Riparian Vegetation Recruitment Tool for Assessing River Management Flexibility, South Fork Boise River

Final report

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Executive Summary

This study presents a native riparian seedling recruitment model for warm temperate to semi-arid fluvial environments that can assist dam operations and planning for ecologically beneficial flow releases when the appropriate hydrologic conditions are present in the South Fork Boise River (SFBR) basin. Field surveys from 2016, 2018, and 2019 were used to calibrate the recruitment parameters for the SFBR. A series of model runs examined hydraulics, sediment transport, and seedling recruitment to evaluate two recent disturbances below Anderson Ranch Reservoir for their ability to assist riparian seedling recruitment success for dam operations during both average and wet hydrologic conditions. These results are put in context to the general evolutionary trend occurring in the coupled river-floodplain system below Anderson Ranch Dam.

Since dam closure in 1950, reduced peak flows and limited sediment supply below the dam have led to channel narrowing over time. This occurs when reduced flood disturbance allows riparian vegetation to colonize the former wide sediment bars that were present in the active channel pre-impoundment. Surveyed tree transects on the floodplain show that median tree density increased 59% between 1957 and 2011. Seral advancement of the riparian forest community provides further geomorphic stabilization of the floodplain as root networks provide biomechanical reinforcement to the sediment matrix. This increased stability of the floodplain limited the impacts of a 50-year flood (2017) to provide a geomorphic disturbance and form subsequent seedling habitat in the floodplain.

The resulting decreased channel width, stabilized floodplain area, increased tree density, and limited flows to flush out downed wood from the forest floor likely led to a riparian corridor with a larger quantity of forest fuel than the pre-dam condition. In 2013, the Elk Fire provided a range of burn severity across the floodplain in which to observe riparian forest regeneration processes and how they relate to native seedling recruitment. Post-wildfire riparian forest regeneration on the floodplain was spatially variable in response to burn severity, with increasing tree density corresponding to burn severity. Five years after the fire (2018), tree density on the floodplain was 33% greater than the pre-fire condition. Field observations show the primary post-fire forest regeneration mechanism on the floodplain was via clonal coppice and root sprouting, particularly by the black cottonwood population. While clonal regrowth resets the apparent age class of the riparian forest, it does not provide for sexual reproduction that affects the genetic diversity of the forest community. Post-fire native seedling recruitment processes on the floodplain was directly related to dam operations.

For pioneer riparian forest species that are dependent upon high river discharge to distribute seeds, remove existing vegetation competition, and maintain soil moisture content, an overbank flood event is required in the few years after a fire disturbance while disturbed conditions persist. In the two years immediately following the wildfire, dam releases were kept below bankfull

during average hydrologic conditions in the basin. This resulted in no floodplain inundation that limited the primary seed dispersal mechanism (hydrochory) for both cottonwoods and willows, as well as the surface and subsurface soil moisture to support initial seedling growth. In the third year following the fire, bankfull dam releases during average hydrologic conditions (2016) could only inundate the near-channel and low-elevation floodplain areas that encountered very low burn severity and associated tree mortality. As a result, the existing vegetation prohibited seedling recruitment in these areas and no observed recruitment occurred along the floodplain. Four years following the fire (2017), high dam releases related to wet hydrologic conditions inundated 78% of the floodplain and were capable of recruiting seedlings across a wider variety of riparian environments. However, vigorous tree sprouts had already reduced much of the available light in the potential seedling habitat areas by forming dense willow and cottonwood thickets, as well as reduced bare sediment from the colonization of grasses on the floodplain. Seedling recruitment on the floodplain was limited to only 5% of all observed seedling recruitment within the riparian corridor. Therefore, successful seedling recruitment for vegetation dependent upon hydrochory may be possible after a low to moderate burn severity, but only if overbank flows are provided within the first year or two after the fire to inundate the floodplain, provide a disturbance, and increase soil moisture.

The wildfire also initiated a series of debris flows within the study site that temporarily increased sediment supply to the river-riparian system below the dam. With 95% of all seedling recruitment occurring within the active river channel, the role of erosional and depositional processes on seedling recruitment was examined separately. Cumulative surveyed seedling recruitment patches during both average and wet years show deposition processes provided more than an order of magnitude greater recruitment area than erosion processes. The average year had 100% of all seedling recruitment occurring in depositional areas within the active river channel, whereas 84% of seedling recruitment was related to depositional processes during dam releases related to wet hydrologic conditions. Collectively, these results illustrate that depositional processes drive successful riparian seedling recruitment within the active channel in the SFBR. Once the sediment supply from the debris fans is exhausted, the stability of the new depositional islands and bars is uncertain.

Development of the riparian seedling recruitment model used field surveys to refine the recruitment parameters for average and wet hydrologic years in the SFBR. The resultant model correctly predicted average-year (2016) seedling recruitment in 75% of the surveyed patches and 25% occurred on new features. Model prediction for the wet year (2017) was able to predict successful recruitment in 40% of the surveyed patches and failed in 3%. Furthermore, 57% of patches occurred on new features. New features constitute the bars and modified island features that were not present during the bathymetric LiDAR survey in 2007 and could not be captured in the model. Simulations for dam releases during average water years predict 1 ha (0.60% of available floodplain area) of collectively favorable seedling recruitment area, leading to an average favorable riparian habitat density of 0.04 ha/km. While these areas are located at elevations high enough to satisfy the minimum recruitment model parameters, their location within the channel makes their survival unlikely in subsequent years. As a result of higher peak flows and greater inundated area in 2017, an overall increase in seedling recruitment occurred within the floodplain. The recruitment model predicted 11.4 ha (7% of available floodplain area) of collectively favorable area. These results show larger contiguous areas of potential riparian habitat that is an order of magnitude larger than the average hydrologic conditions, with a habitat density of 0.50 ha/km. Finally, the recruitment model was used to identify the location and spatial extent of potential areas for restoration planting activities during average hydrologic conditions. Simulated favorable area during average hydrologic conditions for restoration planting reached 25.6 ha (15.5% of available floodplain area). As restoration planting does not require existing forest removal in many places, site selective planting in open areas can potentially increase the existing riparian habitat density by 1.11 ha/km. The most limiting factor for seedling recruitment during average hydrologic conditions (2016) is insufficient disturbance, characterized in the model as shear stress. This allows only 1.6% of the available floodplain area to be viable for seedling recruitment. Alternatively, the limited recruitment success for wet conditions illustrates that greater inundated area alone is not enough for increased riparian seedling recruitment. In fact, elevation values become the most limiting factor of favorable recruitment area (10.2% of available floodplain), with similar limitations from shear stress (11.3% of available floodplain) on the floodplain. Results imply that a target hydrograph with peak flows less than the 2017 flood ($Q<240$ m^3/s) would provide the best target for dam releases when hydrologic conditions allow.

Introduction

Riparian vegetation occurs on less than 1% of the western North American landscape, yet it provides habitat for more bird species than all other vegetation types combined and is critical habitat for many species of mammals (Knopf et al. 1988; Bunnel et al., 2002; Marcot et al., 2010). Additional benefits from healthy native riparian forests include streambank stabilization, reduced channel migration rates, flood peak attenuation, organic and sediment trapping, channel shading, seasonal nutrient inputs to the channel, and the addition of large woody debris (LWD) that acts to increase physical complexity of channels and improve instream habitat for aquatic species (Naiman, et al., 1993; Braatne et al., 1996; Friedman et al., 1996; Abernethy and Rutherford, 2000, 2001; Fierke and Kauffman, 2005; Gurnell et al., 2005; Braudrick et al., 2009; Tal and Paola, 2010; Zong and Nepf, 2010; Cierjacks et al., 2011; Gurnell, 2014; Pollock and Beechie, 2014; Dixon et al., 2016). Native riparian forests of southern Idaho and much of the western U.S. consist of cottonwoods (*Populus* spp.) and willows (*Salix* spp.) that support many of the structural and ecological benefits listed above (Hughes, 1999; Katz et al., 2005).

Sustainability of these native riparian communities requires successful recruitment of new seedlings for genetic diversity in order to provide long-term resilience (Legionnet and Lefevre, 1996; Luikart and Cornuet, 1998; Booy et al., 2000; Smulders et al., 2008; Tiedemann and Rood, 2015), especially in regards to potential impacts of climate change that may include increased fungal and insect invasion, drought severity, and riparian forest fire intensity. Increased genetic diversity is especially important in response to increasing hydrologic stress from climate change that has shown to skew sex ratios within black cottonwood forests (Hultine et al., 2018). In managed river systems located below dams and diversions, the reduction in historic flood disturbance regime has detrimentally impacted the riparian vegetation communities that rely on hydrochory for sexual reproduction and recruitment processes of native riparian species (Rood and Mahoney, 1990; Auble and Scott, 1998; Rood et al., 1999; Shafroth et al., 2002; Lytle and Merritt, 2004; Braatne, et al., 2007; Burke et al., 2009; Dixon et al., 2015). The lack of flow disturbance leads to an altered stream channel morphology as bars vegetate and the channel narrows, tree stands tend to have more homogenous ages on the floodplain, older forest communities shade out seedlings and young trees, and greater amount of snags and deadwood builds up on the riparian forest floor (Rood et al., 1995; Dykaar and Wigington, 2000; Fierke and Kauffman, 2005). If flood disturbances are not periodically introduced to managed river corridors, native pioneer riparian species that depend on such processes for sexual reproduction and genetic diversity may see a shift in the age structure of the riparian community and potential long-term collapse of the existing riparian vegetation community (Johnson, 1992; Friedman and Lee, 2002; Dixon et al., 2012).

A further threat to riparian forests and associated ecosystems in the western U.S. is the increasing recurrence, duration, and severity of wildfire in the landscape (Westerling et al., 2006; Dennison et al., 2014; Jolly et al., 2015). While riparian ecosystems and environments have historically been subject and evolved in response to wildfire events (Arno, 2000; Everett et al., 2003; Olson and Agee, 2005), regional wildfire impacts are projected to increase over the next century (Moritz et al., 2012; Abatzoglou and Williams, 2016), challenging the current management of these critical habitats (Turner, 2010; Westerling et al., 2011). In arid environments of the southwestern U.S. riparian forests are increasingly experiencing wildfire, which in combination with reduced flood peaks, is becoming a dominant ecological disturbance factor (Busch, 1995; Johnson and Merritt, 2009; Smith and Finch, 2017). As flood disturbance decreases in managed river-floodplain systems, conditions leave the riparian forest more prone to forest fire and stand clearing burn events (Busch, 1995; Ellis, 2001). Yet little is known about how native riparian forests respond to fire disturbances and whether such events are beneficial for seedling recruitment (Gom and Rod, 1999; Dwire and Kauffman, 2003; Beche et al., 2005; Kobziar and McBride, 2006; Charron and Johnson, 2006; Wonkka et al., 2017).

Successful riparian vegetation recruitment depends on infrequent high discharge events that perform three critical criteria for successful recruitment: 1) induce a sufficient disturbance along streambanks and floodplains to scour (or bury) existing vegetation to produce bare soil, 2) transport seeds during the period of viability to these recently disturbed areas, and 3) maintain soil moisture for sufficient time that root growth can keep up with the recession of groundwater levels (Mahoney and Rood, 1998; Braatne et al., 2007; Burke, et al., 2009; Benjankar, et al., 2014). These parameters were extracted from a two-dimensional (2D) hydraulic model and incorporated into a native riparian vegetation recruitment model to predict seedling recruitment success along the semi-arid South Fork Boise River in Southern Idaho. Additionally, results from a one-dimensional (1D) sediment transport model were analyzed to evaluate the role of erosion and deposition on seedling recruitment processes at the reach scale. The recruitment model was used to evaluate two major recent disturbances, wildfire and flood, which took place within the riparian corridor below Anderson Ranch Dam. The first disturbance was the Elk Fire in August of 2013 that burned through the riparian forest with major canopy and understory loss. The second perturbation in the system was a 50-year flood event that occurred in 2017. Results are intended to guide dam operational flexibility and conservation activities for improved ecological function of the river-riparian system when appropriate hydrologic conditions are available.

Study Area

The South Fork Boise River (SFBR) is located in southern Idaho (Figure 1) and has a contributing drainage area of 3,382 km^2. The basin has a granitic lithology in the upper watershed and basalt canyons below the dam. This study analyzes the SFBR within a 23 km study site downstream of the Anderson Ranch Dam. The semi-confined river runs through the SFBR canyon with an average channel width of 41 m and a channel slope of 0.0043 m/m. Bankfull discharge is spatially variable in the canyon, ranging from 68-84 m^3/s depending on the specific floodplain unit. Canyon width fluctuates between 75 m and 450 m with inset floodplains ranging between 30 m and 250 m within the study site. The river has a mixed morphology of single and multi-thread channels, with discontinuous side channels that remain wet during the summer season and act as backwater environments until they are activated at higher flows. The SFBR canyon supports upland vegetation along the terraces and canyon walls consisting of mixed grasses, sagebrush (*Artemisia tridentata*), and Ponderosa Pine (*Pinus ponderosa*). Riparian vegetation communities along the banks and floodplains consist of a black cottonwood (*Populus trichocarpa* Torr. & Gray) dominant community with an understory of red-osier dogwood (*Cornus sericea*), water birch (*Betula occidentalis*), and mixed willows (*Salix spp.*) along the riparian-aquatic interface. Former floodplains that now act as terraces have a high percentage of established sagebrush indicating its transition to a stable upland habitat.

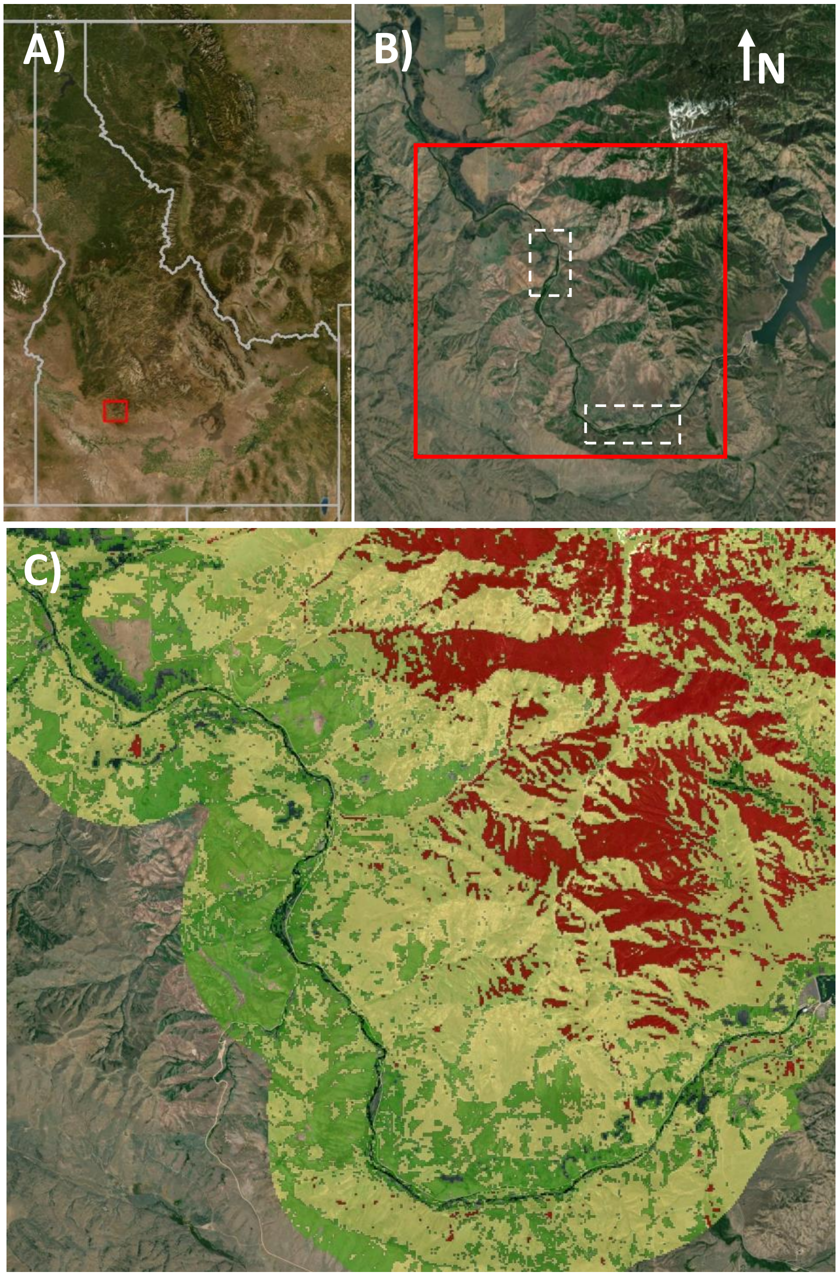
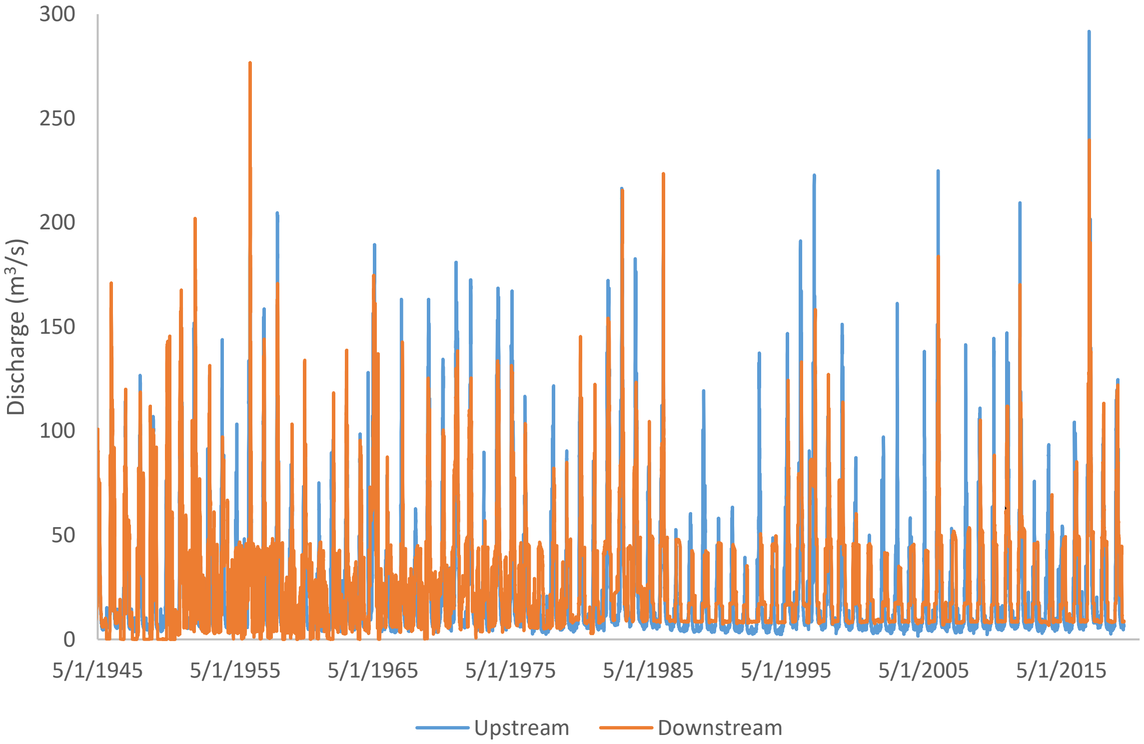


Figure 1. A) Location of SFBR in Idaho. B) Extent of study site downstream of Anderson Ranch Dam. White dashed boxes identify example Reaches A and B. C) Burn severity map illustrating the range of burn conditions within the study site. Red-high severity, yellow-moderate severity, green-low severity, and empty-very low severity.

