Species Status Assessment (SSA) Report for the Roanoke Logperch (*Percina rex*)

Version 1.1

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Roanoke logperch (Photo credit: J.R. Shute, Conservation Fisheries Inc.)

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EXECUTIVE SUMMARY

This report summarizes the results of a species status assessment (SSA) conducted for Roanoke Logperch (*Percina rex*; hereafter "RLP"), a freshwater fish endemic to streams and rivers of the Roanoke, Dan, and Chowan river basins of Virginia and North Carolina. The species was listed as federally endangered under the U.S. Endangered Species Act (ESA) in 1989 based on its small geographic range, vulnerability to anthropogenic impacts like urbanization, reservoir construction, and water pollution, and projected future increases of those threats. This SSA report is intended to serve three primary purposes: (1) synthesize the biology of the species and ecological factors influencing individual fitness and population persistence, (2) evaluate the current status of the species, and (3) forecast the potential status of the species under various future scenarios of environmental and management change. In synthesizing such information, this document is intended to support future ESA documents for RLP, including 5-year reviews and potential classification rules. We have used the established SSA framework of assessing species condition under the "3R" concepts of resiliency, redundancy, and representation.

RLP feed and spawn over clean gravel, pebble, and cobble substrates in large creeks to medium rivers. They spawn in spring, depositing eggs on the substrate with no subsequent parental care. Newly hatched larvae drift downstream for unknown distances on river currents until they settle out in calm backwaters and pool margins. By their first fall, juveniles begin shifting into the deeper, main-channel habitats occupied by older juveniles and adults. The species matures by Age 2-3 and lives up to 6.5 years. Adults appear to undertake extensive upstream spawning migrations, followed by cumulatively downstream migration over ontogeny. All age classes of RLP appear to be intolerant of heavy silt cover and embeddedness, both because silt smothers eggs and because the species feeds primarily by flipping over unembedded substrate particles with its snout. The species is more often found in habitats with unsilted substrate, forested watersheds, and large enough stream size for the species to complete its life history. It avoids heavily silted runs and pools, very small creeks, hydrologically unstable tailwaters below dams, and lentic lakes and reservoirs.

The known geographic distribution of RLP has expanded dramatically over time, from 4 streams by the end of the 1940s to 14 streams by the time of its ESA listing in 1989 to 31 streams as of 2019. Because survey effort also increased dramatically over this time, we cannot determine whether RLP's range increased because of true range expansion via dispersal, new discovery of existing but undiscovered populations, or both. No population extirpations are known, but the species' distribution prior to 1940 is poorly understood, so extirpations prior to 1940 would have gone undetected. The species' present-day distribution spans three river basins (Roanoke, Dan, Chowan) and 4 ecoregions (Ridge and Valley, Blue Ridge, Piedmont, Southeastern Plains). Although these basin/ecoregion distinctions create no major phylogeographic differences (e.g., evolutionarily significant units), they are environmentally distinct enough that we assume that each may harbor unique local adaptations. We therefore assessed representation of RLP across these unique combinations of basin and ecoregion, resulting in four key representation units, which we deemed "metapopulations" (Roanoke Mountain, Roanoke Piedmont, Dan, and Chowan). Each of these metapopulations harbors anywhere from 1 to 5 demographically independent populations, which we deemed "management units" or "MUs". In total, there are 11 MUs currently occupied by RLP. We assessed current condition based on the resiliency of each

of these 11 MUs, the redundancy of resilient MUs within each metapopulation, and the representation of metapopulations harboring resilient and redundant MUs across the range of the species. Species experts also previously identified an additional 7 currently unoccupied but potential future MUs (i.e., currently unoccupied rivers that appeared good candidates for RLP introduction or reintroduction). For analyses of future condition, which considered it possible for these potential MUs to become occupied, we included them in assessing future resiliency, redundancy, and representation.

We deemed that six factors have a particularly strong influence on RLP condition. First, fine-sediment deposition emanating from urbanization, agriculture, and other sources smothers eggs and reduces feeding efficiency, potentially resulting in reduced growth, survival, and recruitment. Second, chronic chemical pollution reduces habitat suitability for RLP and acute pollution events reduce survival and population size. Third, dams and other barriers inhibit fish movement, fragmenting populations into smaller areas and reducing demographic rescue and gene flow among populations. Fourth, climate change may alter hydrology and sediment delivery by increasing flood magnitudes and flow variability in general, reducing flow predictability, decreasing summer/fall base flows, and increasing erosion and runoff of sediment, potentially reducing habitat suitability for all age-classes of RLP and increasing direct mortality of vulnerable juveniles during spring floods. Fifth, existing legal and regulatory mechanisms such as ESA protections, the U.S. Clean Water Act, and state-level equivalents likely benefit the species through prohibitions on activities that may cause take and by facilitating funding opportunities that can be used for RLP research and conservation. Sixth, management activities aimed at improving habitat quality (e.g., riparian revegetation to reduce silt loading), restoring habitat connectivity (e.g., removing dams), and directly manipulating populations through propagation, augmentation, reintroduction, translocation, and introduction of fish (i.e., PARTI) could increase the resiliency and redundancy of populations. Notably, no previous research has directly quantified relationships between these six factors and RLP vital rates (reproduction and survival rates), so in assessing current and future condition, we based our assumptions about the nature of these relationships on a combination of observed correlations with occurrence and relative abundance, ecological theory, expert judgment, and simulation models.

Considering the biology of the species and key factors presumably influencing condition, we assessed current resiliency of occupied RLP MUs based on indices of population density, genetically effective population size (N_e), habitat quality, and geographic range complexity. Five MUs received high resiliency scores, four received intermediate scores, and two received low resiliency scores. Resiliency was high within the Roanoke Mountain, Dan, and Chowan metapopulations but variable within the Roanoke Piedmont metapopulation. Based on the count and resiliency of these MUs, the Dan metapopulation scored the highest redundancy, followed by the Roanoke Mountain and Chowan metapopulations. The Roanoke Piedmont metapopulation scored the lowest redundancy because, although it contains four extant MUs, two of them (Goose and Middle Roanoke) have low estimated resiliency because of small N_e and low population density, respectively. Nonetheless, given that all four representation units currently harbor at least some resilient MUs and exhibit at least some redundancy, species-level representation currently is relatively high. No evolutionarily irreplaceable units have been lost to our knowledge, and none are at imminent risk of being lost.

We assessed future resiliency of RLP MUs using a population viability analysis (PVA) simulation tool that modeled future population size under three categories of future scenarios. These categories assumed either (1) no management intervention, (2) implementation of population restoration through PARTI, or (3) implementation of both PARTI and targeted dam removals to increase connectivity. Within each category, we also contrasted scenarios involving (a) no change to current environmental conditions, (b) greater climate change resulting in worsening range-wide habitat suitability, (c) increasing urbanization resulting in increased risk of catastrophic pollution events, and (d) the combination of worsening habitat suitability and increased pollution risk. Each of these 12 scenarios were simulated 100 replicate times for 50 years into the future, and we estimated future resiliency based on how often each MU remained extant at the end of the simulation. Under "status quo" environmental conditions, anywhere from 9 to all 11 occupied MUs were highly resilient for 50 years, depending on whether PARTI and dam removal were invoked, and under the "best-case" scenario, an additional 4 new, highly resilient MUs were established. Under the "worst-case" scenario of worsening habitat quality, increased risk, and no management, 8 of 11 MUs still remained highly resilient by year 50, though no new resilient MUs were created. A high degree of resiliency and redundancy were consistently attained in the Roanoke Mountain, Dan, and Chowan metapopulations. In contrast, resiliency of Roanoke Piedmont MUs, and hence redundancy of this metapopulation, depended strongly on future environmental and management conditions: under declining habitat conditions, the Roanoke Piedmont metapopulation maintained only 1 highly resilient MU, whereas with PARTI and barrier removal, it maintained 3 highly resilient MUs. We found that species-level representation was relatively high under scenarios where multiple Roanoke Piedmont MUs remained highly resilient, but only partially achieved in situations where the Roanoke Piedmont metapopulation was down to 1 remaining highly resilient MU.

In conclusion, owing to a large geographic range that includes at least some numerically large populations in good-quality habitat, we estimate that species-level representation and redundancy for RLP currently is relatively high, all 4 metapopulations exhibit at least some redundancy of resilient MUs, and most MUs meet resiliency criteria based on population density, N_e, habitat quality, and geographic range. In the future, the Roanoke Piedmont metapopulation and its constituent MUs show the lowest resiliency and redundancy, particularly under scenarios involving worsening habitat quality. However, these declines could be offset through restoration measures like PARTI (augmenting weak populations and establishing new ones) and/or barrier removal (allowing natural augmentation and colonization). Although uninvestigated in models, declining habitat conditions and pollution risks might also be mitigated through streamside habitat protection and restoration, enhanced water pollution controls, and developing conservation-oriented water-management and urban-development plans in watersheds harboring RLP. Additional field research to empirically quantify the demographic and genetic benefits and costs of environmental and management factors should be a high priority for RLP. Resulting information could be incorporated into the assessment framework of this SSA to produce revised estimates of current and future condition.

CHAPTER 1 – INTRODUCTION

1.1 Background

This report summarizes the results of a species status assessment (SSA) conducted for Roanoke Logperch (*Percina rex*; hereafter "RLP"), a fish whose geographic range is restricted to a limited number of stream reaches in the Roanoke, Dan, and Chowan river basins of Virginia and North Carolina. The species was listed as federally endangered under the U.S. Endangered Species Act (ESA) in 1989 (54 FR 34468-34472), a recovery plan was published in 1992 (USFWS 1992, entire), and a 5-year status review in 2007 (USFWS 2007, entire). Since the species' listing and development of the recovery plan, a significant amount of basic and applied research has been directed toward RLP, which has substantially improved scientific understanding of the species. For example, previously unknown RLP populations have since been discovered and the geographic ranges of already-known populations have been expanded through additional, targeted surveys. Biological studies have increased scientific understanding of population ecology, habitat needs, and population genetics. Finally, recent and ongoing viability assessments have provided new quantitative numerical recovery targets and simulation tools that improve science-based forecasting of RLP's present and future status, including under alternative future environmental and management scenarios (Roberts et al. 2016a, entire).

1.2 Analytical framework

This SSA report is intended to serve three primary purposes: (1) synthesize the biology of the species and ecological factors influencing individual fitness and population persistence, (2) evaluate the current status of the species, and (3) forecast the potential status of the species under various future scenarios of environmental and management change. In synthesizing such information, this document is intended to support future ESA documents for RLP, including 5-year reviews and potential classification rules. We also intend this to be a living document, and as such have employed a flexible and transparent analytical framework, so that these analyses could be revisited in the future if new data become available or new scenarios warrant investigation. The SSA report is not a decisional document, but rather an in-depth review of the species' biology and threats, an evaluation of its biological status, and an assessment of the resources and conditions needed to maintain its long-term viability.

Herein, we have used the established SSA framework of assessing species status under the concepts of resiliency, redundancy, and representation (Wolf et al. 2015). Considering the definitions provided by Smith et al. (2018) and USFWS (2020), we summarize these "3Rs" as follows:

- **Resiliency** reflects the ability of a species and its constituent populations to withstand the range of favorable and unfavorable conditions all natural populations face, including demographic and environmental stochasticity. At the population level, resiliency to such factors might be measured using demographic indicators like population size or the vital rates (survival, recruitment, immigration) that sustain it. Resiliency also requires that a population resist the negative effects of inbreeding depression and maintain the potential to adapt to novel selection pressures. These attributes might be measured using genetic indicators like N_e , heterozygosity, and levels of inbreeding.

- **Redundancy** indicates that a species maintains a sufficient number of resilient populations to withstand the extirpation of one or more of these populations, for example during unpredictable catastrophic events. The greater the duplication of resilient populations across a geographic range extent, the lower the overall extinction risk should be for the species as a whole, particularly if (1) the distribution of these populations allows for connectivity and recolonization of extirpated populations following catastrophes, and (2) demographic and environmental fluctuations among these populations are not strongly correlated. Thus, redundancy is best gauged by a count of resilient, connected, demographically uncorrelated populations, either at the scale of the entire species or within regional groups of populations (i.e., metapopulations).

- **Representation** accounts for the need to maintain the full evolutionary legacy and potential of a species, by ensuring that resilient and redundant populations are distributed across the full ecological and evolutionary spectrum of the species. By maximizing representation, we maximize a species' adaptive potential to (unpredictable) future changes to its environment, including novel climatic conditions, pathogens, predators, and habitat conditions. If genetic data are available, evolutionarily distinctive units can be delineated using these data, and representation assured by maintaining resilient and redundant populations across all such units. Whether or not genetic data are available, environmental strata such as river-basin and ecoregion boundaries also can serve as surrogates for evolutionary boundaries, as these strata are likely to strongly influence the evolutionary history and future of aquatic species.

We have employed this 3R conceptual approach, within the SSA framework, to assess the current status of RLP and forecast the potential future condition of RLP under each of several plausible scenarios about future environmental conditions and management strategies. Our primary forecasting tool was a quantitative, spatially explicit population viability analysis (PVA) model. This PVA model was developed specifically for RLP through collaboration with agency stakeholders – many of whom were subsequently on the technical team for this SSA – during a series of workshops from 2018 to 2020. Through these workshops, best available data and expert opinion were elicited regarding the appropriate scales for delineating populations and metapopulations, current estimated population sizes and vital rates, and current habitat conditions and threats for each population. These data, plus additional information compiled during the development of this SSA, allowed for an assessment of current resiliency, redundancy, and representation based on presumed relationships between persistence and positive and negative factors affecting the species (e.g., habitat quantity and quality, connectivity, management actions such as population augmentation, and threats such as catastrophes). These data also served as model inputs to PVA simulations that forecasted how future *changes* to factors affecting the species might influence the 3Rs in the future. Such models can be reanalyzed in the future based on updated data or new understanding of stress-response relationships.

CHAPTER 2 – SPECIES INFORMATION

2.1 Description and taxonomy

The Roanoke Logperch (RLP; *Percina rex*) is a large-bodied member of the darters (Etheostomatinae), a diverse subfamily of freshwater fishes in the perch family (Percidae) endemic to North America. The species was described from the upper Roanoke River by Jordan and Evermann (in Jordan 1889, entire). It is recognized as a valid species by the American Fisheries Society (Page et al. 2013, p. 141) and is listed as such in the Integrated Taxonomic Information System database (www.itis.gov; accessed 4 September 2021). The RLP is the most basal member of the logperch clade (subgenus *Percina*) and is sister to all other extant members of the clade (Near 2002, entire). Near and Benard (2004, p. 2803) estimated that RLP diverged from the remainder of the logperch clade roughly 4.2 million years ago. It is one of only two logperch species native to the Atlantic slope of North America, and it is the only logperch species native to the Roanoke, Dan, and Chowan basins of Virginia and North Carolina.

Intraspecific genetic studies of RLP using mitochondrial DNA genes (George et al. 2010, entire; Roberts 2012a, p. 164) and nuclear DNA microsatellite loci (Roberts et al. 2013, entire) indicate that the Chowan basin houses the most genetically unique population of the species, but overall levels of intraspecific genetic divergence are relatively minor, such that no major sub-specific phylogeographic distinctions (e.g., evolutionarily significant units) are evident. A single hybridization event, apparently between an RLP and a Chainback Darter (*Percina nevisense*), was detected in the upper Roanoke River in 2004 (Roberts 2011, entire), but we are aware of no other records of hybridization or genetic introgression for RLP.

Adult RLP typically measure 115-140 mm total length (TL; Roberts and Angermeier 2006, p. 23; Roberts and Angermeier 2008, p. 39). Adults and juveniles exhibit 8-11 prominent, vertically elongated vertical lateral blotches, a series of dark dorsal “saddle” markings, strongly tessellated dorsal and caudal fins, a prominent subocular bar, and a conical “pig-like” snout that is typical of the logperches (Jenkins and Burkhead 1994, pp. 785-786). Adult males additionally exhibit a bright orange band in the distal portion of the spinous dorsal fin (Figure 1).

Figure 1: Photographs of various life-stages of RLP, taken by staff at Conservation Fisheries Inc. (CFI) of Knoxville, Tennessee.

2.2 Life history and habitat needs

The overwhelming majority of our knowledge on RLP biology and habitat needs is based on research conducted in the upper Roanoke River (e.g., Burkhead 1983, entire; Roberts and Angermeier 2006, entire). We assume these findings to be generally applicable to populations occupying other river basins and ecoregions, but point out comparative studies (e.g., Rosenberger and Angermeier 2003, entire) and contrasting findings where available. Life-history and habitat-need information is summarized by life-stage in Table 1.

Life cycle and longevity – Adhesive, demersal (i.e., sinking, non-buoyant) eggs are laid in gravel in April-May (Burkhead 1983, p. 44; Jenkins and Burkhead 1994, p. 786; Ruble et al. 2009, pp. 5-6; Ruble et al. 2010, p. 4; Table 1). Time to egg hatching is unknown for RLP, but drifting larvae were observed from mid-April to mid-June (Buckwalter et al. 2019, p. 8), suggesting a <1-month egg stage. Larvae transform to juveniles and settle in pool and backwater habitats for their first summer, then begin to transition to the edges of riffle/run habitats by the end of their first fall (Burkhead 1983, p. 41; Rosenberger and Angermeier 2003, p. 1569; Roberts and Angermeier 2006, p. 3). The juvenile stage lasts 2-3 years: females and males reach sexual maturity by Age 2 and Age 2-3, respectively (Jenkins and Burkhead 1994, p. 786). Typical adult age structure is unknown, but the maximum recorded longevity is 6.5 years; males and females appear to live equally long (Burkhead 1983, p. 48).

Reproduction - Spawning has been directly observed only in the Roanoke River and only once. Males exhibited aggressive behavior toward each other and attempted to solicit a female by displaying their orange dorsal fins (Jenkins and Burkhead 1994, p. 786). Spawning occurred over gravel in a deep, swift run. This observation occurred on 20 April at a water temperature of 12-14 °C, but females were observed running ripe from mid-April to early May (Burkhead 1983, p. 44; Jenkins and Burkhead 1994, p. 786). Potential fecundity, deduced from examination of mature ova in ovarian dissections, ranged from 180 to 640 eggs and correlated positively with the length and mass of the female (Jenkins and Burkhead 1994, p. 786; Burkhead 1983, p. 112). In captivity, yolksac larvae, indicative of very recent spawning, were found from 4 April to 26 May, at water temperatures ranging from 18 to 21 °C (Ruble et al. 2009, pp. 5-6; Ruble et al. 2010, p. 4). Eggs are adhesive and demersal (Jenkins and Burkhead 1994, p. 786).

Movement, migration, and dispersal – RLP are too small to fit with telemetry transmitters, so real-time estimates of their movement patterns are unavailable. Existing information is based on mark-recapture studies, which notoriously underestimate movement frequency and extent because of study-design limitations (Albanese et al. 2003, entire), and on population genetic studies, which provide more indirect measures of movement (Roberts et al. 2016b, entire). Presumably, RLP exhibit a life-history typical of many stream fishes, involving relatively strong fidelity of adults to summer-fall feeding habitats, upstream spawning migration in the spring, and cumulatively downstream movement by young fish as they grow older and larger (Hall 1972, entire; Turner 2001, entire). Buckwalter et al. (2019, entire) frequently observed larval RLP drifting downstream in the Roanoke River, but the duration and spatial distance of this drift were unknown. Using genetic methods, Roberts et al. (2016c, entire) observed that juvenile sibling pairs were distributed throughout a 55-km reach of the upper Roanoke River watershed by their second fall, suggesting either that their parents migrated extensively to distribute progeny throughout this area or that the larvae and/or juveniles themselves redistributed across this large area post-hatching. Based on mark-recapture, Roberts et al. (2008, entire) found that adults tended to remain within the same short (<50-m) section of a riffle/run over the course of a summer-fall feeding season, but Roberts et al. (2008, entire) and Burkhead (1983, p. 53) opportunistically observed three long-distance adult movement events of greater than 2 km. The purpose of these movements was unknown but assumed to be either migration or dispersal. On the whole, the prevailing view is that RLP movement occurs extensively throughout whole watersheds unless prevented by a movement barrier like a dam (Roberts et al. 2016b, entire), and therefore that entire connected watersheds should be considered single genetic and demographic populations for management purposes (Roberts et al. 2013, entire).

Feeding – Food preferences of larvae are unknown. Juveniles and adults exhibit the typical logperch feeding behavior of flipping over stones and organic debris with their conical snout, which may provide access to food items unavailable to other benthic fishes (Jenkins and Burkhead 1994, p. 784). Juveniles feed on a variety of benthic invertebrates, especially midge larvae (Jenkins and Burkhead 1994, p. 786). Adults also are generalist benthic invertivores, with caddisfly and midge larvae being particularly common diet items (Jenkins and Burkhead 1994, p. 786).

Habitat needs – As with many stream fishes, our understanding of RLP's micro- and mesohabitat-scale habitat use and needs is far greater than our understanding of macrohabitat ecology. At the microhabitat scale (i.e., 1- to 10-m^2 patches), as with other logperches and most darters in general, all life stages of RLP appear to require unembedded stream substrates with low silt cover for reproduction, feeding, and sheltering (Jenkins and Burkhead 1994, p. 786). As a gravel spawner with no nest-site preparation, silt coverage could smother eggs and reduce their viability (Berkman and Rabeni 1987, entire). Furthermore, heavily embedded substrates contain lower benthic macroinvertebrate densities (Berkman and Rabeni 1987, entire) and cannot be flipped over during RLP feeding. The feeding and spawning requirements of RLP should render it disproportionately vulnerable to anthropogenically-increased sediment deposition, and silt cover and embeddedness is considered the primary microhabitat factor limiting the distribution of RLP (USFWS 1992, entire). However, we emphasize that quantitative relationships between sediment measures like embeddedness and biological measures like growth, survival, and reproduction are unknown for RLP. As such, the prevailing assumption (which is adopted herein) that fine sediment is a primary determinant of habitat suitability and a primary stressor affecting RLP condition is based on two main observations: (1) RLP preferentially selects the least-embedded microhabitat patches, channel-units, stream reaches, and stream segments available (Table 1), with the strength of selection increasing over ontogeny. We assume that there is an adaptive basis to this consistently observed pattern and a fitness cost (i.e., reduced growth and vital rates) associated with occupying siltier locations. (2) Previous studies have shown substantial negative effects of deposited fine sediment on macroinvertebrate density (Rabeni et al. 2005, entire) and hatching success of other gravel-spawning fishes (e.g., Harvey et al. 2009, entire), which we presume would similarly affect a benthic fish like RLP.

Preferences for other microhabitat characteristics are less clear and appear to vary by life-stage and river. Age-0 juveniles have been observed only in the upper Roanoke River. There, early in their first summer, they occupy shallow, low-velocity microhabitats (Burkhead 1983, p. 41;

Rosenberger and Angermeier 2003, p. 1569). As summer progresses, they gain greater swimming ability and begin shifting to deeper, higher-velocity microhabitats (Roberts and Angermeier 2006, p. 3). In contrast to Age-0 juveniles, microhabitat use of adults and Age-1+ juveniles has been compared across river systems. In the higher-gradient Roanoke River, adults occupied deeper depths and higher velocities than juveniles, whereas in the lower-gradient Nottoway River, both life-stages preferentially selected deeper, lower-velocity microhabitats (Rosenberger and Angermeier 2003, entire). Preference for deeper areas likely is an adaptation to avoid terrestrial and avian predators (Power 1987, entire), whereas velocity preferences likely are more a function of covarying silt and embeddedness conditions. In the Roanoke River, low-velocity microhabitats are typically silted and therefore unsuitable; the only unsilted microhabitats occur in higher-velocity areas where flushing flow keeps the substrate clean. In contrast, in the Nottoway River, unsilted low-velocity configurations are more common because of lower silt loading in this system, and from a bioenergenetics perspective, fish should prefer lower-velocity areas if all else is equal (Rosenberger and Angermeier 2003, pp. 1574-1575).

