Final Report: Data provision and projected impact of climate change on fish biodiversity within the Desert LCC

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ABSTRACT

The four primary objectives of this project were to: (1) compile a dataset of fish occurrence records for the entirety of the Rio Grande drainage in the US and Mexico; (2) improve that dataset by reformatting dates, synonymizing species names to a modern taxonomy, georeferencing localities, and flagging geographic outliers; (3) for those species with sufficient data for modeling, create species distribution models (SDMs); (4) use the environmental conditions determined via those models to project the species distributions into the future under two climate scenarios. To accomplish those objectives, we compiled 495,101 fish occurrence records mined from 122 original sources into a single database. We then, on the basis of text string searches of the original sources' verbatim locality fields, extracted 145,426 records that we judged to have a reasonable likelihood of being from the Rio Grande drainage. For those records we edited taxonomy, reformatted dates, and finally georeferenced 59,156 (41%) records, which proved sufficient for constructing SDM's for 36 species that met *a priori* quality assurance criteria. We provide basic interpretation of these models and discuss projections of them into several different future climate forecasts. Products include raw model outputs and symbolized maps helpful in interpretation and comparison, as well as raw data sets and recommendations regarding how all of these product might be used in future management and research efforts.

1 DATA MINING AND PROCESSING

1.1 DATA COMPILATION FROM VARIOUS SOURCES

We queried large online multi-institution data providers as well as our own Fishes of Texas Project (Hendrickson and Cohen 2012) and our smaller internally derived databases, and made direct requests to museums to compile 495,101 North American fish occurrence records from 122 entities. These data consist primarily of specimen-based records that are thus verifiable via examination of museum specimens and other documentation held in museum archives. We started with 15 separate queries of 11 databases (Appendix 1). Those data sources providing the greatest numbers of records were GBIF (Global Biodiversity Information Facility; http://www.gbif.org/), FishNet2 (http://www.fishnet2.net/) and FishBase (http://www.fishbase.org/), all major data providers of global species occurrence data. The other eight sources are datasets derived by us for other projects or derived by affiliates working on their own projects, as well as museum databases. These sources provide data covering the geographic scope of this project and more. This extensive data gathering approach, which ultimately included data from 119 independent contributing entities (Appendix 2), ensured a comprehensive dataset maximizing the number of records for the Rio Grande Basin. This data gathering approach, which includes data from outside the study area of this project, and from large, as well as smaller and lesser known databases that are typically little utilized, but that often hold valuable and sometimes rare occurrence records, allowed us to fulfill our broader research objectives to document fish occurrences in all Texas drainages (including nearby US and Mexican states) as well as satisfy the narrower scope of this project. The relevant data derived from this project will eventually be incorporated into the Fishes of Texas Project (Hendrickson and Cohen 2012) for provision online to researchers around the world.

The final dataset is smaller than what we downloaded directly from these data providers since we were surprised to find records of non-fish taxa in the query results, apparently due to errors in higher taxonomy. We removed those records, as well as records indicated to be based on fossil specimens.

We estimate, based on unique combinations of our formatted "institution" and "catalog number" fields, that the dataset herein provided represents approximately 343,206 unique museum specimen lots. However, the actual number of records is far greater. This is because we chose to retain near duplicate records that resulted from multiple queries to different providers that serve overlapping data. We felt it important to retain these near duplicates since they often differ in data completeness or content in sometimes subtle but potentially important ways, most often due to provision of different fields by different data servers. Removal of such near-duplicates is not easily done with automated methods without compromising some level of data quality and we decided, therefore, to provide all records here. The record reformatting efforts, date parsing, taxa synonymization and georeferencing done for this project will potentially help us to more fully reconcile such duplicates in the future.