The SFBR has a warm temperate to semi-arid climate with high evapotranspiration rates in the summer and light snow accumulation in the winter. The basin has a natural snowmelt driven hydrology that historically peaks between April and mid-June, however, closure of Anderson Ranch Dam in 1950 effectively reduced peak flows, cutoff upstream sediment supply, as well as altered the timing and recession rates in the downstream canyon. The current flow regime below the dam (Figure 2) is principally operated for irrigation delivery and flood control, with hydropower production occurring as a secondary priority. Reservoir operations during average hydrologic years allow a small spring peak release with a return to relatively steady irrigation delivery discharges between 45-51 m^3/s throughout the summer months. Releases are scaled by available water in the reservoir depending upon the annual hydrologic conditions and irrigation demand. Ramping down the flow in the fall is performed stepwise until baseflow conditions are met normally at 8.5 m^3/s for the duration of the winter months. In 2017, high levels of snowpack in the basin provided hydrologic conditions that required flood control releases to occur at Anderson Ranch Dam that exceeded bankfull conditions for 100 days. These high flow releases resulted in the second highest magnitude flood below the dam (240 m^3/s) in recorded history. The historic hydrograph illustrates the range of conditions that are possible in the SFBR below the reservoir.



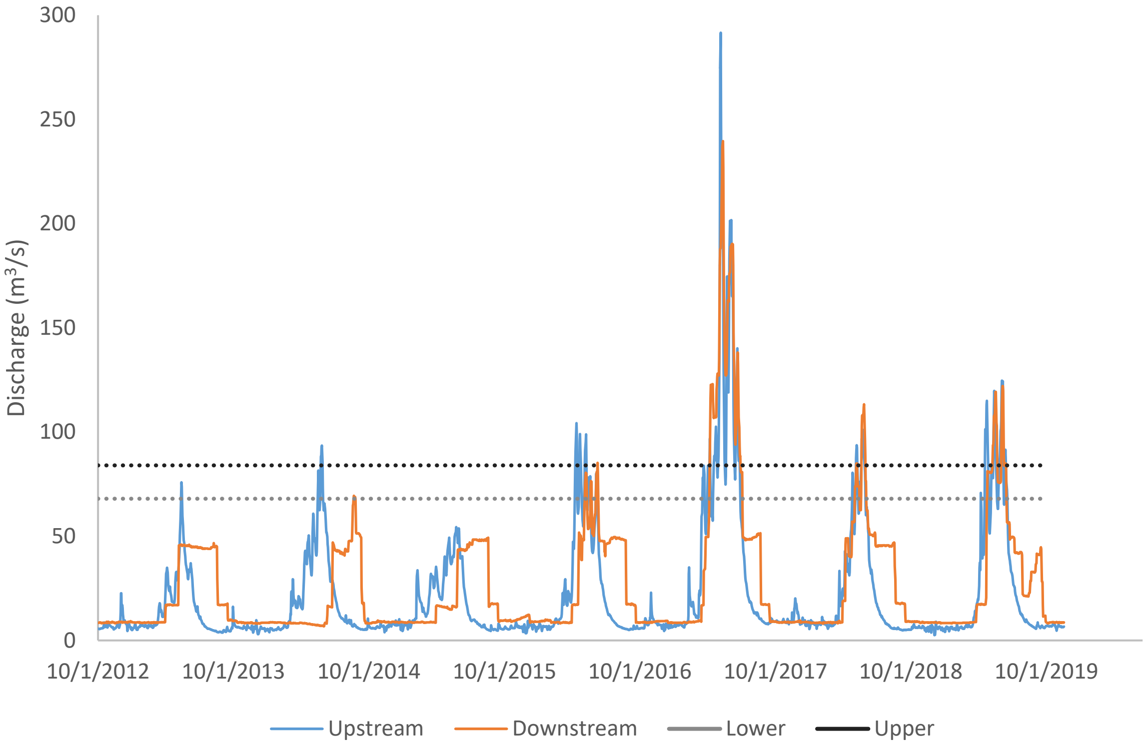


Figure 2. A) Long-term hydrographs for the USGS gages upstream (blue series is near Featherville, ID - 13186000) and downstream (orange series is at Anderson Ranch Dam - 13190500) of Anderson Ranch Reservoir. B) Recent hydrographs for the SFBR since the Elk Fire occurred in 2013. Upper black stippled line (84 m^3/s) shows the upper bound of bankfull discharge and the grey stippled line (68 m^3/s) shows the lower bound of bankfull discharge. Observations in the field suggest flow greater than 84 m^3/s is required to initiate floodplain inundation in most areas.

The 2013 Elk Fire occurred in August and was contained by 08/30/2013. The wildfire extended from the upland Ponderosa and grassland habitat into the riparian area with variable burn severity across the floodplain. Burn severity within the riparian zone was patchy and ranged from very low to moderate (USBLM, 2013). Tree mortality was limited in very low severity areas with light crown and bole scorch, whereas moderate severity areas had greater percentages of top kill. Many top kill trees responded with coppice and root sprouts after the fire, resulting in vigorous regrowth on the streambanks and floodplain. Vegetation loss in the upland tributaries resulted in subsequent debris flows occurring in September (09/13/2013). Debris flows entered the channel as alluvial fans at five locations within the study site that delivered large quantities of sediment directly to the fluvial system. In 2014, experimental high flow releases mobilized these sediments and moved them downstream with limited geomorphic changes in the channel. Dam operations during average hydrologic conditions in 2016 were capable of minor bar redistribution within the active channel, whereas the high dam releases of 2017 redistributed sediment throughout the system forming new bars and modifying islands.

Methodology

This study seeks to improve understanding of riparian seedling recruitment within the managed river corridor of the South Fork Boise River. Recruitment is defined here as seed germination, root extension, and seedling growth over a one growing season. Lessons from this study should be useful in other settings ranging from warm temperate to semi-arid river-riparian systems in the western U.S. and elsewhere. In particular, this study conceptually examines how geomorphic changes below dams affect native seedling recruitment and how the current conditions can be incorporated into parameters for a native seedling recruitment model. Additionally, two system-wide perturbations, riparian wildfire and a 50-year flood, provide an opportunity to evaluate if these events are beneficial for seedling recruitment. The question to address is: *Given these large disturbances in the riparian corridor, were the disturbance events of sufficient magnitude to establish a viable seedling population of native pioneer riparian species?* This study leverages earlier modeling work in the SFBR basin (USBR, 2014a; USBR, 2017; Benjankar et al., 2018) to evaluate the impacts of these perturbation events on riparian seedling recruitment processes.

Historic Aerial Photography

To understand the evolutionary trajectory of the SFBR, historic channel and floodplain conditions were examined through aerial imagery. The earliest available images from 1957 were supplied by the U.S. Forest Service and reflect the conditions shortly after dam closure in 1950. These historic photographs were compared with more recent imagery from before (2011) and after (2015, 2018) the 2013 Elk Fire to assess changes in channel morphology and floodplain vegetation density. Photographs in 1957 and 2018 both occur after the two highest flows on record that differ by 14%, providing insight into how the riparian conditions respond after 68 years of flow regulation. Active channel width was measured in GIS and is defined as total width of the channel that is capable of transporting sediment and causing a disturbance sufficient for native seedling recruitment. This includes all primary and secondary channels, as well as bars and bare sediment features along the channel margins. As a function of interacting disturbing and stabilizing forces, active channel width is considered a surrogate for the extent of geomorphic disturbance and seedling habitat availability.

To generally characterize changes in riparian forest density along the floodplain to perturbations from the pre-dam conditions, tree counts were performed along 200 m transects (n=14) spatially distributed throughout the study site. Each transect ran roughly parallel to the channel and was located within 75 m of the streambank to include a range of morphologic features (e.g. bars and floodplains), as well as burn severities. Burn severity maps were used to identify the distribution and spatial extent of burn severity (USBLM, 2013). All trees that had their canopy intercept the transect were included in the count. Temporal trends in tree surveys only represent tree density and do not capture changes in age class or tree species, although dominant forest canopy was usually black cottonwood. Field tree counts were also performed along select transects (n=10) in

September 2018 to validate counts from aerial photos (Figure 3). Mean percent correct enumeration between 2018 aerial and field surveys was 88% (max % difference = 25%), with a tendency for aerial counts to underpredict owing to difficulties in resolving individual small trees. Root mean square error was computed for tree counts as $RMSE = \sqrt{\sum_{i=1}^{n} \frac{(x_f - x_p)^2}{n}}$, where x_f= field counted trees per transect, x_p= photo counted trees per transect, and n= number of transects. Reported RMSE between aerial and field approaches in 2018 was 5.60. Statistical significance of temporal changes in active channel width and tree density were performed by nonparametric Mann-Whitney tests. All tests were performed for an α=0.05.

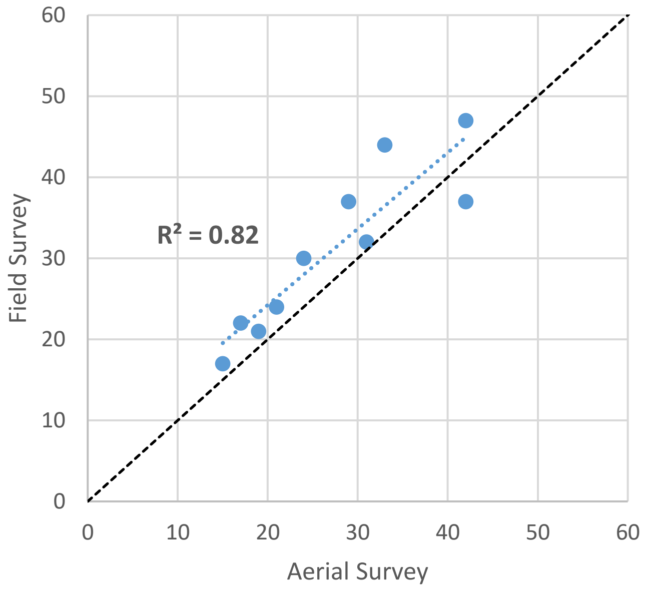


Figure 3. Calibration check between aerial surveys and field surveys. Dashed line indicates 1:1 relation. Stippled line shows linear trend in data.

Seedling Surveys

Field surveys of riparian seedling recruitment were performed in October of 2016 and September of 2018 to evaluate the success of native seedling recruitment during average and wet hydrologic conditions in the basin. Native vegetation patches consisted of the dominant riparian forest species, willow and/or cottonwood seedlings. The 2016 patches were surveyed with a handheld GPS and represent recruitment during the first bankfull flow event after the fire during average hydrologic conditions in the basin. The 2018 survey was surveyed with RTK GPS and used to evaluate seedling recruitment for dam operations during wet hydrologic conditions. Seedling cohort age within a patch was determined by counting the number of intervals between terminal bud scars. Seedling recruitment areas were categorized by morphologic feature that included floodplain, streambank, debris fan, island, and bar. To quantify surface sediment texture, grain size measurements were performed by Wolman pebble counts at eight successful seedling patches and dominant surface size was classified at an additional five patches across the study site. An additional three bulk sediment samples were taken from the floodplain within 50 m of the channel and sieved in the laboratory to compare with surface pebble counts. Results informed the seedling recruitment parameters for the recruitment model.

Groundwater Monitoring

To characterize how the groundwater conditions changed with river flow, the water table (WT) elevation was monitored by pressure transducers located in floodplain observation wells. Three 1.4 m groundwater wells were installed to investigate the channel-groundwater interactions over the course of a growing season. Hobo Troll pressure transducers were installed on April 28, 2019 and removed September 18, 2019. One pressure transducer malfunctioned during the deployment, leaving two reliable timeseries records for the locations in figure 4. Well 01 (upstream) and Well 03 (downstream) were located at 103 m and 41 m away from the main channel, respectively. Cross correlation analysis was used to identify the relationship between river WSE and WT as well as the infiltration time lag associated with elevation changes.

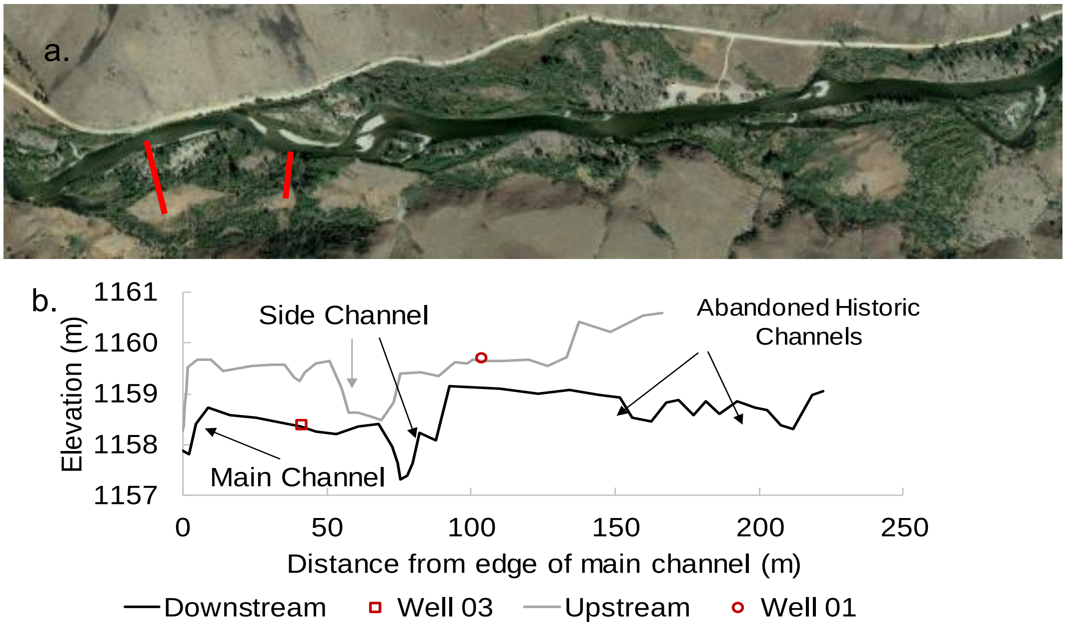


Figure 4. Groundwater monitoring locations and associated floodplain cross sections.

Hydraulic Modeling

The native riparian vegetation recruitment model must be coupled with a separate two-dimensional (2D) hydraulic model to provide the necessary input parameters. In this study, discharge and inundation values were simulated with a calibrated 2D MIKE21 hydraulic model (DHI, 2017) over the study domain for eleven steady state runs that bracket the hydrologic conditions in the basin. Steady state model runs were performed for 4, 8, 17, 28, 45, 57, 68, 102, 142, 184 and 227 m^3/s flow releases from the Anderson Ranch Dam. Channel dimensions were provided by a bathymetric LiDAR flight in 2007 that established a 2 x 2 m resolution continuous

DEM of the channel and floodplain. Model calibration used an iterative optimization of manning's roughness and eddy viscosity values to achieve minimum root mean square error values (RMSE) for measured river water surface elevation (WSE) and flow velocity. Respective RMSE values for WSE and flow velocity ranged from 0.17-0.2 m and 0.07-0.27 m/s depending upon flow. Water surface elevations for discharge between simulated runs were linearly interpolated to provide information on any flow between 4 and 227 m^3/s. For example, WSE, depth, and velocity for a discharge of 61 m^3/s were calculated in each grid cell from linear interpolation of results for the 57 and 68 m^3/s. Full model details can be found in USBR (2017) and Benjankar et al. (2019).

To understand seedling recruitment potential during average and wet hydrologic conditions, simulated seedling recruitment were compared between dam releases during average (2016) and wet (2017) hydrologic conditions (Figure 5). Natural peak discharges upstream of the reservoir at the USGS Featherville gage (13186000) were 104 m^3/s in 2016 and 274 m^3/s in 2017, with respective recurrence intervals of 1.5-year (2016) and greater than 200-year (2017). Peak discharges were reduced below the reservoir, with dam operations limiting peak flood flows to 80 m^3/s (1.25-year) and 240 m^3/s (50-year), for 2016 and 2017 respectively. Spatial extent of bankfull channel was delineated using the River Bathymetry Toolkit (McKean et al., 2009) and overbank flow was initiated at 68 m^3/s in the study site.

