the full model with the nested model with the 'anova' function ('stats' package; R Core Team, 2018) and a cutoff of $p < 0.05$ to select the optimal model. The results are presented in Table 2.

3 | RESULTS

3.1 | Vegetation height distribution (LiDAR)

In the upper gaining reach, the canopy density was relatively constant (0–6 km; Figure 3c), but the distribution (cover and height; Figure 3a, b) changed depending on the aspect with distance downstream. Cover slightly decreased on south-facing banks (from around 75% to around 15%), and canopy height slightly increased on north-facing banks (from an average of about 5 m to about 7 m). On average, canopies in the upper gaining reach were 3 m higher than the canopies in the lower gaining reach (Figure 4a,II). The upper gaining reach contained denser vegetation than the lower gaining reach in the low/mid (1.5–5 m) layer (by 10%) and in the mid (5–9 m) layer (by 15%) (Figures 3c and 4a).

Along the middle transitional reach, there was a sharp decrease in vegetation on both banks (Figure 3). Cover decreased from around 75% just below the reservoir to around 30% at the bottom of this reach. Here, the creek flows through different land uses, including the natural area just below the Red Butte Dam and the Red Butte Garden in the Lower canyon (CAN2) and the University Campus (UC1, UC2 and UC3). Canopies decreased from about 5 m at the start of the middle transitional reach to about 2 m at the bottom. Canopies were lowest in the Campus research park (UC2; 2.5 m) and Sunnyside Park reaches (UC3; 2.6 m) (Figures 3b and 4b,II). There was an overall decrease in canopy density along the stream in the low/mid (1.5–5 m) and mid (5–9 m) layer (Figure 3c,b,III).

In the lower gaining reach, there was a strong increase in canopy height on both banks, as the creek flows through Sunnyside Park (UC3), Miller Park (RES1) and residential neighbourhoods (RES2 and RES3). Average canopy heights increased from about 2.5 m at the start of the lower gaining reach to about 8 m near the bottom of this reach. The sections in this reach containing high canopy height averages corresponded with high densities of vegetation >18 m (RES2 and RES3; Figure 3b,c). The cover was lower in Sunnyside Park (UC3; around 30%) than in the residential neighbourhoods (RES1–RES 3; around 70%). There were two small areas of lower cover in the lower urban reach (Figure 3a), which corresponded with locations of urban structures (a large parking lot; a constructed garden area). Very high vegetation >18 m was most prevalent in the lower gaining reach and was all found in the upper (RES2) and lower residential area (RES3; Figures 3c and 4b,III). Trees of this stature were rarely present outside of the residential areas (Figures 3c and 4b).

TABLE 2 Coefficients for standardized variables of the multiple regression (b ± SE) and associated t-tests for the GLS models for dependent variables cover, canopy height, density and three hydrologic domains, with the number of samples and land use categories in each domain. Fixed effects (main effects and interaction terms), random effects (spatial covariate function with exponential or spherical structure Sp.Exp or Sp.Spher, and VarIdent variance structure for land use), residual standard error are given for the final model, and AIC for the null model (m.null), model with only fixed effects (m.1), model with spatial structure (m.sp), and model with spatial and VarIdent variance structure (m.sp,id). Fixed effects that were not included in the final model are marked with 'NS' in light grey. NA* indicates that no combination of the fixed and random effects was able to significantly predict vegetation structure in this reach, nor were we able to create a model that did not violate assumptions of independence and homogeneity with the measured explanatory variables

		Upper gaining		Middle transitional		Lower gaining	
Dependent variable	**Fixed and random effects in the final model**	***n* = 226 land use cat.: 1**		***n* = 146 land use cat.: 3**		***n* = 88 land use cat.: 4**	
		b ± SE	*t*	*b* ± SE	*t*	*b* ± SE	*t*
Cover	elevation	−17.9 (6.3)	−2.8**	NS		NA*	
	HAR	NS		5.3 (2.0)	2.6**		
	S bank	−10.0 (1.8)	−5.6***	NS			
	interactions	NS		NS			
	Covariance structure	Sp.Exp		Sp.Exp VarIdent			
	Residual se	15.8		21.0			
	AIC(m.null) AIC(m.1) AIC(m.sp) AIC(m.sp,id)	1,946.0 1,885.3 1,808.3		1,286.0 1,277.7 1,235.1 1,232.2			
Canopy height	elevation	−1.0 (0.6)	−1.8*	3.9 (0.8)	4.8***	−8.3 (1.5)	−7.8***
	HAR	−1.2 (0.3)	−4.3***	NS		NS	
	S bank	−1.4 (0.3)	−4.9***	NS		NS	
	har:ele	0.5 (0.3)	2.4*	NS		NS	
	har:bank	0.7 (0.3)	2.4*	NS		NS	
	Covariance structure	Sp.Exp		Sp.Exp VarIdent		VarIdent	
	Residual se	2.1		1.7		1.2	
	AIC(m.null) AIC(m.1) AIC(m.sp) AIC(m.sp,id)	1,002.2 996.5 951.1		598.4 527.5 512.9 506.3			
Density	elevation	−11.9 (4.4)	−2.7**	NS		NA*	
	HAR	NS		3.8 (1.6)	2.6*		
	S bank	−7.0 (1.4)	−5.0***	NS			
	interactions	NS		NS			
	Covariance structure	Sp.Exp		Sp.Exp VarIdent			
	Residual se	12.2		14.9			
	AIC(m.null) AIC(m.1) AIC(m.sp) AIC(m.sp,id)	1,816.6 1,754.0 1,677.8		1,211.6 1,206.4 1,170.5 1,167.6			

*$p < 0.05$.**$p < 0.01$.***$p < 0.001$.