1.2 ISOLATION OF RIO GRANDE DRAINAGE RECORDS

Before applying coordinates to localities and further processing the data, it was necessary to isolate those records potentially from the Rio Grande drainage which are specifically relevant to this project. Identifying occurrences in our dataset that are from within the Rio Grande drainage is problematic since so often those data fields that would allow one to isolate them (state, drainage, locality) are incomplete, misspelled, of irregular format, or contain data that conflict with other locality fields. Our attempts using automated georeferencing techniques, as per our proposal, to aid in this task were determined to be insufficient leaving many multiple georeference choices, and often not assigning records to the Rio Grande drainage that we believed, based on manual inspection, to be in that drainage (and mis-assigning many others to the Rio Grande drainage). Instead we identified these records via a series of text searches, finding 145,426 records that are likely from the Rio Grande drainage including 16,215 records with very high probability of being from the Rio Grande drainage (having specific text strings indicating so, or provided to us specifically because they were from the Rio Grande) and another 129,211 less likely from the Rio Grande drainage (having state fields containing states that include some Rio Grande drainage). This conservative approach ensures that all potential Rio Grande records are provided, but also still results in containing many not from the Rio Grande drainage. The final data set provided here (see "Supplemental data") is derived from 84 unique entities.

1.1 NORMALIZATION AND SYNONYMIZATION

Typical of legacy museum data, the starting dataset for this project suffered from mis-spellings and inconsistent formatting resulting from independent handling by diverse institutions and individuals for sometimes over a century before becoming part of projects like this that strive to normalize such inconsistencies. Field names and data definitions varied across institutions but we were able to match incoming data fields to standard fields with little difficulty. Due to differences in data definitions, original data contents were "broken" apart into our pre-defined and separate fields (often with adjustments to date format and removal of special characters, e.g. diacritical marks - áéíóúñ), but the original "verbatim data" as received from the original sources, albeit sometimes reformatted, were always retained intact. This critical step of normalization of the data content in new, consistently formatted fields now allows the dataset to be searched as a single resource, but for any record any field can always be easily and quickly compared to the "verbatim" fields.

Institutional acronyms (codons) varied across data sources and were synonymized (Appendix 2) to each institution's American Society of Ichthyology and Herpetology standard institutional codon (Sabaj Pérez 2013). For institutions not found in that resource we maintained the codon as received from the data donor.

Except for those records originating from our own Fishes of Texas project (Hendrickson and Cohen 2012), collector and determiner names have not been synonymized or standardized in this database, so users must rely on the verbatim fields for that content.

Dates were typically received as a single field and were interpreted into a six field system (begin year, begin month, begin day, end year, end month, and end day) to facilitate managing of dates. No editing of data content occurred in this step, only a strict transformation into these fields. However, for some records extracted from our Fishes of Texas project, in which dates were previously edited, those edited dates were included.

Working on this dataset caused us to become aware of a date error in our own Texas Natural History Collection's (TNHC) data as served by GBIF. Of the 3,486 records from TNHC that were retrieved through GBIF for this project, we determined that 2,160 had incorrect dates. The correct dates were always more recent (often by decades) than what was provided in GBIF. We have not been able to determine how this error occurred, but have corrected those dates in this project's dataset to match those in our internally maintained TNHC collection database.

Verbatim taxa names were synonymized and brought into compliance with a modern standard taxonomy. This process was facilitated by use of Taxonome (Kluyver and Osborne 2013). This free downloadable tool allows verbatim taxa names to be compared, using "fuzzy" matching algorithms, to a list of accepted names. It scores matches for accuracy and the score produced can be used to aid the decision-making process. Before matching, we edited the verbatim names to remove text that was clearly not part of any formally accepted name (i.e. "sp.", "cf", "unidentified" and other variations of these, as well as what appeared to be stray keystrokes). Then, using Taxonome software, our edited verbatim names were matched to the taxonomy of the American Fisheries Society (AFS; Nelson et al. 2004) and separately the taxonomy provided by the Integrated Taxonomic Information System (ITIS; http://www.itis.gov/; downloaded in parts Nov 15, 2012 and May 13, 2013). When an exact match (score =1) to both was found that name was accepted without examination. When the AFS taxonomy had no match, we accepted the ITIS name if the score was 0.8 or greater. Likewise, when the ITIS taxonomy had no match, we accepted the AFS name if the score was 0.8 or greater. When no match was made to either, we manually processed names. These non-matching names, however, were often attributed to spelling errors that once corrected, easily attributed to AFS or ITIS taxonomies. In some cases, names not in AFS or ITIS were found in FishBase (http://www.fishbase.org/search.php) or the Catalog of Fishes (http:// researcharchive.calacademy.org/ research/ichthyology/catalog/fishcatmain.asp). Names not matching any of these taxonomies and from locations outside of the Rio Grande Basin were often not synonymized, especially if they required manual synonymization. Taxonomy provided by donors only to taxonomic levels above family were not synonymized and were simply labeled as that taxonomic level. Since we used Taxonome to match genus and species names, family names were associated later and were matched to genera following AFS, and records without matches were matched to the ITIS taxonomy. Some names were found not to represent any fish and were labeled as "Out of taxonomic scope". Hybrids were not synonymized and were all called simply "hybrid". After fully synonymizing taxa in the georeferenced Rio Grande drainage dataset, we determined it to include 773 species in 72 families (Table 1), however, many are marine and estuarine species occurring only at or near the system's mouth.