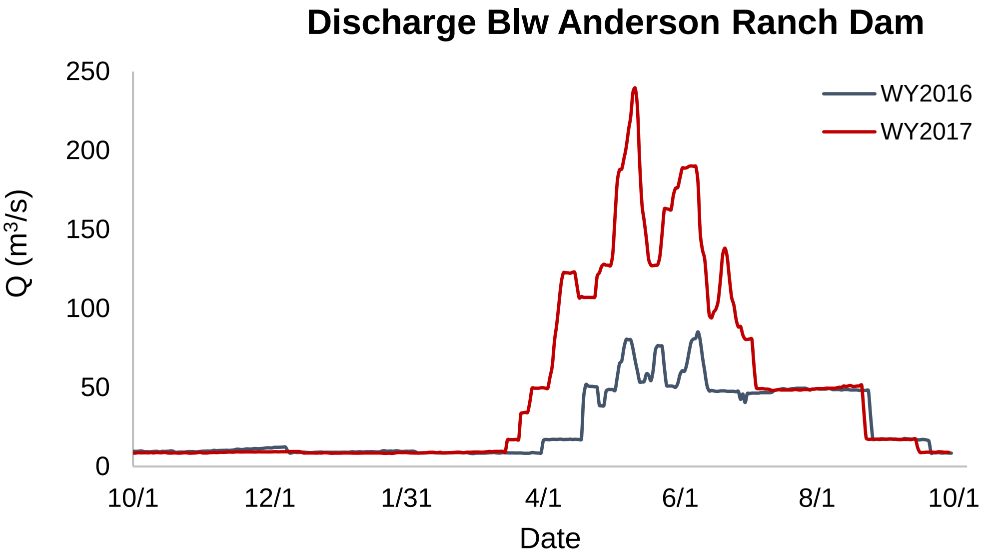


Figure 5. Simulated hydrographs reflecting average (2016) and wet (2017) hydrologic conditions in the South Fork Boise River basin.

Seedling Recruitment Modeling

The native riparian vegetation recruitment model is a fuzzy rule-based model to determine habitat suitability for seed germination and seedling survival through the first growing season

(Benjankar et al., 2014). The model was modified to be relevant for warm temperate to semi-arid conditions of the SFBR canyon. The flow chart depicting the calculation steps within the riparian recruitment model is presented in Figure 6. The recruitment model uses the daily outputs from the hydraulic model over the six month growth season (April 1 through September 30) as input parameters to calculate areas favorable for native riparian seedling recruitment within the riparian corridor. Input parameters for the recruitment model are a) seed dispersal period, b) bed shear stress, c) 3-day moving average water surface recession rate calculated as a mortality coefficient, and d) elevation of topography referenced to the base water level in the channel (Table 1). The recruitment model reports fully favorable, partially favorable, less favorable, and unfavorable conditions for each cell within the model domain. Predictive model outputs were spatially mapped and compared to field surveyed patch extents to refine model parameters for the semi-arid conditions found in the SFBR canyon. Areas in the channel that are submerged by baseflow conditions of 8 m^3/s are excluded from analysis owing to continuous inundation.

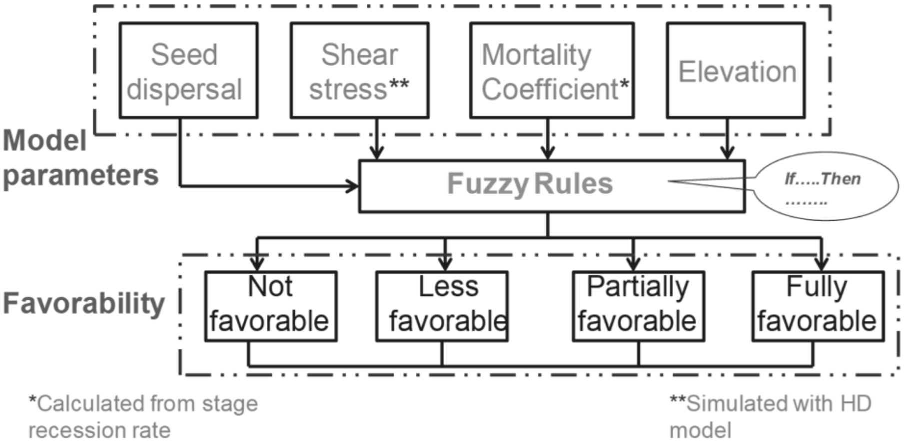


Figure 6. Flow chart of the physical variables and output categories from the riparian recruitment model. Figure is modified from Benjankar, et al. (2014).

As with any model, the riparian recruitment model should be calibrated before using for future prediction. Original model parameters were developed for the Kootenai River near the Idaho-Canada border, where hydrologic, lithologic, and morphologic conditions are considerably different from the environmental conditions found in much of the western U.S. Original model parameters were based on literature values from a limited number of studies on large rivers in the Midwest, Pacific Northwest, and Canada. These values were assessed for the conditions in the SFBR based on field observations and numerical results. Calibration was done through adjusting the threshold values for each parameter according to local conditions in the SFBR basin (Table 1). Threshold parameter values may change based on river type, geographic location, and size of river system. In the current study, peak flows correspond to the period of active seed dispersal in the region and that rule was uniformly assigned to “Good” for all runs. The threshold values for the other parameters were modified/calibrated based on local conditions found in surveyed riparian seedling patches along the SFBR study site.

Table 1: Threshold values of physical parameters considered for riparian vegetation recruitment.

Natural recruitment*	**Plantation**	**Condition**	**Reference**
1. Peak timing		May-20 - July-15	Braatne et al., 1996; Burke et al., 2009
2. Shear stress (N/m^2)$^\alpha$			
>25.00$^\Delta$	>0	Good	Calculated shield's criteria using d_{65} and critical dimensionless shear stress of 0.03 and 0.06
13.00 - 25.00$^\omega$		Fair	
Other (<13.00)		Poor	
3. Mortality coefficient (-)$^\beta$			
< 20	Same as for natural recruitment	Good	Braatne et al., 1996; Braatne et al., 2007; Burke et al., 2009, Benjankar et al., 2014
20 - 30		Fair	
>30		Poor	
4. Elevation (m)$^\gamma$			
0.12 - 0.6	0.12 - 1.0	Good	Mahoney and Rood, 1998; Burke et al., 2009, Polzin and Rood, 2006; Benjankar et al., 2014
0.6 - 1.0	1.0 - 1.4	Fair	
Other	Other	Poor	

*Threshold values can be altered and used as calibration parameters

$^\alpha$Maximum local shear stress during peak flood $^\beta$Mortality coefficient threshold values

$^\gamma$Elevation referenced to river base flow level. These values are estimated based on field condition

$^\Delta$Based on dimensionless critical Shields stress, θ= 0.06 for incipient motion

$^\omega$Based on dimensionless critical Shields stress, θ= 0.03 for incipient motion

The disturbance parameter of shear stress was calibrated according to the grain size distributions within surveyed seedling recruitment patches. From observations in the field, the removal of existing vegetation was based on erosion of the sediment around the stem and rooting zone. The range of threshold shear stress values of 13 and 25 N/m^2 was calculated based on the critical Shields parameter values of 0.03 and 0.06 (Shields, 1936). The bed shear stress is defined by equation (1):

$$\tau = (\rho_s - \rho) g D_{65} \tau^*_{crit} \tag{1}$$

Where τ = bed shear stress (N/m^2), ρ_s = density of sediment (kg/m^3), ρ = density of water (kg/m^3), g = gravitational acceleration (m/s^2), D_{65} (26 mm) = grain size where 65% of the bed is finer, and τ^*_{crit} = critical dimensionless shear stress required to initiate sediment movement and hydraulic disturbance for seedling habitat preparation. $\tau^*_{crit} < 0.03$ was considered to have insufficient disturbance, $0.03 < \tau^*_{crit} < 0.06$ had moderate disturbance, and $\tau^*_{crit} > 0.06$ was considered to have excellent disturbance for seedling habitat creation. Shear stress was considered “Good” when $\tau > 25$ N/m^2, “Fair” when 13 N/m$^2 < \tau < 25$ N/m^2, and “Poor” when $\tau < 13$ N/m^2, as it was considered insufficient for creating bare surfaces. When the model was run specifically for identifying restoration planting areas, mechanical sediment preparation was assumed and shear stress values were considered “Good” for the entire area.

The mortality coefficient accounts for desiccation stress on seedlings by incorporating the recession rate of the river WSE and associated groundwater in the floodplain that maintains soil moisture in the seedling rooting zone. The average recession rate uses the convention of a 3-day moving average of daily stage decline. An average recession rate of 0 to 0.05 m/day is considered favorable, 0.05 to 0.1 m/day was considered stressful, and greater than 0.1 m/day was categorized as lethal (e.g., Benjankar et al., 2014; Braatne et al., 1996; Burke et al., 2009). Water surface recession rates in bars and floodplains (where seedling recruitment occurs) is calculated with an assumption that the groundwater table is directly associated with WSE in the channel (Amlin and Rood, 2002; Busch et al., 1992; Mahoney and Rood, 1998).

Computation of the mortality coefficient (M) uses the 3-day average recession rate in each cell to account for the effects of the capillary fringe and root elongation on seedling desiccation due to lethal recession rates (Braatne et al., 2007; Burke et al., 2009). The coefficient M is based on the principle that a few days of lethal recession rate may stress seedlings, but not necessarily kill them. Furthermore, lethal stress may be compensated by groundwater infiltration, intermittent precipitation during the growing season, and substrate moisture retention within the capillary fringe. A mortality coefficient <20 is considered “Good”, 20-30 is “Fair”, and >30 is “Poor” similar to previous studies (e.g., Benjankar et al., 2014; Braatne et al., 2007; Burke et al., 2009). The same range of coefficients was considered appropriate for survival of planted saplings.

The elevation parameter is based on the topographic elevation of each cell within the surveyed riparian seedling patches that is above the reference base-flow WSE (8 m^3/s). A majority (63%) of field surveyed seedling grid cells (n= 1028) occur within an elevation range of 0.12-1.0 m. From this the elevation range 0.12-0.6 m is considered “Good”, 0.6-1.0 m is considered “Fair”, and elevations <0.12 m and >1.0 m above base flow are considered “Poor” for seedling recruitment. In this study the critical rooting depth was defined as 1 m, which is based on a root growth rate of 4-12 mm/d for riparian seedlings that can tap groundwater at depths of 0.75-1.5 m by the end of the first growing season (Johnson, 1994). For computation of restoration planting parameter thresholds, the elevation range of 0.12-1.0 m is considered “Good” and 1.0-1.4 m is categorized as “Fair”. These elevations are considered appropriate assuming the plantings are one-year old saplings with an existing root length of 0.5-0.75 m or dormant pole cuttings will be planted to this depth.

Model prediction of successful riparian recruitment was evaluated by comparing field surveyed and simulated patches. Simulated predictions were reported as a “success”, “failure”, or occurring on a “new feature”. Simulated “success” was defined when at least one favorable recruitment cell intersected with a field surveyed patch, otherwise it was classified as “failure”. A “new feature” is defined as an area that was not present in 2007 when the model bathymetry was collected (e.g., bar) and is located within the base-flow channel extent defined by 8 m^3/s discharge.

To evaluate recruitment potential within the available floodplain, the collective favorable seedling recruitment area (summation of fully favorable, partially favorable and less favorable areas) was computed for average (2016) and wet (2017) hydrologic conditions, as well as a planting option. From field observations of riparian vegetation extent, the available floodplain was operationally defined as 2 m above the river’s base-flow WSE. Using this definition, the total available floodplain within the SFBR study site is 165 ha. This effective area allows restoration alternatives to be normalized as percentages of total available floodplain area.

Sediment Transport Modeling

A one-dimensional (1D) coupled hydraulic and sediment transport model of the South Fork Boise River between Anderson Ranch Dam and Arrowrock Reservoir was developed to simulate post-fire sediment transport through the river-floodplain system (USBR, 2014a). Cross sections for the model were extracted every 30 m from the same 2007 DEM that was used for the 2D hydraulic model (see hydraulic modeling section). Boundary conditions were established from the upstream Anderson Ranch (USGS 13190500) and downstream Neal Bridge (USGS 13192200) gaging stations for discharge and stage. Hydraulic model calibration was performed through optimizing the Manning’s n roughness parameter to minimize the difference between surveyed and simulated water surface elevations during low (8.9 m^3/s) and intermediate (45.6 m^3/s) discharges. Low flow simulations employed a spatially variable Manning’s n=0.05-0.11 $s/m^{1/3}$, whereas the intermediate discharge had n=0.033-0.072 $s/m^{1/3}$. Roughness values were refined until deviations between modeled and observed water surface elevations had RMSE<0.15 m, which was approximately equivalent to the vertical accuracy of the model bathymetry (McKean et al., 2009). Complete model details can be found in USBR (2014a).

The process-based coupled hydraulic and sediment transport model used the Ackers and White total sediment load transport equation. Boundary conditions for sediment influx below the dam, from tributaries, and hillslopes were set to zero as these sources are limited outside the influence of the debris flows. The delivered sediment volume from the post-wildfire debris flows was distributed over the streambed cross-section uniformly where the debris flows entered the channel. The modeled sediment sizes included 0.22, 2.0, 11.31 and 38.89 mm that were determined by bulk sieved sediment samples from the debris fans. Percentage of grain sizes from each fan and the river channel that informed the model sediment gradation curves are reported in Table 2. The sediment transport model was not calibrated due to lack of sediment transport data. Therefore, all results represent relative trends through the system instead of absolute transport values.

Table 2. Percentage of grain sizes used in the sediment transport gradation curve from the riverbed and each debris flow.

Location	**0.22 mm**	**2 mm**	**11.31 mm**	**38.89 mm**
Riverbed	2%	10%	20%	68%
Debris Fan 1	45%	33%	22%	0%
Debris Fan 2	37%	32%	15%	16%
Debris Fan 3	43%	35%	22%	0%
Debris Fan 4	22%	48%	29%	1%

Simulations were run for a 5-year duration (2013-2018) to examine cumulative erosion/deposition after the 2013 wildfire and debris flows. Results are spatially limited by the 1D modeling approach to provide data every 30 m through the model domain. Surveyed seedling patches often extend over numerous cross sections or are located between cross sections of the sediment transport model; therefore, sediment transport results employ a three-cross section moving average (90 m) to illustrate general trends in deposition or erosion within the reach. Cumulative sediment transport within the model domain was spatially compared to surveyed seedling patches to illustrate whether erosional or depositional processes facilitate seedling recruitment in the SFBR.

Results

Historic Channel and Floodplain Analysis

Dam construction and operations in the SFBR system have resulted in reduced peak stream flows and sediment supply from the upstream basin that have resulted in geomorphic stabilization of the riparian corridor downstream of Anderson Ranch Dam. The earliest aerial images show broad sediment bars and sparse riparian forest coverage on the floodplain, illustrating high alluvial turnover rates and associated seedling recruitment potential of the natural system (Figure 7). Historic channel morphology included a wide active channel with a complex mosaic of attached and medial bars that were dissected by secondary channels and chute cutoffs. The dynamic geomorphic processes provided a diverse array of erosional and depositional surfaces for seedling colonization and recruitment. However, 61 years (1950-2011) of regulated flows and reduced sediment supply in the SFBR led to active channel narrowing, reduced alluvial bar area, and coarsening of the active channel substrate that collectively stabilized the river planform. With reduced geomorphic disturbance, dense cottonwood and willow forests colonized the bars and floodplains that were present before reservoir closure. This expansion of pioneer riparian vegetation into these formerly open areas increased the total riparian tree population and forest cover along the floodplain in both Reaches A and B. As the riparian forest further colonized and matured on the floodplain, streambanks, and islands, seedling recruitment processes were reduced by 1) elimination of bare sediment patches, 2) shading potential habitat under the forest canopy, and 3) stabilizing the streambanks and floodplain surfaces with a root network to effectively eliminate erosional processes during high flow events. Without disturbance or available bare sediment, pre-fire seedling recruitment habitat in the SFBR was spatially restricted to the narrow margins of streambanks and bars. The recent perturbations to the riparian corridor resulted in little geomorphic alteration to the channel planform or floodplain extent. Photos two years after the wildfire (2015) show there is little evidence of geomorphic change to either the channel or floodplain resulting from vegetation loss. Additionally, photos one year after the flood (2018) illustrate some evidence of geomorphic change in the channel, with new medial and point bars forming and deposition at the head and tail of vegetated islands. However, no geomorphic changes are visible on the floodplain.