3.2 | Species composition of woody vegetation (field)

The species composition was similar on both sides of the stream (see Appendix SB, Figure SB1), so we combined both banks in Figure 5. All woody species found in the montane reaches, including the protected upper canyon and Red Butte Garden, were native to Utah. Bigtooth maple (*Acer grandidentatum*) and box elder (*Acer negundo*) were the most abundant species in these reaches. In the upper campus (research park and VA), 2% of observed species were nonnative, and their abundance increased further downstream (to 100% introduced in the lower residential area; see Figure 5a). Three species were labelled as introduced. These three species were not invasive and were introduced through horticulture: horse chestnut (*Aesculus hippocastanum*), sweet cherry (*Prunus avium*) and Norway maple (*Acer platanoides*).

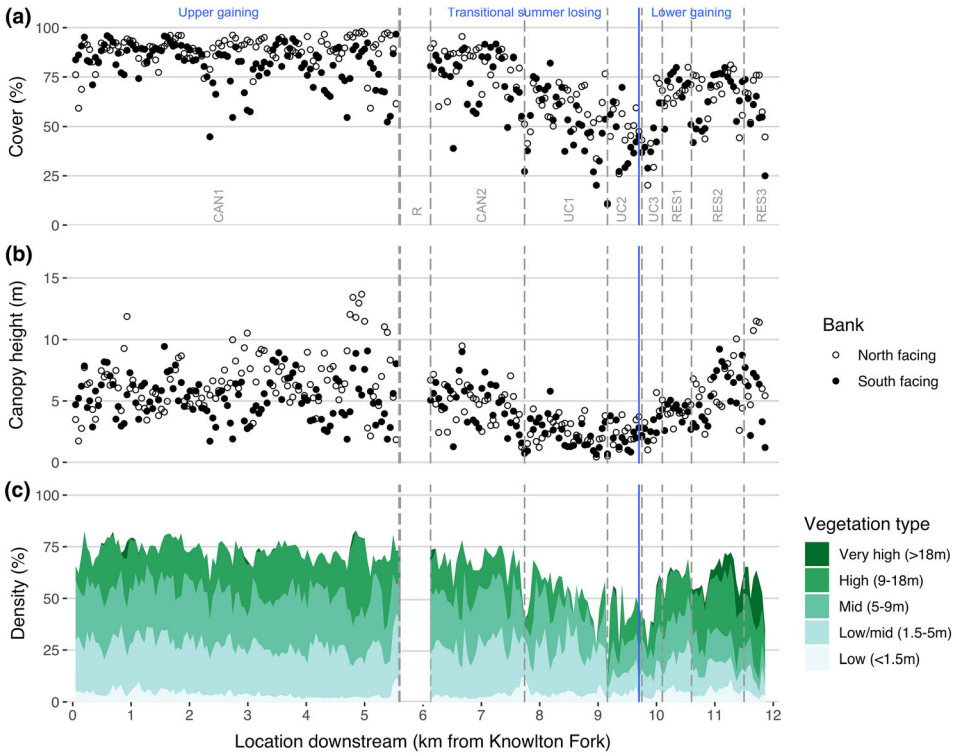

FIGURE 3 LiDAR profiles of (a) vegetation cover (% of ground covered by vegetation >0.4 m high), (b) canopy height (average height of topmost vegetation layer) and (c) canopy density for five height intervals (the remaining white space not indicated in the legend accounts for all returns <0.4 m) along Red Butte Creek, given as percentage or average for 50 × 50 m plots on both sides of the stream. Hydrologic domains are shown in blue (upper gaining; transitional [summer losing]; lower gaining). Dotted lines represent transitions in land use along the stream: Upper Canyon (CAN1); Reservoir (R); Lower Canyon (CAN2); Campus Research Park (UC1); Campus VA (UC2); Campus Sunnyside Park (UC3); Residential Miller Park (RES1); Residential Upper (RES2); and Residential Lower (RES3; Table 1). Vegetation around the reservoir was omitted

Typical riparian species (facultative wetland; Figure 5b) were most abundant in the upper gaining reach: 28% of the community in the upper canyon consisted of these species, including western water birch (*Betula occidentalis*) and red osier dogwood (*Cornus sericea*). Typical riparian species were barely found in the more urbanized lower gaining reach flowing through Sunnyside Park and the residential areas (where 0% and 2% of the canopy structure comprised typical riparian species). The typical riparian species in the residential area were only observed in Miller Park and consisted of red osier dogwood (*C. sericea*) and grey alder (*Alnus incana*). Two observed species were categorized as typical upland species: Gambel oak (*Quercus gambelii*) and horse chestnut (*A. hippocastanum*). The highest density of upland species was found in the middle transitional reach, particularly in the campus reaches (research park, VA and Sunnyside Park), where 45% of the riparian community was categorized as upland and consisted entirely of Gambel oak (*Q. gambelii*). Gambel oak did not occur downstream from the University Campus. The upland species observed in the lower residential was horse chestnut (*A. hippocastanum*).

There was a shift in community composition along the stream, with few overlapping woody species between the sites near the top and bottom of the stream (see Appendix SB, Figure SB2). Only one species, *A. negundo*, was present along the full extent of the stream. Apart from *A. negundo*, which represented 33% of the total density of the woody vegetation in the upper canyon and 8% in the residential area (Miller Park, upper and lower residential), none of the species present near the headwaters were also found in the lower urbanized reaches of the stream. A profile of the community composition along the stream (Figure SB2), a list of observed species and their density at each transect (Table SB1) and WIS and native status for each species (Table SB2) can be found in Appendix SB.

3.3 | Vegetation height distribution at five distances from the stream (LiDAR)

Across all land use types and each hydrologic domain, the variation in vegetation cover increased away from the stream (Figure 6). The upper gaining reaches had a sharper gradient from tall high cover to shorter low cover on south-facing aspects compared to the north-facing aspects (Figures 6 and 7).