At the mesohabitat scale (i.e., channel-units to stream reaches, spanning 10s to 100s of meters), RLP habitat selection is likewise dependent on life-stage and river. Larval mesohabitat use is completely unstudied but given that larvae may drift hundreds to thousands of meters (Buckwalter et al. 2019, entire), they technically utilize all mesohabitats in reaches downstream of spawning sites. The specific habitats into which they settle is also unknown. In the Roanoke River in early summer, Age-0 juveniles inhabit off-channel backwaters and the margins of pools and slow runs (Burkhead 1983, p. 41; Rosenberger and Angermeier 2003, p. 1569). As summer progresses, they begin shifting to the heads and margins of riffles (Roberts and Angermeier 2006, p. 3). Mesohabitat use by Age-0 RLP in other rivers and regions is unknown, but we posit that it would be similar. Adult and Age-1+ juveniles in the Roanoke River both occur in riffles and swift runs over gravel-cobble substrates during the summer-fall feeding season (Rosenberger and Angermeier 2003, entire). In winter, when water temperature drops below 8 °C, RLP become quiescent and move to interstices of cobble, boulders, and bedrock on the stream bottom in pools and deep slow runs (Burkhead 1983, pp. 41-42; Rosenberger and Angermeier 2002, entire). In contrast to the Roanoke River, in the lower-gradient Nottoway River, adults and Age-1+ juveniles more often occupy pools over sand-gravel substrates during the feeding season. As with microhabitat, Rosenberger and Angermeier (2003, entire) hypothesized that unsilted pools are a bioenergetically advantageous resource that is available in the Nottoway River but not in the Roanoke River.

At the macrohabitat scale (stream segments to whole watersheds, spanning 10s to 100s of kilometers), RLP appear more likely to occur in areas with intermediate stream-size (500-4000 km^2 watershed areas), lower gradient, more-forested upstream watersheds, cooler water temperatures, and higher mean stream velocity (Anderson 2016, p. 30). The intermediate stream-size preference may reflect that smaller streams do not provide enough room for RLP to complete its migratory life-history, whereas larger rivers are more likely to be impounded and/or impacted by watershed urban and agricultural development. Similarly, preference for lower gradient may reflect avoidance of very small streams, preference for cooler water temperatures may reflect avoidance of very large warm rivers, and preference for forested areas may reflect intolerance of impacts (e.g., sedimentation) stemming from deforestation. As described above, high average stream velocity could flush fine sediment from the substrate of riffles and runs, thus allowing RLP to persist in these mesohabitats in upland areas with high sediment loading.

In addition to stream size, land use, topography, and climate, given that RLP appears to be adapted for a migratory lifestyle and large-scale population dynamics, we assume that the connectivity of suitable micro- and mesohabitats has a large effect on macrohabitat suitability for the species. In other words, when a variety and abundance of highly suitable habitat patches are in close proximity and without substantial barriers to movement between them, we expect habitat suitability to be higher and persistence to be more likely. This situation seems to apply to the upper Roanoke River and its tributaries, for example (James Roberts, personal observation). In contrast, when suitable micro- and mesohabitats are separated by barriers or by long reaches of unsuitable habitat, the macrohabitat suitability of that region is reduced because fish may be less likely to successfully move among habitat patches to complete their lifecycle, demographically rescue declining subpopulations, or recolonize patches after a disturbance. This situation may apply, for example, to the Otter River, where suitable riffle-run channel-units often are separated by many kilometers of heavily-silted, unsuitable run habitat (James Roberts, personal observation). Anthropogenic barriers to fish movement – most notably dams – can occur anywhere, whereas for RLP, long reaches of unsuitable habitat are most common in the Piedmont of the Roanoke and Dan basins, where agriculturally-derived silt and naturally low gradient are common.

Table 1, part 1: Summary of life-history information for RLP, by life-stage

Life-stage	Life-history observations	Source(s)
Eggs, larvae, and fry	Spawning has been directly observed only in the Roanoke River and only once; males exhibited aggressive behavior toward each other and attempted to solicit a female by displaying their orange dorsal fins; spawning occured over gravel and rubble in deep, swift runs	Jenkins and Burkhead (1994, p. 786)
	In the wild, spawning has been observed only once, on 20 April at a water temperature of 12-14 °C, but females were observed running ripe from mid-April to early May. In captivity, yolksac larvae, indicative of very recent spawning, were found from 4 April to 26 May, at water temperatures ranging from 18 to 21 degrees C;	Burkhead (1983, p. 44); Jenkins and Burkhead (1994, p. 786); Ruble et al. (2009, pp. 5-6); Ruble et al. (2010, p. 4)
	Eggs are adhesive and demersal; based on ovarian counts, potential fecundity ranges from 180 to 640 mature ova, correlating positively with the length and weight of the fish	Jenkins and Burkhead (1994, p. 786); Burkhead (1983, p. 112)
	In captivity, yolksac larvae measured approximately 6.8 mm TL	Ruble et al. (2010, p. 4)
	In the Roanoke River, drifting larvae were captured between 12 April and 11 June, with catch peaking around 10 May; the temporal duration and spatial extent of drift are unknown	Buckwalter et al. (2019, p. 8)
Age-0 juveniles	In the Roanoke River, typical size 45-75 mm TL in July-August, 55-95 mm TL in September-October	Roberts and Angermeier (2006, p. 23)
	In the Roanoke River, during early summer, young of year occupy shallow, low-velocity microhabitats in backwaters and the margins of pools and slow runs; as summer progresses, they gain greater swimming ability and begin shifting to deeper, higher-velocity microhabitats in the heads and margins of riffles; by fall they occupy habitats similar to the habitats occupied by Age-1+ fish	Burkhead (1983, p. 41); Rosenberger and Angermeier (2003, p. 1569); Roberts and Angermeier (2006, p. 3)
	In Roanoke River riffle/runs in late summer and fall, Age-0 juveniles occupied an average depth of 20-45 cm, an average water-column velocity of 0-25 cm/sec, typically sand or small gravel substrate, and typically patches that were < 50% covered by silt; these velocities and substrate sizes were smaller than those used by Age-1+ fish, but depths and silt coverages were not different	Roberts and Angermeier (2011, p. 43)
	Age-0 abundance in the fall of their first year was negatively related to the standard deviation of stream flows during the spring (April-June) of that year	Roberts et al. (2007, p. 43)
Age-1 juveniles	Difficult to differentiate from Age-2+ fish based on length, but probable typical size in summer and fall is 90-115 mm TL	Roberts and Angermeier (2006, p. 23)
	Age-1 juveniles feed on a variety of benthic macroinvertebrates, especially midge larvae	Jenkins and Burkhead (1994, p. 786)
	Genetic studies indicate that juveniles widely disperse throughout the upper Roanoke River watershed within the first two years of life	Roberts et al. (2016b, entire)

Table 1, part 2: Summary of life-history information for RLP, by life-stage, continued.

Life-stage	Life-history observations	Source(s)
Adults	Typical size 115-140 mm TL; largest known specimen is 165 mm TL	Roberts and Angermeier (2006, p. 23); Roberts and Rosenberger (2008, p. 439)
	In the Roanoke River, females and males reached sexual maturity by ages 2 and 3, respectively	Jenkins and Burkhead (1994, p. 786)
	Oldest known specimen is 6.5 years old; males and females appear to live equally long	Burkhead (1983, p. 48)
	During summer/fall active feeding period, adults prefer higher velocities and gravel/cobble substrates in riffle/run meshohabitats in the Roanoke River, but prefer lower velocities and sand/gravel substrates in pool mesohabitats in the Nottoway River; in both systems, adults occupy deep microhabitats and avoid silt; it is hypothesized that this difference between rivers is due to the rarity of unsilted low-velocity habitats in the Roanoke River and relative commonness of such habitats in the Nottoway River	Rosenberger and Angermeier (2003, entire)
	During winter quiescent period, when water temperature drops below 8 °C, RLP move to interstices of cobble, boulders, and bedrock on the stream bottom	Burkhead (1983, pp. 41-42); Ensign et al. (1999, entire); Rosenberger and Angermeier (2002, entire)
	Adult RLP are generalist feeders on a variety of benthic invertebrates, especially caddisfly and midge larvae	Jenkins and Burkhead (1994, p. 786)
	Three long-distance migration events (>2 km) by adults have been detected, purpose unknown	Burkhead (1983, p. 53), Roberts et al. (2008; p. 379)
All stages	The majority of biological and ecological data on RLP have been collected in the upper Roanoke River	
	In general, the species appears to specialize on unembedded substrates with low silt cover, with silt-intolerance increasing with age	Jenkins and Burkhead (1994, p. 786), Roberts and Angermeier (2006, entire)
	Like other logperches, RLP possesses conical snout used to flip larger substrate items over to forage underneath; dependence on loosely embedded substrates may render the species particularly vulnerable to fine sediment deposition	Jenkins and Burkhead (1994, p. 787)
	Occurrence probability is higher at sites with 500-4000 km^2 watersheds, gradient less than 10 m/km, >80% forested watersheds, <13 °C mean annual temperature, and >0.5 m/sec mean stream velocity	Anderson (2016, p. 30)
	Environmental DNA surveys have not detected RLP in any new habitats	Strickland and Roberts (2019, entire); Environmental Solutions and Innovations (2020, entire)
	Based on field catch records, adult densities range among rivers from 9.7 to 46.8 fish per km	Appendix of this SSA
	In upper Roanoke River watershed, fish kills affecting RLP occurred on average every 5 years and affected an average of 10.1 km of stream	Roberts et al. (2016a, p. 53)
	In the Roanoke River, population growth appears to be strongly density-dependent	Roberts et al. (2016a, p. 53)

2.3 Geographic distribution over time

The RLP is endemic to the Roanoke, Dan, and Chowan basins of Virginia and North Carolina and has never been observed outside these basins. It was first collected in the 1880s in the upper Roanoke River (Roanoke basin) by David Starr Jordan and described by Jordan and Evermann (in Jordan 1889, entire) based on these collections. Formal collection records in Virginia Department of Wildlife Resources (VDWR) and North Carolina Wildlife Resource Commission (NCWRC) natural heritage databases date back only to 1940, so we are unaware of observations between the 1880s and 1940. Our analysis of temporal changes to RLP's known geographic distribution is based on 1082 collection records between 1940 and 2019, comprising 1043 records from the VDWR database, 37 records from the NCWRC database, and 2 additional reservoir records contained in the species account in Jenkins and Burkhead (1994, p. 787).

Collection records for RLP increased rapidly by decade from the 1940s through the 2000s, then decreased slightly in the 2010s (Figure 2). This likely stemmed from an overall increase in ichthyological and fisheries survey effort in both states over this time period (Jenkins and Burkhead pp. 10-11). With this increasing survey effort, the number of streams in which RLP had been detected grew from 4 streams in the 1940s (Roanoke River, its tributaries Mason Creek and Pigg River, and Sappony Creek of the Chowan basin), to 14 streams by the time of the species' ESA listing in 1989, to 30 streams by the end of the 2000s (Table 2, Figure 2). Only one new stream was added in the 2010s, Wolf Island Creek in the Dan basin, which brings the current total to 31 streams. Unlike the Roanoke basin, which was known to be occupied by the 1880s, and the Chowan basin, which was known to be occupied by the 1940s, the first RLP detection in the Dan basin did not occur until the 1970s, in Town Creek (VA). In the 1980s, only the upper Smith River was added to the occupied streams list in the Dan basin, but in the 1990s and 2000s, RLP were detected in 10 additional stream segments in the Dan basin. In addition to stream and river observations, RLP have been observed in two reservoirs, Smith Mountain Lake and Leesville Reservoir (Table 2), but because lacustrine habitat is considered unsuitable for the species, these individuals have been considered waifs rather than reservoir residents (Jenkins and Burkhead 1994, p. 787), and we have omitted them from the present analyses. Two recent distributional studies employed environmental DNA (eDNA) methods to survey rivers that appear suitable for RLP but where the species has never been captured via traditional methods (e.g., Blackwater, Meherrin, and Falling rivers), but neither study detected RLP in any new locations (Strickland and Roberts 2019, entire; Environmental Solutions and Innovations 2020, entire). Other apparently suitable but unoccupied tributaries of the Dan River (e.g., Banister River, Sandy River, and North and South Forks of the Mayo River) were the focus of intensive electrofishing surveys in 2011, but RLP were not observed in any new locations (Roberts 2012b, entire).

Another way to view temporal changes to RLP's known distribution is by occupied 12-digit U.S. Geological Survey hydrologic unit codes (HUCs). The number of these small watersheds in which RLP have been detected has increased dramatically over time. At the time of the species' ESA listing in 1989 (i.e., based on 1940-1989 surveys), RLP had been detected in 18 HUCs in the Roanoke and Dan basins (Figure 3, top panel) and 9 HUCs in the Chowan basin (Figure 3, top panel). By contrast, in the two decades following listing (i.e., based on 1990-2019 surveys), RLP was detected in 41 HUCs in the Roanoke and Dan basins (Figure 3, bottom panel) and 14 HUCs in the Chowan basin (Figure 3, bottom panel). This overall increase includes 35 new HUC-level detections post-1989. These include first observations in the Goose Creek and Otter River systems, much of the lower Smith River, other tributaries of the Dan River, and the Dan mainstem itself, as well as a significant downstream and upstream expansion of the species' known range in the Nottoway River. There also were 8 HUCs where RLP were observed pre-listing but have not been detected post-listing. These include Mason Creek and Elliott Creek in the upper Roanoke watershed, a segment of the middle Roanoke (Staunton) River near Brookneal, VA, Leesville Reservoir, one section of Smith Mountain Lake, and Butterwood Creek and Sappony Creek of the Nottoway watershed. These apparent "disappearances" may reflect lack of survey effort rather than the actual extirpation of the species from these streams (see below). Jenkins (1977, entire) and Burkhead (1983, entire) hypothesized that RLP once had a more continuous distribution that connected, for example, Piedmont sections of the middle Roanoke and Dan Rivers, but that extensive agricultural and silvicultural development during early European settlement caused the extirpation of these connecting populations. Although this seems plausible, there are no collection records from this time period, and thus no empirical records of watersheds that have become unoccupied or populations that have become extirpated since the species' description.

Notably, the analysis above was based only on positive RLP detections; we had no information on how often a surveyor attempted to capture RLP but did not observe the species. As such, we cannot discriminate whether RLP's apparent absence from a particular area (e.g., Goose Creek in the 1980s) was due to true absence versus inadequate survey effort to detect it. Likewise, we cannot discriminate whether any "new" observation of RLP in a previously unknown location (e.g., Dan River in the 2000s) was due to increased survey effort or effectiveness versus real range expansion by the species. Nonetheless, assuming recent detections indicate current occurrence, the currently known range of RLP is dramatically larger than the known range of the species at the time of its listing.

Table 2: Summary of RLP collections, by waterbody and decade. Scientific collection records were obtained from VDWR and NCWRC databases and covered the time period 1940-2019. Values indicate the total number of sampling events in which RLP were collected, not the total number of individuals that were observed (i.e., in many collection events, multiple RLP were observed).

			Decade							
Basin	Management unit	Waterbody	1940-49	1950-59	1960-69	1970-79	1980-89	1990-99	2000-09	2010-19
Roanoke	Upper Roanoke	Roanoke River	1	4	11	37	96	142	147	132
		Mason Creek	2		1					
		Elliott Creek		1						
		South Fork Roanoke River		6	12	21	42	56	3	1
		North Fork Roanoke River		2	2	6	4	24	2	2
		Smith Mountain Lake					1	1		
		Tinker Creek					1	1		3
		Glade Creek						1		
	Pigg	Pigg River	1		3	5	10	1	32	4
		Leesville Lake					1			
		Big Chestnut Creek							3	2
		Snow Creek							1	
	Goose	Goose Creek							14	1
	Otter	Big Otter River							20	1
		Little Otter River							3	
	Middle Roanoke	Roanoke (Staunton) River				1				3
Dan	Upper Smith	Smith River					3	11	12	19
		Rockcastle Creek						2		
		Otter Creek							1	
		Runnett Bag Creek							1	
	Middle Smith	Town Creek				1		1	4	2
		Smith River						5	23	
	Lower Smith	Smith River						3	3	8
	Lower Mayo	Mayo River							1	11
	Middle Dan	Dan River							1	7
		Cascade Creek							2	1
		Big Beaver Island Creek							1	2
		Wolf Island Creek								2
Chowan	Nottoway	Sappony Creek	1							
		Stony Creek			1	2	4	7	8	1
		Nottoway River					6	11	24	17
		Butterwood Creek					1			
		Waqua Creek						1		1
		Cumulative total streams	4	7	8	10	14	19	30	31

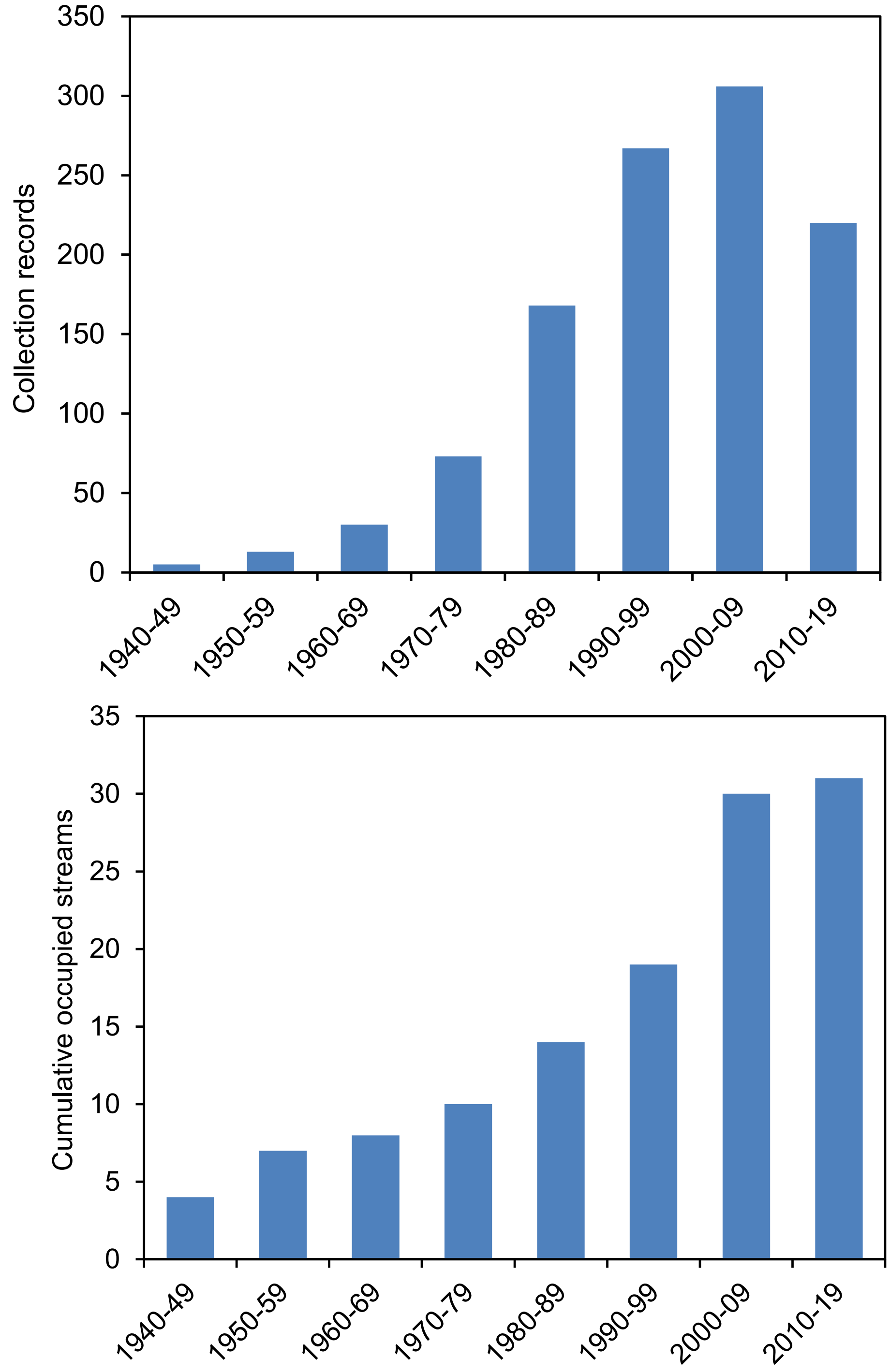

Figure 2: Summary of RLP field collections over time, based on records in the VDWR and NCWRC databases. Top panel: Frequency of RLP collection records by decade. Note that each collection record may represent multiple individual RLP collected on the same occasion as the same site. Bottom panel: The cumulative number of stream segments in which RLP have been detected, by decade. Reservoir collections are not included in the latter.

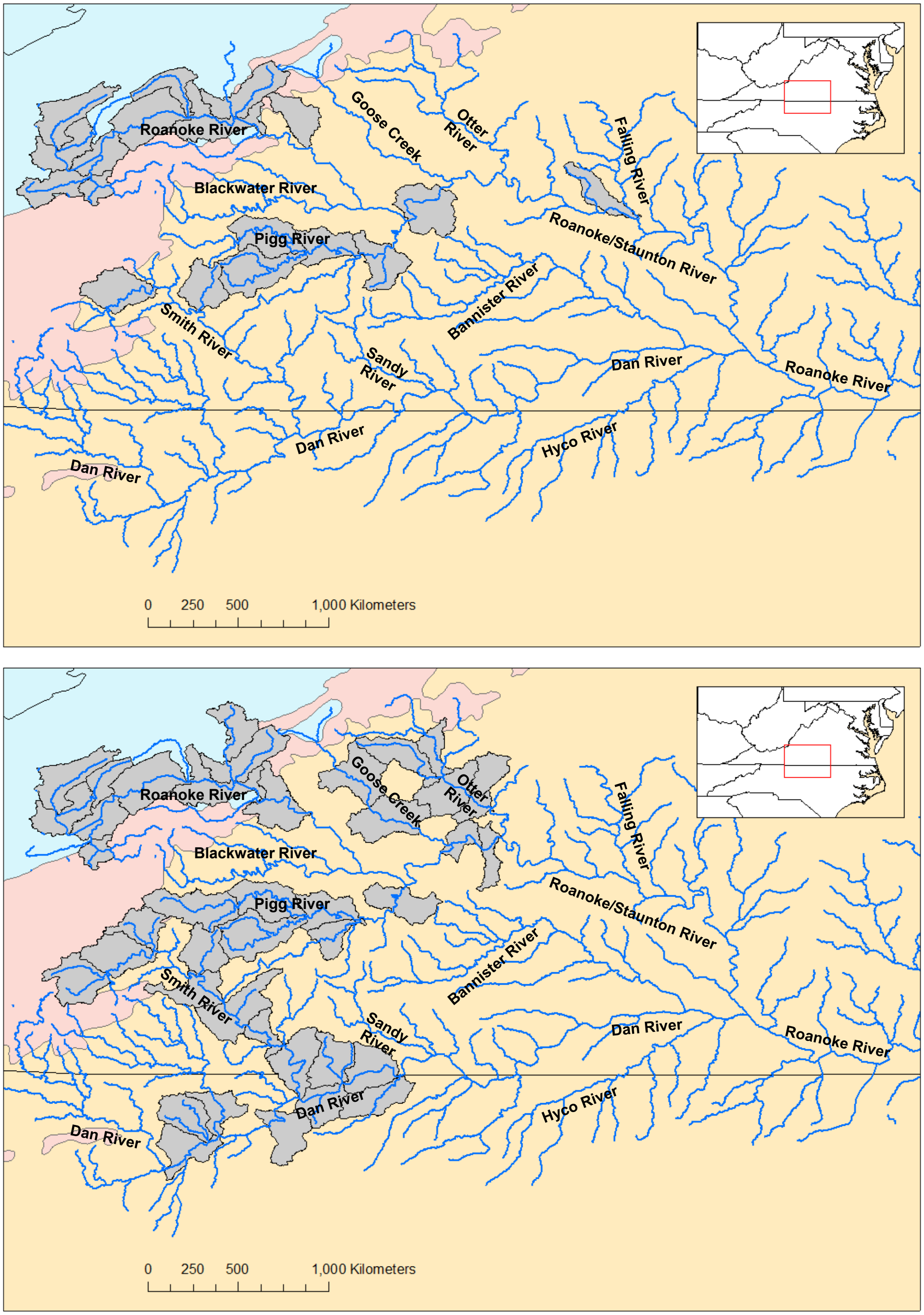

Figure 3: Changes over time in RLP's known occurrence in the Roanoke basin. Gray polygons indicate 12-digit hydrologic units with at least one collection record during two time periods: 1940-1989 (top panel) and 1990-2019 (bottom panel). Background shading indicates EPA level-3 ecoregion (blue = Ridge and Valley, pink = Blue Ridge, orange = Piedmont).