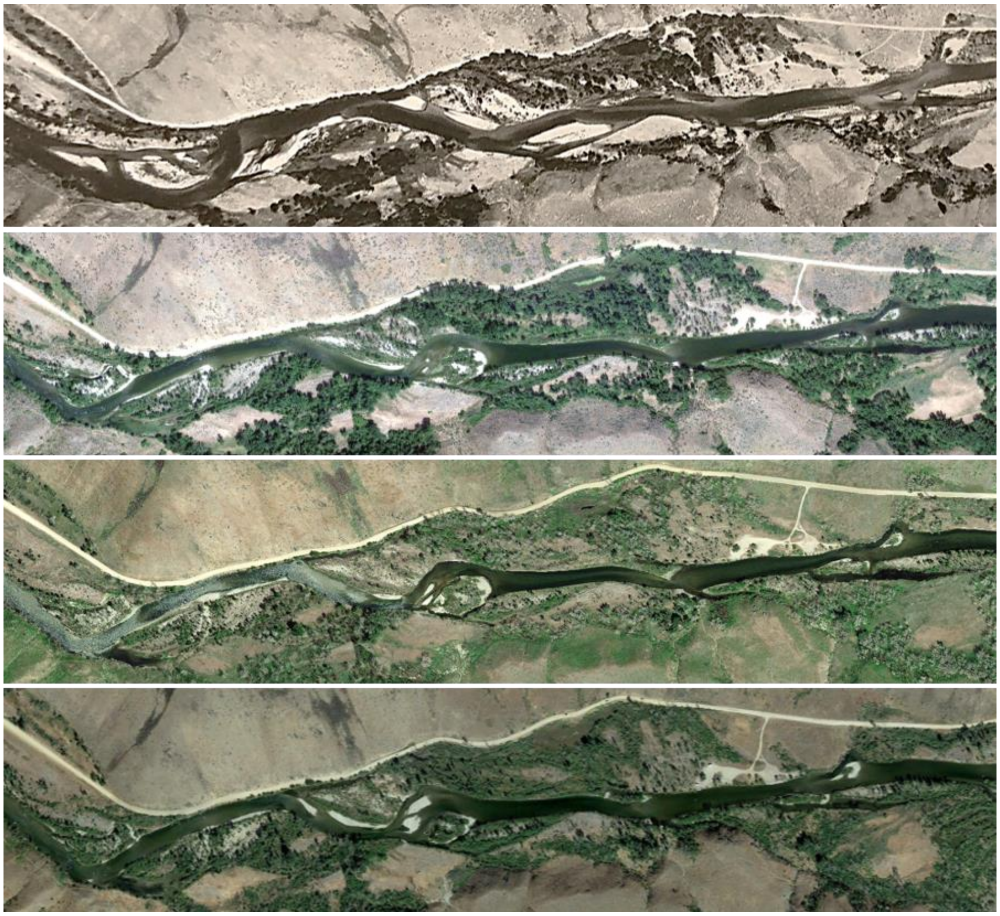


Figure 7. Timeseries of A) Reach A located 5 km below Anderson Ranch Dam, B) Reach B located near Cow Creek 12.5 km below Anderson Ranch Dam. Top panel – 1957, second panel – 2011, third panel – 2015, bottom panel – 2018.

As vegetation colonized the bars and encroached on the river, channel narrowing occurred in the years following dam closure. Reduced peak flows that no longer provide sufficient hydraulic disturbances to mobilize sediment or clear vegetation in the floodplain allowed seral advancement of the riparian forest community and further geomorphic stabilization. Stabilization of streambanks and floodplain surfaces occurred from biomechanical strengthening of the sediment matrix via the addition of fibrous root bundles from trees and shrubs. Channel narrowing has occurred on other western rivers when dam operations or drought conditions have reduced historic flood peaks (Friedman et al., 1996; Shafroth et al., 2002; Stromberg et al., 2010). In the SFBR, significant channel narrowing occurred between 1957 and 2011 ($p=1x10^{-16}$), whereas the combined influences of riparian forest fire (2015) and flood (2018) led to no significant width changes ($p \geq 0.36$). Comparison of active channel width (Figure 8) quantifies the stabilizing impacts of river regulation and ability of riparian wildfire and subsequent flood to provide available habitat for seedling recruitment at the reach scale. Historic median active channel width within the alluvial floodplain was 105 m, which narrowed over time to its current median width of 40 m. The effects of river regulation significantly reduced active channel width and the associated seedling recruitment habitat by 62%, owing to reduced hydraulic disturbance and bar colonization.

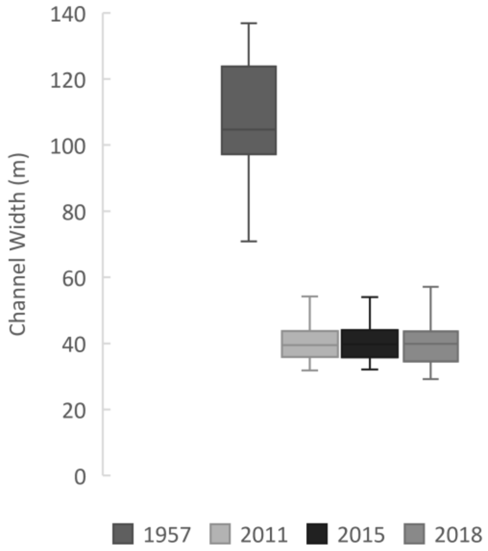


Figure 8. Distribution of active channel widths within the alluvial floodplain reaches of the study reach.

For further context into the effects of floodplain stabilization from riparian vegetation, the 1957 photographs were taken one year after a major flood event was released from the dam (Q_{peak} = 277 m^3/s) and show broad, unvegetated bars up to 137 m wide. While these photos show the system response to an extreme flow, the 2017 flood (Q_{peak} = 240 m^3/s) was within 14% of the 1956 peak discharge and did not show a similar geomorphic response to the high flow event. Active channel width after the flood showed only local erosion of streambanks, leading to a small increase in variance between the pre-flood conditions in 2011 (Var=140.0) and 2015 (Var=144.2) and the post-flood conditions in 2018 (Var=166.5). This indicates that the stabilizing force of riparian vegetation can increase the threshold of disturbance above the pre-dam condition, requiring either an extreme event greater than a 50-year flood or intervention from management to attain periodic channel dynamics in the river corridor.

The processes of channel narrowing along the floodplain and bar stabilization provided greater surface area for riparian vegetation to colonize. The greater available floodplain area without hydraulic disturbances initially allowed for increased cottonwood and willow populations after dam closure. The initiation of flow regulation and reduction in hydraulic disturbance led to an overall increase in riparian forest population that scaled with the colonization of bars and reduction in active channel width. Surveyed tree transects on the floodplain show that median tree density increased 59% between 1957 and 2011, owing to riparian colonization of the formerly exposed bars (Figure 9). One growing season after the wildfire (2015), tree density was reduced to approximately similar density as the pre-dam floodplain. However, tree density had increased five years after the wildfire as trees recovered from the burn and/or responded via root sprouting. The 2018 survey has the greatest variation in response as it covers a range of burn intensities across the floodplain, but median values show a significant increase of 33% (p=0.02) above the pre-fire (2011) tree density. This increased density occurs mainly as greater light availability, existing root networks with access to the shallow water table, and spatially distributed root sprouting provide ideal regrowth conditions on the floodplain. Therefore, five years after the fire (2018) tree density on the floodplain was greater than before the wildfire.

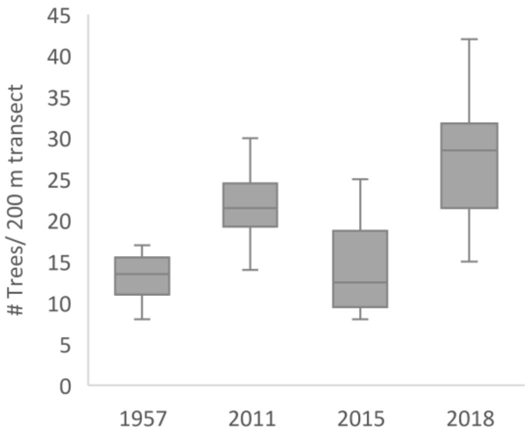


Figure 9. Tree density estimates in the SFBR from aerial photographs.

Riparian Wildfire Response

From the earliest historic imagery in 1957, floodplain vegetation density was very low owing to periodic flood disturbances and vegetation export downstream. The 1957 photos were taken the year after a major flood in 1956, showing sparse tree population near the active channel and grasslands in higher elevations (Figure 7). Hence, the bulk of riparian forest fuels that built up prior to the 2013 Elk Fire accumulated over the 56 years of managed flows. Dry temperate to semi-arid climates like that of the SFBR basin may have increased fuel loads and increased fire risk owing to preservation of downed wood on the floodplain, lack of flood disturbance to provide a mechanism for exporting downed wood from the floodplain, and dry fuel conditions that persist over most of the summer and fall seasons (Skinner, 2002; Gould et al., 2008). In combination with the decreasing channel width, stabilizing floodplain area, increasing tree density, and limited flows to flush out downed wood from the forest floor, the riparian corridor had a larger quantity of forest fuel than in 1957. With a higher density of older trees, the riparian forest was likely more prone to wildfire than historic conditions, which has been seen in other riparian forests (Smith and Fischer, 1997; Ellis et al., 1998; Ellis, 2001). To reduce fire hazard and potential fire severity in floodplains, managed disturbances from fire or flood may be required in riparian areas to remove fuels from the understory and thin forest population. Floods may be particularly effective forest fuels management option below dams that block all upstream LWD from the upstream basin that would otherwise deposit and build up in the floodplain forest.

Little information is currently available on riparian fire response (Hall and Hansen, 1997; Smith and Fischer 1997; Kobziar and McBride, 2006; Petitt and Naiman, 2007), making any determinations on whether the disturbance is ecologically beneficial for riparian forest regeneration challenging (Zasada et al. 1983; Agee, 1991; Brown, 1996; Gom and Rood, 1999; Wonkka et al., 2017). Riparian wildfire response is complicated further by its relation to the burn severity, which can show high spatial variation along a river corridor. The 2013 wildfire removed much of the tree canopy and understory along the streambanks and floodplain, providing a window of opportunity for geomorphic disturbance and seedling recruitment to occur before vegetative competition removed both bare sediment and light availability. In general, moderate burn severity occurred upstream, closer to Anderson Ranch Dam and low burn severity took place in the downstream direction (Figure 10A). On the floodplain the fire ranged in severity from very low to moderate that resulted in top kill of most cottonwoods and willows but did not kill the root structures of most trees. While canopy cover was removed from much of the floodplain, field observations show that existing riparian root systems were prone to vigorous sprouting and clonal propagation that rapidly regenerated much of the floodplain vegetation in the years following the fire. This resets the apparent age class of the riparian forest, but not the genetic diversity of the population.

Figure 10. Example of burn severity along Reach A of SFBR below Anderson Ranch Dam (top). Mixed survival of cottonwoods and willows within the riparian corridor based on low (middle) and moderate (bottom) burn severity.

The variable burn severity across the floodplain resulted in a mosaic of tree survival (Figure 10B, C). Post-fire riparian forest regeneration on the floodplain was spatially variable in response to burn severity (Figure 11), with increasing tree density corresponding to burn severity. Field observations show the primary post-fire forest regeneration mechanism on the floodplain was via coppice and root sprouting, particularly by the black cottonwood population. Willow species mainly grew in low-elevation wet areas and along the bars, which generally encountered lower burn severity and reduced mortality. In the areas of very low burn severity most trees recovered with the ratio of post-fire/pre-fire population very close to unity (median=1.03). Low severity burn areas had a statistically insignificant ($p=0.06$) increase in post-fire/pre-fire ratio (median=1.26), as damaged trees showed mixed coppice and root sprouting responses. The highest burn severity on the floodplain reached moderate levels and had the highest post-fire/pre-fire regrowth ratio (median=1.57), a significant increase above the very low and low severities (p<0.014). The principal regrowth mechanism in moderate burn severity areas was by root sprouts from top killed trees, with very few observed coppice sprouts. This increased tree density along transects is related to clonal regeneration from root suckering and limited coppice sprouting, with little to no signs of seedlings away from the river margins. This agrees with other studies that found riparian fire impacts tend to favor clonal sprouting and regrowth over seedling recruitment but is dependent upon burn severity and subsequent flood disturbance (Gom and Rood, 1999; Ellis, 2001; Wonkka et al., 2017).

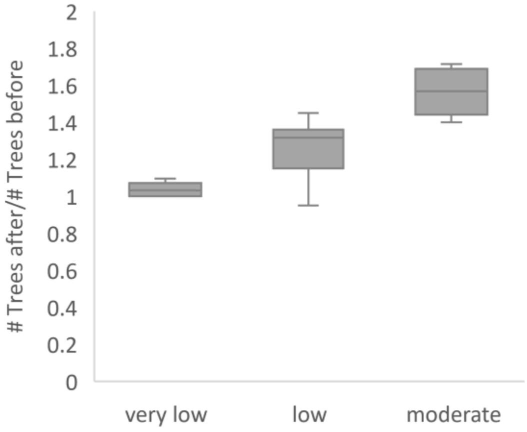


Figure 11. Ratio of post-fire/pre-fire tree counts in floodplain transects based on burn severity (n=14).

Vigorous clonal sprouting and shoot growth has been observed after moderate severity fires and in riparian areas that can lead to fast stem growth and canopy development, especially when the water table is accessible to established root systems (Hall and Hansen, 1997; Gom and Rood, 1999; Miller, 2000). Asexual clones have faster growth rates than seedlings owing to greater reserves of carbohydrates and nitrogen in their root systems that provide a greater chance of survival (Hartman and Kester, 1975; Burgess et al., 1990; Francis, 2007). In river systems across the Northern Hemisphere, asexual clones have been observed to grow 2-3 times faster than seedlings in the same river system (Rood et al., 1998; Gom and Rood, 1999; Francis et al., 2006). Therefore, clonal growth from root suckers and coppice sprouting can outcompete seedlings that would otherwise establish after a fire disturbance that opens the canopy and provides bare mineral soil for establishment sites. For species dependent upon high river discharge to distribute seeds, remove existing vegetation competition, and maintain soil moisture content, an overbank flood event is required in the few years after a fire disturbance when these conditions persist (Johansson et al., 1996; Shafroth et al., 1998, 2002). In the semi-arid floodplains of the Rio Grande, seedling recruitment was observed when floods were released from the upstream dams within one to two years after wildfire (Ellis, 2001; Smith and Finch, 2018). In the SFBR, the wildfire disturbance removed the canopy and understory that opened a window of opportunity for seedling recruitment by creating both bare sediment and light availability on the floodplain. However, as sprouting and regrowth occurred from existing trees and root networks, the window of seedling recruitment reduced as a function of time since the burn.

Observed and simulated seedling recruitment within this window was fundamentally dependent on dam operations. In the two years immediately following the fire, dam releases were kept below bankfull during average hydrologic conditions in the basin (Figure 2B). This resulted in no floodplain inundation, which limited the primary seed dispersal mechanism (hydrochory) for both cottonwoods and willows as well as the surface and subsurface soil moisture to support initial seedling growth. Maintaining dam releases less than bankfull (Figure 12A) that provide a high water table in the floodplain (see groundwater monitoring section) for already established roots to access may actually favor clonal sprouting (Ellis, 2001; Smith et al., 2009). Consequently, much of the floodplain responded via root sprouts (Figure 12B and 12C). In the third year following the fire, bankfull dam releases during average hydrologic conditions (2016) could only inundate the near-channel and low-elevation floodplain areas that encountered very low burn severity and associated tree mortality. As a result, the existing vegetation prohibited seedling recruitment in these areas and no observed recruitment occurred along the floodplain. Four years following the fire (2017), high dam releases related to wet hydrologic conditions inundated 78% of the floodplain and were capable of recruiting seedlings across a wider variety of riparian environments. However, vigorous tree sprouts had already reduced much of the available light in the potential seedling habitat areas by forming dense willow and cottonwood thickets, as well as reduced bare sediment from the colonization of grasses on the floodplain (Figure 10).

Figure 12. A) Near-bankfull flow conditions provide a high groundwater table that is accessible to existing tree roots along the SFBR but does not distribute seeds over floodplain. B) Clonal root suckers growing well overhead four growing seasons after the fire in areas without flood disturbance. C) Clonal root sprouts on the floodplain that at first glance appear to be seedlings but are connected to other sprouts via arterial roots.

Seedling Recruitment Processes

Field surveys identified the locations and spatial extent of seedling patches along the floodplain and active channel. Given the strong regrowth on the floodplain from clonal regeneration, by the time bankfull flows occurred in the SFBR three years after the wildfire there was substantial competition for seedlings to overcome and effectively all seedling recruitment occurred in and along the margins of the active channel (Figure 13A). For dam releases during average hydrologic conditions (2016) no seedling patches were found on the floodplain (Figure 13B) indicating greater flows are required to substantially inundate these surfaces and distribute seeds. Overbank dam releases during wet hydrologic conditions (2017) led to high floodplain inundation extent, but seedling recruitment on the floodplain was limited to 5% of the total observed seedling patches along the river corridor. These recruitment patches occurred in erosional areas where existing tree density was low and overbank velocities were not suppressed by vegetation. Hydraulic modeling results below show ineffective seedling recruitment on the floodplain of the SFBR because of two main influences, 1) lack of hydraulic disturbance on the floodplain and 2) floodplain surfaces were underwater for much of the hydrograph. These results combined with the post-wildfire vegetation response indicate that the window of disturbance on the floodplain following riparian fire in a semi-arid environment was reduced within 3 years of the fire and almost gone by the fourth year.