Moving downstream along the middle transitional reach, cover and height appeared to decrease much more rapidly as one moves away from the channel (Figures 6 and 7). This narrowing of the riparian zone was particularly visible in the campus area, where canopy height quickly diminished to >20 m from the stream, with average canopy heights of 5 m close to the stream (within 10 m) and canopy heights of 1.5–2 m far from the stream. The vegetation in the campus reach generally became less dense >20 m from the stream (Figure 8) and more so in higher than in lower statured vegetation.

The lower gaining reach and the residential area had increasing cover and canopy height as one moves down the stream (Figure 6 and 7). In the residential areas, almost all the tall vegetation was located close to the stream. Trees >18 m were rare further than 30 m from the stream and were largely confined to 10 m from the stream.

3.4 | Local topography (LiDAR)

HAR was more variable between plots in the upper montane reaches of the stream than in the lower urban reaches of the stream (Figure 9). In the upper canyon (CAN1), HAR was generally higher on the south-facing bank. Below the reservoir where the creek flows

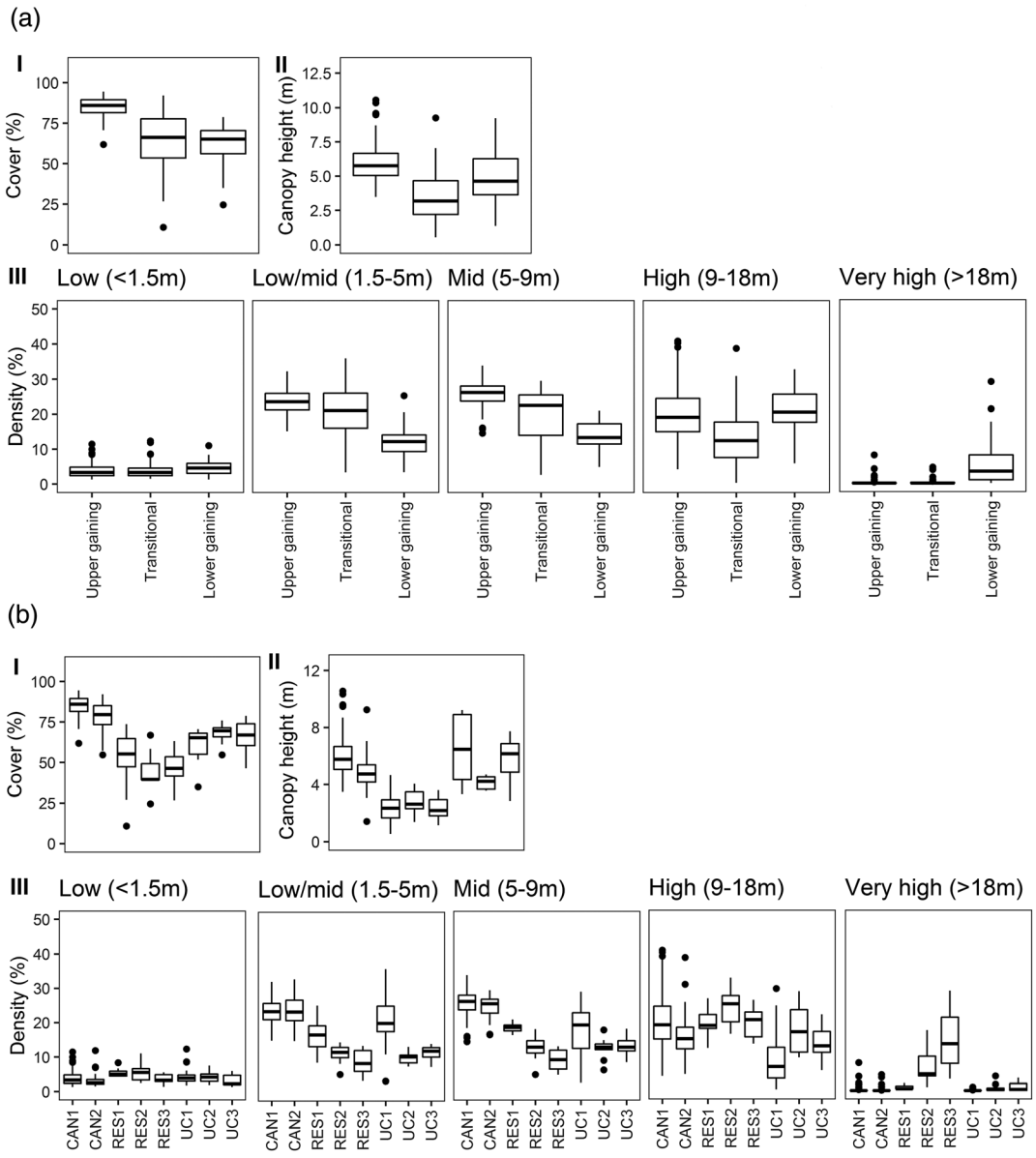

FIGURE 4 Variability in vegetation structure in the different (a) hydrologic domains and (b) land uses, given for (I) cover, (II) canopy height and (III) density of five height layers, corresponding with Figure 3. Number of samples per hydrologic domain: upper gaining, n = 113; middle transitional, n = 73; lower gaining, n = 45. Per land use type: Upper Canyon (CAN1), n = 226; Lower Canyon (CAN2), n = 66; Campus Research Park (UC1), n = 60; Campus VA (UC2), n = 14; Campus Sunnyside Park (UC3), n = 22; Residential Miller Park (RES1), n = 14; Residential Upper (RES2), n = 22; and Residential Lower (RES3), n = 36. Vegetation around the reservoir was omitted

through Red Butte Garden (CAN2), HAR was higher on the north-facing bank. HAR was similar for the north- and south-facing banks in the urban area (UC1–RES3; Figure 9).