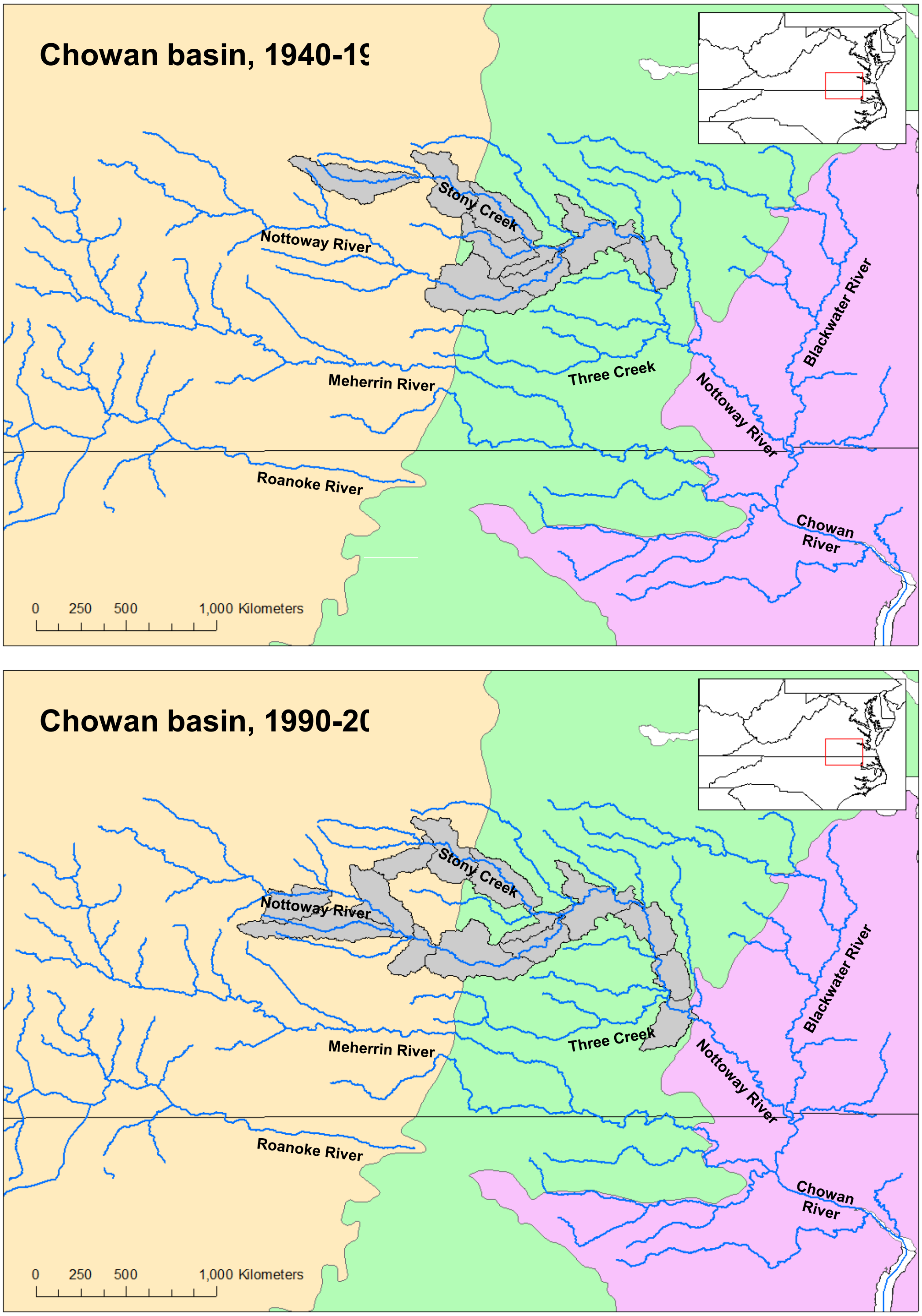

Figure 4: Changes over time in RLP's known occurrence in the Chowan basin. Gray polygons indicate 12-digit hydrologic units with at least one collection record during two time periods: 1940-1989 (top panel) and 1990-2019 (bottom panel). Background shading indicates EPA level-3 ecoregion (orange = Piedmont, green = Southeastern Plains, purple = Middle Atlantic Coastal Plain).

CHAPTER 3 – CURRENT CONDITION

3.1 General approach

To assess the current condition of RLP throughout its range, we used best available information, which consisted of a combination of empirical data from peer-reviewed articles and agency reports, survey records provided by agencies, and expert opinion elicited from species experts. As described in the section 3.2, an important first step was establishing the analytical units within which the 3Rs were to be measured. After delineating these local management units and regional metapopulations, we identified factors likely to affect the persistence of RLP, connected these to indices of population persistence, and developed demographic-, habitat-, and genetic-based estimates of current condition.

3.2 Definitions of analytical units

We considered the population structure of RLP to be hierarchical in nature (Figure 5). At the smallest spatial grain, we defined a “management unit” (MU) as a group of individuals occupying a discrete, local geographic area in which demographic exchange is common and habitat conditions are relatively homogeneous. At a larger grain, we defined a metapopulation as a group of MUs located in an evolutionarily similar setting and in close-enough proximity that some dispersal and gene flow among MUs within that metapopulation likely has occurred in recent ecological time, at least prior to anthropogenic habitat alteration. The species as a whole was the sum of all metapopulations. Our rationale for these delineations follows.

During a workshop between 28 and 29 August 2018, a team of RLP experts met in Blacksburg, Virginia to develop a structured decision-making (SDM) approach to making translocation decisions for RLP and other aquatic species. Among the objectives of this group (hereafter the “SDM team”) was the delineation of discrete MUs at a spatial grain practical for assessing viability and enacting translocation plans. These MUs were designed to be geographically large enough to ensure data availability for each MU and to ensure tractability for subsequent demographic modeling, yet small enough to avoid crossing presumed population boundaries (demographic or evolutionary) or presumed significant barriers to fish movement such as dams and reservoirs. Because the SDM team also was considering the potential for new introductions as a management tactic, the group delineated not only known extant MUs, but also currently unoccupied MUs in waterways the group deemed good candidates for future populations based on suitable habitat conditions. This process resulted in the delineation of 18 total MUs: 11 currently occupied and 7 currently unoccupied (Table 3). We have intentionally avoided calling these “populations”, to avoid confusion with population definitions the USFWS has used in previous analyses, though differences among these delineation schemes are minor. We assessed current condition based on the resiliency of each of the 11 occupied MUs, the redundancy of resilient MUs within each metapopulation, and the representation of metapopulations harboring resilient and redundant MUs across the range of the species (Figure 5). Currently unoccupied “potential” MUs were not used for assessing current condition. However, for analyses of future condition, which considered it possible for these potential MUs to become occupied, we included them in assessing future resiliency, redundancy, and representation.

We defined RLP metapopulations based on a combination of river-basin and ecoregion membership. Basins are functionally isolated from each other over ecological time, which provides opportunities for reproductive isolation and the development of important local adaptations that may be important to represent for species conservation. Based on genetic analysis of RLP, Roberts et al. (2013, entire) found a substantial genetic distinction between the Chowan and Roanoke basins, and a further distinction between the Roanoke proper and its main tributary, the Dan River. The fish fauna of the Dan also differs somewhat from that of the rest of the Roanoke proper (Jenkins and Burkhead 1994, p. 78), suggesting a distinct evolutionary history, so we treated the Roanoke, Dan, and Chowan as three separate basins – and three potentially distinct evolutionary units – when defining metapopulations. In addition to spanning these three basins, the geographic range of RLP spans several EPA level-three ecoregions (Omernik 2004, entire), including the Ridge and Valley, Blue Ridge, Piedmont, and Southeastern Plains. The differing geology, topography, water chemistry, and climate of these regions strongly influences stream fish ecology (Frimpong and Angermeier 2010, entire) and may have produced important local adaptations in RLP that are important to represent for the species' conservation. For example, although we have no data regarding specific genetic adaptations to these conditions, Rosenberger and Angermeier (2003, entire) found that RLP uses different microhabitat conditions in these different ecoregions, suggesting the potential for local adaptation. We defined metapopulations of RLP based on unique combinations of these ecoregions and the three basins. In so doing, we consolidated the Ridge and Valley and Blue Ridge into a single ecoregion category for the Roanoke basin and we consolidated the Piedmont and Southeastern Plains into a single ecoregion category for the Chowan basin, as these ecoregion boundaries create no apparent distributional breaks for RLP in the Roanoke or Chowan basins, respectively. This resulted in the delineation of four unique metapopulations, or representation areas: "Roanoke Mountain" (Roanoke basin, Ridge and Valley and Blue Ridge ecoregions), "Roanoke Piedmont" (Roanoke basin, Piedmont ecoregion), "Dan" (Dan basin, Piedmont and Blue Ridge ecoregions), and "Chowan" (Chowan basin, Piedmont and Southeastern Plains ecoregions) (Table 3). Each of the 18 MUs nests within one of these 4 metapopulations (Figure 6). These delineations accounted for the locations of distributional hiatuses and significant dams (Table 4), which presumably affect MU and metapopulation boundaries. We assessed redundancy of MUs within each of these metapopulations, and we assessed redundancy and representation of these metapopulations within the species as a whole (Figure 5).

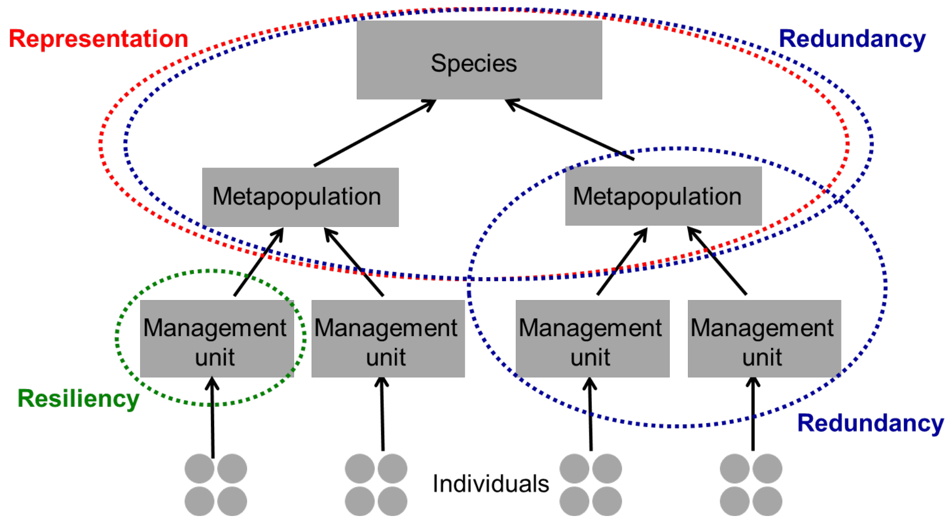

Figure 5: The biological levels at which we have assessed redundancy, resiliency, and representation in this SSA.

Table 3: Geographic grouping of waterbodies into the management units and metapopulations employed in this SSA. Potential, but not currently occupied, management units are in italics.

Metapopulation	Basin and primary ecoregion(s)	Management unit	Presumed status	Constituent waterbodies where RLP have been observed
Roanoke Mountain	Roanoke basin; Ridge and Valley / Blue Ridge ecoregions	Upper Roanoke	Occupied	Roanoke River, South Fork Roanoke River, North Fork Roanoke River, Elliott Creek, Mason Creek, Tinker Creek, Glade Creek, Smith Mountain Lake
Roanoke Piedmont	Roanoke basin; Piedmont ecoregion	*Blackwater*	Unoccupied	None - never observed
		Pigg	Occupied	Pigg River, Big Chestnut Creek, Snow Creek, Leesville Lake
		Goose	Occupied	Goose Creek
		Otter	Occupied	Big Otter River, Little Otter River
		Middle Roanoke	Occupied	Roanoke (Staunton) River
		Falling	Unoccupied	None - never observed
Dan	Dan basin; Piedmont / Blue Ridge ecoregions	Upper Smith	Occupied	Smith River, Rock Castle Creek, Otter Creek, Runnett Bag Creek
		Middle Smith	Occupied	Smith River, Town Creek
		Lower Smith	Occupied	Smith River
		Upper Mayo	Unoccupied	None - never observed
		Lower Mayo	Occupied	Mayo River
		Upper Dan	Unoccupied	None - never observed
		Middle Dan	Occupied	Dan River, Cascade Creek, Wolf Island Creek, Big Beaver Island Creek
		Lower Dan	Unoccupied	None - never observed
		Banister	Unoccupied	None - never observed
Chowan	Chowan basin; Piedmont / Southeastern Plains ecoregions	*Meherrin*	Unoccupied	None - never observed
		Nottoway	Occupied	Nottoway River, Stony Creek, Sappony Creek, Waqua Creek, Butterwood Creek

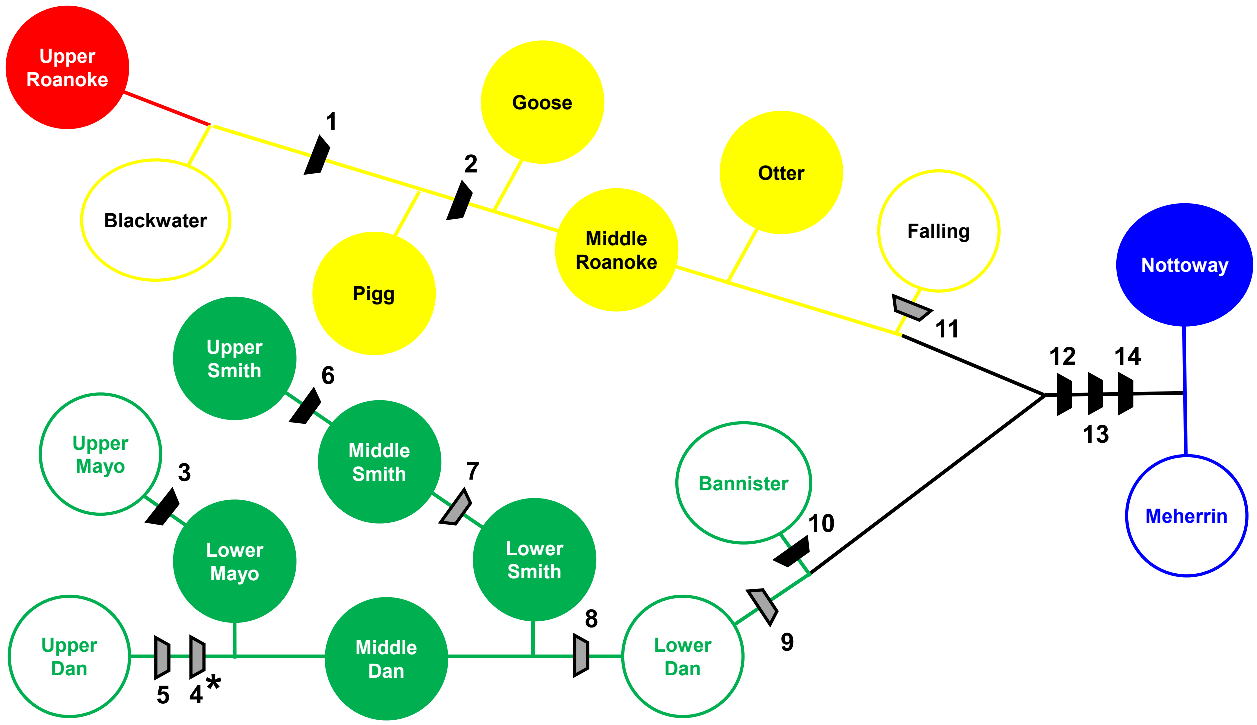

Figure 6: Schematic representation of spatial relationships among the MUs (circles) and metapopulations assessed for this SSA. Filled circles indicate occupied MUs; open circles indicate habitats that are presently unoccupied but potentially suitable for future occupancy by RLP. Color-coding indicates membership in the Roanoke Mountain (red), Roanoke Piedmont (yellow), Dan (green), or Chowan (blue) metapopulation. Black and gray trapezoids represent dams presumed to allow either no passage or one-way (upstream to downstream) passage, respectively. Lindsey Bridge Dam, indicated with an asterisk, was removed in 2020. This dam was considered an MU boundary for current-conditions analyses but not for future-conditions analyses. See Table 4 for dam names and characteristics.

Table 4: Descriptions of key barriers (dams) presumed to affect connectivity and MU boundaries for RLP. Code numbers correspond to the schematic map in Figure 6. Based on dam height and consultation with biologists, some dams were assumed to allow fish to move from upstream to downstream of the dam (one-way barrier), whereas others were assumed to allow no fish passage (two-way barrier).

Code	Dam	Waterbody	Approximate construction date	Approximate dam height (m)	Assumed one- or two-way barrier?
1	Smith Mountain Lake	Roanoke River	1963	72	Two
2	Leesville Lake	Roanoke River	1963	27	Two
3	Washington Mill / Avalon	Mayo River	1896-1900	9	Two
4	Lindsey Bridge	Dan River	late 1960s	2	One
5	Jessup's Mill	Dan River	1910	4	One
6	Philpott	Smith River	1951	67	Two
7	Martinsville	Smith River	1924	10	One
8	Eden	Dan River	1894	2	One
9	Schoolfield	Dan River	1904	8	One
10	Banister	Banister River	1907	13	Two
11	Falling	Falling River	unknown	4	One
12	Kerr	Roanoke River	1952	44	Two
13	Gaston	Roanoke River	1964	30	Two
13	Roanoke Rapids	Roanoke River	1955	22	Two

3.3 Factors affecting current condition

The current condition of RLP likely is affected by a variety of environmental and management factors that directly or indirectly influence habitat, demographic, and genetic conditions of populations, thereby affecting the resiliency of MUs and the redundancy of MUs within metapopulations (Figure 7). Below, we describe in detail six factors we presume to have the greatest influence on RLP condition. Notably, no previous research has directly quantified relationships between these six factors and RLP vital rates (reproduction and survival rates), so in assessing current and future condition, we based our assumptions about the nature of these relationships on a combination of ecological theory, expert judgment, and simulation models.

Fine sediment deposition – Fine sediment is produced through erosion and enters streams and rivers through runoff, especially during storm events (Waters 1995, entire). A variety of human activities accelerate erosion and thereby increase sediment inputs to streams, but urbanization and agriculture are the two most prominent of these activities in RLP's range. During watershed urbanization, formerly vegetated soil cover (trees, shrubs, and herbaceous vegetation) is removed, and this disturbed soil is easily eroded and washed into streams and rivers during storm events (Paul and Meyer 2001, entire). Eventually, disturbed soil is converted to impervious surfaces (paved parking lots, paved highways and bridges, and rooftops), which decreases infiltration and increases overland runoff (Wheeler et al. 2005, entire). During storm events, this runoff has high erosive potential which, combined with the loss of stabilizing vegetative cover, accelerates hillside and streambank erosion. Urbanization also is often accompanied by flood-control measures such as river channelization and levee construction; these activities destabilize stream geomorphology and increase channel erosion (Waters 1995, entire). Impacts of urbanization on stream habitat and biota have been observed even at low levels of urbanization, but generally become substantial once urbanization crosses a threshold of ~10% watershed urbanization (Paul and Meyer 2001, pp. 337-338; Schueler et al. 2009, entire; Wenger et al. 2008, entire).

Agricultural and silvicultural activities also tend to amplify sediment inputs to streams. When livestock are given access to stream channels, they may cause bank erosion (Waters 1995, entire). Soil disturbance during row-crop tilling or timber harvest exposes easily eroded soils that run off into streams and rivers during rain events (Allan et al. 1997, entire). Legacy sediment inputs from widespread row-crop agriculture and destructive forestry practices in Virginia and North Carolina go back at least as far as European colonization (Jenkins and Burkhead 1994, pp. 62-63). Pre-European Native American agricultural practices may have been impactful as well (Peacock et al. 2005, entire). Jenkins and Burkhead's (1994, p. 63) description of sedimentation in the Piedmont is exemplary: "Today the middle and lower Dan River is so turbid during much of the year that it appears plowable".

Fine sediments originating from the watershed or channel of a stream remain suspended until they reach a low-velocity area and deposit on the stream substrate. Although suspended sediment can reduce feeding efficiency for a sight feeder like RLP, we hypothesize a greater negative impact from sediment once it deposits on the stream bottom. Deposition of fine sediments like silt and clay on stream substrate likely reduces the fitness and survival of RLP adults and the survival and recruitment of Age-0 juveniles (Figure 7). RLP are invertivores that feed almost exclusively on the bottom; they require substrate particles (pebbles, leaves, sticks, etc.) to be mostly unembedded by fine sediment, in order to flip over these particles and access food underneath. Heavily embedded substrates contain lower benthic macroinvertebrate densities and fewer benthic invertivorous fishes as a result (Berkman and Rabeni 1987, entire). Although uninvestigated to date, we assume that as deposition and embeddedness increase, RLP food intake at all life-stages will decrease and individual growth and survival rates will decrease. Moreover, silt coverage could smother eggs and reduce their hatching rate, particularly for a simple gravel spawner like RLP (Berkman and Rabeni 1987, entire). Reduced egg-to-larva survival, along with reduced benthic feeding efficiency for Age-0 juveniles, could translate to overall lower recruitment rates for RLP populations. As described previously in "Habitat Needs" (section 2.2), empirical relationships between stressors like fine sediment (or other stressors below) and RLP growth, recruitment, and survival rates have not been quantified, which limits our models linking stressors to habitat and population health (e.g., when assessing current and future condition) to semi-quantitative relationships based on expert judgement. Nonetheless, as described in section 2.2, assumed negative relationships between sedimentation and RLP occurrence and abundance are consistent with previous observations for RLP and other stream fishes.

Chemical pollution – By definition, water pollution is anthropogenic in origin and alters the chemical composition of a receiving waterbody (https://www.epa.gov/cwa-404/clean-water-act-section-502-general-definitions). Pollutants include organic nutrients such as fertilizer, livestock manure, and human sewage effluent, along with myriad natural and synthetic chemicals including heavy metals, pesticides, cleaners, solvents, pharmaceuticals, and petroleum products, among others. Water pollution can occur accidentally, for example during transportation accidents or the failure of infrastructure like pipelines and holding ponds. Water pollution can also occur intentionally, for example in a permitted discharge. Water pollution can be sudden and severe and originate from a single obvious source and event, such as the accidental examples above, or it can be more dilute and chronic, and originate from diffuse sources across the landscape, such as the runoff of nutrients and chemicals from agricultural fields, residential lawns, roads, and parking lots. In fact, chronic runoff of nitrogen and phosphorous is the most widespread chemical pollutant of U.S. streams and rivers (USEPA 2017, entire), and resulting eutrophication and hypoxia is a common stressor of aquatic biota.