Table 1. Taxonomic breadth of the georeferenced dataset expressed as number of records for each family. Note that many of these are marine families having occurences near the mouth of the Rio Grande and some are families that are likely erroneous and have been flagged..

Family	N records
Achiridae	7
Acipenseridae	1
Amiidae	1
Anguillidae	11
Aphredoderidae	1
Ariidae	16
Atherinopsidae	739
Balistidae	6
Batrachoididae	2
Belonidae	28
Blenniidae	3
Carangidae	49
Carcharhinidae	2
Catostomidae	1480
Centracanthidae	2
Centrarchidae	3524
Centropomidae	29
Chaetodontidae	1
Characidae	2076
Cichlidae	2992
Clupeidae	765
Cynoglossidae	3
Cyprinidae	11847
Cyprinodontidae	3139
Dasyatidae	1
Diodontidae	1
Doradidae	2
Elassomatidae	1
Eleotridae	53
Elopidae	10
Engraulidae	53
Ephippidae	5
Esocidae	4
Exocoetidae	2
Fundulidae	1366
Gerreidae	54
Gobiidae	92
Gymnuridae	1
Haemulidae	12
Hemiramphidae	1
Hybrid	28
Ictaluridae	1711
Kyphosidae	2
Labridae	1
Lepisosteidae	137
Lobotidae	1
Loricariidae	39
Lutjanidae	13
Monacanthidae	1
Moronidae	44
Mugilidae	109
Narcinidae	1
Ophichthidae	1
Ostraciidae	2
Paralichthyidae	30
Percidae	540
Petromyzontidae	1
Phycidae	1
Pimelodidae	1
Poeciliidae	4707
Pomatomidae	1
Pristidae	2
Salmonidae	817
Sciaenidae	138
Scorpaenidae	3
Serranidae	6
Sparidae	24
Sphyraenidae	3
Stromateidae	1
Syngnathidae	14
Synodontidae	5
Tetraodontidae	1
Trichiuridae	2
Unknown	149
Uranoscopidae	1

Specimens were not examined for verification of ID's since that was outside of the scope of this project, so all determinations were derived from the verbatim fields. However, since *Dionda episcopa* was recently split by Schönhuth et al. (2012) into many geographically allopatric species, we assumed, based on that work, that all *Dionda* records from the study area could be attributed to one of the species defined in that publication on the basis of geography. In addition, though the evolutionary history of *Astyanax* in Northeast México is complex and still being actively debated (Gross 2012; Bradic et al. 2012), we synonymized all occurrences to *A. mexicanus*. All *Cycleptus* sp. from the mainstem of the Rio Grande were synonymized to *Cycleptus elongatus*, although this disjunct population likely represents a unique and undescribed species (Lozano-Vilano 2010).

1.3 Georeferencing

Each of the records isolated as possibly from the Rio Grande drainage was considered for georeferencing and georeferencing priority was given to those locations considered, on the basis of locality descriptions, likely to have error radii under 6 kilometers, since occurrences with larger errors are of little use for many applications, including our Species Distribution Models.

The final database delivered by this project includes 59,156 georeferenced fish occurrence records collected between 1851 (earliest discrete date) to 2011 (Figure 1) from 4,759 unique localities within the Rio Grande drainage of the US and Mexico (Figure 2).