To further assess relationships between vegetation structure and bank orientation, elevation, HAR and land use, we used multiple regression analysis using a GLS approach. We created separate models for the upper gaining, middle transitional and lower gaining reaches of the stream and separate models for each LiDAR vegetation metric (cover, canopy height and density; Table 2). Model coefficients (b ± SE) are given for the standardized variables and therefore indicate the relative importance of the fixed effects included in the model.

Cover, canopy height and density were all spatially correlated in the upper gaining reach, and adding a spatial structure decreased AIC by 77.0, 45.4 and 76.2, respectively (Table 2). In the middle transitional reach, all three metrics were spatially correlated as well, with AIC decreasing by 42.6 for cover, 14.6 for canopy height and 35.9 for density after adding a spatial covariance structure. We needed to account for the heterogeneity of variance in the land use categories in all our models in the middle and lower hydrologic domain. We were unable to fit a model for cover or density with our explanatory variables in the lower reach, with the available random and fixed effects. We did find spatial autocorrelation in the null model (i.e., in the cover

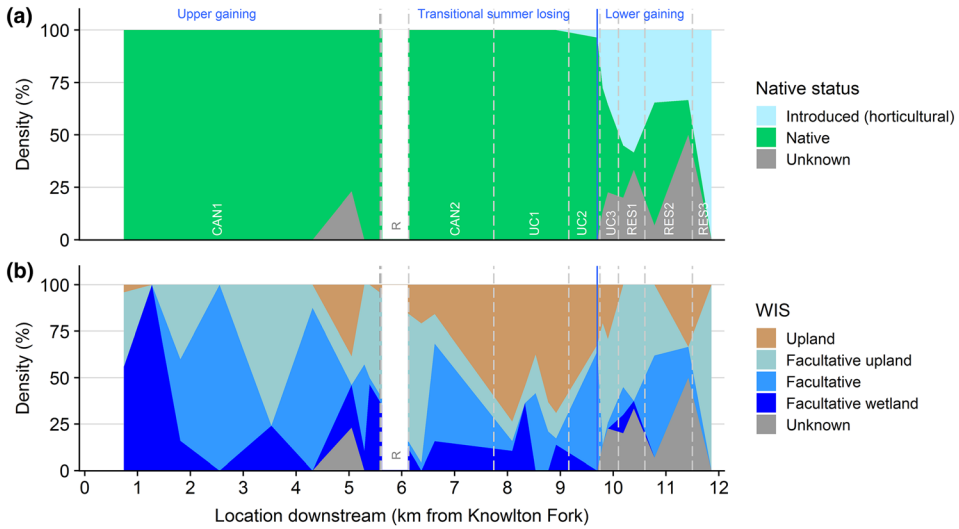

FIGURE 5 Woody species community composition extrapolated from 23 transects along Red Butte Creek, extending 10 m on either side of the stream channel (locations are shown in Figure 1). (a) Percentage of species according to native status: native species (green) and introduced species (horticultural) (blue). (b) Percentage of species according to wetland indicator status (WIS). Categories are upland; facultative upland; facultative; facultative wetland; and unknown. 'Unknown' category (grey) consists of six species that could not be identified to species level and 1 hybrid. Hydrologic domains are shown in blue: upper gaining; transitional (summer losing); lower gaining. Dotted lines represent transitions in land use along the stream: Upper Canyon (CAN1), n = 8; Reservoir (R); Lower Canyon (CAN2), n = 2; Campus Research Park (UC1), n = 5; Campus VA (UC2), n = 0 (inaccessible private property); Campus Sunnyside Park (UC3), n = 3; Residential Miller Park (RES1), n = 2; Residential Upper (RES2), n = 1; and Residential Lower (RES3), n = 2 (see Table 1)

and density variables) in this reach, still suggesting a pattern but controlled by other factors.

Canopy height in the upper gaining reach was best explained by our explanatory variables and was negatively associated with elevation, HAR and bank orientation (Table 2). Interaction effects between elevation and HAR, and elevation and bank orientation were also significant in this reach, although at a low confidence level ($p < 0.05$). Models for the other vegetation metrics (cover and density) in the upper gaining reach showed negative relationships with elevation and bank orientation.

HAR was a strong predictor for canopy height in the upper gaining reach (after bank orientation, with $b = -2.6 \pm 0.6$ and $b = -1.6 \pm 0.6$, respectively) and showed up as the only predictor for cover and density of the vegetation in the middle transitional reach. None of the predictors were significant in the lower gaining reach for these metrics.

4 | DISCUSSION

The main objective of this study was to evaluate the effect of land use and hydroclimate on species composition and canopy structure of the riparian forest of a semiarid stream. Specifically, we first examined how land use and hydrologic status (gaining or losing) influenced the riparian forest by creating profiles of vegetation structure and community composition along the stream. Subsequently, we evaluated how riparian vegetation structure varied with aspect, HAR and elevation. Our results suggest that the structure of riparian vegetation in the natural upper canyon reflects patterns of energy availability as a function of aspect and water availability, which varies due to distance from the stream and gaining losing character of local groundwater. These predictable patterns in energy and water availability associated with topography and groundwater are well recognized in upland systems and are beginning to be applied more commonly to understand riparian vegetation structure (Hoylman et al., 2019; Love et al., 2019; Swetnam et al., 2018; Swetnam, Brooks, Barnard, Harpold, & Gallo, 2017; Tai, Mackay, Anderegg, Sperry, & Brooks, 2017; Weintraub, Brooks, & Bowen, 2017). In contrast, the effect of these patterns is diminished in stream reaches with rapid transitions in land use. This suggests that where the riparian structure was dominated by human alteration and cultivation of vegetation, the riparian forest was in effect decoupled from the stream hydrology.