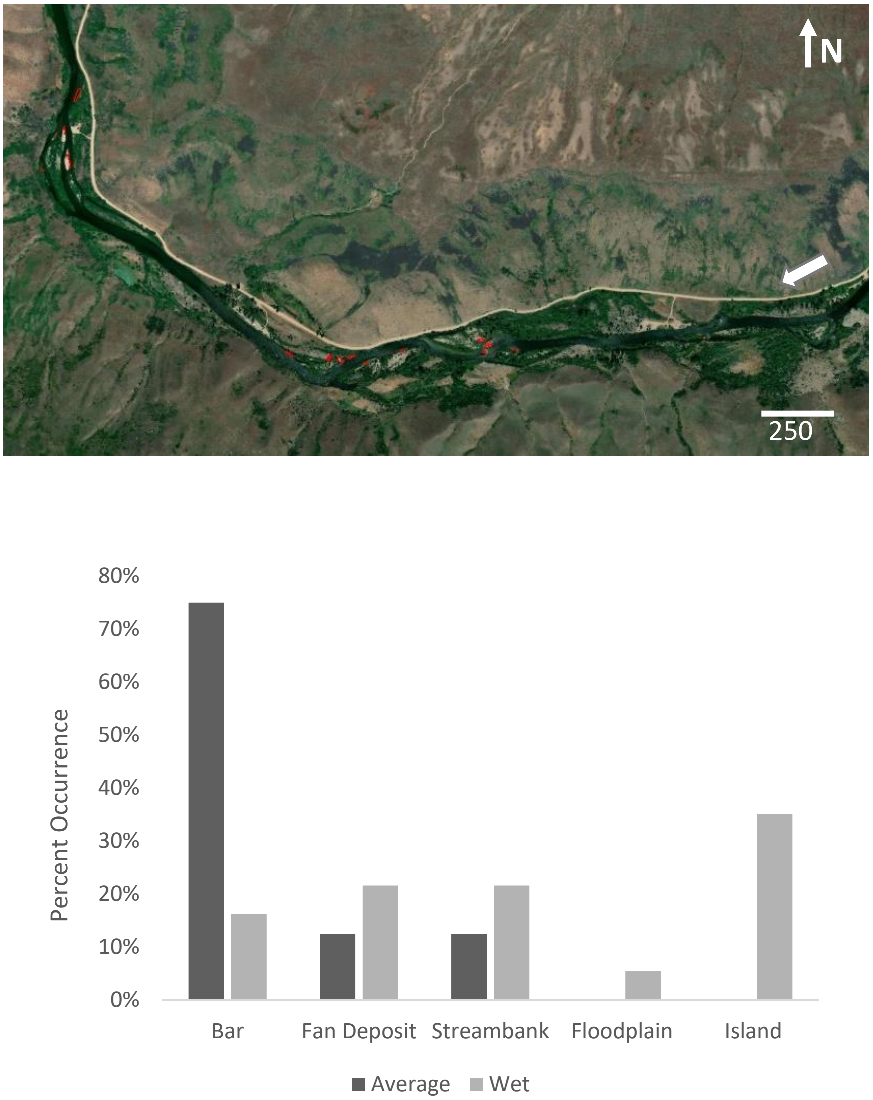


Figure 13. A) Observed seedling recruitment patches for both average and wet hydrologic conditions in example Reach A of the SFBR study site. Patches are outlined in red. Arrow indicates direction of flow. B) Percent occurrence for field observed seedling recruitment on morphologic features in the SFBR study site for dam releases during average and wet hydrologic conditions.

With limited post-fire seedling recruitment on the floodplain, successful recruitment occurred within the active channel, ranging from 100% during average flow releases and 95% during wet-year dam operations (Figure 13B). Riparian seedling recruitment occurred as small, spatially distributed patches (median area = 40.5 m^2) along bars, streambanks, floodplains, margins of debris fans, and at the head and tail of vegetated islands (Figure 13A). Sediment deposits on bars and islands were the most commonly observed recruitment areas, with streambanks and fan deposits providing secondary areas. During the average hydrologic year (2016), all recruitment occurred at low elevations along the streambanks, debris fans, and bar surfaces, with the majority of recruitment (75%) occurring on unvegetated bars. The unvegetated bars had the largest areal patch size as recruitment tended to occur over the entire emergent bar surface. Patches ranged from 33-2,952 m^2, with median patch size of 361.3 m^2. Seedling patches larger than 170 m^2 were usually associated with bar top recruitment. During the wet hydrologic year (2017), recruitment tended to occur across a wider variety of morphologic features, including higher elevations along the streambanks and debris fans and on sediment deposits at the head and tail of vegetated islands (Figure 13B). Seedling patch sizes ranged from 7-679 m^2, but recruitment areas during the flood conditions usually resulted in smaller patch sizes (median area=35.6 m^2) than during average hydrologic conditions. During the 2017 flood, less frequent recruitment occurred on bars (16%) and more frequent recruitment occurred on newly deposited sediment around vegetated islands (35%).

Riparian forest regeneration within the active channel was directly related to erosion and deposition processes that provided for seedling recruitment habitat and sexual propagation. The post-wildfire debris flows added the requisite sediment for bar building and sediment deposition that were reworked during the average and wet flow releases from the dam. Cumulative surveyed seedling recruitment patches during both average and wet years show deposition processes provided more than an order of magnitude greater recruitment area than erosion processes (Figure 14A). The average year had 100% of all seedling recruitment occurring in depositional areas within the active river channel. The wet year had 62% of recruitment occurring in depositional areas and 16% occurring in erosional areas. Additionally, 22% of the patches were located on the margins of debris fans where recruitment occurred on depositional features from upland sources. These depositional features were not formed by fluvial sediment transport processes but did occur as depositional features that provided new sediment to the river channel. Therefore, including both geomorphic features shows that 84% of seedling recruitment was related to depositional processes during dam releases related to wet hydrologic conditions. In depositional areas where recruitment occurred, higher percentages of fine sediment were present that supplemented the moisture retention capacity of the coarse armored cobbles on the bed.

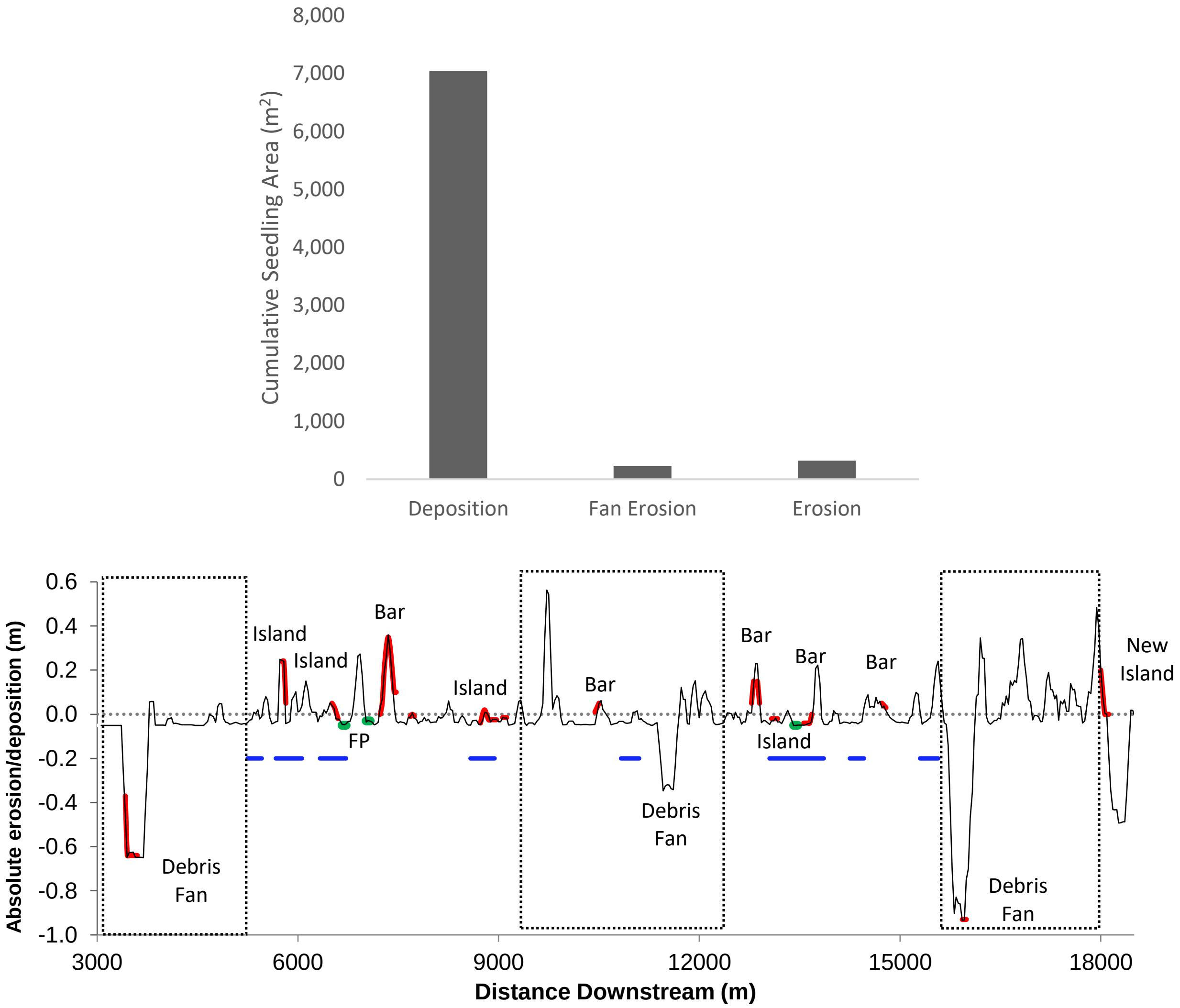


Figure 14. A) Cumulative surveyed seedling recruitment area related to sediment transport process for dam operations during average and wet hydrologic conditions. B) Simulated erosion/deposition over a five-year period within the SFBR study site. Red lines indicate depositional recruitment patches, green lines identify erosional recruitment. Blue lines show where islands occur and split the flow. Stippled boxes show confined reaches.

To quantify the role of erosional and depositional processes across the larger spatial scale of the study site, results from the 1D morphodynamic model (Figure 14B) illustrated the trends of cumulative sediment transport in the five years after the fire (2013-2018). The horizontal stippled line indicates the initial detrended bed elevation and the solid black line shows the 90 m moving average of cumulative erosion or deposition over the simulation period. Overall bed erosion of 0.04 m has occurred within the study site as there is no upstream sediment supply outside of the debris fans and local bank erosion, which leads to general bed incision through the reach below Anderson Ranch Dam. This bed incision has likely been occurring during high flow events since dam closure in 1950. The consequences of this bed incision and channel enlargement are greater channel conveyance, whereby flows that historically inundated the floodplain are no longer capable of leaving the channel. This effectively increases the river discharge that is required to provide a disturbance in the floodplain. While the 2D hydraulic model results show that in 2007 bankfull flow was approximately 68 m^3/s, field observations in 2019 show that bankfull discharge might be closer to 84 m^3/s owing to changes in channel morphology after the 2017 flood.

The general erosional trend in Figure 14B is punctuated with strong periodic erosional and depositional spikes. The erosional spikes identify the scour occurring at the four debris fans that enter the river within the study site. As the principal post-fire source of sediment to the channel these debris fans provide sediment that is distributed downstream during high flows, superposing depositional features on top of the generally erosional reach trend. Debris flows in semi-confined canyon environments provide the required sediment to form new depositional alluvial features like bars, islands, and floodplains, especially in supply-limited river systems (Benda et al., 2003; Tranmer et al., 2015). In 2014, limited experimental flow releases were employed to redistribute sediment downstream. The limited duration flow release in August 2014 removed sediment from the debris fans but was insufficient to redistribute the sediment throughout the valley bottom. The 2017 flood, with greater magnitude and duration, was successful in redistributing both fine and coarse sediments from the debris fan derived material, as well as local bank erosion sources. Deposition occurred where there was a reduction in channel slope or in areas of canyon expansion. Simulated depositional areas spatially aligned with the existing morphologic features that support riparian forest species including floodplains, vegetated islands, and instream braid-bars, indicating long-term sediment transport processes are ultimately responsible for the creation and maintenance of riparian forest habitat. Early aerial photos (Figure 3a) confirm that the bars and secondary channels were present in these locations prior to dam construction before sediment supply limitations impacted the river system.

The greatest observed seedling recruitment occurred in these areas of complex channel morphology, where bars and vegetated islands split the flow and deposited sediment in their wakes to create dynamic seedling habitat conditions. Reach-scale modeling shows that observed seedling patches (red points) occur in many of the depositional areas within the study site (Figure 14B). These recruitment patches occur mainly at the head and tail of morphologic features like point bars and islands, particularly in the wake of existing vegetation that can encourage sediment deposition. Limited recruitment occurred in erosional areas (green points) either on the floodplain or across large islands with low existing vegetation density. Additionally, seedling recruitment was not observed in every depositional area. There was very little seedling recruitment within the confined reaches of the canyon, even in simulated depositional areas. Deposition in these reaches tended to create submerged bars that remained mobile during high flows and migrated through the reach without providing emergent habitat for seedling colonization.

As unique morphologic features, the debris fans provided a large depositional surface for seedling colonization. While they erode over the subsequent years after the initial event, debris fans maintain broad bands of fine sediment along the channel margins and often an upstream backwater environment that can store sediment and create medial bars and islands (Figure 15A). The seedling recruitment area along the margins of these fans can provide habitat at variable flood magnitudes, resulting in generations of seedling recruitment (Figure 15B). Recent surveys show that three of the four debris fans in Figure 14 above have had significant seedling recruitment since the 2017 flood. In the depositional areas upstream of the debris fans, dynamic medial bar features formed after the 2017 flood and are active areas of recruitment (Figure 15C). However, given the low elevation of the bar successful recruitment is challenged by subsequent flows that will inundate these features for long periods in the spring and kill successful seedlings from the previous year.

Figure 15. A) Debris flow related depositional features along the channel margins and in the upstream backwater zone. Riparian seedling recruitment B) as generational bands along margins of debris fan and C) vegetation recruitment on the medial bar upstream of a debris fan.

Outside of where the debris fans enter the channel, most surveyed seedling patches (red points) occur in depositional areas at the head or tail of established islands or gravel bars (Figure 13A). Those that do not directly align with simulated areas of channel deposition occur in areas where secondary channels (blue lines) allow for flow expansion and a reduction in sediment transport capacity to form new islands/bars in the channel. The 1D model does not capture the hydraulics of flow expansion across split channels well and cannot predict these areas in the model with high accuracy. However, collectively these results illustrate that depositional processes drive successful riparian seedling recruitment in the SFBR, especially following the 2017 flood. Once the sediment supply from the debris fans is exhausted, it is unclear how stable the new islands and bars will be. If they have reached a vertical elevation that is high enough to establish perennial vegetation they may persist, but if they are frequently inundated and cannot maintain vegetation cover it is likely that they will be eroded by subsequent high flows. Therefore, post-wildfire debris flows below reservoirs are critical sediment sources to support riparian recruitment processes that can serve as natural surrogates to understand management options concerning sediment augmentation programs below dams.

Riparian Seedling Recruitment Model

Model Parameters and Performance

The riparian seedling recruitment model of Benjankar et al. (2014) was modified to incorporate the above environmental conditions for predicting successful seedling recruitment in warm-temperate to semi-arid environments like that of the SFBR. Four principal parameters are used to broadly characterize both the biological and physical seedling habitat requirements: a) seed dispersal period, b) mortality coefficient, c) bed shear stress, and d) elevation above baseflow. The first two parameters are dependent upon biological drivers related to specific plant species and genotypic variation, such as the timing of seed dispersal, the vigor of seedling root growth, and tolerance to the period of inundation. These biological processes are broad but can generally be accounted for by the model parameters of seed dispersal timing and the mortality coefficient, based on species of interest and local site knowledge. For example, temperature, latitude, and elevation play significant roles in the timing of seed dispersal and peak snowmelt runoff based on specific location (Stella et al., 2006). Additionally, the mortality coefficient relates to the recession rate of the hydrograph and its impact on the water table in the floodplain. The existing model parameters for seed dispersal timing and the mortality coefficient (Table 1) were determined to be appropriate for the riparian vegetation community in the SFBR and could be applied to most Salicaceae species in mid-latitude and mid-elevation riverine environments.

The other recruitment model parameters that describe physical seedling habitat conditions are bed shear stress and elevation above baseflow, which were both adjusted to capture the local grain sizes, channel gradient, and river morphology in the SFBR. The bed shear stress parameter incorporates many of the physical environmental properties that may have high spatial variation over short distances and contain high levels of uncertainty. For example, the shear stress required to remove sediments from the base of a patch of vegetation will vary based on both the vegetation community and the sediment properties within the patch. Existing vegetation conditions that include plant species, vegetation community composition, leaf area, root density, stem spacing, and stem drag coefficients can change spatially based on forest community, as well as seasonally for annual growth characteristics (Schnauder and Moggridge, 2009; Diehl et al., 2017). Sediment grain size distribution and grain packing configuration can also be spatially variable and change over timescales ranging from singular storm events to multiple years. However, in the SFBR below Anderson Ranch Dam, sediment supply is extremely limited and a coarse armor layer exists on most bars and low floodplains that range between 10-100 mm. While grain size distribution will change from one river to the next based on local lithology and stream power, these armored conditions exist for many channels downstream of dams. Therefore, the D_{65} (grain size for which 65% of the distribution in the patch is finer) was selected as the representative grain size in the surface layer to define the threshold bed shear stress for sediment disturbance in the SFBR.

The elevation above baseflow parameter defines the vertical band along the river bars and banks where viable vegetation establishment is possible. It is defined at the lower end by elevations that will be frequently disturbed from active removal/erosion processes or extended inundation periods. At the upper end, it is less well defined by limited water availability for seedlings. The upper bound reflects the lumped influence of the depth to the groundwater table, the influence of the capillary fringe and pore water within the sediment matrix, the hydrologic connectivity between the surface and groundwater, the range of water surface fluctuations in the channel, the local vertical grain size distribution of the patch, the amount of seasonal precipitation, and local climate. In broad, low gradient river-floodplain systems with summer precipitation and fine sediments like those in the Midwestern U.S., the groundwater table and associated capillary fringe could remain largely dissociated from the recession rate in the stream and support water availability for riparian species year-round. Alternatively, drier, steeper river-reservoir systems like those of the Western U.S. have more responsive floodplain groundwater conditions and are directly coupled to the water surface elevation in the river channel (see groundwater section). In the semi-arid climate of the SFBR canyon the distance between baseflow and the seedling patch surface was limited to a distance of 0.12-1.0 m from observed seedling recruitment patches (Figure 16). This vertical range is limited because of the warm daytime temperatures, high seedling evapotranspiration rates, and high hydraulic conductivity of the sand/gravel floodplain sediments that requires seedlings to be closer to the baseflow water table.