Roberts et al. (2016a, entire) found the population dynamics of RLP to be particularly sensitive to acute pollution events that cause substantial one-time reductions in population size. The same study found that, in the upper Roanoke River watershed alone, 7 pollution events resulting in RLP mortality occurred over a 35-year period, an average of once every 5 years. These involved a variety of different pollutants and affected anywhere from 2 to 19 km of river. Such catastrophes presumably act by temporarily reducing survival of all age-classes until the chemical has dissipated (< 1 year; Ensign et al. 1997, entire). Yet if fish kills happen frequently enough, affect a large-enough area, or happen to an already small population, they could threaten the viability of an entire population. Like fine sediment, water pollution emanates from a variety of sources, including urban, mining, or agricultural runoff, and transportation of chemicals by road, rail, or pipeline. Chemicals are transported and stored everywhere, and indeed, some recent fish-kill events impacting RLP stemmed from non-urban causes, such as a liquid manure spill in 1991 and a golf-course fungicide spill in 2007 (Roberts et al. 2016a, entire). However, in general we would expect the risk of a pollution event to be higher in a watershed with greater urbanization, because with urbanization we expect a greater concentration of manufacturing chemicals, industrial and municipal chemical effluents, and chemical transportation via roads, rails, and pipelines. Thus, we expect urbanization to be a primary driver of pollution events affecting RLP.

Dams and other barriers – European settlers began constructing milldams and other low-head dams on rivers soon upon arrival to the Atlantic states (Walter and Merritts 2008, entire). These barriers may have affected connectivity and habitat conditions for RLP, but as described in section 2.3, we lack distribution and abundance data for RLP prior to 1940. Large hydroelectric dams were installed on a number of large rivers in RLP's range between the 1920s and the 1960s (Table 4). Although none of these dams were equipped with fish passage technologies, some are short enough and have a modest enough spillway drop that they may allow for one-way fish movement (from upstream to downstream) over the spillway. For example, Roberts et al. (2013, entire) found that Martinsville Dam on the middle Smith River did not form a genetic population boundary between RLP upstream and downstream of the dam, and they hypothesized that the dam allowed one-way gene flow. However, many of the dams in Table 4 are much larger, form an extensive impoundment that would not be suitable habitat for RLP, and therefore probably constitute complete two-way barriers to RLP movement. As described in section 2, RLP appear to have a relatively migratory life history that, in the absence of movement barriers, utilizes multiple sections of a watershed over a lifetime. Although genetic data indicate that RLP populations currently have sharp, discrete boundaries (Roberts et al. 2013, entire), these boundaries mostly coincide with dams. Prior to the construction of these dams, population structure might have been more continuous, with more frequent dispersal among now-disconnected streams (Jenkins 1977, entire; Burkhead 1983, entire). Thus, the barrier effect created by dams has potentially fragmented a once-more-continuous range into a series of geographically smaller, more isolated populations. This reduces resiliency because a declining population cannot be naturally demographically or genetically "rescued" by another population.

In addition to a movement barrier, dams can create habitat degradation and loss for RLP. Impoundments upstream of dams convert formerly riverine, potentially suitable habitat to lacustrine habitat that is not suitable for RLP. Although the species has been observed occasionally in Smith Mountain Lake and Leesville Reservoir, these have been interpreted as waifs attempting dispersal through the reservoirs, rather than resident fish (Jenkins and Burkhead 1994, p. 787). Although completely unstudied, reservoirs upstream of dams may directly increase mortality for RLP larvae, if they drift in from upstream spawning sites and settle in unsuitable lacustrine microhabitats. Habitat conditions downstream of hydroelectric dams may be unsuitable for RLP as well. Hydropeaking discharges from Leesville Dam have rendered habitat conditions immediately downstream in the middle Roanoke River unstable and relatively poor for RLP, and population density there is relatively low (Scott Smith, VDWR, personal communication). Hydropeaking, combined with a cold hypolimnetic release, has likewise rendered the middle Smith River immediately downstream from Philpott Dam unsuitable for RLP. Not only are RLP apparently absent from this reach (Krause et al. 2005, entire), based on genetic results, the cold unsuitable tailwater acts as a movement barrier between Town Creek, an occupied tributary that flows into the unoccupied reach, and the occupied section of middle Smith River just 4 km downstream (Roberts et al. 2013, p. 2060). These habitat losses effectively shrink the adjoining populations to a smaller geographic area, which reduces their potential for resiliency.

Climate change – Changes to the climate of RLP's geographic range may affect precipitation, runoff patterns, and stream hydrology in ways that negatively affect RLP vital rates and resiliency. In coming decades, RLPs range is expected to average 5-8° Fahrenheit warmer with around 1 more inch of rain per year (see section 4.2.1). Although a modest increase in total rainfall, this rain is expected to come in less predictable, less frequent, more intense storm events (Ingram et al. 2013, entire; Burt et al. 2016, entire). Increased air temperature has the potential to increase evapotranspiration rates, decrease groundwater recharge into streams, and reduce the magnitude of summer baseflows (Ingram et al. 2013, entire; Lynch et al. 2016, pp. 349-350). Increased storm intensity may likewise reduce summer baseflows by raising the runoff:infiltration ratio. More irregular but intense rainfall means "flashier" streamflows overall, with higher high flows, lower low flows, and steeper rising and falling limbs of the hydrograph, a situation exacerbated by urbanization and watershed imperviousness (Roy et al. 2010, entire). Stronger storm events also increase the probability that fine sediment will be mobilized in runoff and carried into streams.

Relationships between hydrology and RLP habitat suitability or vital rates have not been thoroughly investigated. However, in the upper Roanoke River, Roberts and Angermeier (2007, p. 43) found that Age-0 abundance in the fall of their first year was negatively related to the standard deviation of stream flows during the spring (April-June) of that year. Highly variable flows may directly increase mortality of vulnerable larvae and small juveniles. They also may reduce habitat quality and availability. Age-0 RLP have very specific habitat needs during their first summer, requiring unembedded, shallow, very-low-velocity microhabitats, often in the margins of pools (Roberts and Angermeier 2006, p. 4). These microhabitat conditions change rapidly with stream flows: drying of shallow areas forces RLP into deeper areas where they are more vulnerable to aquatic predators, while elevated flows increase velocity beyond the swimming abilities of small fish. Given that storm intensity and stream flashiness are predicted to increase, we predict that it will be more difficult for Age-0 RLP to locate and track suitable microhabitat configurations, resulting in reduced survival and recruitment. Further, reduced baseflow magnitude may crowd adult RLP into smaller areas of suitable habitat within riffle-runs, resulting in increased competition for resources, and potentially reduced fitness and survival of adults. In any event, we presume that the higher erosion and sediment transport rates likely to result from predicted greater storm intensity would negatively affect growth, recruitment, and survival of RLP.

Regulatory mechanisms – Over time, RLP likely has benefitted from the protections and resources provided by state and federal laws and regulations. The species has been listed as federally endangered under the ESA since 1989. Federal listed status has affected the course of large proposed and completed projects within the geographic range of the species. For example, construction plans for the Roanoke River Flood Reduction Project were adjusted to reduce instream construction traffic, minimize silt runoff, and closely monitor water quality and RLP population levels, all in an attempt to minimize incidental take of the species (Roberts et al. 2016c, entire). Time-of-year restrictions on construction projects during the species' spawning window (March 15-June 30) presumably have reduced streambed and floodplain disturbance and sediment loading during this key time in the species' lifecycle. Listed status also has allowed access to funding mechanisms available only for use on listed species, including ESA Section 6 funds. These funds have been used to restore riparian habitats to reduce sediment inputs, remove barriers to RLP movement, and fund a range of university research studies that have advanced understanding of the basic biology (e.g., Rosenberger and Angermeier 2003, entire), distribution and abundance (e.g., Roberts 2012b, entire), and genetics and evolution of the species (e.g., Roberts et al. 2013, entire). However, in assessing the status of a listed species, the USFWS assumes the species is not listed under the ESA. As such, we have not considered protections, funding, or other benefits of listed status, including any other federal, state, or local protections or benefits arising solely as a result of ESA listing, when assessing risks to RLP in the future. Rather, we have focused only on non-ESA-related regulations, protections, and restoration activities that we are reasonably confident will occur in the future, regardless of the species' ESA status, such as state-level protection and population management, habitat restoration, and dam removal.

The RLP has been listed as state endangered by Virginia since 1989 and state endangered by North Carolina since its discovery in that state in 2007. The species is given high priority in both states' wildlife action plans, allowing access to funding mechanisms such as State Wildlife Grants. As with Section 6 funds, State Wildlife Grants monies have been used to restore riparian habitats, remove barriers, and fund research studies. These state listings are independent of the species' federal status, and there is no reason to expect any change in federal status to necessarily be followed by the states, both of which are currently building momentum on RLP propagation and translocation capacity. Thus, we expect state-level emphasis on protections and population restoration to carry into the future, regardless of federal status. Furthermore, there is considerable inertia toward dam removal in the eastern U.S., for human safety, fish passage restoration, and river channel restoration, none of which hinge on the presence of a federally listed species. We therefore expect removal of dams and other barriers to continue within the range of RLP, regardless of the species' listing status.

In addition to the direct protections provided by the ESA and state-level listings, RLP and other stream fishes indirectly benefit from the provisions of the U.S. Clean Water Act (CWA; 33 USC §§ 1251 et seq.). For example, the CWA's National Pollutant Discharge Elimination System (NPDES) permitting system regulates point sources of water pollution and has reduced some of the most egregious chronic chemical pollution impacts of the early to mid 20th century. Although controlling nonpoint source pollution – in particular runoff of fine sediment, nutrients, and other contaminants – has been more difficult, CWA provisions such as Total Maximum Daily Load standards, which states are required to develop and achieve, have helped spur watershed-level management plans aimed at stemming pollutants potentially harmful to RLP such as nutrients and sediment.

Restoration activities – Three types of restoration activities have the potential to positively impact RLP habitat and population conditions: (1) habitat restoration, (2) connectivity restoration, and (3) population restoration. Habitat restoration initiatives for RLP primarily seek to reduce erosion potential and fine sediment inputs to streams. Projects include riparian zone reestablishment, fencing livestock out of streams, and placing lands in conservation easements that prevent deforestation. The end goal of all these projects is to reduce new inputs of fine sediment into RLP habitats. We expect such activities to continue in watersheds harboring RLP, regardless the ESA status of the species. Unfortunately, there is no way to remove existing deposited sediment, which has accumulated in some cases over the course of centuries and can only be removed very gradually through downstream transport during flushing flow events (Walter and Merritts 2008, entire). Given that it may take decades or centuries to see responses of RLP habitat resulting from habitat restoration, the near-term resiliency of RLP populations is not likely to be as strongly affected by these management activities as by connectivity and population restoration activities.

Connectivity restoration involves the removal of barriers to RLP movement among stream reaches, most notably dams. Multiple dams have been removed within the range of RLP in recent decades, including Wasena dam on the upper Roanoke River near Roanoke, VA in 2009, the Rocky Mount power dam on the Pigg River near Rocky Mount, VA in 2016, and the Lindsey Bridge dam on the Mayo River near Madison, NC in 2020. Removal of additional dams is plausible, given the current trend toward dam removal in the eastern U.S. (Bellmore et al. 2017, entire). Barrier removal could increase the effective area of adjacent populations and allow increased dispersal among populations, in both cases potentially increasing resiliency (Gido et al. 2016, entire).

Population restoration would involve the intentional anthropogenic movement of fish across movement barriers they otherwise would be unable to cross. The individual fish being stocked could be translocated wild fish or propagules produced in a hatchery. Stocking could occur into a currently occupied population, in order to augment the demography or genetic diversity of that population, it could involve reintroduction of fish into a previously occupied habitat that is no longer occupied, or it could involve the introduction of fish into a habitat that has never been occupied by the species. Augmentation is intended to bolster resiliency by increasing vital rates, total population size, and genetic diversity, whereas introduction and reintroduction are intended to bolster redundancy by increasing the number of populations on the landscape. Collectively, propagation, augmentation, reintroduction, translocation, and introduction (hereafter "PARTI") form a suite of interrelated population restoration tactics that have been successfully used in the recovery of a variety of imperiled fish species (Minckley et al. 2003, entire; Vrijenhoek 1996, entire; Yamamoto et al. 2006, entire). Although no PARTI activities have yet been pursued for RLP, propagation procedures have been established (Ruble et al. 2009, entire; Ruble et al. 2010, entire), a decision document is in place to provide a scientific basis to PARTI decisions (Roberts 2018, entire), and an online decision-support tool has been developed based on input from the SDM Team to guide hatchery and PARTI activities (https://daniel-gibson.shinyapps.io/RLP_MODEL/). As such, there is strong potential to incorporate PARTI into recovery actions for RLP in the future. As described above, regardless of the ESA status of RLP, we expect the states of Virginia and North Carolina to still prioritize RLP population restoration in the future, as they do with other state-listed fishes and freshwater mussels.

Other factors – Figure 7 illustrates the complex interplay of factors affecting habitat and species condition for RLP. The majority of these direct and indirect influences were described above, and the six factors we considered most important to RLP condition (fine sediment, water pollution, movement barriers, climate change, regulatory mechanisms, and restoration activities) were described in detail and carried forward into the assessment of current and future condition.

An additional factor merits some discussion here. Water withdrawals from ground and surface water supplies are expected to increase dramatically over the next century, as human population size and water needs increase (Roy et al. 2012, entire). Water abstraction can stress aquatic biota by decreasing the magnitude of base and low flows, reducing habitat availability, and increasing competition and individual stress (Baron et al. 2002, entire). Although we expect water withdrawals in RLP's range to increase over time, and potentially negatively impact fish fitness and population vital rates, we did not attempt to account for these impacts when assessing condition for three reasons. First, with the exception of a few large water users, withdrawal rates are very difficult to estimate, such that we had no way to estimate geographic variation in water abstraction or project it into the future. Second, although surface water withdrawal has obvious effects on the availability of water in the source river, the surface effects of groundwater withdrawal are much more geographically widespread and difficult to map and predict. Third, although less available stream flow intuitively would negatively affect habitat availability for RLP or any other benthic stream fish, we have no quantitative model to relate a given amount of water abstraction to a given percent change in habitat availability.

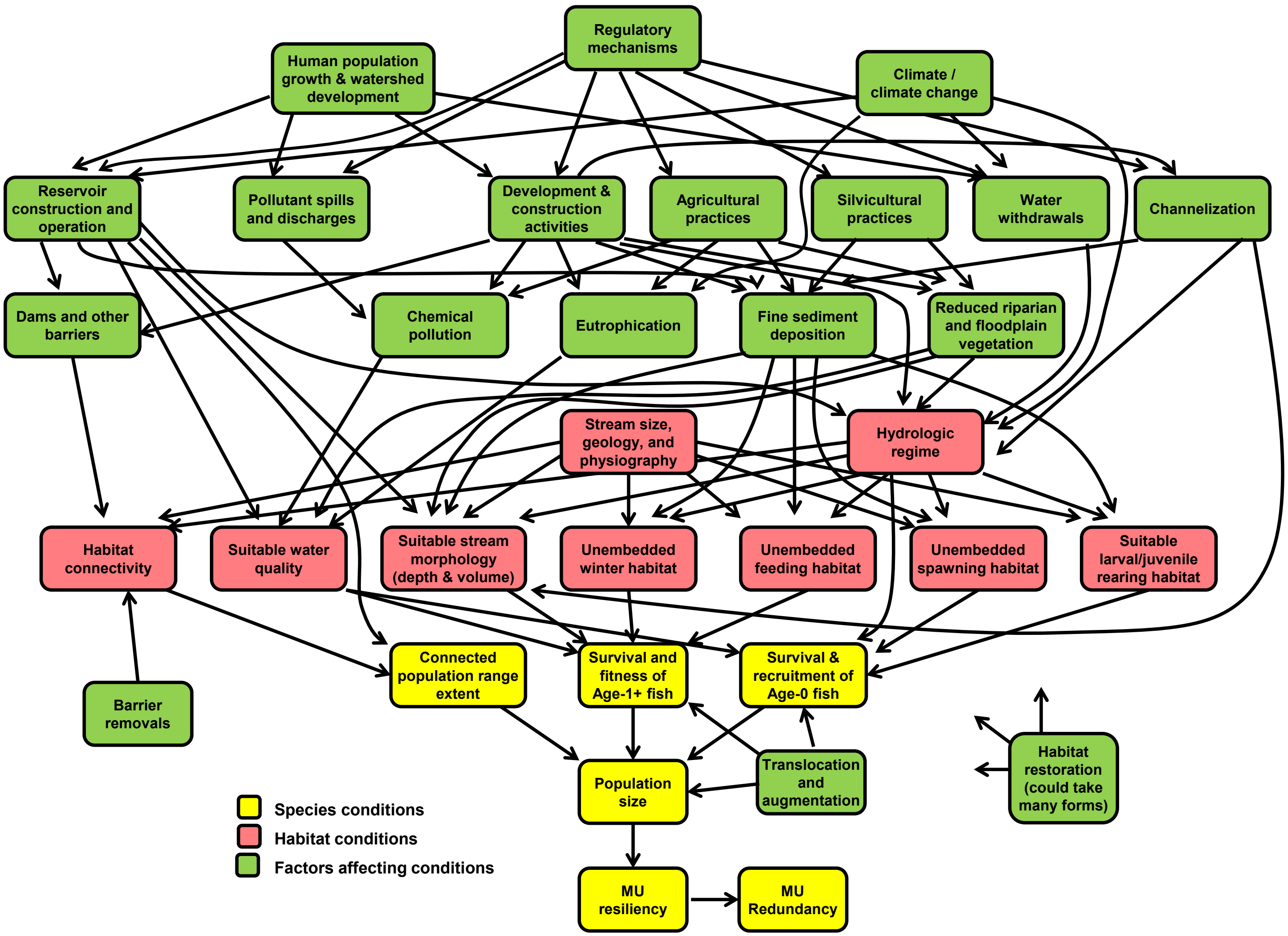

Figure 7: Influence diagram showing relationships among environmental and anthropogenic factors (green boxes), habitat conditions (pink boxes), and species conditions for RLP (yellow boxes).

3.4 Methods for assessing current condition

We utilized multiple metrics to gauge the current resiliency of RLP MUs, including information on population density and size, genetic diversity and N_e , and available habitat area, quality, and security from risks like pollution events. An overall index of current MU resiliency was developed that combined all these types of information. We considered only the 11 occupied MUs in the current condition analysis.

Current population size was estimated for each MU by taking the arithmetic mean of two different estimators (Table 5). The first estimator was elicited from species experts during SDM team meetings. These values represent expert judgement based on knowledge of relative variation in habitat quantity and quality among MUs. The second was based on the approach described by Roberts (2012a) and Roberts (2018), which involved using previously-collected empirical habitat and fish data to: (1) estimate the linear extent of each MU, as the stream distance between the downstream-most and all upstream-most collection locations in each MU, (2) estimate the mean distance between suitable habitat patches (i.e., riffle-run channel-units) in that MU, (3) estimate the mean number of adult RLP per habitat patch, and (4) by combining these quantities, estimate the total population size of the MU (Appendix 1). Resulting estimates differ from those reported by Roberts (2018) for several reasons: (1) range extent was updated based on input from the SDM team, (2) we divided the single "Dan metapopulation" of Roberts (2018a) into its four extant MUs, each with its own population size, and (3) in converting raw catch to true abundance, we used a revised estimate (0.31) of the catch:abundance ratio (i.e., sampling efficiency) based on the average of Roberts' (2003) and Roberts and Angermeier's (2011) three-pass-depletion-based estimates of RLP electrofishing sampling efficiency in the Roanoke River and its North and South Forks (Appendix 1).

Although total population size often is used to evaluate the viability of populations (Frankham et al. 2014, entire), reliance on population size alone might be misguided for RLP because it would not account for how individuals are distributed within the geographic area of an MU. For example, 2000 fish distributed across 50 km indicates a relatively high population density (40 fish km^{-1}), potentially indicating a highly productive habitat, whereas this same abundance distributed across 300 km indicates much lower population density (6 fish km^{-1}) and potentially a lower-quality habitat in which fish have a harder time finding mates. We therefore focused on population density rather than total abundance as a demographic indicator of current condition. The overall estimate of current population size for each MU was divided by the linear extent of the MU (as assigned by the SDM team), to obtain an estimate of current population density (adult fish km^{-1}) for each MU (Table 5). To estimate a "minimum viable population density" (MVP) for RLP, we used the simulation model described in section 4.1.2 to forecast the extinction probability of "generic" RLP populations 50 years in the future. Each replicate population was assigned a starting density of anywhere from 2 to 36 fish km^{-1}. All populations had 195 km of available habitat (the average across all 18 MUs) and were assigned average habitat quality and low catastrophe risk (see below). Each starting density was replicated 100 times and we counted the proportion of these replicates in which population size fell below two individuals by year 50. Extinction risk was nearly 100% when density was less than 10 fish km^{-1}, decreased rapidly as density increased to 20 fish km^{-1}, and was close to zero at larger population densities (Appendix 2). We therefore considered MUs with a density $\geq$ 20 fish km^{-1} to have the highest resiliency, those with a density < 10 fish km^{-1} to have the lowest resiliency, and those in between to have intermediate resiliency.

An important component of resiliency is being able to resist the influence of inbreeding depression on individual fitness, and ultimately, being able to adapt to changing future conditions. This is also an important aspect of species' representation. Franklin (1980, entire) estimated that a genetically N_e of 50 is needed in the short term (several generations) to avoid inbreeding depression, while a larger N_e of 500 is needed over the long term (dozens to hundreds of generations) to maintain adaptive variation in the face of genetic drift. This line of reasoning led to the highly influential "50:500 Rule", which has been used by conservation groups like the International Union for Conservation of Nature (Frankham et al. 2014, entire) to assess viability for imperiled species. We obtained N_e estimates for each MU from Roberts (2018). Roberts (2018) reported only one estimate of N_e for the entire Dan basin (minus Upper Smith); we developed separate N_e estimates for each of the four MUs in this region by partitioning Roberts' (2018) total N_e by MU in proportion to each MU's linear extent in kilometers. We considered MUs with $N_e \geq 500$ to have the highest resiliency, those with $N_e < 50$ to have the lowest resiliency, and those in between to have intermediate resiliency.

In addition to population status, we considered two aspects of the habitat conditions of each MU. Current habitat quality was qualitatively assigned by the SDM team as an aggregate assessment of that habitat's ability to support RLP population growth, on an ordinal scale (poor, low, average, or high). We considered MUs with high quality to have highest resiliency, MUs with average quality to have intermediate resiliency, and those with low or poor quality to have lowest resiliency. Regardless of habitat quality, populations are less likely to go extinct when they are more extensively distributed across a broader diversity of independent habitat patches (Campbell-Grant 2011, entire). This broader distribution essentially conveys internal redundancy to the population. Using this logic, we assumed that an MU distribution spanning more stream segments would confer demographic independence and refugia from a negative event occurring in part of the stream network. For each MU, we tabulated the number of stream segments (separate named streams) in which RLP previously have been observed (Table 2) and used this as an index of habitat resiliency. Reservoir observations were excluded from this calculation. This index assumed that all stream segments where RLP have been observed are either currently or potentially occupied by RLP. We considered MUs with 3 or more stream segments to have highest resiliency, MUs with 2 stream segments to have intermediate resiliency, and those with only 1 occupied stream segment to have lowest resiliency.