Overall, the riparian zones of upper gaining reaches were characterized by the predominance of native species, minimal upland vegetation, high cover and tall trees and a sharper gradient from tall high cover to shorter, lower cover on south-facing compared to north-facing aspects. In contrast, the middle transitional reaches (which are mostly losing) had an increasing representation of upland species, as well as narrower zones of high canopy height and cover, which became more pronounced further downstream. Unlike in the upper gaining reach, aspect did not influence the width of riparian influence in this reach. In the lower gaining reach, increasing height, cover and width of riparian influence, as well as minimal obligate upland flora

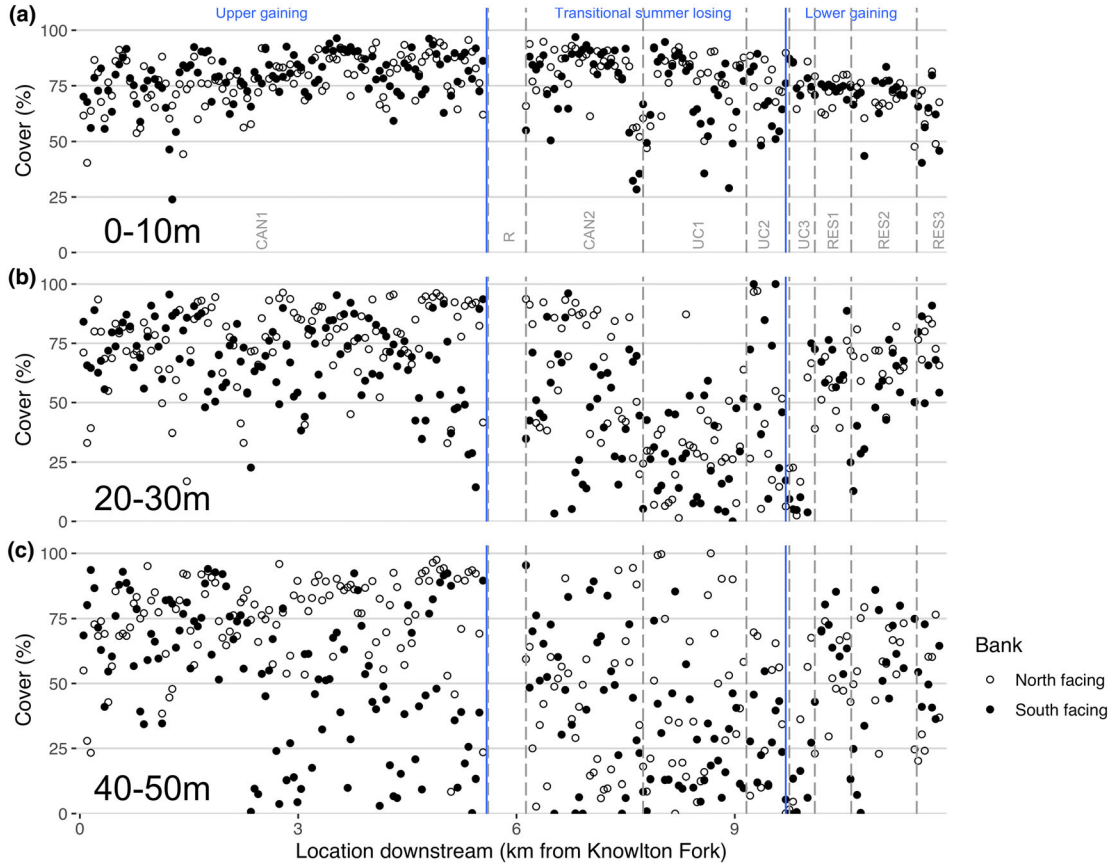

FIGURE 6 Vegetation cover at 0–10 m (a), 20–30 m (b) and 40–50 m (c) from the stream channel, on the north- and south-facing banks. Hydrologic domains are shown in blue (upper gaining; transitional [summer losing]; lower gaining). Dotted lines represent transitions in land use along the stream: Upper Canyon (CAN1); Reservoir (R); Lower Canyon (CAN2); Campus Research Park (UC1); Campus VA (UC2); Campus Sunnyside Park (UC3); Residential Miller Park (RES1); Residential Upper (RES2); and Residential Lower (RES3; Table 1)