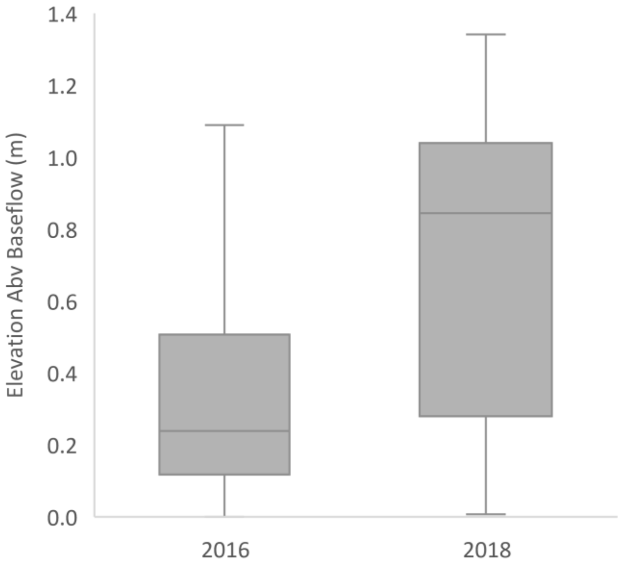


Figure 16. Boxplots depicting the distribution of elevations above baseflow for cells within surveyed vegetation patches.

The above parameters were employed to predict areas of potential seedling recruitment within the river-floodplain corridor. Simulated favorable recruitment areas were compared with field surveys to evaluate general model success (Figure 17). The recruitment model predicted similar spatial patterns for seedling recruitment potential when compared to the field surveys. The model correctly predicted average-year (2016) seedling recruitment in 75% of the surveyed patches and 25% occurred on new features. Model prediction for the wet year (2017) was able to predict successful recruitment in 40% of the surveyed patches and failed in 3%. Furthermore, 57% of patches occurred on new features. New features constitute the bars and modified island features that occurred after a temporary sediment supply was introduced to the channel via post-wildfire debris flows, which were not present during the bathymetric LiDAR survey in 2007. The survival of seedling patches on new depositional features is uncertain, given their location in low channel elevations and lack of further sediment supply below the dam once the debris fans are exhausted. However, even with the recent morphologic changes happening within the river corridor the predicted locations for favorable recruitment during average and wet hydrologic conditions aligned well with the observed seedling recruitment patches.

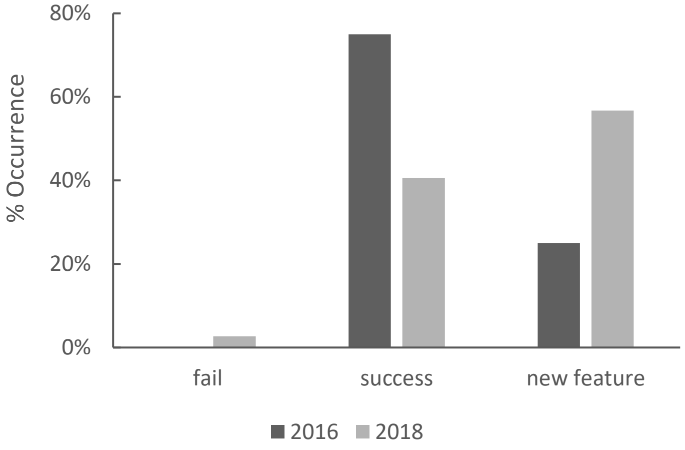


Figure 17. Percent occurrence for model prediction of field surveyed seedling recruitment patches.

While the recruitment model was successful at predicting observed seedling patches it tends to over-predict potential seedling habitat within the model domain for dam operations during both average and wet conditions. Figures 18 and 19 show the recruitment potential during average and wet hydrologic conditions for the two most alluvial sections in the canyon, Reaches A and B. Much of this over-prediction area occurs from cells located along the streambanks that lie within the appropriate elevational bands that were already populated with existing riparian vegetation. The model does not account for competition from existing vegetation and cannot filter this vegetation constraint. However, this limitation can be circumvented for management decisions by combining recruitment results with recent aerial photographs to illustrate where existing vegetation limits seedling recruitment. Additionally, some overprediction occurs within the channel that is inundated during summer irrigation flows and would eventually die from extended inundation of the roots (drowning). Those cells were eliminated by masking the channel with the average summer irrigation flow of 45 m^3/s.

Figure 18. Simulated recruitment areas in Reach A for 2016 (top), 2016 with river mask of 45 m^3/s discharge (second), 2017 with river mask (third), and 2016 planting option with river mask (fourth). Green is fully favorable conditions, yellow is partially favorable conditions, and orange is less favorable.

Figure 19. Simulated recruitment areas in Reach B for 2016 (left), 2016 with river mask of 45 m^3/s irrigation discharge (second), and 2017 with river mask (third), and 2016 planting option with river mask (fourth). Green is fully favorable conditions, yellow is partially favorable conditions, and orange is less favorable.

Predictive limitations in the SFBR seedling habitat model stem from both data inaccuracies and mechanistic simplifications. The principal limitation in the data comes from the LiDAR survey that was taken in 2007. Since the initial data collection, there was the 2013 fire related debris flows and the 2017 flood that has since altered the bathymetry substantially in some areas. Therefore, the 2D hydraulic model results, as well as the bathymetry that make up the input parameters to the seedling recruitment model may have local accuracy limitations. This can be seen for most of the surveyed seedling patches that are located on new sediment deposits at the head of vegetated islands or on new bars in the middle of the river, which geomorphic adjustments have modified to usually increase habitat suitability. Limitations to the existing recruitment model derive from attempting to capture all of the complex biological and physical processes of river-riparian systems via four input parameters. Potential limitations within the model include the simulation period that runs over a six-month growth season from April 1 to September 30 to account for the timing of active growth in most regions. Potential limitations can arise during extended growing seasons, where seedlings are stressed from hot days in early October when the irrigation flows have been reduced in the river and the seedlings have not yet gone dormant. Additionally, the mechanical disturbance parameter predicted by the bed shear stress has a range that does not account for species-specific vegetation removal such as individual riparian trees, Reed canary grass, or other stabilizing vegetation types that may have interlocking roots with other vegetation in the riparian zone. The shear stress parameter was adjusted to better account for grain sizes at the reach scale, but cannot account for local variations of grain size at the patch scale or added cohesion from fibrous root bundles, mats, etc. If seeds are able to germinate owing to a proper disturbance and sufficient soil moisture, there is no means of accounting for 1) competition from other pioneer plants that are also trying to germinate in the same space, 2) the overhead forest canopy that may shade out otherwise successful young seedlings, or 3) trampling from grazing of livestock or wildlife. Finally, the recruitment model is also only run for a single year and cannot account for subsequent high flows that may kill young seedlings. As a future development to the model, running a multiyear simulation could provide guidance for dam operations to support seedlings through the first few years when seedling mortality can be high.

Model Results

Recruitment model results show limited suitable habitat for seedling recruitment during average hydrologic conditions (Figures 18 and 19). Dam releases during average water years have variable peak flows, but usually attain bankfull conditions that inundate ~40 ha (24% of available floodplain) of low-elevation floodplain. These bankfull discharge values leave large areas of the available riparian floodplain dry, limiting the dispersal of seeds across the floodplain. Therefore, favorable seedling recruitment was primarily located along the margins of the main channel banks and islands that provide physical characteristics similar to floodplains, but at a smaller spatial scale. The model simulated 1 ha (0.6% of available floodplain area) of collectively favorable seedling recruitment area (Figure 20), which includes all fully favorable (FF), partially favorable (PF) and less favorable (LF) areas. These locations were sparse and spatially distributed, leading to an average favorable riparian habitat density of 0.04 ha/km within the study site. While these areas are located at elevations high enough to satisfy the minimum recruitment model parameters, their location within the channel makes their survival unlikely in subsequent years. Repeat field surveys in 2018 and 2019 confirmed the removal of many of these patches.

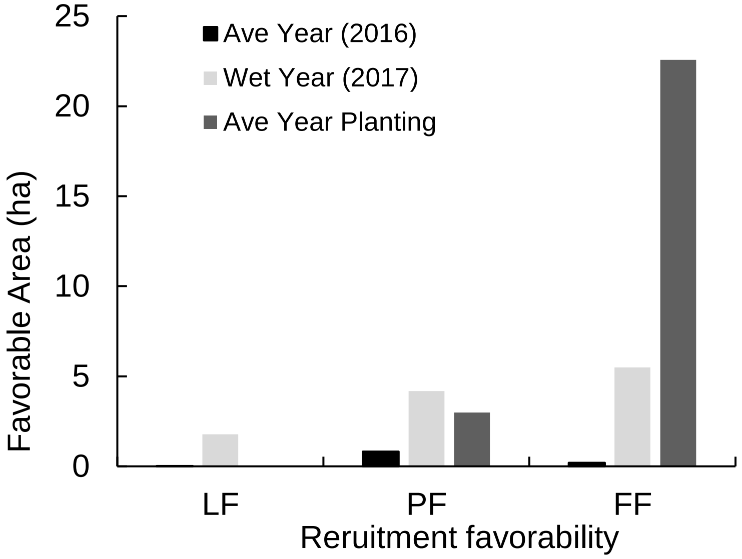


Figure 20. Simulated favorable area for dam operations during average year recruitment, wet year recruitment, and average planting conditions. FF- fully favorable, PF- partially favorable, and LF- less favorable.

Simulated dam releases during wet hydrologic conditions show 129 ha of floodplain are inundated, approximately 78% of the total available floodplain area. As a result of higher peak flows and greater inundated area, an overall increase in seedling recruitment occurred within the floodplain (Figure 20). The recruitment model predicted 11.4 ha (7% of available floodplain area) of collectively favorable area. These results show larger contiguous areas of potential riparian habitat that is an order of magnitude larger than the average hydrologic conditions, with a habitat density of 0.5 ha/km.

As an alternative to natural seedling recruitment, restoration planting habitat is presented to identify short-term habitat gains. Modeled restoration planting habitat in the model domain was computed by categorizing the entire inundated area as fully favorable with regards to shear stress, thereby sapling success was reduced to only a function of the recession rate and elevation above base flow. Simulated favorable area during average hydrologic conditions for restoration planting reached 25.6 ha (15.5% of available floodplain area). As restoration planting does not require existing forest removal in many places, site selective planting in open areas can potentially increase the existing riparian habitat density by up to 1.11 ha/km.

Given the low seedling recruitment potential below the dam for both average and wet hydrologic conditions, the model was used to identify seedling recruitment failure mechanisms for each hydrologic condition. While seedling recruitment during average hydrologic conditions is principally limited by inundation extent (40 ha during average years vs the 129 ha during wet years), specific failure mechanisms were identified for each cell in the model domain. Figure 21 below summarizes the percent inundated area that satisfies the recruitment parameters in each cell. The physical variable with the least area is considered the limiting parameter for recruitment. The most limiting factor during average hydrologic conditions (2016) is insufficient disturbance, characterized in the model as shear stress. This allows only 1.6% of the available floodplain area to be viable for seedling recruitment. Secondarily, recruitment success is limited to 8% of the available floodplain area based on elevations that are unlikely to be eliminated by subsequent high-water events (elevations >0.12 m) and mortality due to desiccation (elevations <1 m). The recession rate under current dam operations allows for 12.6% of the available floodplain area to be favorable for recruitment. Alternatively, the limited recruitment success for wet conditions illustrates that greater inundated area alone is not enough for increased riparian seedling recruitment. In fact, elevation values become the most limiting factor (10.2% of the available floodplain area) for the wet hydrologic condition (2017), owing to the fact that most of the seedling habitat on the floodplain is underwater and floating seeds cannot germinate on a stable surface. Shear stress is the secondary limitation on the floodplain with 11.3% of the available floodplain area considered favorable, because of slow velocities through the vegetated floodplain. Finally, the mortality coefficient provided 23.8% of favorable floodplain area for seedling recruitment.

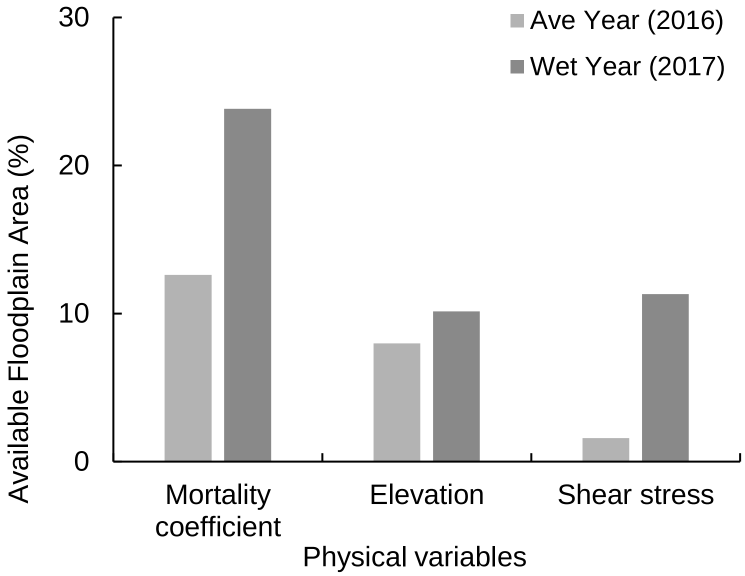


Figure 21. Percent of available floodplain area identifying limiting recruitment mechanisms in the SFBR floodplain.

Floodplain Groundwater Monitoring

Analysis of the floodplain water table (WT) timeseries shows that groundwater levels track the flow of the river closely (Figure 22). Cross correlation analysis shows that there is a two-day lag between the river WSE and the floodplain WT in Well 01 farthest from the channel (103 m), whereas Well 03 (41 m from the channel) had only a one-day lag. During discharge greater than bankfull (May 4th to June 21st, n=49) Well 01 had water within the critical rooting depth (~1 m) and there was good correlation (r=0.83) between the simulated daily river WSE and the WT, with a mean difference of 0.09 m. During the same time period at the downstream Well 03, both correlation (r=0.92) and mean difference (Diff=0.05 m) illustrate the closer hydraulic connection with the river owing to its lower elevation and closer proximity to the channel. Examining the Well 03 record over the entire summer growth season, May 4th to September 14th (n=134), correlation (r=0.99) and mean difference (Diff=0.14 m) both increase. This implies that the WT responds almost linearly to the WSE in the river and changes in discharge but remains approximately 0.2 m higher when flows are less than bankfull. Therefore, in confined and semi-confined fluvial environments that may inhibit groundwater losses, the WT may be influenced more by the WSE at the upstream end of floodplains and islands than in the adjacent channel and should be confirmed in the field. Collectively, these results show that the WT in the SFBR is responsive to changes in discharge and may support root networks during the post-wildfire recovery period. When dam releases are maintained below bankfull discharge during the spring, existing root networks can readily access the WT, but seedlings may have trouble surviving if the top 10 cm of soil dries out before their roots can reach the WT.

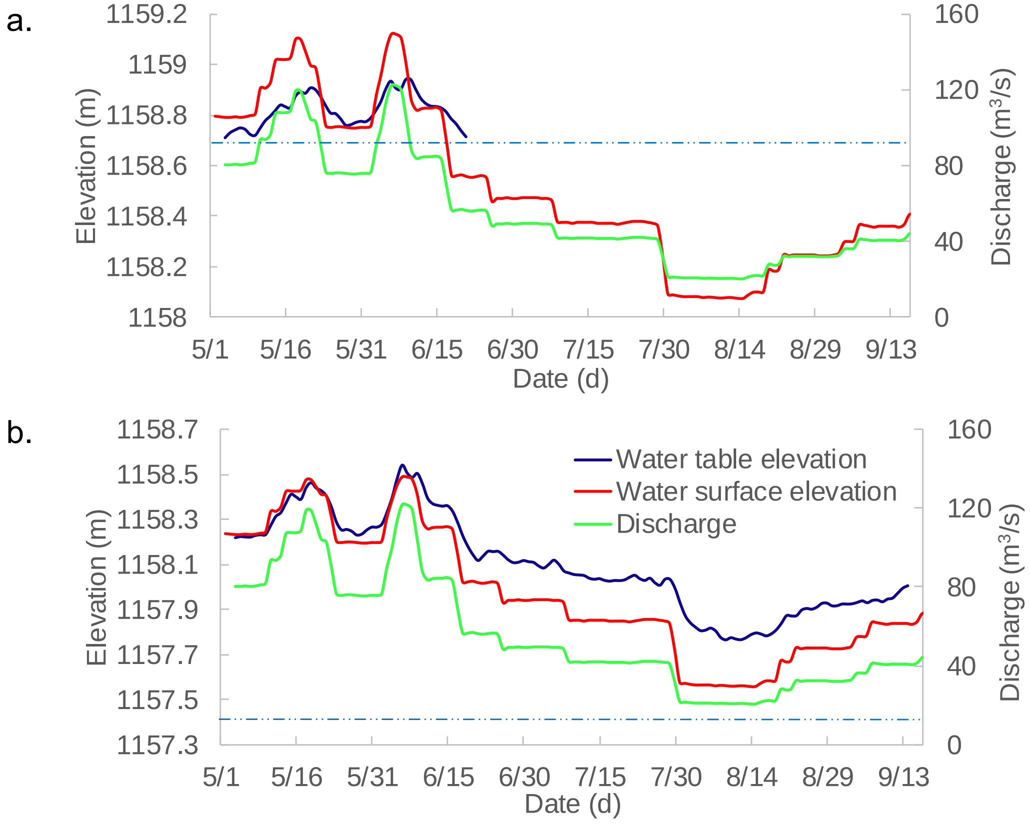


Figure 22. Floodplain groundwater monitoring results in relation to simulated water surface elevations in the river for a) Well 01 and b) Well 03. Horizontal dashed lines show the lower limit of the critical rooting depth of 1 m.