Index scores (high, intermediate, low) for population density, N_e, habitat quality, and number of stream segments were equally weighted and combined into an overall index of current resiliency. For each MU, the overall score was the sum of the high scores (max of 4) minus the sum of the low scores (max of 4), plus 3 (to scale the final index to have a minimum of one). Any MU with an overall score ≥ 5 exhibited at least three "high" indices, so we considered these MUs to have highest resiliency. In contrast, any MU with an overall score of 1 exhibited at least two "low" indices and no "high" indices, so we considered these MUs to have the lowest resiliency. MUs with scores of 2-4 were considered intermediately resilient.

Once the current resiliency of each MU was calculated, we used this information to assess redundancy and representation. For each metapopulation, a redundancy index was calculated as follows: (1) for each MU, the overall resiliency score was multiplied by the number of stream segments occupied, then (2) these values were summed across all MUs in a given metapopulation. This calculation acknowledges the fact that each MU's contribution to redundancy is a function of both the resiliency and the geographic complexity of that MU. In other words, holding resiliency constant, a very large and complex MU adds more redundancy than a small and geographically restricted MU. Given that each metapopulation is a unique combination of river basin and ecoregion, with potentially unique evolutionary information that is important to conserve, we gauged species-level representation for RLP based on the number of historical metapopulations currently occupied and achieving high resiliency and redundancy.

Table 5: Current population and geographic characteristics of all occupied and potential RLP MUs. Mean population size was the arithmetic average of two estimates made using different approaches: (1) "SDM" was based on the expert opinions of the SDM Team, and (2) "demographic" was based on field-based empirical estimates of fish catch, habitat spacing, and range extent. Population density was calculated as mean population size divided by the estimated linear range extent (km) of that MU. Potential, but not currently occupied, management units are in italics.

Metapopulation	Management unit	Current population size (SDM)	Current population size (demographic)	Mean current population size	Range extent (km)	Mean current population density (fish km^{-1})
Roanoke Mountain	Upper Roanoke	12000	16557	14279	354.0	40.3
Roanoke Piedmont	*Blackwater*	0	0	0	197.2	0.0
	Pigg	9000	5160	7080	233.2	30.4
	Goose	2000	1891	1945	145.1	13.4
	Otter	2000	2062	2031	213.5	9.5
	Middle Roanoke	4000	unknown	4000	294.4	13.6
	Falling	0	0	0	174.2	0.0
Dan	Upper Smith	3200	3338	3269	116.0	28.2
	Middle Smith	1000	1386	1193	48.2	24.8
	Lower Smith	1000	1968	1484	68.4	21.7
	Upper Mayo	0	0	0	195.6	0.0
	Lower Mayo	1000	1559	1280	54.2	23.6
	Upper Dan	0	0	0	157.2	0.0
	Middle Dan	1000	3531	2266	122.8	18.5
	Lower Dan	0	0	0	149.8	0.0
	Banister	0	0	0	43.5	0.0
Chowan	*Meherrin*	0	0	0	562.8	0.0
	Nottoway	10000	5296	7648	383.9	21.1

3.5 Estimated current condition

3.5.1 Current resiliency

Seven of the 11 occupied MUs exhibited population density ≥ 20 fish km^{-1} and high resiliency for this metric, whereas one MU (Otter) had a density < 10 fish km^{-1} and low resiliency for this metric; the three other MUs were intermediate (Table 6). Seven of the 11 occupied MUs exhibited N_e values ≥ 500 and high resiliency for this metric, whereas one MU (Goose) exhibited N_e < 50 and thus low resiliency for this metric; two other MUs were intermediate and Middle Roanoke was not scored because its N_e is unknown. Only the Upper Roanoke was assigned "high" habitat quality and only the Middle Roanoke was assigned "low" habitat quality, giving these 2 MUs high and low resiliency scores, respectively, while 9 other MUs were intermediate. Finally, the number of stream segments in which RLP have been detected ranged among MUs from 1 (Goose, Middle Roanoke, Lower Smith, Lower Mayo) to 7 (Upper Roanoke), with other MUs featuring from 2 to 5 segments. Five MUs scored high for this metric, 4 scored low, and 2 scored intermediate.

Based on the 4 constituent metrics, the overall resiliency index was lowest in Goose and Middle Roanoke, both scoring relatively low overall resiliency (Table 6). The index was highest in Upper Roanoke, Pigg, Upper Smith, Middle Dan, and Nottoway. For each of these MUs, at least 2 of the 4 constituent metrics scored high, and the overall resiliency score was relatively high. In the remaining four MUs (Otter, Middle Smith, Lower Smith, and Lower Mayo), low or intermediate scores outnumbered high scores, and the overall resiliency score was intermediate. The "number of stream segments" metric most frequently brought the overall score down. The other three metrics only attained low scores within the Roanoke Piedmont metapopulation (each within a different MU). Comparing the two metapopulations housing multiple MUs, resiliency was substantially higher in the Dan than the Roanoke Piedmont metapopulation.

3.5.2 Current redundancy and representation

The overall current redundancy score was highest in the Dan metapopulation, followed by the Roanoke Mountain and Chowan metapopulations, and was lowest in the Roanoke Piedmont metapopulation (Table 6). The Dan metapopulation contains 5 MUs, each with at least an intermediate resiliency, and spreads across a total of 12 stream segments. The Roanoke Piedmont metapopulation also contains multiple MUs, but 2 of 4 of them have a low estimated resiliency and contribute only one stream segment each. Although the Roanoke Mountain and Chowan metapopulations each contain only one delineated MU, both of those MUs are geographically extensive and highly resilient; as such, these metapopulations appear well buffered against catastrophic events and scored relatively high redundancy.

Representation describes the ability of a species to adapt to changing environmental conditions over time. By maximizing representation, a species' adaptive capacity to face unpredictable future changes to its environment are also maximized (see section 1.2). Our evaluation of the resiliency metric for N_e, as well as overall distribution of resilient populations across evolutionary units (or representation areas) informs RLP's current representation. Given that all four evolutionary units (combinations of ecoregion and basin) within the known range of RLP have multiple (redundant) MUs with intermediate or high N_e, we deemed that species-level adaptive capacity, or representation, is relatively high. The high estimated resiliency and redundancy of the Chowan metapopulation is particularly important for species-level representation, given that this evolutionary unit is the most genetically distinctive metapopulation (Roberts et al. 2013, entire), occurs in the most ecologically distinct environment (Jenkins and Burkhead 1994, pp. 786-787; Rosenberger and Angermeier 2003, entire), and therefore potentially contributes disproportionately to the evolutionary diversity of the species.

Table 6: Overall current resiliency for each occupied RLP MU and current redundancy for each metapopulation based on population, habitat, and genetic conditions. Potential MUs (e.g., Falling, Blackwater, etc.) with no known previous or current population of RLP were excluded from this analysis. Green, yellow, and red color coding indicates higher, intermediate, or lower potential for resiliency, respectively. Overall current resiliency is calculated for each MU, whereas overall current redundancy is calculated at the scale of metapopulations.

Metapopulation	Management unit	Population density	Effective population size	Habitat quality	Stream segments	Overall current resiliency score	Overall current redundancy score
Roanoke Mountain	Upper Roanoke	40.3	4792	High	7	7	49
Roanoke Piedmont	Pigg	30.4	2404	Average	3	6	24
Roanoke Piedmont	Goose	13.4	44	Average	1	1	
Roanoke Piedmont	Otter	9.5	396	Average	2	2	
Roanoke Piedmont	Middle Roanoke	13.6	Unknown	Low	1	1	
Dan	Upper Smith	28.2	784	Average	4	6	60
Dan	Middle Smith	24.8	458	Average	2	4	
Dan	Lower Smith	21.7	651	Average	1	4	
Dan	Lower Mayo	23.6	516	Average	1	4	
Dan	Middle Dan	18.5	1168	Average	4	5	
Chowan	Nottoway	21.1	1200	Average	5	6	30

CHAPTER 4 – FUTURE CONDITION

4.1 Methods for assessing future condition

4.1.1 General approach

We assessed future condition for RLP using a PVA model that forecasted population size and viability 50 years into the future. We assumed a current date of 2020, thus forecasting population size to year 2070. We chose a 50-year timeframe because we had information to reasonably assess urbanization and climate change and risks over this timeframe. Assuming a 4.5-year generation time for RLP (Roberts 2012, p. 89), 50 years represents just over 10 RLP generations. A shorter timeframe would have questionable utility, given the longevity of the species, whereas a longer timeframe would risk overextension of model results. As with current condition, future condition was assessed through the 3R framework, with resiliency gauged by assessing MU persistence probability over the 50-year timeframe and metapopulation redundancy and species representation gauged based on counts of resilient MUs. Future conditions were forecast under 12 different scenarios, featuring different assumptions about future environmental conditions and management decisions. These scenarios and the PVA model itself are described below.

4.1.2 Descriptions of future scenarios

We focused on four factors when assessing how future conditions might influence the 3Rs for RLP: (1) watershed urbanization, (2) climate change, (3) population restoration via PARTI, and (4) connectivity restoration via barrier removal (Figure 8). For each of the four factors, we developed different scenarios representing higher and lower magnitudes of effect, bracketing the range of possible futures. Alternate urbanization and climate change scenarios were grouped into three categories of management intervention (no conservation, PARTI only, or PARTI plus barrier removal), resulting in a total of 12 future scenarios (Table 6).

As described in section 3.3, watershed urbanization alters hydrology, increases the delivery of fine sediment, and increases the frequency and severity of chemical pollution events and fish kills (Paul and Meyer 2001), all of which could chronically or acutely reduce vital rates for a riverine fish like RLP. To characterize current and potential future levels of urbanization, we downloaded and analyzed datasets generated by the SLEUTH Projected Urban Growth modeling tool (USGS 2020, entire) developed by U.S. Geological Survey and North Carolina State University. The SLEUTH models use a cellular automata approach to produce probabilistic estimates of urban development at decadal intervals from 2020 to 2100 based on likely patterns of population growth and development. We downloaded SLEUTH projections for each 10-digit hydrologic unit in which RLP have been captured, then aggregated these data by MU. The year-2020 data layer represented current urbanization, whereas data layers from 2030, 2050, and 2070 represented predicted urbanization 10, 30, or 50 years, respectively, in the future. We considered raster cells with ≥ 95% probability of urbanizing to be urban land cover and cells with < 95% probability to be non-urban, then calculated the percentage of each MU in urban land cover in a given year. We adopted this conservative probability threshold when assigning urbanization to account for the high uncertainty in projecting future human development patterns, but note that as a result, our projections of urbanization extent may be conservative. Because the population projections utilized a 50-year time horizon, we focused primarily on urbanization patterns between 2020 and 2070.

Watersheds with greater urbanization and impervious surfaces exhibit a variety of biological impacts, including reduced fish egg and larvae survival rates, the loss of sensitive fish species and guilds, and reductions in overall fish species diversity and biotic integrity (Paul and Meyer 2001, pp. 337-338). These impacts result from a variety of changes resulting from urbanization, including altered hydrology and increased sediment loading, biological oxygen demand, and organic and inorganic pollution (Paul and Meyer 2001, entire; see section 3.3). Previous work by Roberts et al. (2016a, entire) suggested that the population dynamics of RLP are particularly sensitive to acute pollution events, which we would expect to increase in frequency as a watershed urbanizes. In particular, streams in watersheds with ≥10% urban land cover have commonly been observed to exhibit the chronic and acute disturbances and associated biotic impacts described above (Paul and Meyer 2001, pp. 337-338; Schueler et al. 2009, entire). We therefore assumed that RLP MUs in such watersheds would face elevated risk of catastrophic disturbances (e.g., pollution events) that could adversely affect vital rates. Specifically, we assumed that MUs with ≥10% urban land cover would exhibit high risk, whereas MUs with <10% urban land cover would exhibit low risk. Relationships between urban land cover and RLP vital rates have not been characterized. However, Roberts et al. (2016a, p. 53) found that fish kills in the upper Roanoke River watershed, which is ~20% urban (see section 4.2.1), occurred on average every 5 years and affected on average 10.1 km of stream. The average linear extent of RLP MUs is 195 km, such that an average fish kill would affect 6% of an average population. Therefore, in PVA models, MUs with high risk were assigned a 20% chance of a catastrophe per year (i.e., every 5 years on average), MUs with low risk were assigned a 5% chance of a catastrophe per year (i.e., every 20 years on average), and each catastrophe reduced survival rates of all age-classes by 6% in that year. We evaluated two alternative urbanization scenarios: (1) urban land cover remains unchanged from 2020 levels, or (2) urban land cover increases to levels predicted by SLEUTH for 2070. Thus, under the second of these scenarios, a given MU could exhibit low risk at the beginning of the simulation if its urban cover was <10% in 2020, but transition to high risk by the end of the simulation if its urban cover was expected to increase to >10% by 2070. In cases where an MU's risk level changed to a new category between 2020 and 2070, the new vital rates went into effect midway through the simulation (i.e., at year 2045).

Climate change potentially alters rainfall, temperature, evapotranspiration, and storm patterns, which could affect runoff, stream flows, fine-sediment delivery, and vital rates for RLP, particularly during early life history (see section 3.3). For example, in the upper Roanoke River, Roberts and Angermeier (2007, p. 43) found that Age-0 abundance in the fall of their first year was negatively related to the standard deviation of stream flows during the spring (April-June) of that year. Fine-sediment deposition, on the other hand, is expected to negatively impact all life-stages of RLP. The nature, speed, and magnitude of future climate changes are subject to much uncertainty, based partly on uncertainty about future policy decisions that will affect anthropogenic greenhouse gas emissions. We selected two potential climate-change scenarios that bracket a plausible range of futures: the "RCP 4.5" scenario assumes a leveling-off of greenhouse gas emissions by mid-century, whereas the "RCP 8.5" scenario assumes increasing emissions through 2100 (IPCC 2014, entire). To assess the extent to which these climate changes might differentially affect MUs, for example in the mountains versus the coastal plain, we used the State Climate Office of North Carolina's Climate Voyager toolkit (https://legacy.climate.ncsu.edu/voyager/index.php) to estimate the projected changes in temperature and rainfall for each MU over the next ~50 years. We selected a geographic location at the centroid of each MU, then downloaded the projected change in June-August temperature (degrees Fahrenheit) and precipitation (inches) between the 1950-2005 versus 2060-2079 time periods, under each of the two climate scenarios. Because we observed very little spatial variation in projected climate (see section 4.2.1), we considered the main difference to be between RCP 4.5 and RCP 8.5. Relationships between temperature and rainfall, hydrology, and RLP vital rates have not been characterized. However, we assumed that the greater the magnitude of climate change, the greater hydrology would differ from historical conditions (Donnelly et al. 2017, entire), and the greater the potential impacts to habitat suitability and population vital rates. For modeling purposes, we assumed that under RCP 4.5, vital rates would not differ from current values, but that under RCP 8.5, the habitat suitability of all MUs would decrease by one categorical level (e.g., from "good" to "average"; see section 4.1.2), equivalent to an ~2% reduction in the annual population growth rate. In scenarios involving this change in habitat suitability, the new vital rates went into effect midway through the simulation (i.e., at year 2045).

In contrast to urbanization and climate-change impacts, conservation interventions such as PARTI or the removal of barriers separating populations could positively affect vital rates and increase population size and the 3Rs. We modeled the future condition of RLP MUs with and without the implementation of these activities. In models without intervention (Scenarios 1-4; Tables 7, 8), natural bi-directional dispersal was allowed only between MUs not separated by barriers (dams) and uni-directional dispersal (upstream to downstream) was allowed only across select, smaller barriers (dams), where it is more likely that fish could flow over the dam (Table 4; Figure 6). No PARTI intervention occurred. In models featuring PARTI but no barrier removal (Scenarios 5-8; Tables 7, 8), we simulated intentional hatchery propagation and annual stocking of RLP into occupied (augmentation) or unoccupied MUs (introduction or reintroduction) based on a PARTI decision model embedded in the overall PVA model (see section 4.1.2). For models allowing PARTI, we assumed an annual hatchery capacity of 1000 fish, the ability to stock up to 3 different MUs per year, a minimum stocking size of 100 fish per MU per year, and a maximum stocking size of 1000 fish per MU per year. The PARTI decision process was revisited every three years to determine which MUs would be stocked in the next three years, based on progress towards recovery and the prioritization scheme of the decision model (see Appendix 3). These hatchery and stocking constraints were selected based on consultation with the SDM team.

In models with both PARTI and barrier removal (Scenarios 9-12; Tables 7, 8), we simulated the influences of both annual RLP stocking (see above) and the "removal" of three smaller dams and allowing bi-directional dispersal between the now-connected MUs. These dams, which isolate either the Upper Mayo (Washington Mill and Avalon) or Upper Dan (Jessup's Mill), were identified as barriers whose removal could open large areas of new suitable habitat for colonization and therefore potentially increase MU resiliency. For modeling, purposes, Washington Mill and Avalon were treated as the same barrier, as these dams are only ~2.5 km apart. In reality, dam removal is a politically and logistically challenging management action, and it is important to note that these particular dams were targeted because of the perceived benefit of their removal, not necessarily because of the feasibility or imminence of their removal.

In applicable scenarios, all three barriers were “removed” in the first year of the simulation, while PARTI was carried out annually in years 1-45, allowing a 5-year buffer at the end of the simulation to observe whether any population increases resulting from translocation were sustainable.

As described in section 3.3, in applying PARTI and barrier removal in some future scenarios, we have assumed that these conservation measures could feasibly occur in the future, regardless of whether or not RLP are federally listed.

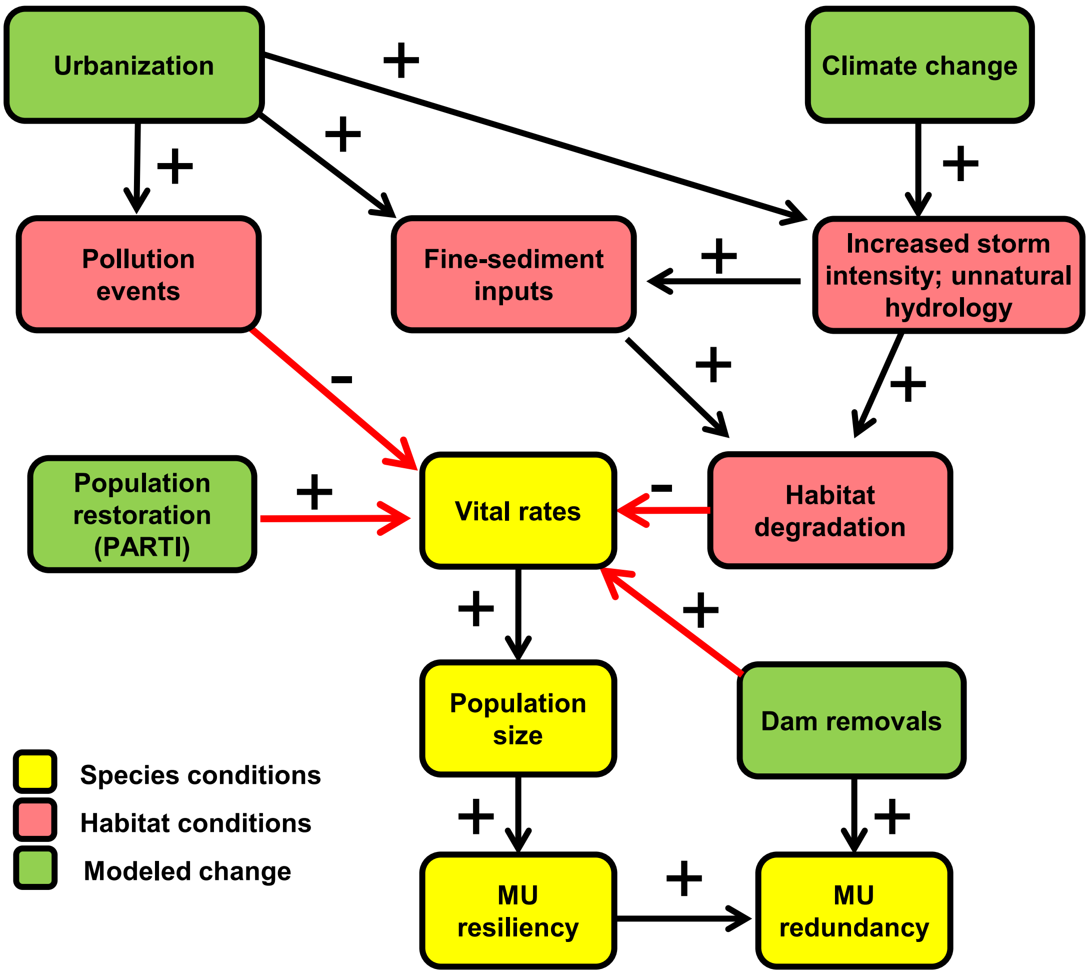

Figure 8: Reduced influence diagram focusing on key relationships investigated by this SSA for their influences on current and future condition for RLP. Red arrows indicate relationships directly addressed by population viability analyses of future condition.

4.1.3 Description of the quantitative PVA forecasting model

Forecasting of future condition was implemented in a stochastic, stage-based PVA simulation model developed by Dr. Dan Gibson (formerly of Virginia Tech, currently of Colorado State University) and colleagues and implemented in an online graphical user interface (https://daniel-gibson.shinyapps.io/RLP_MODEL/). The model allows the user to input a variety of demographic and habitat parameters, as well as constraints based on logistics and desired recovery outcomes, and uses simulations to assess the effect of varying these parameters on future RLP population size. The model was developed with the input of the SDM team between 2018 and 2020 primarily to help guide decisions about whether, when, and where to undertake PARTI activities to recover RLP. As such, it contains a complex decision model allowing the user to influence the PARTI decision process based on numerous alternative goals (e.g., emphasize occupied over unoccupied populations, prioritize growing populations, avoid difficult-to-access areas, etc.). We used the default setting of assigning equal priority to all of these goals. Technical details of the population, habitat, and decision-making components of the PVA are described in Appendix 3. Below we describe only the key model decisions and inputs germane to the current SSA objectives.

In the PVA, three key mechanisms influence population dynamics (Figure 8). First, *habitat suitability* influences average survival and fecundity, which jointly determine the population growth rate. The user assigns each MU an ordinal habitat suitability score which results in a corresponding population growth rate (High~1.04, Average~1.02, Low~1.01, Poor~0.99; Appendix 3). We presume that both climate change and urbanization ultimately influence habitat suitability (Figure 8), though for forecasting purposes, we focused on how habitat suitability was affected by increasing intensity of climate change, assuming that climate-related changes in hydrology and sediment delivery/deposition would consistently reduce habitat suitability and vital rates of RLP. Second, *risk level* influences the temporal variability of survival. The user assigns each MU an ordinal risk score that gives that MU an annual probability of 0.2 (high risk) or 0.05 (low risk) of going through a catastrophic event that reduces all life-stages' survival rate by 0.06. For forecasting purposes, we focused on how risk was affected by increasing intensity of urbanization, assuming that in more urbanized watersheds, catastrophic disturbances like chemical spills would be more likely to acutely but temporarily reduce vital rates of RLP (Figure 8). Third, *connectivity* generally increases population size, whether this connectivity is accomplished via the unassisted dispersal of wild individuals among connected MUs, or the assisted movement of propagated individuals among MUs isolated from each other by barriers such as dams (Figure 8). Natural dispersal occurred in the model according to a dispersal kernel that allowed up to 5% emigration per year (Appendix 2). When applicable given the scenario, assisted movement occurred according to the PARTI decision process described previously.