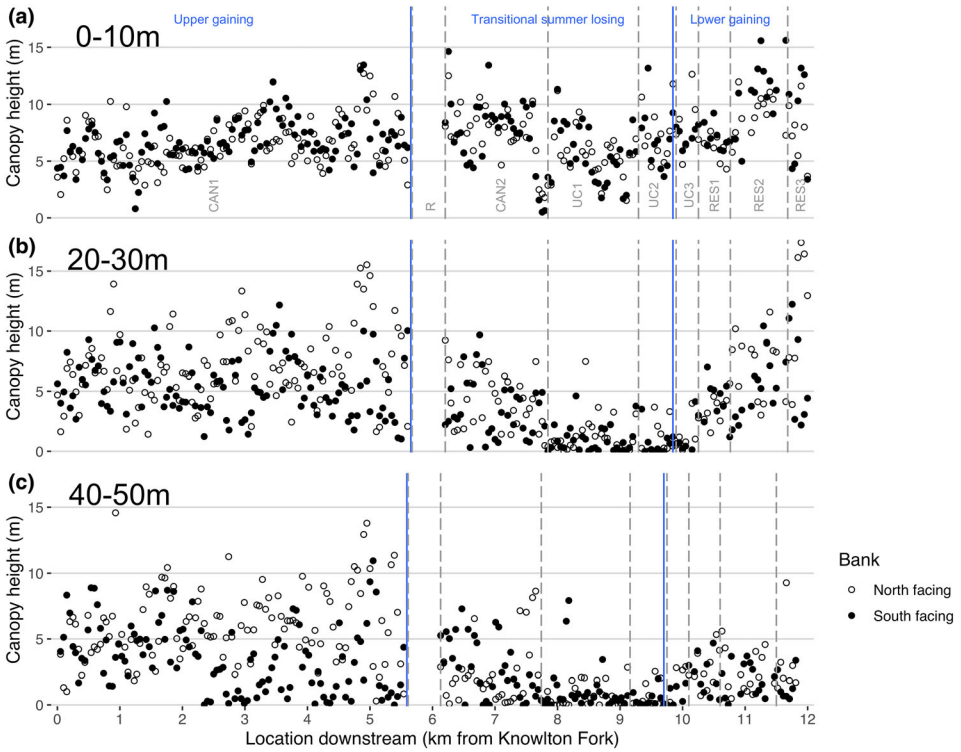

FIGURE 7 Canopy height at 0–10 m (a), 20–30 m (b) and 40–50 m (c) distance from the stream channel, on the north- and south-facing banks. Hydrologic domains are shown in blue (upper gaining; transitional [summer losing]; lower gaining). Dotted lines represent transitions in land use along the stream: Upper Canyon (CAN1); Reservoir (R); Lower Canyon (CAN2); Campus Research Park (UC1); Campus VA (UC2); Campus Sunnyside Park (UC3); Residential Miller Park (RES1); Residential Upper (RES2); and Residential Lower (RES3; Table 1)

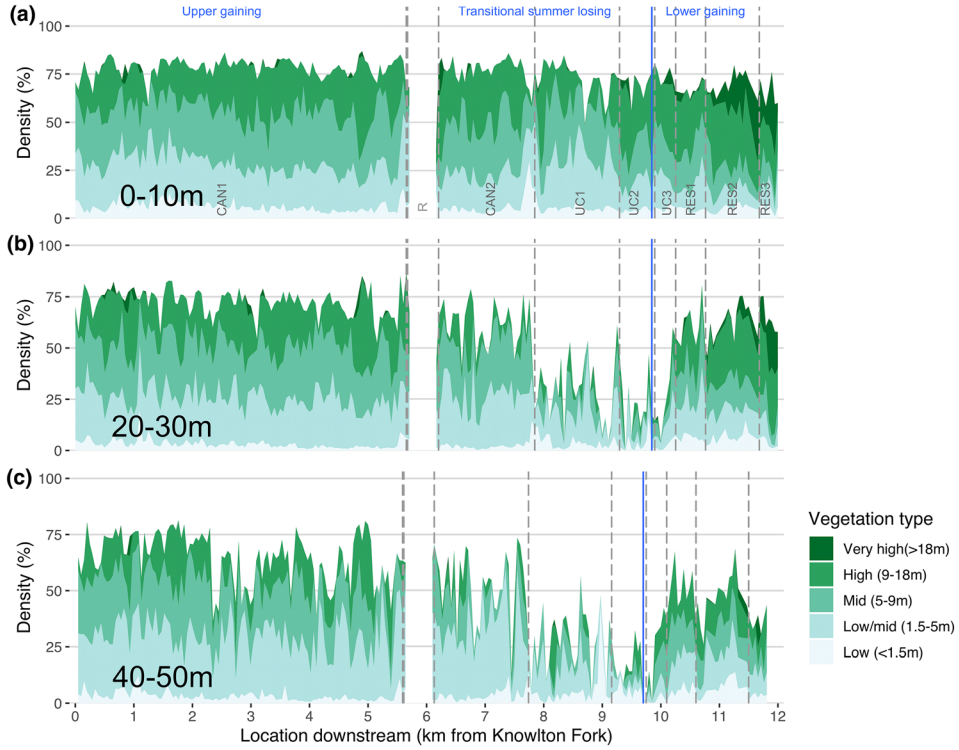

FIGURE 8 Canopy density for five height intervals shown as the percentage of the canopy classified as low vegetation (<1.5 m), low/mid vegetation (1.5–5 m), mid vegetation (9–18 m), high vegetation (9–18 m) and very high vegetation (>18 m) for 0–10 m (a), 20–30 m (b) and 40–50 m (c) from the stream channel. This percentage is computed as a count of lidar returns in each respective vertical range normalized by the total number of lidar returns. The remaining percentage not indicated in the legend accounts for all returns <0.4 m. Hydrologic domains are shown in blue: (upper gaining; transitional (summer losing); lower gaining). Dotted lines represent transitions in land use along the stream: Upper Canyon (CAN1); Reservoir (R); Lower Canyon (CAN2); Campus Research Park (UC1); Campus VA (UC2); Campus Sunnyside Park (UC3); Residential Miller Park (RES1); Residential Upper (RES2); and Residential Lower (RES3; Table 1)

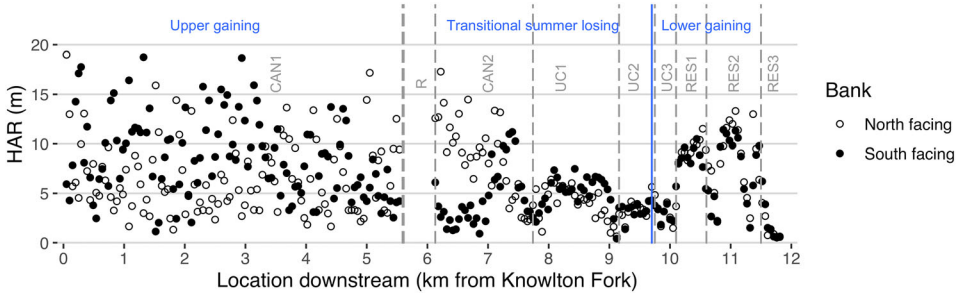

FIGURE 9 Average height above the river (HAR) for each 50 × 50 m plot along Red Butte Creek on the north and south-facing banks. Hydrologic domains are shown in blue: upper gaining; transitional (summer losing); lower gaining. Dotted lines represent transitions in land use along the stream: Upper Canyon (CAN1); Reservoir (R); Lower Canyon (CAN2); Campus Research Park (UC1); Campus VA (UC2); Campus Sunnyside Park (UC3); Residential Miller Park (RES1); Residential Upper (RES2); and Residential Lower (RES3; Table 1)