To understand if the groundwater would support newly recruited seedlings or planted saplings the WT and the rate of recession were examined within the critical rooting depth. At the upstream transect in Well 01, the WT is approximately equal to the river WSE during bankfull discharge and above. When dam operations reduce the river discharge below approximately bankfull after June 21st, the WT drops below the critical rooting depth of 1 m, indicating mortality for both seedlings and newly planted saplings. This does not occur in Well 03, whereby the WT remains within the 1 m critical rooting depth over the entire growth season. The WT decreases in both wells proportionally with the river WSE. However, while the drawdown rate in the river is rapid owing to dam operations, a lag exists within the floodplain water table that dampens the rate of WT recession in the floodplain that is a function of the hydraulic conductivity of the floodplain sediments. In the SFBR, the average WT recession rates were 28% (Well 01) and 39% (Well 03) of the recession rate in the river channel. This trend is for only one floodplain unit within the study site, but indicates that changes in the WT are 30-40% slower than those occurring in the river channel, which may prolong beneficial soil moisture conditions within the rooting depth during the receding limb of the hydrograph. This lag will likely change by setting and sediment composition in the floodplain, but local groundwater monitoring could be incorporated to the seedling recruitment model to inform the mortality coefficient and elevation parameters.

Discussion and Recommendations

Model Limitations and Refinement

In coupled reservoir-river systems that must balance societal water demand and ecosystem function, numerical models can provide resource managers the tools required to increase operational sustainability (Benjankar et al., 2012; Shafroth et al., 2010; Tranmer et al., 2018; Tranmer et al., 2020). Process-based ecohydrology models have previously been used to quantify human impacts on ecosystems and to predict the areas for natural riparian seedling recruitment (e.g., Benjankar et al., 2012; Carmel et al., 2001), as well as guide restoration design for ecologically degraded systems (e.g., Hammersmark et al., 2005). This study has shown the capability of coupled hydraulic-riparian seedling recruitment models for predicting the location and spatial extent of riparian seedling recruitment, as well as restoration planting for native riparian species.

Successful seedling colonization and recruitment requires a specific combination of environmental factors that includes hydraulic disturbance, flood recession, and period of no subsequent disturbance that are a collective result of the geomorphic processes in the watershed (Benjankar et al., 2014; Braatne et al., 2007; Burke et al., 2009; Mahoney and Rood, 1998). The proposed recruitment model effectively captures these parameters (Table 1) to successfully identify the locations and spatial extents of seedling recruitment within the SFBR study site. However, there are some model limitations that must be acknowledged. Principally, the predicted favorability of seedling recruitment in each cell can only represent the maximum recruitment potential, as it does not account for all the environmental conditions that impact seedling colonization and growth. Therefore, the model naturally overpredicts favorable areas that may be further limited by shade from existing forest canopy, competition from existing understory vegetation (e.g. Reed canary grass), grazing pressure, disease, and insects. Additionally, the model does not explicitly include parameters that may improve predictive accuracy but are subject to high spatial variability like sediment grain size or nutrient availability.

Because pioneer riparian species are poor competitors with established vegetation, the creation of bare sand/gravel bars or open floodplain areas are critical for successful seedling recruitment (Johnson, 1994). However, from a process standpoint the greatest uncertainty in the recruitment model concerns the shear stress values required to erode existing vegetation in these locations (e.g., Friedman and Auble, 1999; Prosser and Slade, 1994). This uncertainty stems from the different types of soil, vegetation type, and density that exist as spatially heterogeneous patches within riparian communities. Physical extraction and removal of rooted vegetation requires physical rupture of the roots or stem through hydraulic forces that can be exceptionally high, on the order of $1x10^6$-$1x10^8$ N/m^2 (Abernethy and Rutherfurd, 2001; Bywater-Reyes et al., 2015; Karrenberg et al., 2003). These combined lift, drag, and gravitational forces are rarely realized by hydraulic forces in riverine environments; therefore, physical disturbance of the topographic surface surrounding vegetation requires the erosion of the sediment matrix. Riparian vegetation in sand-bed channels and adjacent floodplains with labile sediments will likely be eroded more easily than in armored gravel channels near the threshold of motion (Church, 2006). Therefore, the disturbance of existing vegetation in the recruitment model is based on erosional processes that act to undermine and topple vegetation based on the intensity of the near-bed shear stress (Maturana et al., 2013). In the SFBR, recruitment favorability was overpredicted in cells that were able to move the D_{65} based on critical Shields stress, but may have been locally modified by the influence of existing vegetation that can act at scales finer than the model grid resolution (Bouma et al., 2007; Kleinhans et al., 2018; Li and Hodges, 2020). Additionally, different vegetation types have unique biomechanical parameters such as frontal leaf area, stem and branch pronation, and resultant fluid drag that have variable impacts on the local flow field that change with relative submergence (Bywater-Reyes et al., 2018; Politti et al., 2018). Collectively, this complicates identifying a singular threshold parameter that is capable of removing existing vegetation for natural recruitment processes (Jamieson and Braatne, 2001a; Polzin and Rood, 2000). While model results show remarkable accuracy in predicting the surveyed recruitment patches under different hydrologic conditions, to reduce overpredicted areas more information is necessary on the hydraulic flow field near vegetation and the resultant erosion and removal processes.

The mortality coefficient in the model provides an index for the rate of recession of the water table with regard to theoretical root growth rate. This is based on the assumption that the WT is equivalent to the WSE in the channel. In the coarse floodplain sediments of the SFBR, the observed WT recession rate in both wells decreases proportionally with the river WSE. However, while the drawdown rate in the river is rapid owing to dam operations, a lag exists within the floodplain groundwater that dampens the rate of recession in the floodplain. The reduced river flow from the dam initiated a lag between river drawdown and groundwater elevation of two days in Well 01 and one day in Well 03, illustrating the effects of distance from the channel and hydraulic conductivity of the floodplain sediments. The time lag observed between the river WSE and WT in the floodplain might support moisture conditions within the rooting depth that buffer rapid reductions in dam releases based on observations in two wells. Alternatively, the existing lag could also impact flashy river systems where steep terrain leads to short flood peaks or hydropeaking below dams that limits the infiltration of river water into the floodplain groundwater system. If the duration of the peak is shorter than the time lag required to raise the water table, riparian root systems may not benefit from the increased WSE in the river. Nevertheless, more well observations throughout the study area or a groundwater model would inform local WT information in the floodplain. In conjunction with the capillary fringe that rises above the water table as a function of soil characteristics, this lag could dampen rapid changes in dam releases that can be added to the model in future iterations.

Riparian seedlings that recruit in higher elevations can be destroyed by drought stress, whereas scour or drowning at low elevations can occur during subsequent flows (Johnson, 1994; Mahoney and Rood, 1998; Rood et al., 1998; Scott et al., 1997). Therefore, seedling recruitment is only successful within an intermediary band of elevation where seedlings are safe from drought stress and still avoid scour disturbances from successive floods (Mahoney and Rood, 1998). Definition of the lower elevation limit in managed streams should be linked to the lowest flow over the growing season. This study used the base winter dam release as the reference, but acknowledged that higher irrigation releases over the summer eliminated any favorable habitat below that level because seedlings would be drowned from constant inundation. This contributes to model overprediction and is evident in Figures 18 and 19, where favorable cells along the streambanks fall below the summer irrigation discharge of 45 m^3/s. Once the lower elevational limit is defined in the system, the environmental conditions will set the upper vertical extent of favorable conditions. In the Kootenai River this elevational band was up to 4 m owing to large variable flows that could change the water surface elevation dramatically. In the SFBR, the favorable elevation range was limited between 0.12 to 1.0 m above mean baseflow because of the steep channel slope, low range of water surface variability, and coarse, non-cohesive sediments that readily drain.

Native Riparian Vegetation Recruitment Processes in SFBR

While mechanistic models can capture many of the complex biological and physical processes observed in river-floodplain environments, additional details of seedling recruitment processes can assist conservation and management activities within specific river systems. Therefore, additional information that is relevant to the SFBR and potentially other semi-arid river-riparian systems is provided that can put the model outputs in greater context.

Pioneer species in the Salicaceae family, like cottonwoods and willows, are the dominant forest species within the riparian corridor of the SFBR. Black cottonwoods provide the primary overstory canopy along the floodplains with various willow species populating much of the streambank and low-elevation bars. These riparian species reproduce via hydrochory, whereby prolific seed release in the early summer is distributed by flowing water. Successful seedling recruitment depends upon the complex interactions of magnitude and timing of streamflow, channel and floodplain morphology, existing vegetation, sediment transport processes, and the ambient environmental conditions (Mahoney and Rood, 1998; Amlin and Rood, 2002; Stella et al., 2006). In natural systems, periodic large floods correlate with seed dispersal periods to distribute seeds along wet depositional surfaces. As the water surface recedes, seeds are deposited at intermediate locations between the high flow and base flow elevations along the lateral floodplain gradient. Seeds are viable for an estimated 3-50 days, but once seeds are wetted they require deposition within a 3 day window (Braatne et al., 1996; Karrenberg et al., 20002; Gage and Cooper, 2005; Stella et al., 2006). When bare mineral soil with sufficient moisture is present, germination rates are high (Karrenberg et al., 2002; Gage and Cooper, 2005). After germination, seedling survival requires root growth and vertical extension to keep pace with the declining water table (Mahoney and Rood, 1991; Johnson, 1994).

Seedling mortality occurs when soil moisture is depleted faster than root extension can access the capillary fringe, with high rates of mortality ranging from 77-100% in most riverine settings (Hughes et al., 2001; Karrenberg et al., 2002). Surface moisture levels tend to be higher in fine sediment distributions, making sediment texture an important habitat component for seedling survival (Niiyama, 1990; Karrenberg et al., 2002; Cooper et al., 2003; Moggridge and Gurnell, 2009). Fine sediment availability within the current river channel is limited in the SFBR below Anderson Ranch Reservoir, with coarse substrate along most of the channel and bars (Figure 23A). Historic conditions in the river and floodplain likely had ample sand and smaller size sediment influx from the upstream basin owing to the granitic lithology. Evidence for this can be seen in the depositional delta at the upstream end of Anderson Ranch Reservoir (Figure 23B). Without the presence of the reservoir, the large quantities of sand that deposit at the reservoir inlet would be available for distribution within the SFBR canyon, likely altering the sedimentary character of the bars and islands along the channel toward a finer distribution that favors seedling growth.

Figure 23. A) Mixed cottonwood and willow seedlings growing on a coarse medial sediment bar in the SF Boise River that represent the current near channel substrate conditions. B) Fine sediment storage in Anderson Ranch Reservoir near Fall and Castle Creeks, 2013. Image from Wikimedia Commons (https://commons.wikimedia.org/wiki/File:Anderson_Ranch_Reservoir_1.jpg)

The finer sediment size distribution of the SFBR floodplains is likely more characteristic of the historic bar conditions when finer material was supplied from the upstream basin. These surfaces with finer sediment size distributions tend to support the greatest seedling and sapling success within the SFBR system (Figure 24A, B). Studies have shown that sediment texture and its role in maintaining soil moisture is important for seedling recruitment, but limited information is available to suggest ideal sedimentary conditions (Niiyama, 1990; Rood et al., 1998; Gurnell et al., 2001; Gage and Cooper, 2004). Grain size distributions were measured at eight sites near the channel and visually estimated at another five sites in the SFBR where successful riparian seedlings were established. Seedlings grew in sediment ranging from pure 1 mm sand deposits to coarse bars with a median grain size of 128 mm and no sand visible in the surface layer. No existing upper limit exists for the size of surface sediments that can support riparian seedlings, but data from the SFBR show that median grain sizes (D_{50}) within the patches are usually less than 40 mm and the coarser material in the distribution (D_{84}) is less than 90 mm (Figure 24C). Additionally, three floodplain locations were bulk sampled to capture the grain size distribution in the floodplain and represented as dashed lines in Figure 24C. Floodplain sediments are spatially heterogeneous and the shaded area illustrates the range of grain size distributions that span the near-channel conditions to much finer sediments in depositional areas. In general, sediment distributions in the floodplain share similarities in the upper grain sizes with the river channel and streambanks, but has a higher percentage of fine material in the sediment matrix that may support seedling recruitment if appropriate moisture conditions are present.

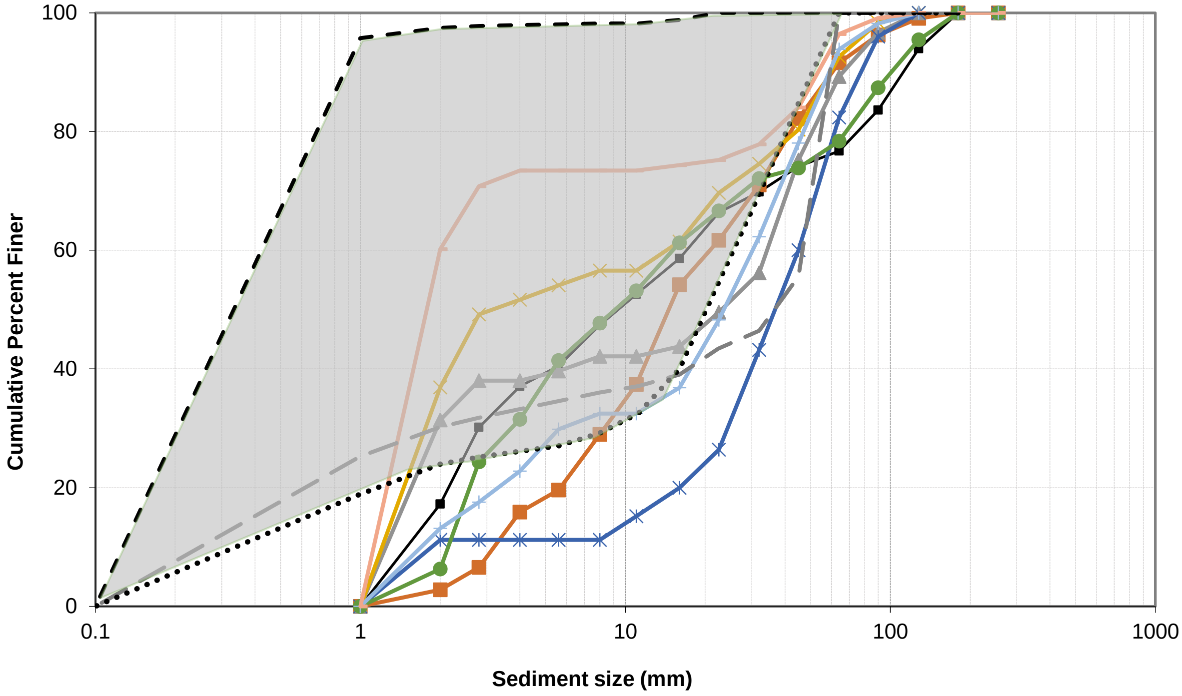


Figure 24. Successful A) seedlings and B) saplings along limited areas of the SFBR corridor with finer substrate than surrounding areas. C) Distribution of measured grain sizes at locations where seedlings were successful. Dashed lines represent bulk sieved floodplain samples and solid lines show near channel Wolman counts. Shaded area represents potential range of grain sizes within the floodplain.

In addition to seedbed substrate, topographic elevation of the floodplain surface is also critical to seedling success. Riparian areas with the greatest seedling establishment are located in areas that do not flood annually owing to the repetitious disturbance that occurs at lower elevations along bars and streambanks (Auble and Scott, 1998; Cooper et al., 2003; Gage and Cooper, 2004). Seedlings that successfully recruited in the low channel elevations during the spring of 2016 were all removed during the 2017 flood. Therefore, high flows that have the ability to both disturb the sediment and deposit seeds above normal water elevations are critical in the recruitment process (Braatne et al., 1996; Benjankar et al., 2014). Under natural flow conditions, high stream discharges that provide mass seedling establishment are most successful when periodic overbank inundation can occur (Braatne et al., 1996; Rood et al., 1998; Hughes et al., 2001). Along the SFBR floodplain, seedling recruitment occurred in limited areas along meander bends and low-elevation floodplain areas where the 2017 flood waters were able to produce a significant hydraulic disturbance. Figure 25 shows an example of such an environment with a close up of high seedling success seen in Figure 24A above.

Figure 25. Low-lying floodplain area with fine sediment that fostered heavy seedling recruitment after 2017 flood. Figure 24A above shows close up of sediment texture and seedling density.

Seedling growth rates depend on local combinations of water and nutrient availability, sunlight exposure, temperature, elevation, genotype, and soil profile (Merigliano, 1998; Gage and Cooper, 2005). Water availability is critical in riparian environments where water levels fluctuate rapidly and mortality occurs most commonly when root growth cannot keep pace with water table recession later in the year (Kranjcec et al., 1998). Root growth rates are high for black cottonwood seedlings, reaching up to 1.2 cm/day (Braatne et al., 1996; Mahoney and Rood, 1998). Therefore, water table recession and the associated capillary fringe cannot exceed this average rate until the end of the first growing season. Alternatively, seedlings that remain submerged for long periods of time can be killed via inundation and drowning. Mortality has been reported when seedlings remain inundated for periods ranging between two and eight weeks, with tolerance that depends on species and soil texture (Hosner, 1958; Bradley and Smith, 1986; Harrington, 1987; Smit, 1988). Therefore, if high flows persist in the river for long durations before the water surface recedes, anoxia can kill young seedlings that were established during the previous year. Within low elevation riparian areas in SFBR, inundation of existing seedlings occurred for 51 continuous days in 2019 (Figure 26) leading to spatially variable mortality. However, given the periodic monitoring of the areas it could not be definitively confirmed that inundation was the sole cause of mortality.

Figure 26. Inundation of mixed cottonwood and willow seedlings in low floodplain areas in SFBR in April 2019.