As described above, we simulated population-size changes and future condition under 12 scenarios featuring alternative combinations of urbanization, climate change, and conservation intervention. These influences were implemented by manipulating the habitat suitability, risk level, and/or connectivity of individual MUs in PVA models (Tables 7, 8). Across all scenarios, a given MU began with the same starting population size (mean population size from Table 5), starting available habitat extent in kilometers (elicited from the SDM team), starting habitat quality (elicited from the SDM team), and starting risk level (based on 2020 land cover).

However, a given MU's ending habitat suitability and risk level varied among models depending on the assumptions of the scenario. In scenarios assuming no increase in urbanization (1, 2, 5, 6, 9, and 10), ending risk levels were set based on 2020 land cover, whereas in scenarios assuming increasing urbanization (3, 4, 7, 8, 11, and 12), ending risk levels were set based on 2070 SLEUTH land cover (Table 8). In scenarios assuming no impact of climate change (RCP 4.5; scenarios 1, 3, 5, 7, 9, 11), ending habitat suitability was equal to starting habitat suitability, whereas in scenarios assuming RCP 8.5 (scenarios 2, 4, 6, 8, 10, 12), all MUs' ending habitat suitabilities were reduced by one ordinal level (e.g., from "average" to "low"), equivalent to an ~2% reduction in the population growth rate. Other input parameters were held constant across scenarios and are described in Appendix 3.

We conducted 100 replicate simulations under each scenario. At the end of these simulations, we calculated persistence probability for each MU as the frequency with which population size remained above 1 individual at the end of the 50-year simulation. We considered MUs with a >95% chance of persistence to be highly resilient, whereas MUs below this threshold were not considered resilient.

Table 7: Scenarios evaluated when assessing future condition for RLP.

Scenario	Urbanization	Climate change	PARTI implemented?	Barriers removed?
1	Constant at 2020 levels (no change)	RCP 4.5 (no change)	No	No
2	Constant at 2020 levels (no change)	RCP 8.5 (reduced habitat suitability)	No	No
3	2070 prediction (increased risk)	RCP 4.5 (no change)	No	No
4	2070 prediction (increased risk)	RCP 8.5 (reduced habitat suitability)	No	No
5	Constant at 2020 levels (no change)	RCP 4.5 (no change)	Yes	No
6	Constant at 2020 levels (no change)	RCP 8.5 (reduced habitat suitability)	Yes	No
7	2070 prediction (increased risk)	RCP 4.5 (no change)	Yes	No
8	2070 prediction (increased risk)	RCP 8.5 (reduced habitat suitability)	Yes	No
9	Constant at 2020 levels (no change)	RCP 4.5 (no change)	Yes	Yes
10	Constant at 2020 levels (no change)	RCP 8.5 (reduced habitat suitability)	Yes	Yes
11	2070 prediction (increased risk)	RCP 4.5 (no change)	Yes	Yes
12	2070 prediction (increased risk)	RCP 8.5 (reduced habitat suitability)	Yes	Yes

Table 8: Key PVA model inputs for assessing future condition. Starting population size, available habitat length, starting habitat quality, and starting risk level were constant for a given MU across all scenarios, whereas ending habitat quality and ending risk level varied by scenario as shown. In scenarios where PARTI was permitted, the final column indicates whether a given MU was allowed to receive stocked individuals. Potential, but not currently occupied, management units are in italics.

Management unit	Starting population size	Available habitat (km)	Starting habitat All scenarios	Ending habitat Scenarios 1,3,5,7,9,11	Ending habitat Scenarios 2,4,6,8,10,12	Starting risk All scenarios	Ending risk Scenarios 1,2,5,6,9,10	Ending risk Scenarios 3,4,7,8,11,12	Potential recipient Scenarios 5-12
Upper Roanoke	14279	354.0	High	High	Average	High	High	High	No
Blackwater	0	197.2	Low	Low	Poor	Low	Low	Low	Yes
Pigg	7080	233.2	Average	Average	Low	Low	Low	Low	No
Goose	1945	145.1	Average	Average	Low	Low	Low	High	Yes
Otter	2031	213.5	Average	Average	Low	Low	Low	Low	Yes
Middle Roanoke	4000	294.4	Low	Low	Poor	Low	Low	Low	No
Falling	0	174.2	Low	Low	Poor	Low	Low	Low	Yes
Upper Smith	3269	116.0	Average	Average	Low	Low	Low	Low	No
Middle Smith	1193	48.2	Average	Average	Low	Low	Low	High	No
Lower Smith	1484	68.4	Average	Average	Low	High	High	High	No
Upper Mayo	0	195.6	Average	Average	Low	Low	Low	High	Yes
Lower Mayo	1280	54.2	Average	Average	Low	Low	Low	High	No
Upper Dan [1]	0	77.2	Average	Average	Low	Low	Low	High	Yes
Middle Dan[1]	3742	202.8	Average	Average	Poor	Low	Low	High	No
Lower Dan	0	149.8	Low	Low	Poor	Low	Low	High	Yes
Banister	0	43.5	Low	Low	Poor	Low	Low	Low	Yes
Meherrin	0	562.8	Low	Low	Poor	Low	Low	Low	Yes
Nottoway	7648	383.9	Average	Average	Low	Low	Low	Low	No

[1] In 2020, Lindsey Bridge dam was removed to allow fish passage. This effectively moved the boundary between the Middle and Upper Dan MUs 80 river kilometers upstream, to Jessup's Mill Dam. To account for this in forecasting models, we added 80 km of habitat to Middle Dan and removed 80 km of habitat from Upper Dan. We also added 1476 fish to the starting population size of Middle Dan. The latter choice assumed that, for the majority of the 50-year simulated time span, RLP density would be identical (18.5 fish per km) downstream and upstream of the former Lindsey Bridge barrier.

4.2 Estimated future condition

4.2.1 Estimated future climate and land-use

Based on SLEUTH model predictions, only 2 MUs (Upper Roanoke and Lower Smith) exhibited high current risk (i.e., had ≥10% watershed urbanization in the 2020 dataset), but an additional 7 MUs crossed this threshold by 2070 (Table 9). Particularly large increases in urbanization were predicted in the watersheds around the Upper Mayo, Lower Mayo, and Middle Dan MUs. Based on examination of predicted urbanization maps at years 10, 30, and 50 of this time sequence, much of the predicted urbanization is expected to have occurred by year 30 (i.e., 2050; Figure 9). Unlike with urbanization, Climate Voyager predicted very little spatial variation in summer temperature and precipitation across the range of RLP (Table 10). Rather, the main axis of variation was between RCP 4.5 and 8.5. All MUs were predicted to experience an ~5° Fahrenheit increase in temperature under RCP 4.5, an ~8° Fahrenheit increase under RCP 8.5, and an approximately 1 inch per year increase in precipitation for both RCP 4.5 and 8.5, within the next 50 years. These climate changes were predicted to occur gradually rather than abruptly: under RCP 4.5, temperature increase in 10 years was predicted to be 2.8° and in 30 years was predicted to be 4.2°, whereas under RCP 8.5, temperature increase in 10 years was predicted to be 3.1° and in 30 years was predicted to be 5.3° (data not shown).

Table 9: Estimated watershed urbanization rates for current (2020) and future (2070) time periods based on the SLEUTH Projected Urban Growth Modeling tool. Percentages ≥10, presumed to correspond with high risk to RLP populations, are indicated in red. Potential, but not currently occupied, management units are in italics.

Metapopulation	Management unit	Projected percent of MU area with ≥95% urban probability 2020	2070	% increase in urbanization
Roanoke Mountain	Upper Roanoke	19.9	21.9	2.0
Roanoke Piedmont	*Blackwater*	5.8	5.9	0.1
	Pigg	3.2	3.7	0.5
	Goose	7.4	18.9	11.4
	Otter	7.1	7.9	0.8
	Middle Roanoke	2.6	5.4	2.8
	Falling	3.3	4.1	0.8
Dan	Upper Smith	3.1	6.2	3.0
	Middle Smith	7.5	13.4	5.8
	Lower Smith	12.7	20.9	8.2
	Upper Mayo	5.1	21.8	16.7
	Lower Mayo	5.1	21.8	16.7
	Upper Dan	1.9	10.3	8.4
	Middle Dan	7.5	28.5	21.0
	Lower Dan	6.1	15.0	8.9
	Banister	3.1	8.6	5.5
Chowan	*Meherrin*	2.2	4.6	2.4
	Nottoway	1.8	4.5	2.8
All	Grand total	5.9	12.2	6.4

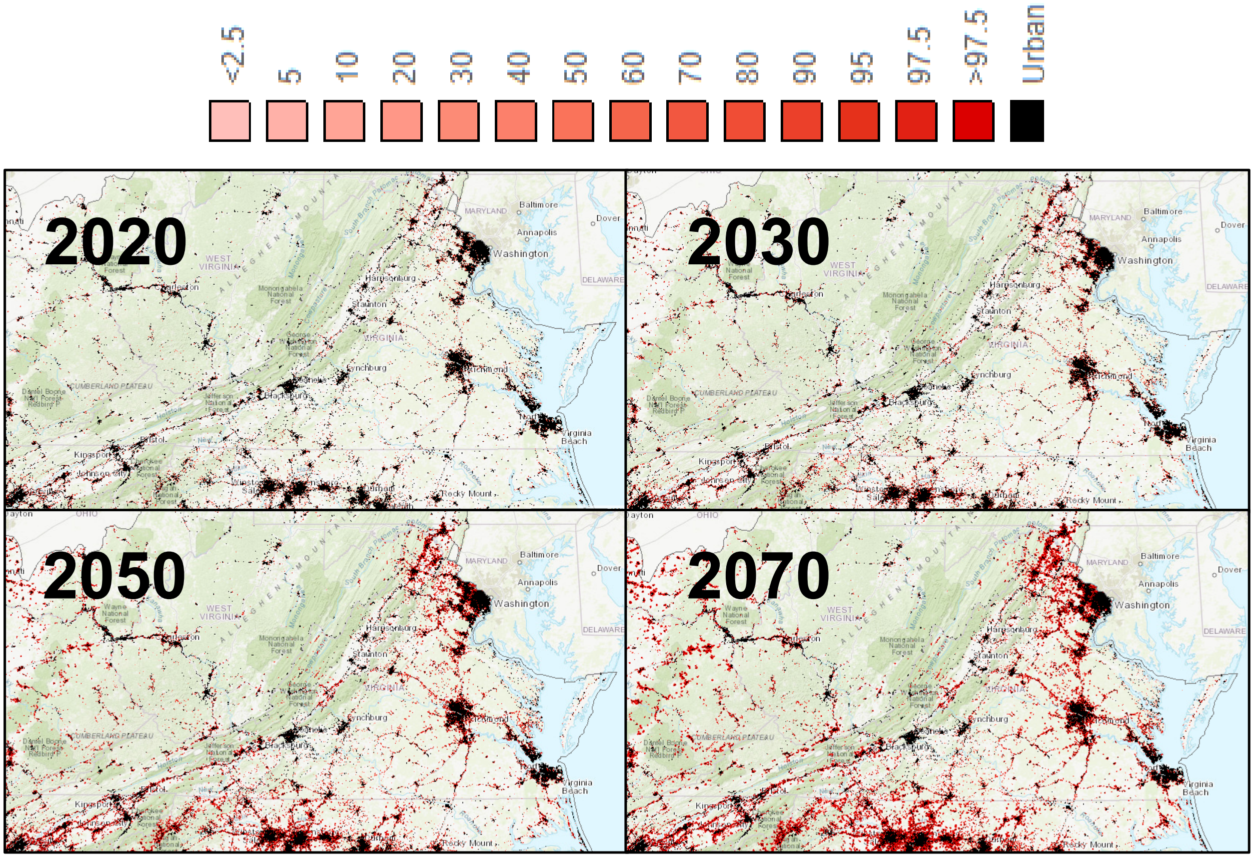

Figure 9: Maps showing projections of the SLEUTH Projected Urban Growth modeling tool, for years 2020, 2030, 2050, and 2070. Black pixels indicate regions already urbanized as of 2015; red pixels indicate regions with varying probabilities of urbanizing. For this SSA, we focused on the percentage of each MUs area with a probability ≥95% of becoming urban.

Table 10: Predicted *changes* in June-August temperature (degrees Fahrenheit) and precipitation (inches) in the time period spanning 2060-2079, relative to conditions from 1950-2005, as estimated by the Climate Voyager modeling tool. Values are multi-model means, with intervals in parentheses representing lowest and highest likely values. Predictions are shown for RCP 4.5 (lower emissions) and RCP 8.5 (higher emissions) climate change scenarios. Potential, but not currently occupied, management units are in italics.

		Predicted change from 1950-2005 to 2060-2079			
		RCP 4.5		RCP 8.5	
Metapopulation	Management unit	Temperature	Precipitation	Temperature	Precipitation
Roanoke Mountain	Upper Roanoke	5.0 (2.3-7.7)	0.9 (-1.0-2.7)	7.9 (3.9-11.9)	0.9 (-1.6-3.3)
Roanoke Piedmont	*Blackwater*	5.0 (2.3-7.7)	0.9 (-1.0-2.7)	7.9 (3.9-11.9)	0.9 (-1.6-3.3)
	Pigg	5.0 (2.3-7.7)	0.9 (-1.0-2.7)	7.9 (3.9-11.9)	0.9 (-1.6-3.3)
	Goose	5.0 (2.3-7.7)	0.9 (-1.0-2.7)	7.9 (3.9-11.9)	0.9 (-1.6-3.3)
	Otter	5.0 (2.3-7.7)	0.9 (-1.0-2.7)	7.9 (3.9-11.9)	0.9 (-1.6-3.3)
	Middle Roanoke	5.0 (2.3-7.7)	0.9 (-1.0-2.7)	7.9 (3.9-11.9)	0.9 (-1.6-3.3)
	Falling	5.0 (2.3-7.7)	0.9 (-1.2-3.0)	7.9 (4.0-11.8)	0.9 (-1.7-3.5)
Dan	Upper Smith	4.9 (2.3-7.6)	0.9 (-1.3-3.1)	7.8 (3.8-11.8)	0.9 (-1.5-3.2)
	Middle Smith	4.9 (2.3-7.6)	0.9 (-1.3-3.1)	7.8 (3.8-11.8)	0.9 (-1.5-3.2)
	Lower Smith	4.9 (2.3-7.6)	0.9 (-1.3-3.1)	7.8 (3.8-11.8)	0.9 (-1.5-3.2)
	Upper Mayo	4.9 (2.3-7.6)	0.9 (-1.3-3.1)	7.8 (3.8-11.8)	0.9 (-1.5-3.2)
	Lower Mayo	4.9 (2.3-7.6)	0.9 (-1.3-3.1)	7.8 (3.8-11.8)	0.9 (-1.5-3.2)
	Upper Dan	4.9 (2.3-7.6)	0.9 (-1.3-3.1)	7.8 (3.8-11.8)	0.9 (-1.5-3.2)
	Middle Dan	4.9 (2.3-7.6)	0.9 (-1.3-3.1)	7.8 (3.8-11.8)	0.9 (-1.5-3.2)
	Lower Dan	4.9 (2.2-7.6)	1.0 (-1.0-3.0)	7.8 (3.8-11.7)	1.0 (-1.5-3.5)
	Banister	5.0 (2.3-7.7)	0.9 (-0.8-2.7)	7.9 (3.9-11.9)	1.0 (-1.3-3.3)
Chowan	*Meherrin*	4.8 (2.3-7.2)	0.9 (-1.4-3.1)	7.5 (4.9-10.1)	0.7 (-2.4-3.9)
	Nottoway	4.8 (2.3-7.3)	0.9 (-1.3-3.1)	7.5 (4.1-10.9)	0.7 (-2.5-4.0)

4.2.2 Future condition in the absence of management (scenarios 1-4)

Scenario 1 represents the *status quo* of no changes to habitat suitability (from climate change) or catastrophe risk (from urbanization) and no management intervention through PARTI or barrier removal over the next 50 years. Comparing population projections under this scenario to current population sizes provides a way to assess whether the PVA tends to forecast increasing or decreasing trends, even in the absence of change. With the exception of the Upper Roanoke MU, which was forecasted to be significantly larger 50 years from now, most occupied MUs were forecasted to exhibit relatively little change in size over the next 50 years, with no consistent tendency to be larger or smaller than they currently are (Appendix 4). This suggests that the model is generally unbiased (i.e., is neither overly optimistic nor overly pessimistic).

Regardless of increases in urbanization (higher risk) or climate change (lower habitat suitability), and even in the absence of PARTI or barrier removal, all occupied MUs in the Roanoke Mountain, Dan, and Chowan metapopulations had high persistence probabilities and therefore relatively high resilience (Table 11). In contrast, in the Roanoke Piedmont, although the Pigg MU was resilient under any scenario, the Otter and Middle Roanoke MUs were not considered resilient under any scenario. The Goose MU was resilient if habitat suitability did not decline (scenarios 1 and 3). Most presently unoccupied MUs remained so throughout the simulations, and the presently unoccupied Lower Dan MU tended to be naturally colonized by downstream dispersal from Middle Dan (Table 12). This resulted in a new resilient population under status quo conditions, but not under worsening environmental conditions.

Based on forecasted future resiliency of currently occupied and currently unoccupied MUs, the Dan metapopulation achieved the highest redundancy, with 5 to 6 resilient MUs, depending on the scenario. Roanoke Mountain and Chowan metapopulations still contained only one resilient MU each, but for reasons described in section 3.5.2, these robust MUs add an “internal” type of redundancy to these metapopulations. The Roanoke Piedmont metapopulation, on the other hand, harbored only 1 to 2 resilient MUs, depending on the scenario. Although Pigg is a relatively robust MU, Goose is not, so the redundancy of this metapopulation is relatively low. Given that all four metapopulations persisted to year 50, with multiple resilient MUs in each, species-level adaptive capacity, or representation, is predicted to remain high into the future.

4.2.3 Future condition with PARTI (scenarios 5-8)

Resiliency results from scenarios 5-8 were similar to those from scenarios 1-4, except that, apparently as a result of implementing PARTI, (1) the Goose MU remained resilient in all scenarios, (2) the Otter MU was resilient in all scenarios except the combination of greater climate change (decreased habitat quality) and urbanization (increased risk), and (3) additional presently unoccupied MUs became occupied and resilient, including Falling in scenario 5, and Upper Dan in scenario 7 (Tables 11 and 12). Although Blackwater and Banister MUs also were often colonized as a result of PARTI, these efforts never resulted in persistent, resilient populations.

Based on forecasted future resiliency of currently occupied and currently unoccupied MUs, the Dan metapopulation achieved the highest redundancy, with 5 to 7 resilient MUs, depending on the scenario. Roanoke Mountain and Chowan metapopulations still contained only one resilient MU each, but for reasons described in section 3.5.2, these robust MUs add an internal type of redundancy to these metapopulations. The Roanoke Piedmont metapopulation harbored 2 to 4 resilient MUs, depending on the scenario. Thus, the potential redundancy of this metapopulation was substantially increased through PARTI. Similar to the outcome of scenarios 1-4, for scenarios 5-8 all four metapopulations persisted to year 50, with multiple resilient MUs in each, thus species-level adaptive capacity, or representation, is predicted to remain high into the future.

4.2.4 Future condition with PARTI and barrier removal (scenarios 9-12)

In the final group of scenarios, PARTI initiatives were complemented with the removal of two key barriers. Findings from these scenarios generally are similar to those from scenarios 5-8, except that, apparently as a result of barrier removal, (1) the Otter MU remained resilient under all scenarios, (2) the Middle Roanoke MU achieved resiliency under *status quo* environmental conditions, (3) the currently unoccupied Banister MU became occupied and remained resilient under *status quo* environmental conditions, and (4) the currently unoccupied Upper Mayo and Upper Dan MUs were likely to achieve resiliency, as long as habitat suitability did not decline due to climate change (Tables 11 and 12). Given that the dam removals reconnected Upper Mayo and Upper Dan to neighboring MUs, it makes sense that these MUs would have benefitted from these scenarios. The benefits of those barrier removals to occupied MUs like Otter and Middle Roanoke are less immediately obvious. However, we assume that re-established connectivity for Upper Mayo and Upper Dan allowed natural immigration to these MUs, allowing more stocking output to be directed away from these MUs and toward other MUs that needed augmentation to achieve resiliency, like Otter and Middle Roanoke. The dynamic decision model underlying stocking decisions continually balances goals of establishing new populations with supplementing existing ones that are growing, which causes annual stocking priorities to shift over the course of a simulation, if some MUs achieve recovery targets and others appear to be beyond recovery.

Based on forecasted future resiliency of currently occupied and currently unoccupied MUs, the Dan metapopulation achieved the highest redundancy, with 5 to 9 resilient MUs, depending on the scenario. Roanoke Mountain and Chowan metapopulations still contained only one resilient MU each, but for reasons described in section 3.5.2, these robust MUs add an internal type of redundancy to these metapopulations. The Roanoke Piedmont metapopulation harbored 3 to 4 resilient MUs, depending on the scenario, which confers redundancy to this metapopulation. Again, similar to the outcome of scenarios 1-8, for scenarios 9-12 all four metapopulations persisted to year 50, with multiple resilient MUs in each, thus species-level representation is predicted to remain high into the future.

Table 11: Forecasted future condition for each occupied RLP MU, under each of 12 alternative scenarios of future urbanization, climate change, and conservation management. Table values are the percent chances of persisting (i.e., remaining above a population size of zero) for the next 50 years, based on 100 replicate simulations per scenario. MUs in green exhibited a > 95% chance of persisting, whereas MUs in red exhibited a ≤ 95% chance of persisting.

	Category	No conservation				PARTI, no barrier removal				PARTI plus barrier removal			
	Scenario	1	2	3	4	5	6	7	8	9	10	11	12
	Increased risk	no	no	yes	yes	no	no	yes	yes	no	no	yes	yes
	Decreased habitat suitability	no	yes	no	yes	no	yes	no	yes	no	yes	no	yes
	Population augmentation	no	no	no	no	yes	yes	yes	yes	yes	yes	yes	yes
	Barrier removal	no	no	no	no	no	no	no	no	yes	yes	yes	yes
Metapopulation	**Management unit**	**Percent chance of persisting to year 50**											
Roanoke Mountain	Upper Roanoke	100	100	100	100	100	100	100	100	100	100	100	100
Roanoke Piedmont	Pigg	100	100	100	100	100	100	100	100	100	100	100	100
Roanoke Piedmont	Goose	99	95	100	91	100	100	100	100	100	100	100	100
Roanoke Piedmont	Otter	94	52	78	39	100	96	100	83	100	100	100	100
Roanoke Piedmont	Middle Roanoke	62	8	52	5	88	22	56	8	99	62	88	28
Dan	Upper Smith	100	100	100	100	100	100	100	100	100	100	100	100
Dan	Middle Smith	100	100	100	100	100	100	100	99	100	100	100	99
Dan	Lower Smith	100	100	100	100	100	100	100	100	100	100	100	100
Dan	Lower Mayo	100	100	100	100	100	100	100	100	100	100	100	100
Dan	Middle Dan	100	100	100	100	100	100	100	100	100	100	100	100
Chowan	Nottoway	100	100	100	100	100	100	100	100	100	100	100	100

Table 12: Forecasted future condition for each potential (i.e., currently unoccupied) RLP MU, under each of 12 alternative scenarios of future urbanization, climate change, and conservation management. These MUs could become occupied in the future through natural colonization and/or anthropogenic stocking via PARTI. Table values are the percent chances of being colonized and subsequently persisting (i.e., remaining above a population size of zero) for 50 years, based on 100 replicate simulations per scenario. MUs in green exhibited a > 95% chance of persisting, whereas MUs in red exhibited a ≤ 95% chance of persisting.