and increasing nonnative cover downstream, are suggestive of land use effects. The strong shift in community structure to more upland species may be an effect of changes in hydrology. The abrupt increase in nonnative species in the urban area and high percentage of exceptionally tall canopies in residential neighbourhoods, in combination with the decline of riparian forest in the University Campus, demonstrates the importance of decision making of individual landowners in shaping the vegetation in this reach.

4.1 | Local topography and hydroclimate

In the upper canyon, bank orientation was a predictor of cover, canopy height and canopy density (Table 2). We found high cover and tall canopies on north-facing slopes (Figures 3a and 4a), consistent with general theories on energy and water availability on north-facing slopes (e.g., Swetnam, Brooks, Barnard, Harpold, & Gallo, 2017). Since the substrate type is similar on the north- and south-facing banks

of Red Butte Creek (Ehleringer, Arnow, Arnow, McNulty, & Negus, 1992), the differences in vegetation are likely driven by solar radiation rather than soil water conductivity. In upland systems, various studies have shown differences in vegetation structure and composition on different slope aspects (Enright, Miller, & Crawford, 1994; Holland & Steyn, 1975; Sternberg & Shoshany, 2001), with north-facing slopes associated with more shading and lower evaporative demand (Reid, 1973; Shreve, 1915). Moving downstream, we could reasonably expect that lower energy north-facing slopes would be less water limited, and thus there should be a continuation of the trend with aspect observed in the upper reach. However, in the upper portion of the middle transitional reach (between 6 and 7.5 km), north-facing slopes are much higher above the river than slopes on the opposite side (Figure 9), so they may simply be too far above the water table to benefit from any potential water subsidy. The absence of an aspect effect in the lower two reaches is most likely due to human influence, a conclusion supported by the increases in canopy height and the abrupt changes in species composition in these reaches.

Elevation additionally was a strong predictor of cover and canopy density and a weak predictor of canopy height in the gaining upper canyon. As in virtually all semiarid montane streams, conditions are drier and warmer in arid valleys and wetter and colder at higher elevations in Red Butte Canyon. This moisture gradient leads to changes in woody species dominance (Patten, 1998). We observed a shift in community composition around 1,500 m in elevation that was similar to the general pattern described by Patten (1998) along elevational gradients in the Rocky Mountains. We observed Cottonwood species (*Populus*) at lower elevations and a higher abundance of (native) Acer species (*A. grandidentatum* and *A. negundo*) in the higher elevations along Red Butte Creek. Changes in vegetation cover and canopy height 0–10 m from the stream channel are in part caused by this shift in community composition.

Since stream water and groundwater are the major sources of water availability along arid streams, the relationship between HAR and canopy height along the natural upper section of Red Butte Creek followed our expectation of higher water availability with lower HAR. Globally, there is evidence for increased canopy height in forests with greater water availability (Klein, Randin, & Körner, 2015; Tao, Guo, Li, Wang, & Fang, 2016). Stromberg, Lite, and Dixon (2010) found shorter canopies with increasing site dryness along the arid San Pedro River in Arizona. We expected increased HAR to have a larger influence on vegetation structure along a losing reach, where the distance to the water table (and thus water availability) is generally greater, to begin with. However, in the middle reach, we found no relationship between HAR and canopy height, and greater HAR was associated with lower density and cover here. The typical complexity of groundwater–surface water interactions in urban systems (Garcia-Fresca & Sharp, 2005; Hardison, O'Driscoll, DeLoatch, Howard, & Brinson, 2009; Sanzana et al., 2019; Tubau, Vázquez-Suñé, Carrera, Valhondo, & Criollo, 2017) makes it difficult to draw conclusions about the causal effects of HAR in this more urbanized reach, flowing partly through the University Campus. It is surprising that HAR was a relatively weak predictor of vegetation structure overall (affecting canopy height in the upper canyon, cover and density in the middle reach and not affecting any of our vegetation metrics in the lower reach), although the patterns we observed were consistent with water supply as a dominant influence on larger trees in the upper section of the stream. Individual residents may prefer tall trees in their yard, and some streets are ornamented with particularly high tree species (like American sycamore [*Platanus occidentalis*; pers. obs.]). Typical irrigation of planted ornamental trees in residential yards and on streets contributes to taller canopies as well.

The riparian zone appears to be narrower along the middle transitional reach (which contains a narrower zone of high cover and tall vegetation, Figures 6–8) than in the lower gaining reach. As the middle transitional reach is generally losing, this may be caused by the losing hydrologic dynamics. Similarly, gradual declines in cover, height and canopy density and increase in upland species predominance along this reach are consistent with increased water limitation along a losing reach. However, this pattern is paired with increases in nonnative species and canopy height as HAR increases on both north- and south-facing stream banks. This again suggests a strong human influence through planting and irrigating vegetation. We argue that these effects are more likely controlled by land use, via removal of historical vegetation during the development of the institutional campuses (University of Utah and Veteran Affairs) through which this reach flows.