Additionally, sunlight exposure and competition are critical factors in seedling success. Black cottonwoods are shade intolerant and successful seedling recruitment rarely occurs where existing vegetation is established (Roe, 1958). Therefore, shoot growth rates that can outcompete nearby competitors is critical for successful establishment. Growth rates vary depending upon local environmental conditions and can range from < 1 cm/yr to 30 cm/yr (Rood et al., 1998). Assuming an average seedling growth rate of 15 cm/yr after recruitment, young trees would require at least 5 years to attain a height of 0.75 m that could outcompete invasive species like Reed canary grass. Thus, continuous management of grazing and invasive vegetation would be required for at least that many years after a riparian wildfire or mechanical land disturbance to support native seedling recruitment success.

Implications in the SFBR

Results of this study indicate that the floodplain habitat below Anderson Ranch Dam is a disturbance-limited system, which is negatively impacting the successful recruitment of native vegetation seedlings. Without future operational flexibility introduced into dam operations, riparian forest recruitment within the river corridor will remain limited and the long-term persistence of these native species is uncertain. Therefore, a program of managed intervention will be required to provide for successful seedling recruitment and resultant genetic diversity to the native riparian forest ecosystem. This may come in a variety of approaches that can be combined based on hydrologic conditions, recent wildfire activity, long-term maintenance operations, active restoration projects, and/or volunteer programs. The long-term goal of these collective activities is to maintain sustainable native riparian forests in the SFBR and the ecological benefits that they provide to the aquatic-riparian ecosystem. As short-term goals, these actions are intended to increase heterogeneity of the physical structure and the hydrologic connectivity of the river-floodplain system in order to support coupled ecosystem function. The principal existing limitation to native seedling recruitment is reduced geomorphic turnover and resultant habitat complexity along the channel floodplain interface arising from reduced physical process dynamics. Native seedling recruitment would benefit from a) greater inundation of the floodplain to both disturb surfaces and distribute seeds for germination, especially in a post-fire environment, b) increased sediment supply to provide greater depositional surfaces within the active channel, and c) increased distribution of large woody debris in the floodplain and at the channel interface to provide local scour and deposition areas for increased seedling habitat.

Dam operations during average hydrologic conditions in the SFBR resulted in limited observed and simulated seedling recruitment, whereas dam operations during wet hydrologic conditions with large peak floods provide more favorable habitat. Conversely, dam operations during dry years usually provide irrigation releases without any high spring release. These stable conditions are similar to dam operations during average hydrologic years and would likely provide no seedling recruitment owing to the lack of disturbance or bare exposed sediment. Seedling recruitment would likely improve with tailored dam releases and greater geomorphic turnover of habitat surfaces. These separate processes likely would require different magnitudes of hydraulic disturbance on the floodplain. Simulations show that bankfull dam releases do not have sufficient inundation or disturbance to create habitat outside of the main river channel and the immediate streambanks. While greater overbank discharges are required to support native riparian recruitment processes, inundation alone is insufficient to produce ideal germination and recruitment. The high discharge event of 2017 inundated a large percentage (78%) of the floodplain and maintained those levels for a long duration. However, field results show that even after a 50-year flood (2017) only 5% of observed seedling recruitment occurred on the floodplain. This occurred because much of the floodplain was underwater and seeds that had germinated were not able to reach stable surfaces within their 3-day window of viability. Therefore, overbank dam releases less than the 50-year flood would benefit seedling recruitment processes in the SFBR. Tailoring a target hydrograph to support native riparian vegetation in advance that can be released when annual hydrologic conditions allow, would provide the best approach for native riparian forest regeneration on the floodplain.

Additionally, large floods can remove existing vegetation, create open, bare surfaces on the floodplain, and initiate morphodynamic channel change for new seedling habitat. Unfortunately, the regulated flow conditions in the SFBR have allowed existing vegetation to stabilize the floodplain and streambanks, which resulted in little geomorphic change below the dam even during a 50-year flood. This agrees with experimental floods in other managed river systems that have been effective in restoring some riparian ecosystem function through natural recruitment processes (e.g., Benjankar et al., 2012; Rood et al., 2005; Stevens et al., 2001), but were incapable of initiating major geomorphic change outside the active channel (Stevens et al., 2001; Dixon et al., 2015; Johnson et al., 2015; Kui et al., 2017). Without large areas of bare sediment that may accompany a channel avulsion or meander cutoff event, the increased seedling recruitment in the SFBR occurred in small isolated patches of 20-60 m^2 (Figure 13A) that were located across a wide range of habitat types (e.g., islands, floodplain, bars). This differs from observations on larger, low-slope rivers where long bands of riparian cohorts developed along the banks of the Oldman, South Saskatchewan, and Kootenai rivers during high flow events (Jamieson and Braatne, 2001b; Rood et al., 2005). Therefore, seedling recruitment in the SFBR may require a flood of greater magnitude than the 50-year return interval to initiate dynamic geomorphic turnover processes or some form of physical disturbance in the floodplain to provide large areas of cohort recruitment that lead to a mosaic of age classes within the riparian corridor.

Additionally, the majority of seedling recruitment in the SFBR during wet hydrologic condition occurred in depositional environments, where fine, bare sediment was available. The most successful of these areas were found at the head and in the wake of stable vegetated islands and bars, where velocity was reduced and fine-grained sediment could accumulate within the cobbles. Similar results have been found around established riparian vegetation in the laboratory and field when fine sediment is available for transport in the system (Chen et al., 2012; Gurnell et al., 2019; Kim et al., 2015). Once these bar surfaces are colonized with established vegetation, they become very stable features that provide a locus for further deposition and vegetation growth. Even during the high flow conditions that were equivalent to a 50-year recurrence interval in the watershed, the vegetated bars within the study site acted as net depositional areas. Field observations and seedling surveys indicate that fresh sediment deposits along the margins of vegetated islands and new medial bars provide the best recruitment habitat in the SFBR. These features can be locally modified to enhance seedling recruitment processes in the SFBR.

Additionally, examination of the sediment transport model results illustrate that areas with strong depositional tendencies spatially correlate well with seedling recruitment. Therefore, the wildfire-initiated debris flow in combination with the extended 2017 flood releases provided both the sediment supply and transport capacity to establish the majority of new riparian vegetation habitat along the study site. From an ongoing management perspective in the SFBR, this effectively provided a natural test of a sediment augmentation approach in the years following the 2013 Elk Fire. It follows that further sand and fine gravel augmentation in the reaches below Anderson Ranch Dam could be beneficial for native vegetation recruitment processes by providing for vertical accretion to sufficiently build medial bars above the water surface that can successfully support seedling recruitment and multiyear sapling growth. Such sediment augmentation strategies have been applied in the Yuba and Trinity Rivers in Northern California for salmonid habitat (Bunte, 2004; Wheaton et al., 2004; Brown and Pasternack, 2013; Gaeuman and Stewart, 2019) and are increasingly applied to European and Japanese rivers for geomorphic stability, aquatic habitat, and water quality improvements (Kantoush et al., 2010; Ock et al., 2013; Arnaud et al., 2017). Conceptually, extending this approach to support riparian vegetation succession could build on the lessons learned from these ongoing experiments in other watersheds and support an erodible corridor concept (Florsheim et al., 2008; Kondolf, 2013) for holistic river management. In the SFBR, there are optimal conditions to allow dynamic river processes to occur in support of aquatic-riparian processes, as bridges are located in stable straight reaches and houses and roads are setback from the active river channel. An active sediment augmentation program could be instituted below Anderson Ranch Dam to facilitate seedling recruitment and sexual regeneration of native riparian forest species. An active sediment management program could be instituted as a series of measures that 1) attempts to create in-situ seedling recruitment patches in strategic afforestation areas during average-year dam operations and/or add introduce areas of sediment supply similar to the debris flow examples that add sediment piles or slides along the banks that could be redistributed when wet hydrologic years require high discharge releases from the reservoir for accommodation space in the reservoir or flood control activities in the basin. In such applications, ecological function could be improved during years when operational flexibility of the dam is possible.

If holistic sediment management strategies are impractical in the SFBR, local physical alterations could also be pursued in the channel and floodplain to increase hydraulic connectivity between the river and adjacent areas. To locally increase water surface elevations of the river that increase inundation depths and duration along specific areas of the floodplain various options are available. Mechanical alteration of the channel could build bars and expand islands in an effort to reduce the cross-sectional area and hydraulic conveyance of the channel. For the same discharge from the dam, this would locally increase overbank floodplain disturbances along expansion areas in the canyon without increasing the flood hazard on downstream infrastructure. This option would provide both physical instream features for seedling recruitment in addition to expanding the inundation area of specific floodplain areas. Further off-channel mechanical adjustments can be made to the floodplain to support seedling habitat, without instream restoration activities. Construction of near-channel swales would provide low-elevation, moist habitat in the floodplain where seedlings can establish with appropriate sunlight exposure. This requires an understanding of the riparian water table dynamics to ensure proper moisture conditions are available for seedlings throughout the growing season. All construction activities and mechanical disturbances should be timed to capitalize on seedling dispersal in order to limit competition from invasive species. If such mechanical activities are completed after the seed dispersal period, it is likely that other vegetation will occupy the newly constructed areas.

The diminished flood peaks and lack of sediment influx from the upstream basin limits deposition/erosion processes that constitute the drivers of bar building and channel migration.

These geomorphic processes provide the bare mineral soil surfaces for seeds to germinate and successfully recruit. In the absence of historic flood magnitudes to deposit sediment and erode streambanks, riparian wildfire may provide an additional disturbance that could benefit native seedling recruitment. Riparian forest response on the floodplain was dependent upon burn severity and should be accounted for if prescribed burns are used as a treatment in riparian areas, especially populated by black cottonwoods. This potential benefit is contingent upon upstream dam operations to provide at least moderate overbank spring flows in the year following the burn event to maximize ecological function and reduce competition. Intentional post-fire disturbance in the floodplain can challenge traditional management approaches, especially in sensitive aquatic systems managed for threatened or endangered fisheries. Such post-fire floods could even be performed as short duration pulses to limit major geomorphic channel changes while still delivering seeds and replenishing soil moisture content in the floodplain.

Introduction of large wood debris (LWD) to the channel margins can provide hydraulic complexity and fish habitat, in addition to inducing local scour and deposition features that can support seedling recruitment. In particular, flow separation zones in the wake of obstructions like LWD create fine sediment deposition zones that are optimal for seedling establishment (Dixon, 2003; Schnauder and Moggridge, 2009; Kondziolka and Nepf, 2014; Corenblit et al., 2016; Gurnell et al., 2019). A greater density of LWD as either individual pieces or combined structures in or near the channel provide for passive localized mechanisms to enhance native seedling habitat. Post-fire conditions in the SFBR floodplains provide large quantities of LWD as either standing top-killed trunks or downed partially burned trunks (Figure 27). These LWD materials were not mobilized during the 2017 flood and have little opportunity to interact with the channel owing to the lack of flood disturbance to move them downstream. To increase their impact and provide local scour and deposition near the channel, these LWD materials could be placed in near-channel environments or used to construct LWD jams along the channel margins. Concerns about their mobility during high flows and impact on downstream infrastructure are valid and must be accounted for during this process. In general, downed LWD mobilization on the floodplain will be determined by site specific conditions including flow depth and velocity, tree size (root wad, bole, branch complexity, trunk length), surrounding forest tree matrix alignment and density, wood density in relation to hydraulic forces (will the wood break into smaller pieces), and management activities like notching or limbing (Wohl, 2013). Definitions of LWD fall in two general categories to support 1) geochemical and ecological functionality and 2) physical/structural heterogeneity of the channel. Those in support of the former define LWD as greater than 1 m in length and 0.10 m in diameter (Fetherston et al., 1995; Wohl et al., 2011; Wohl, 2017; Martin et al., 2018), whereas those that promote physical structure and habitat define LWD to be greater than 3 m in length and 0.30 m in diameter (USDA, 2003; USBR, 2014b). To accrue physical near-channel habitat improvement, 1 m long is of little use for creating hydraulic flow separation, inducing physical scour or deposition to increase physical diversity, or produce channel shading in rivers greater than small headwater streams. Hence, LWD >3 m long are recommended for use, but downstream infrastructure limitations like bridge openings should guide the maximum size of LWD allowable for these projects.

Figure 27. Current LWD present on the SFBR floodplain after the 2013 Elk Fire.

For long-term management of LWD, the quantity of LWD available to the near-channel environment has been found to increase with forest age (Warren, 2009). Therefore, as the riparian forest recovers from the 2013 Elk Fire LWD loading to the channel margins should become increasingly self-sustaining. However, there are numerous challenges to maintaining near-channel LWD in the SFBR basin. Principally, willows are dominating the majority the channel margin recruitment area, but are insufficient to meet LWD criteria that facilitates flow separation, fine sediment deposition, and further seedling recruitment. Secondly, recreational camping and firewood collection is very active along the riparian floodplain and may limit local streamside/floodplain LWD distributions. Finally, it should be noted that historic LWD composition in the channel would have consisted of mixed conifers from the upstream basin and local cottonwood, but with the presence of the reservoir to capture upstream LWD now only cottonwood is possible. If insufficient quantities of LWD sources are available in the floodplain, large wood can additionally be captured in the upstream reservoir and transported to the downstream riparian environment.

If seedling recruitment is simply not economically viable in the SFBR, a managed planting regime to introduce clustered age classes to the floodplain ecosystem would provide genetic diversity and a mosaic of structural forest habitats to support ecological function. As hydraulic disturbances are limited in the floodplain, a planting regime of established seedlings or saplings would alleviate the overbank flow requirement to provide bare mineral sediments and seedling survival would simply depend upon the water table that could be monitored at specific locations (see groundwater monitoring section). In the SFBR, restoration planting has the greatest favorable continuous area (Figures 18, 19, and 20), which allows wide floodplain areas to be identified and targeted for restoration activities that are not limited to the patch scale. This greater favorable area was an expected outcome, as a hydraulic disturbance was not required for saplings to be planted, which relies on a mechanical disturbance during planting operations. Also, the favorable elevation range was expanded from 1 m to 1.4 m owing to the assumption of existing roots. Saplings with an established root system or cuttings that can begin to grow root systems from an initial depth have substantial advantages for accessing the water table. This in turn, allows planted cuttings or saplings to survive at higher elevations within the floodplain and avoid subsequent hydraulic disturbances. Planting also has the implicit benefit of human site selection within the larger favorable area that can target areas with high light exposure and beneficial soil conditions. These open canopy areas were expanded by the wildfire in 2013 that reduced cottonwood canopy and understory shading in the floodplain. This recent disturbance allows for increased sunlight exposure to much of the floodplain where low to moderate burn severity occurred and an opportunity to introduce a planting strategy without the removal of large existing trees.

To facilitate management and decision-making, the riparian recruitment model provides useful information for identifying location and spatial extent of seedling recruitment and restoration planting potential over a 23 km river reach. It is emphasized that priority should be given to restoring riparian functions rather than simply vegetation conditions when performing restoration activities within a river corridor. Therefore, natural seedling recruitment should be pursued while restoration planting should be employed as a means of supporting ecosystem function at the intermediate timescale if necessary. Identified habitat for restoration planting in the SFBR can support dormant period (late fall to early winter) plantings of cuttings and bare root stock or spring planting of saplings (1-2 years old) with 0.50-0.75 m root length. For cottonwoods, a minimum planting density of 40-80 trees per ha is recommended (Elefritz et al., 1998). Planting activities could be accomplished by volunteer organizations in the basin that would be led under Reclamation oversight. This alternative management strategy requires a long-term commitment to forest management but provides the flexibility to occur during average to wet years when there is ample spring precipitation and groundwater tables are supported by high flows in the river.

Finally, highly competitive species are also present in the SFBR canyon, which can potentially outcompete native pioneer species in riparian environments. In particular, Reed canary grass is establishing on bars, islands, and streambanks, creating competition for bare surfaces and light exposure. Fierke and Kauffman (2005) found that once established, these grass mats can substantially limit forest regeneration processes at approximately 15% coverage (Figure 28A). Given its increased inundation tolerance, Reed canary grass will provide serious competition for available mineral sediments because it can establish at lower topographic elevations near the water’s edge. For example, areas that may provide suitable native seedling habitat with future sediment deposition, like the tails of vegetated islands and bars will already be populated by Reed canary grass (Figure 28B and C). Active removal of these potentially problematic species in the SFBR system may assist in native seedling recruitment success.

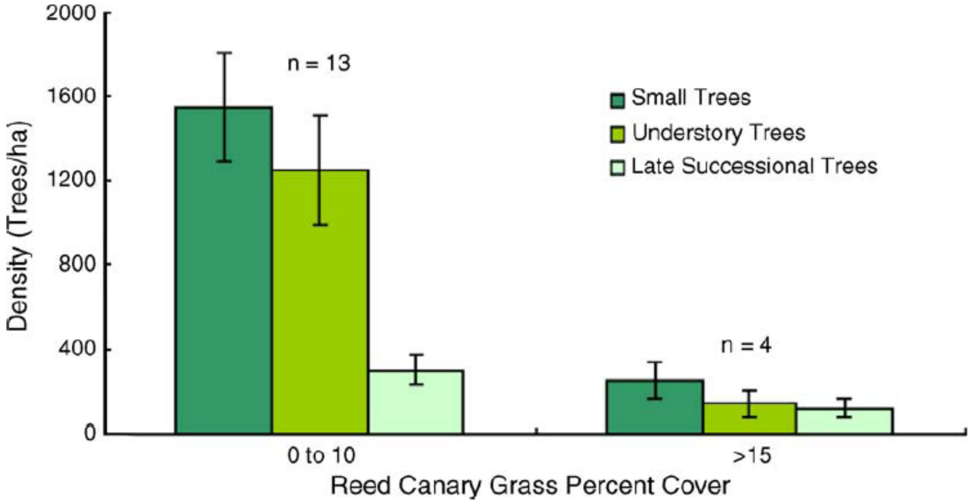


Figure 28. A) Influence of Reed canary grass on small riparian tree populations [from Fierke and Kauffman, 2005]. Reed canary grass establishing on B) streambanks and C) exposed sediments along the tail of islands.

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