	Category	No conservation				PARTI, no barrier removal				PARTI plus barrier removal			
	Scenario	1	2	3	4	5	6	7	8	9	10	11	12
	Increased risk	no	no	yes	yes	no	no	yes	yes	no	no	yes	yes
	Decreased habitat suitability	no	yes	no	yes	no	yes	no	yes	no	yes	no	yes
	Population augmentation	no	no	no	no	yes	yes	yes	yes	yes	yes	yes	yes
	Barrier removal	no	no	no	no	no	no	no	no	yes	yes	yes	yes
Metapopulation	**Management unit**	**Percent chance of being colonized and persisting to year 50**											
Roanoke Piedmont	Blackwater	0	0	0	0	62	54	56	54	88	90	93	88
Roanoke Piedmont	Falling	0	0	0	0	96	85	86	88	87	91	93	91
Dan	Upper Mayo	0	0	0	0	41	45	40	49	100	89	100	69
Dan	Upper Dan	0	0	0	0	89	89	96	90	100	89	100	71
Dan	Lower Dan	100	75	95	43	100	74	98	46	100	73	94	44
Dan	Banister	0	0	0	0	42	58	75	53	96	90	95	82
Chowan	Meherrin	0	0	0	0	0	0	1	0	1	3	0	2

4.2.5 Caveats and uncertainties

- Our assessment of temporal changes in RLP's geographic range and our delineation of MUs and metapopulations assumed that available distribution data [VDWR and NCWRC collection records plus the species account in Jenkins and Burkhead (1994, pp. 785-788)] encompassed the entire historical range of the species. In other words, we assumed that no additional watersheds or entire basins have been occupied in recent ecological time but were extirpated prior to first collection records. This decision affects our impression of representation, in that all four major evolutionary units (i.e., metapopulations = unique combinations of basin and ecoregion) ever known to be occupied were estimated by us to exhibit current resiliency and redundancy, as well as future resiliency and redundancy under most future scenarios. If additional metapopulations once existed but have been lost (which we likely will never know), then our results would be overestimating representation.
- When estimating current and future habitat and species condition, we assumed that habitat and demographic conditions were spatially constant throughout a given MU. For example, we assumed that each MU exhibited constant fish density, vital rates, habitat quality, and catastrophe risk in all geographic areas of that MU. The values we selected for these parameters were averages of judgements made by experts on this species, so we are confident that they adequately represent the average conditions of MUs. For analytical tractability and because of data limitations, we were forced to collapse conditions to this spatial grain. However, we acknowledge that in reality, these MUs exhibit heterogeneous habitat and demographic conditions, both systematic (e.g., changes with stream size) and idiosyncratic (e.g., changes based on locations of point source pollutants). Although this heterogeneity may have reduced the precision of our projections, we think it unlikely that it created significant bias.
- For clarity in developing future scenarios, we considered climate change and urbanization to each have one type of effect (decreased habitat quality and increased catastrophe risk, respectively), when in fact both climate change and urbanization are likely to have both chronic and acute effects on RLP vital rates (see section 3.3). In future-condition modeling, we nominally attributed declines in habitat quality and annual vital rates to climate change. However, we might also expect increasing urbanization to reduce habitat quality and vital rates, particularly through increased sedimentation (Figure 8). Unfortunately, disentangling the effects of climate change and urbanization is nearly impossible, as these factors interact and will co-occur (Lynch et al. 2016, entire). However, this uncertainty does not negate our main findings about how declining quality might affect RLP persistence. It simply decreases our ability to pinpoint the ultimate cause of those habitat declines (climate change, urbanization, or a combination of the two). In reality, scenarios involving a decline of habitat quality (scenarios 2, 4, 6, 8, 10, 12) can be viewed as a means of assessing how declining habitat conditions might affect future RLP condition *regardless the cause* of that habitat decline.
- For modeling tractability and to reduce the dimensionality of scenarios, the PARTI decision model we used for future condition modeling applied simplifying assumptions such as a constant annual hatchery capacity, readily available monitoring data (such that true population trajectories were known to managers), range-wide coordination of stocking efforts regardless of state or other administrative boundaries, and no political or administrative hurdles to stocking. In the event PARTI is pursued for RLP, we expect

additional constraints and priorities to factor into the decision process, which might alter the future course of RLP condition in ways we cannot now foresee.

- Because of structural limitations in the PVA model, habitat changes were implemented instantaneously rather than gradually. This approximates reality for some scenarios like dam removal (which occurred in simulation year 1) but is less realistic for other environmental changes like decreased suitability (due to climate change) and increased risk (due to urbanization), which were implemented in simulation year 25. Although we acknowledge that climate and urbanization are likely to change more gradually during the next 50 years, significant temperature and urban-land-cover changes are expected by year 30 (2050; see section 4.2.1), suggesting that our modeling approach was reasonable.
- The PVA models assumed that some dams were complete (2-way) barriers to movement between MUs, whereas others were only 1-way barriers, blocking upstream but not downstream movement. This decision was based on the apparently high gene flow of RLP across the Martinsville Dam (Roberts et al. 2013, entire) a medium-sized dam. Eschenroeder and Roberts (2020, entire) also observed high gene flow of Roanoke bass (*Ambloplites cavifrons*) across the mid-sized Falling River dam, suggesting that this dam also might permit downstream dispersal of RLP. Although these, and perhaps other small to medium dams may allow gene flow over ecological time, we lack information on the influence of such barriers on movement probabilities or demographic connections in any given year. As such, our assumptions about partial permeability should be considered tenuous, though we anecdotally observed that even when two MUs were connected in models, immigrants were relatively rare.
- Given that RLP population sizes are not constant but are on trajectories, impressions of resiliency will depend on what point in the trajectory they are examined. We focused on a 50-year time horizon when assessing future condition. However, population size at year 50 is the endpoint of a trajectory that might be examined at other points along the way. For example, under both the "status quo" (scenario 1) and "worst case" (scenario 4) scenarios, all occupied MUs exhibited 100% persistence rates to year 30. At year 40, all occupied MUs exhibited ≥95% persistence under scenario 1, and all MUs except Otter and Middle Roanoke exhibited ≥95% persistence under scenario 4. The Goose MU did not fall below the 95% persistence threshold until approximately 48 years into the simulation under scenario 4, and it remained above this threshold through year 50 under scenario 1.
- Future habitat restoration initiatives were not considered in terms of their potential effects on future condition. Although such initiatives are likely, whether or not they are focused on RLP habitat in particular, we considered these activities too unpredictable to merit inclusion in future modeling. However, the potential effects of such initiatives could be explored by comparing the results of future scenarios that featured different habitat suitability scores but were otherwise identical. The effect of habitat restoration should manifest as an increase of habitat suitability (e.g., from "average" to "good"), so to the extent that *reduced* habitat suitability had a negative effect on MU persistence in model results, we might expect habitat restoration and *increased* habitat suitability to have a similar positive effect on MU persistence.
- We did not consider the effect of listing status on future protection, funding, and the ability to conduct management. Rather, we assumed consistent hatchery capacity, monitoring capability, partner cooperation, etc. into the future. As described previously,

regardless of the ESA status of RLP, the species is likely to remain a high-priority, and potentially a state-listed species in the states of Virginia and North Carolina. Given this emphasis, inertia from ongoing projects, and funding streams it entails (e.g., State Wildlife Grant funds), we expect continued population management of the species, and continued habitat restoration efforts within the range of the species.

- Finally, implementation of this SSA highlighted key remaining knowledge gaps that injected uncertainty into our assessment of habitat needs, factors affecting condition, and current and future condition. First, the spatial ecology and habitat needs of larval RLP are almost completely unknown. It is plausible that, like other *Percina*, larval RLP drift hundreds to thousands of meters and therefore are particularly vulnerable to hydrologic alteration and reservoir construction, both potentially creating conditions that prevent larvae from settling in suitable micro- or mesohabitats. As such, the ecology of this life-stage could be the primary bottleneck for population persistence, but because so much more is known of juvenile and adult ecology, our analyses and assessments are biased towards these older stages. Second, our understanding of relationships between factors we considered important to RLP (e.g., fine sediment, pollution events, dams) and indicators of resiliency is relatively coarse, being based on observed correlations with occurrence and relative abundance, theory, expert judgement, and simulation models. To our knowledge there have been no empirical studies of relationships between individual fitness measures or population vital rates and these key factors. For example, we do not know how much a given percentage increase in watershed urbanization will increase the percentage embeddedness of riffle gravel, or how much this increase in embeddedness will decrease individual growth or population recruitment. In this SSA, we attempted to bracket a plausible range of uncertainty in the (a) expected magnitude of possible changes to habitat conditions, and (b) expected magnitude of possible biological responses to these habitat changes. Nonetheless, additional research aimed at (1) better describing the early-life ecology of RLP and (2) quantifying relationships between vital rates and factors like embeddedness, pollution, hydrology, and movement barriers should be a high priority for the future. Resulting information could be incorporated into the assessment framework of this SSA to produce revised estimates of current and future condition.

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APPENDIX 1: Development of demographic estimates of population size

Table A1: Demographic estimates of population size for each occupied RLP MU, based on empirical fish-catch and habitat data. See footnotes for sources of information.

Population	Range extent (km)[a]	Patch density (patches km^{-1}) [b,c]	Catch per patch (fish $patch^{-1}$) [b,c,d]	Catch:abundance ratio [e]	Abundance per patch (fish $patch^{-1}$)	Fish density (fish km^{-1})	Population size (fish)
Upper Roanoke	354.0	5.8	2.5	0.31	8.1	46.8	16557
Pigg	233.2	12.3	0.6	0.31	1.8	22.1	5160
Goose	145.1	10.1	0.4	0.31	1.3	13.0	1891
Otter	213.5	9.1	0.3	0.31	1.1	9.7	2062
Upper Smith	116.0	5.5	1.6	0.31	5.3	28.8	3338
Middle Smith [f]	48.2	5.5	1.6	0.31	5.3	28.8	1386
Lower Smith [f]	68.4	5.5	1.6	0.31	5.3	28.8	1968
Lower Mayo [f]	54.2	5.5	1.6	0.31	5.3	28.8	1559
Middle Dan [f]	122.8	5.5	1.6	0.31	5.3	28.8	3531
Nottoway	383.9	3.1	1.4	0.31	4.4	13.8	5296

[a] SDM Team expert opinion

[b] Roberts (2018, entire)

[c] Patch density and catch-per-patch were estimated for the Upper Roanoke MU, including Roberts' (2003, entire) data from the North and South Forks of the Roanoke River

[d] Catch-per-patch was re-estimated for the Nottoway MU by multiplying the Upper Roanoke's value by 0.55, based on the relationship determined by Rosenberger (2002, entire)

[e] Catch:Abundance ratio (the ratio of first-pass catch to true abundance estimated from three passes) was re-estimated from 3-pass depletion studies of Roberts et al. (2011, entire) and Roberts (2003, entire) in the mainstem and forks of the Roanoke River

[f] No independent estimates of patch density or catch were available for these populations, so the Upper Smith MU's values were applied

APPENDIX 2: Details of the population viability analysis model

Rationale and general overview

The population viability analysis (PVA) model integrates a series of biological process and decision-making models (e.g., Figure 1) to (1) track future population size in response to variable environmental and management inputs, and (2) determine the most effective strategy to implement PARTI to maximize a series of population recovery targets (e.g., abundance, growth, spatial representation) conditioned on a series of management constraints (e.g., hatchery capacity, spatial limitations in release locations). Each model component will be described in greater detail, but in brief, the general modeling philosophy uses an age-structured Leslie matrix model (Fig. A2; Forecasting model) based on a) site-specific, density-dependent demographic rates and b) current age and site-specific abundances to produce an annual population forecast (x) for all possible translocation strategies j, for each site, s, over a length of time, t, in which each translocation strategy involved the theoretical release of a cohort of translocated individuals of varying numbers. The annual population forecast can be interpreted as a quantifiable and ranked list describing the extent to which the conditions at a particular site, at a particular site were in alignment with all management objectives (e.g., local population growth, abundance, improvements to regional connectivity). Next, the individual population outcomes from the theoretical release of a specific cohort of individuals at a specific site is weighed against the population outcomes from the theoretical releases of all other cohorts of individuals at the same site, as well as all theoretical releases at each other site (Fig. A2; Decision-making model) to 'solve' for the series of translocation decisions that can be applied to maximize the effectiveness of a set number of cohorts released to certain sites (T) conditioned on a series of management constraints, Z (see Decision-making model section). Lastly, the outcome (i.e., translocation decision) of this decision-making model is then applied to a secondary population model (Fig. 1C; Application Model), which describes the realized outcomes (i.e., age and site-specific abundance) as a function of these chosen translocation activities given additional temporal variation in demographic rates, specifically, survival costs associated with rare, environmental perturbations (ω) and emigration of adults to neighboring populations (ψ). After a specified period of time in which the model-generated translocation strategy is applied (e.g., 5 years), the forecasting model is updated using the current age and site-specific abundances from the Application model, and the process starts over.

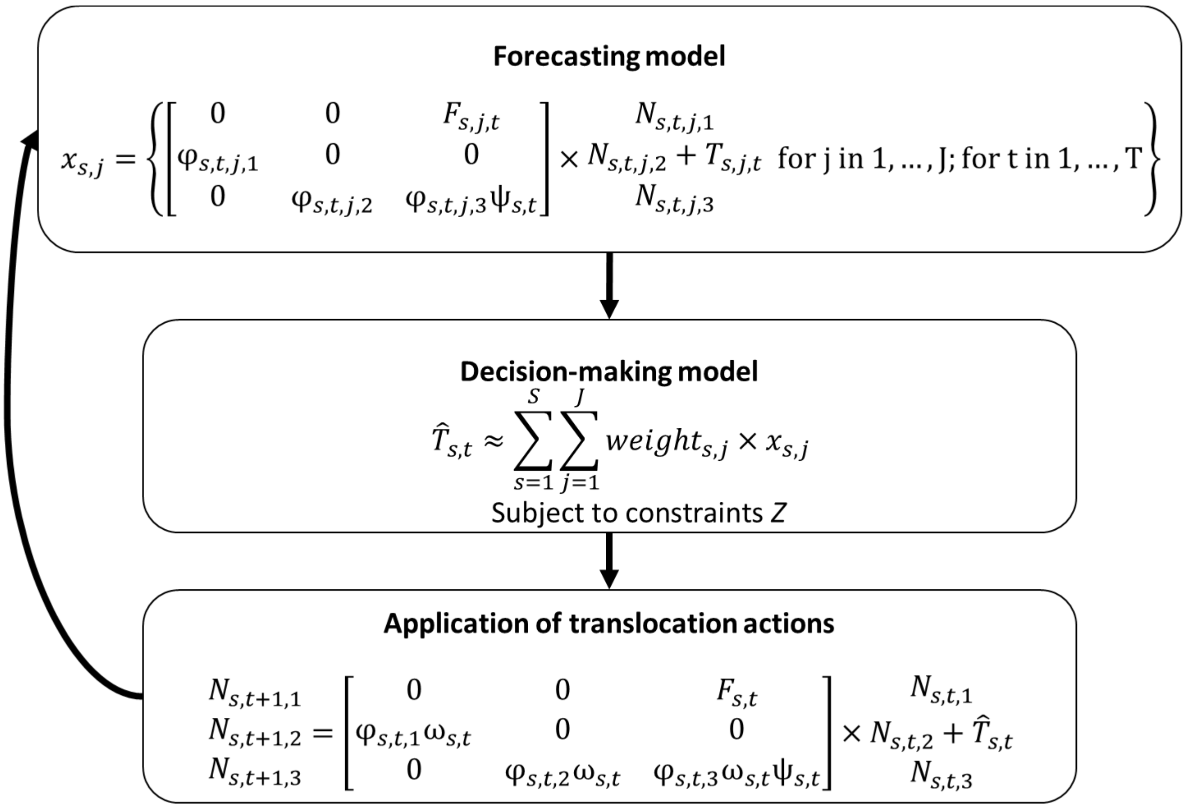


Figure A1: An example of a life history-informed structured decision-making model in which the predicted patterns generated from a (A) simulated population model inform (B) decision making options, which are than applied to the (C) simulated population, shifting its population trajectory.

Population Model

Inputs into population model – Data-driven information regarding spatial and temporal variation of demographic rates for the Roanoke Logperch (RLP), as well as the associations between population dynamics and environmental conditions were, in general, not available. Thus, we made a series of assumptions regarding broad patterns in population dynamics and used expert opinions to provide starting points for regional vital rates. More importantly, all inputs into the final end-product, the user-driven decision support tool, were adjustable. Thus, all assumptions made regarding a specific demographic process can be modified by the end-user as a function of their beliefs about each process. Through a structured decision-making exercise involving local and regional experts for these species, a network of waterways was developed for RLP that was either known have 1) active populations of RLP, or 2) were areas that were perceived to have the constituent elements to potentially maintain populations of either species if individuals were (re)introduced into the system. Given the sites specified as possible targets for translocation, we asked the panel of experts to classify the environmental conditions associated with each area to be one of the following: 1) Poor [generally decreasing population size]; 2) Low [potentially stable population size over short time periods, but declining over long time periods]; 3) Average [generally stable population size, but periods of population increase possible]; and 4) High [generally increasing population size]. Next, we asked the panel to consider how likely a broad-scale environmental disruption, anthropogenic or otherwise, would be to occur at a specific site, at a particular point in time. Following the development of these subjective measures of each site, we gathered from species experts coarse estimates of initial adult population sizes for each location and extracted approximate measurements of the amount of linear habitat available to RLP at each site.

Demographic Rates - In the absence of environmental perturbations and density-dependent processes, the geometric mean annual population growth rate for each site was a function of the assigned habitat quality (e.g., $\lambda_{poor} = 0.99; \lambda_{low} = 1.01; \lambda_{average} = 1.02;\ \lambda_{high} = 1.04$), which, based on preliminary model runs, (a) represented a continuum of population growth ranging from consistently shrinking to consistently growing, (b) produced plausible long-run estimates of population size for relatively well-studied populations like that of the Roanoke River, and (c) bracketed population growth estimates from the Roanoke River. Annual and spatial variation in each demographic rate was modeled as random normal process and was allowed to vary among simulated trials and scenarios. In addition to mean patterns in population growth, temporal and spatial variation in vital rates was further modified by density-dependent processes that influenced reproduction, 1st year survival, and site emigration. First, we applied a density-dependent constraint on reproductive success (F) that represented the consequences of a population approaching carrying-capacity, which was modeled as Ricker model similar to the approach from Murphy et al. (2019), and constrained the realized reproductive success ($\hat{F}$) to approach zero as the adult female breeding population, *N,* at site, *s,* in year, *t,* approach *K*, where K was a fixed value describing a theoretical population limit (in individuals per km of habitat).

$$\hat{F}_{s,t} = F_{s,t} \times exp\left(-\beta_F \times \left(\frac{N_{s,t}}{K_s}\right)\right)$$

Second, we modeled the realized site emigration rate ($\hat{E}$) to be represented by an inverse Ricker model, which constrained the emigration rate of adult females out of the system to approach the maximum emigration rate ($\bar{E}$) of 0.15 as the population approached the aforementioned carrying-capacity threshold.

$$\hat{E}_{s,t} = \bar{E} \times exp\left(-\beta_E \times \left(\frac{K_s}{N_{s,t}}\right)\right)$$

Lastly, we also modeled the realized juvenile survival rate (φ) to be represented by an inverse Ricker model, which constrained the realized juvenile survival rate to rapidly approach zero if breeding densities achieved extremely low levels ($minK$ =1.5 females/km). β_φ was designed to be not meaningfully influence φ until population sizes were extremely low, but after this threshold was reached, juvenile survival is minimized.

$$\hat{\varphi}_{s,t} = exp\left(-\beta_\varphi \times \left(\frac{minK_s}{N_{s,t}}\right)\right)$$

Environmental Perturbations – In addition to variation in demographic processes governed by habitat conditions and density-dependent, vital rates were also impacted by random density-independent perturbations that were allowed to vary in frequency and impact. During each year of a simulation, the occurrence of an environmental perturbation at a specific site was the outcome of random Bernoulli trial, ψ_s, with a probability of p_{risk}, which was a function of how environmentally at-risk a specific site was considered to be. If ψ_s indicated a perturbation occurred, the survival rate of all individuals was reduced by a fixed quantity that was specified for each simulation.

Decision-making model

The primary objective of the original SDM modeling exercise was to rank the population outcomes associated with *all* possible PARTI decisions into a reduced subset of decisions that influenced the likelihood of reaching specified recovery targets in the most efficient way possible, which could then be implemented in either an exploratory manner or applied in practice. The ranking of the efficiency of specific management actions was performed through a decision-making model that weighed the relative benefits to various metrics of population health (e.g., spatial distribution, population growth, abundance, and achieving specified recovery targets) associated with particular translocation actions against the benefits of all other actions available. From the perspective of the model, this was performed by setting a series of checkpoints (e.g., every 5 years) within the population model, in which the decision to translocate individuals into each population was revisited by using information based on predictions of population health in the near future as a function of translocation decisions. The most effective set of decisions to distribute the individuals available for translocation across sites to maximize management objectives was solved through mixed-integer linear programming (MILP) using the R package OMPR. The formula for the distribution of resources was modeled as a set of possible translocation targets, or sites, *S* = {1 …*I*} and possible translocation decisions *D* = {1 …*J*}, which represented a series of pre-determined quantities of individuals that could be translocated into a site (e.g., 0, 50, 100, 150, and 200), in which the decision to translocate *D* individuals into site *S* was informed by a model that attempts to maximize a series of population objectives based on predicted outcomes from all possible translocation decisions across all sites (Equation 4).

Utility function:

$$\sum_{i=1}^{I}\sum_{j=1}^{J} weight_{i,j} \times x_{i,j}$$

Subject to the following constraints:

$$a)\sum_{i=1}^{I} x_{i,j,t} \leq hatchery\ capacity_t, j = 1, \ldots, J; t = 1, \ldots T$$

$$b)\sum_{j=1}^{J} x_{i,j,t} \leq 1, i = 1, \ldots, I; t = 1, \ldots T$$

$$c)\sum_{i=1}^{I}\sum_{j=2}^{J} x_{i,j,t} > 0; t = 1, \ldots T$$

$$d)\sum_{i=1}^{I}\sum_{j=2}^{J} x_{i,j,t} \leq 5; t = 1, \ldots T$$

$$x_{i,j,t} \in \{0,1\}, i = 1, \ldots, I; j = 1, \ldots, J; t = 1, \ldots T$$

Where *weight* represented a utilization-function based on predicted population outcomes if *j* individuals were translocated into site *i* for each year in decision point *t.* Specifically, the benefit function represents the standardized rank placement of the following features following 5 years of different magnitudes of translocations into a site. And *Hatchery capacity* (a) represented the total number of individuals of the correct age-class available for translocation across all sites for each year of decision period, *t,* which serves as an absolute constraint for the amount translocated in a given year. Other constraints forced that (b) a single decision to translocate *j* individuals is made for each site (e.g., 0, 50, or 100, but not 50 and 100 into one site) individuals in a single year; and (c) a minimum of 1, and a maximum of (d) 5 sites were able to receive translocations in a given year. Following the outcome of the decision-making process, the proposed translocation strategy was implemented identically for 5 years until a new decision-making process was set forward and implemented.