It is tempting to assume that urbanization is typically paired with the removal of vegetation and thus systematically leads to a decline in vegetation. Even though this narrative that riparian forests decline through urbanization has long dominated the literature, in recent decades, authors have found evidence for canopy expansion along many urban streams in (semi)arid regions (Grossinger, Striplen, Askevold, Brewster, & Beller, 2007; Solins, Thorne, & Cadenasso, 2018; Villarreal, Drake, Marsh, & Mccoy, 2012; White & Greer, 2006). Along Red Butte Creek, we argue that vegetation along the urban reaches is largely determined by decision making on the institutional (the University) and individual (private homeowners) level. The urban area is heavily irrigated, adding water to the system. Furthermore, people may remove or add trees and cultivate trees that may otherwise not survive in the riparian zone. This is consistent with the lack of difference between north- and south-facing aspects along the urban reaches of this particular stream. Early settlers removed vegetation, but in modern semiarid cities, individual property owners often make different choices—some add or remove vegetation according to individual preferences and constraints.

In terms of community composition, there is a consensus that increases in nonnative species occur along gradients of urbanization around the globe across multiple taxa (McKinney, 2006). A similar trend has been observed in riparian forests in the context of the urban stream syndrome, both in humid (Burton, Samuelson, & Pan, 2005; Loewenstein & Loewenstein, 2005; Maskell, Bullock, Smart, Thompson, & Hulme, 2006; Pennington, Hansel, & Gorchov, 2010) and arid regions (Sung, Li, Rogers, Volder, & Wang, 2011). Increases in nonnative species have also been placed

in the context of changes in hydrologic regimes due to channel incision that causes 'urban riparian drought' (Groffman et al., 2003), with similar observations in arid regions (Solins & Cadenasso, 2020; Sung, Li, Rogers, Volder, & Wang, 2011). Although there may be indications of decreased water availability along Red Butte Creek's more developed areas (e.g., the low occurrence of wetland species), the underlying causes may be different. We cannot conclude definitively that this is an effect of urban hydrologic drought since we did not measure drought or incision directly. However, the community composition along Red Butte Creek does follow a typical urban increase in nonnatives, with higher abundances of nonnative Norway maple (*A. platanoides*), sweet cherry (*P. avium*) and horse chestnut (*A. hippocastanum*). However, these are all horticultural species that are commonly planted as street trees (Kuhns, 1998; Kuhns & Rupp, 2000; Salt Lake City, 2019; Tree Utah, 2019). The occurrence of horticultural species close to the stream suggests that these trees were either directly planted in the riparian zone or dispersed through nearby planted trees, demonstrating the strong influence of historical development and direct human influence on the riparian forest in this area.

Like most arid streams, Red Butte Creek has regulated flow, which could have altered the vegetation structure below the dam. Unfortunately, we have no direct, long-term records of how long-term downstream flow has been altered by the dam. We do know that the dam results in lower flows early in the spring when vegetation is less water limited and higher flows later in the summer. High spring flows recharge local groundwater in the middle reach, which supplements streamflow in the lower urban reach (Gabor et al., 2017). To really understand the effects of human impact, including flow regulation and land management, on the patterns of vegetation along Red Butte Creek, it would be interesting to collect historical records of the area. Investigating the temporal change may point to specific historic events leading to vegetation change in the watershed.

In addition to the patterns in species composition, patterns of canopy structure also differed among stream reaches in different land use types. The urban reaches along Red Butte Creek (including the University Campus and Residential reaches) were characterized by lower vegetation cover, with the lowest cover in the University Campus, particularly further than 10 m from the stream channel. Plant density decreased quickly throughout the canopy further away from the stream in all urban reaches and especially in the Campus area. We found similar patterns of diminishing vegetation cover in the lower parts of the residential neighbourhood, where Red Butte Creek directly bordered private yards, and buildings occurred within 10 m of the stream channel. This narrowing of the riparian zone likely demonstrates the infringement on the historical extent of the riparian forest due to urban development in these reaches. This finding is supported by aerial images which showed that buildings, paved surfaces and cultivated landscapes often occur within the 50-m wide plots that were used to analyse the riparian forest in this study. However, most of the riparian zone is located within privately owned land, and some of the trees in the riparian zones have likely been planted and managed by residents. This might also explain the abundance of taller trees in these neighbourhoods, particularly in older neighbourhoods which were settled and planted as early as 1857, indicating the importance of land use legacies as well as land ownership on riparian forest structure.

5 | CONCLUSIONS

The results of this study highlight the importance of land use legacies and land ownership in altering vegetation structure beyond patterns resulting from interactions between topography and groundwater that control broad-scale energy-water relationships. The resulting vegetation profiles along this stream show multiple clear transitions in community composition as well as cover, canopy height and density of different height intervals in the canopy that largely overlap with changes in hydrologic state (gaining and losing) and with rapid transitions in land use in more urbanized reaches. Even though the 3D structure of the riparian forest was clearly correlated with land use, observed patterns of canopy height, cover and canopy density did not follow a general gradient of urbanization effects as described in the urban stream syndrome. Rather, they overlapped with transitions in land ownership, demonstrating local footprints of current and past land use. In recent years, the universal applicability of the urban stream syndrome has been challenged, and several authors have discussed the importance of incorporating the regional and local history of urban development in stream management (Booth, Roy, Smith, & Capps, 2016; Hale, Scoggins, Smucker, & Suchy, 2015). The clear influence of decision making by individual landowners on the vegetation structure along Red Butte Creek, which appears to decouple the riparian vegetation from the stream hydrology, demonstrates this importance. The use of LiDAR can be very helpful in efforts to identify stream reaches that offer potential for conservation efforts and landscape management in urban areas, as it is possible to evaluate vegetation at small spatial scales (0.3 m) with extensive spatial coverage.

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DATA AVAILABILITY STATEMENT

The LiDAR dataset that support the findings of this study are openly available in OpenTopography at https://doi.org/10.5069/G9TH8JNQ, reference number OT.122014.26912.1.

The line transect data for woody species is available in the supporting information.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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