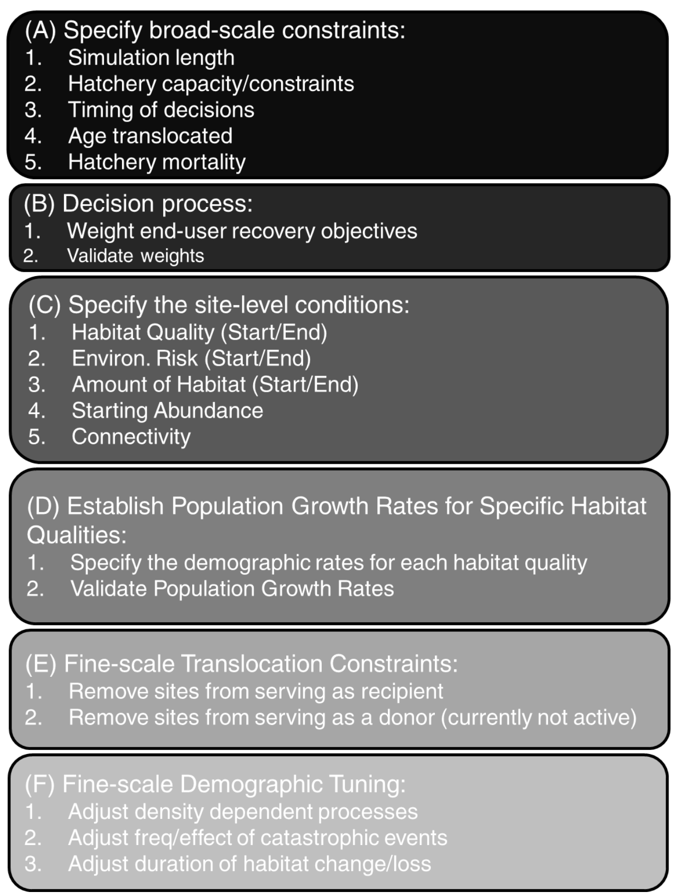
Together, this model simulates population growth for a number of populations that consist of individuals that, to an extent, can move among other populations, reproduce, and ultimately die as a function of environmental variation that is partially defined by the user and partially outcomes of random perturbations of vital rates. Additionally, a series of short-term population projections are performed to determine how sensitive each metric of population health is to a range of translocation batches (i.e., varying group sizes of potential translocees) for each population, which the decision-making model interprets to produce a translocation strategy that most effectively meets the specific conservation objectives conditioned on the limitations to conservation resources. Given the lack of empirical data regarding many aspects of the population model, and the inherent subjective nature of the decision priority model, this decision support tool was design to allow for almost all aspects of the ecological and conservation processes to be adjustable by the user.

Study System

Following discussions with species expert stakeholders (i.e., the SDM team), a consensus was reached in which 18 river segments were considered to be potential target sites for population recovery actions within southwestern Virginia and northern North Carolina. Of these 18 waterbodies, 11 were currently occupied by RLP and 7 were believed to have either have had RLP in the past or had the constituent elements that could potentially allow for population persistence under varying levels of certainty. Baseline habitat conditions were derived from expert opinion and represent general patterns in population growth based on these perceived conditions in which sites classified as Poor, Low, Average, and High. Risk represents the perceived probability of a significant adverse phenomena (e.g., chemical spill, pollution event), in which Low and High were equivalent to a 5% and 20% annual risk of an event occurring that resulted in an extreme mortality event (6% reduction in survival). Other user-defined system constraints are described in greater detail below.

Graphical User Interface

A graphical user interface (GUI) for the user-driven decision support tool was developed using the shiny platform in R to provide end users with access to most of the simulation capabilities for the RLP PVA model described in this report. Currently, RLP GUI products can be found at:
Roanoke Logperch: https://daniel-gibson.shinyapps.io/RLP_MODEL/
The original objectives of the GUI PVA were to 1) improve decision-makers' abilities to weigh the consequences and benefits of conservation decisions; and 2) improve the transparency behind how conservation decisions in data-limited systems, such as the RLP. The tool achieves this by providing the framework for users to produce simulated scenarios that predicts the best suite of PARTI decisions conditions on system constraints and environmental variability specified by the user. Given that there was very little data available to inform demographic parameters, the tool provides a substantial amount of flexibility in what demographic or environmental values inform the simulation, but this requires end-user input to build the simulation that is desired.



There is a step-by-step process of developing a user-specific simulation with this tool (see graphic below). The tool is physically structured by grouping similar constraints/variation to improve user workflow. Each step in the flow chart is expanded in greater detail below, but in brief, the process starts by 1) identifying the system-level constraints; followed by 2) the importance of specific recovery objectives; 3) spatially variation in habitat quality, connectivity, and abundance; 4) spatial variation in vital rates; and concludes with finer-scaled modifications of 5) translocation constraints and 6) demographic processes.

System Constraints

The 'Study System' landing page serves as the location to adjust broad-scale, simulation-level parameters, which determine the types of questions or assessments a specific model simulation would be functionally test. Some of the critical parameters include the 1) length of the study simulation (in years); 2) Hatchery capacity, or maximum number of breeding individuals that would attempt to be reared in a given year for translocation purposes; 3) the minimum and maximum number of individuals that should be considered to be releases in a specific site, in a single year; 4) the age that individuals should be translocated; and 5) the average survival rate of individuals within the hatchery. Together, these traits combine to determine how many individuals of a particular age class are available for translocation as well as system specific constraints regarding the types of translocation decisions that may be available in a manager's toolkit. Additionally, the recovery objective, in breeding female density, is specified here, which depending on the end-user's goal, will a primary determinant if a specific suite of simulated conditions is ultimately deemed to result in population recovery.

Habitat Constraints

The habitat constraints section of the GUI provides the end user the opportunity to modify current and future habitat conditions as well as critical starting conditions (initial breeding abundance, local and regional connectivity) for each river length within each ecogeographical region. In brief, this section is the primary mechanism for the end-user to create spatial variation in current or future conditions to assess or predict the likelihood of reaching recovery targets given a variety of simulated conditions. To minimize visual clutter and improve user accessibility, the GUI is structured to allow for region-by-region visualization of each site-specific trait (current habitat quality, future habitat quality, current environmental risk, future environmental risk, current amount of habitat, future amount of habitat, connectivity potential, and starting abundance). However, given that a substantial number of variables that may need to be edited for a specific assessment, starting conditions can be 1) saved as a .csv file for future use; and 2) and edited outside of the GUI (e.g., in Microsoft excel) and bulk loaded into the GUI from a .csv file conditioned on following the data upload formatting guidelines. Within the GUI, an end-user can modify each parameter for each site by 1) selecting the region; and 2) the specific parameter of interest; which will provide user to hidden menus that describe the possible range of values that a particular parameter, within a particular region, at a specific site may be assigned.

Current Habitat – Specify the starting habitat conditions (1: Poor; 2: Low, 3: Average; 4: High), which determines the mean age-specific vital rates for individuals with a specific site. The vital rates for each habitat quality level is specified in the Vital Rates section.

Habitat Change- Allows for a specific site to 'change' habitat qualities as a function of either habitat improvements or habitat degradation during the simulated study period. The duration of habitat changes (i.e., how many years it takes to reach the final habitat quality from the starting conditions) is a linear process and specified in the Miscellaneous Information tab. Conditions cannot be improved or degraded beyond 'High' or 'Poor' conditions, respectively. Default conditions are set for no site to experience a change in habitat quality, therefore end-users should verify that any changes made to the starting or changed habitat conditions match their designed goals. If multiple sites are specified to change habitat quality, the timing of habitat change currently must be constant across all sites.

Current Risk – In addition to habitat quality, end-users can specify how environmentally-at-risk a specific site is now, as well as in the future. Although specific use, and interpretation of the environmental risk term is flexible, variation in risk results in variation in the occurrence of rare, but random events that are associated with mass mortality of individuals across all age classes. At the site-level the user can classify a site as either low (1) or high (2) risk. Following this distinction, the probability of a rare event occurring, as well as the underlying mortality rate related to two classes of risk are available to be changed in the Miscellaneous Information tab.

Risk Change – Similar to habitat quality, the model can assess the consequences of increasing or decreasing how environmentally at risk a site is. This parameter can resemble conditions associated with climate change or increased anthropogenic intrusion, and operates in a similar fashion as the habitat change parameter. Initial conditions are specified that no change occurs, and users can modify this by increasing or decreasing how much risk is associated with a site. Likewise, the duration that this pattern in increased or decreased riskiness occurs is specified in the Miscellaneous Information tab. If multiple sites are specified to change riskiness, the timing of this event currently must be constant across all sites.

Connectivity – We incorporated a connectivity surface to allow for users to assess the extent to which current barriers to movement (or their removal) may influence local and regional population dynamics that was based on expert opinion regarding whether individuals currently have the ability to unidirectionally move (themselves or via a secondary host) from their natal location into another river length during their most vagile life stage (RLP: adult, James spinymussel: glochidia). Movements were generally limited to only consider movements among sites associated with the same ecoregion, but certain cross-region movements were allowed when geographical conditions suggested movements were reasonable. Inputs into the connectivity surface are visualized in the decision support tool as (0): Movement from 'row site' to 'column site' not possible; and (1) Movements from 'row site' to 'column site' possible. Given that the connectivity surface is presented as bidirectional matrix, movements can be unidirectional meaning individuals can move from Site A into Site B, but not from Site B to Site A, which may be the case when a dam is obstructing travel to higher reaches. The connectivity surface only determines what site movements are possible, the density-dependent emigration rate (Miscellaneous Information) determines the extent to which immigration/emigration dynamics influenced population dynamics.

Abundance – Population growth models require an estimated starting abundance to serve as starting conditions at the scale of inference, which in this model was age-class specific female abundance for each river length, or site. However, detailed assessments of site-specific abundance were lacking for both of the species considered. Similar to other knowledge gaps, estimates of the breeding female abundance were based on expert knowledge. However, following the acquisition of novel information or based on specific simulation goals, end-users can modify the breeding female abundance for each site within the decision support tool. Importantly, the user only needs to specify the breeding adult female abundance at the start of the study, and the model will generate an abundance estimate for each other age-class based on the stable age-ratio associated with the underlying vital rates for each site.

Amount of Habitat – In addition to testing the consequences of habitat degradation or improvement on population growth or the likelihood of achieving recovery targets, users may also change the amount of habitat at either the beginning of the study or during the study to assess the consequences of habitat loss (End < Starting Conditions) or habitat creation (End > Starting Conditions). Given that 1) multiple demographic processes are influenced by density dependent processes; and 2) recovery targets are based on population densities; changing the absolute amount of habitat impacts individual demographic processes and ultimately population growth and successfully reaching a recovery target. A critical point is that adjustments to the amount of starting available habitat will shift the recovery target to match the starting conditions. However, adjustments to the ending habitat availability will not shift the recovery target. In other words, specifying that Site A will lose 25% of habitat during the course of the study will not allow the site to reach its recovery target with 25% fewer individuals, as it will be calculated as function of its local density based on the initial amount of habitat but demographic processes will be penalized due to the loss of habitat. Similar to the habitat degradation module, users can specify the duration (relative to year 1) in which habitat loss will occur, and that habitat will be lost/gained in a linear manner as a function of the starting and ending conditions and the duration specified. Default conditions are set for no site to experience a change in habitat amount. If multiple sites are specified to change in the amount of habitat, the timing of habitat change currently must be constant across all sites, but the direction of effect does not have to be identical (certain sites can lose habitat and certain sites can gain habitat during the same model run).

Vital Rates

Specify Vital Rates –In previous sections of the decision support tool (i.e., *Current Habitat, Habitat Change*), each site was assigned a habitat quality type (i.e., Poor, Low, Average, High). These metrics of site quality are functionally linked with the rate of population growth for a specific site, which are the outcomes of the values specified in the *Vital Rates* section. Here, age-specific survival rates (i.e., 3 for RLP) and an adult fecundity parameter are provided for each level of habitat quality, which constrains the mean population growth rate for a specific site as a function of the vital rates associated with a particular habitat quality and the previously established habitat quality assigned to a specific site. Lastly, and critically, the specified vital rates, and their corresponding population growth rate represent the idealized conditions when not impacted by density dependent forces, environmental perturbations, or random variation. The impact of density dependent processes on these idealized conditions can be viewed and modified in the *Miscellaneous Information* tab.

Calculate Population Growth – Given that unrealistic population growth rates can be generated from seemingly realistic combinations of vital rates, a population growth estimator is provided to validate the habitat quality-specific vital rates generate a mean population growth rate (i.e., dominant eigenvalue at stable age distribution) that corresponds to the end-user's beliefs or objectives. An estimated population growth rate will be calculated as a function of the current slider positions (*Specify Vital Rates*) by clicking the *"Estimate Lambda"* button and navigating to the '*Population Growth*" tab. There is no inherent constraint forcing that population growth rates for each quality following in magnitude as intended (i.e., High > Average > Low > Poor), thus it is up to the end-user to verify the initial conditions resemble the goals of a particular simulation.

Translocation Constraints

In addition to system-wide constraints to the translocation process (e.g., numbers available, decision timing, and objective weights) that were previously described, translocation actions can be further modified from the lens of potential targets. In brief, each river length can be manually flagged to be excluded from consideration to receive translocated individuals. Additionally, future iterations of the decision support tool may require translocations to come from a local source (i.e., a site within the same eco-region), thus a preliminary structure has been placed to allow for the specification of which sites may be considered as source material for translocations.

Miscellaneous Information

The miscellaneous information tab serves as a repository for a series of fine-scale adjustments to the various 1) timing or consequences of environmental risk, 2) density-dependent mechanisms; and 3) habitat/environmental change processes; which each operate within the biological model and shift population growth rates away the proposed mean value.

Consequences of Risk – As mentioned above, environmental risk was simplified to represent spatial variation in how likely a catastrophic event would occur at a site as a function of its surrounding constituent elements (e.g., relative proximity to industry, cities, agriculture, sensitivity to climate change). The occurrence of a catastrophic event in a given year was drawn from a Bernoulli distribution with a probability, p, in which p was a function of whether a specific site was considered to be a high or low risk of a catastrophic event, which are both specified on this tab. If a catastrophic event occurs (i.e., successful Bernoulli trial), the consequence of that event, c, is represented as a value between 0 and ~1, which is multiplied against the age-specific survival rate for that site in the absence of an environmental disturbance. In other words, it represents the proportion of individuals that would have inherently survived in a normal year that additionally survived this event (i.e., 0 = all individuals die, ~ 1 = approximately no additional individuals die). The model assumes that the consequence of a catastrophic event is identical between high and low risk areas, it is simply the frequency in which these events may occur that determine how environmentally-at-risk a site is.

Carrying Capacity – The realized population growth rate as a function of breeding female density is specified by a series of features that represent the extent (i.e., slope) by which 1) fecundity, 2) site fidelity; and 3) 1st year survival is negatively impacted by local density (see

Demographic Rates above) and operational constraints (i.e., inbreeding depression threshold and carrying capacity threshold) that places limits on the non-linear relationships between density and each demographic rate. For most users, the specific values used for a given density dependent process will not be meaningful as long as the corresponding visualization provided by the decision support tool is in alignment with the user objectives. However, in brief, the three slope parameters interact with one another to influence the curvature of the non-linear function, whereas the operational constraints shift the curved line along the x-axis, and together dictate what female-population densities are associated with which level of population growth as a function of habitat quality (color). The horizonal gray line represents the point of population stationary, and the vertical red line represents the highest density in which a population can remain stable in the best quality habitat. It is critical that users carefully balance the densities specified as a recovery target versus the realized, optimal carrying capacity (red line), as specifying recovery targets greater then the optimal carrying capacity may never be successful. But specifying an unreasonably large optimal carrying capacity will, depending on other system parameters, allow for population densities to become so large than inference will be low.

Data Upload/Data Download

Given the near large number of adjustable parameters and their potential influence on model results, a data file describing the site-level habitat constraints can be saved as a .csv file as well as bulk loaded from a similarly formatter .csv file.

Data Formatting Guidelines – In short, the format of the downloaded data file is the formatted correctly for the data upload function. Therefore, if the user modifies an input file that was previously downloaded from the decision support tool, but maintains the general form of the input file, it should generally be uploaded without issues. For both species, the first column should be left without a header name, and represents the Site ID # and is functionally linked with a specific site name. Although Site ID #'s can be inputted in any order (i.e., sorted or unsorted), disconnecting the correct ID # for a specific Site will result in an incorrect data upload. Misspelling a site name in the data upload will not impact model function as long as the ID number remains correctly linked with the site in question. Data describing the beginning (Habitat) and end habitat quality (End Habitat), the beginning (Risk) or end risk (End Risk), and site access (Access) can be uploaded as a mixture of a limited number of numeric and categorical descriptors, as shown in Table X. For the habitat variables, the upload function will accept: 1 or Poor, 2 or Low, 3 or Average, and 4 or High. For the risk variables, the upload function will accept: 1 or Low, and 2 or High. For the access variable, the model will accept: 0 or N or No, and 1 or Y or Yes. Data describing the Starting and Ending amount of habitat or the starting breeding female abundance (Start N) should be a positive value (discrete or continuous) or zero.

APPENDIX 3: Development of a minimum viable population density for RLP

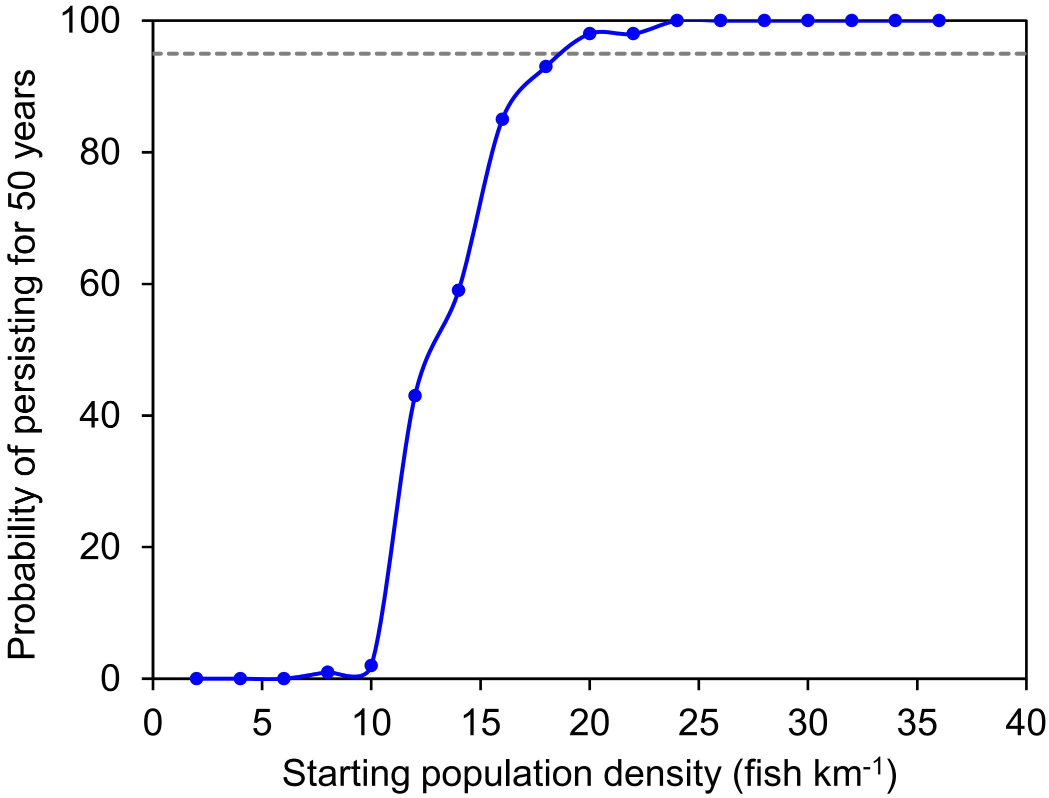


Figure A2: The relationship between starting population density and the probability of persisting to year 50, for a generic RLP population with an available habitat extent of 195 km, "average" habitat quality, and "low" risk. The dotted line indicates a persistence probability of 0.95; thus, populations with a density of at least 20 fish km^{-1} had a >95% chance of persistence.

APPENDIX 4: Relationship of estimated current and future population sizes

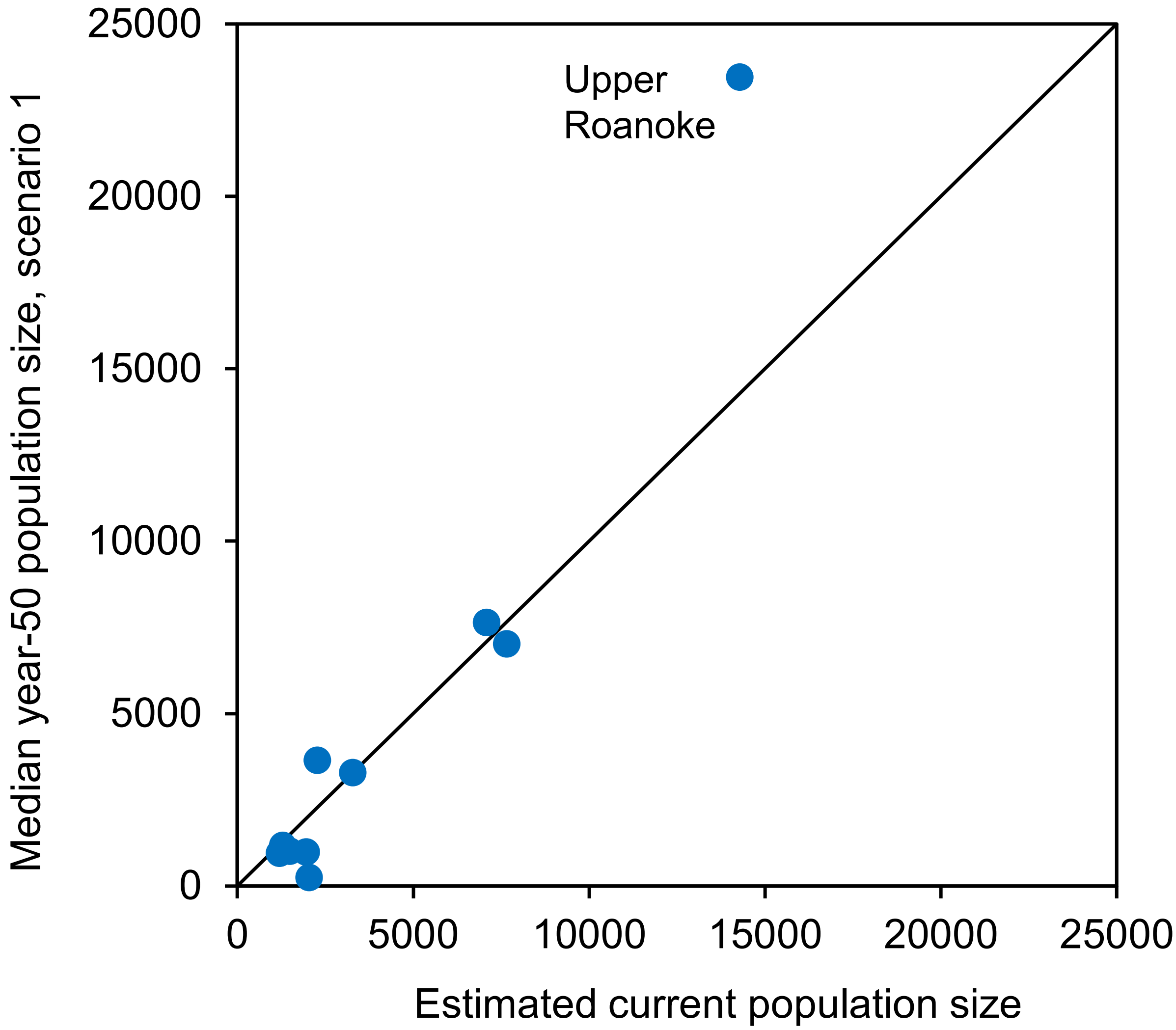


Figure A3: Relationship between estimated current population size (equal to starting population size in simulation models) and median population size at year 50 forecasted under the "status quo" scenario 1, for occupied MUs. Middle Roanoke was excluded because its current population size is poorly known. A 1:1 line is shown for perspective. Other than the Upper Roanoke outlier, the model does not consistently predict increases or decreases in population size.