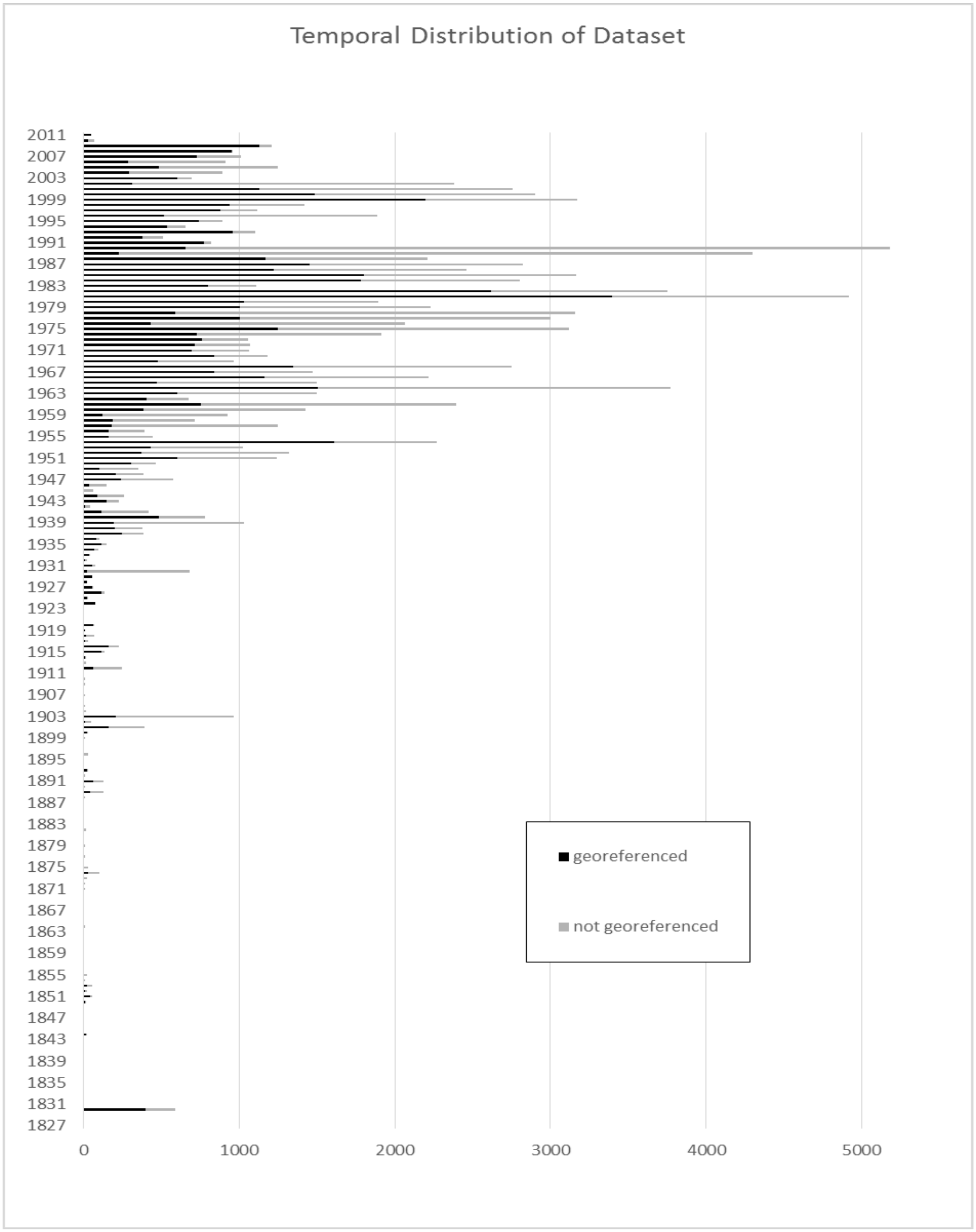

Figure 1. Temporal distribution of the dataset delivered for this project showing both georeferenced and ungeoreferenced records.

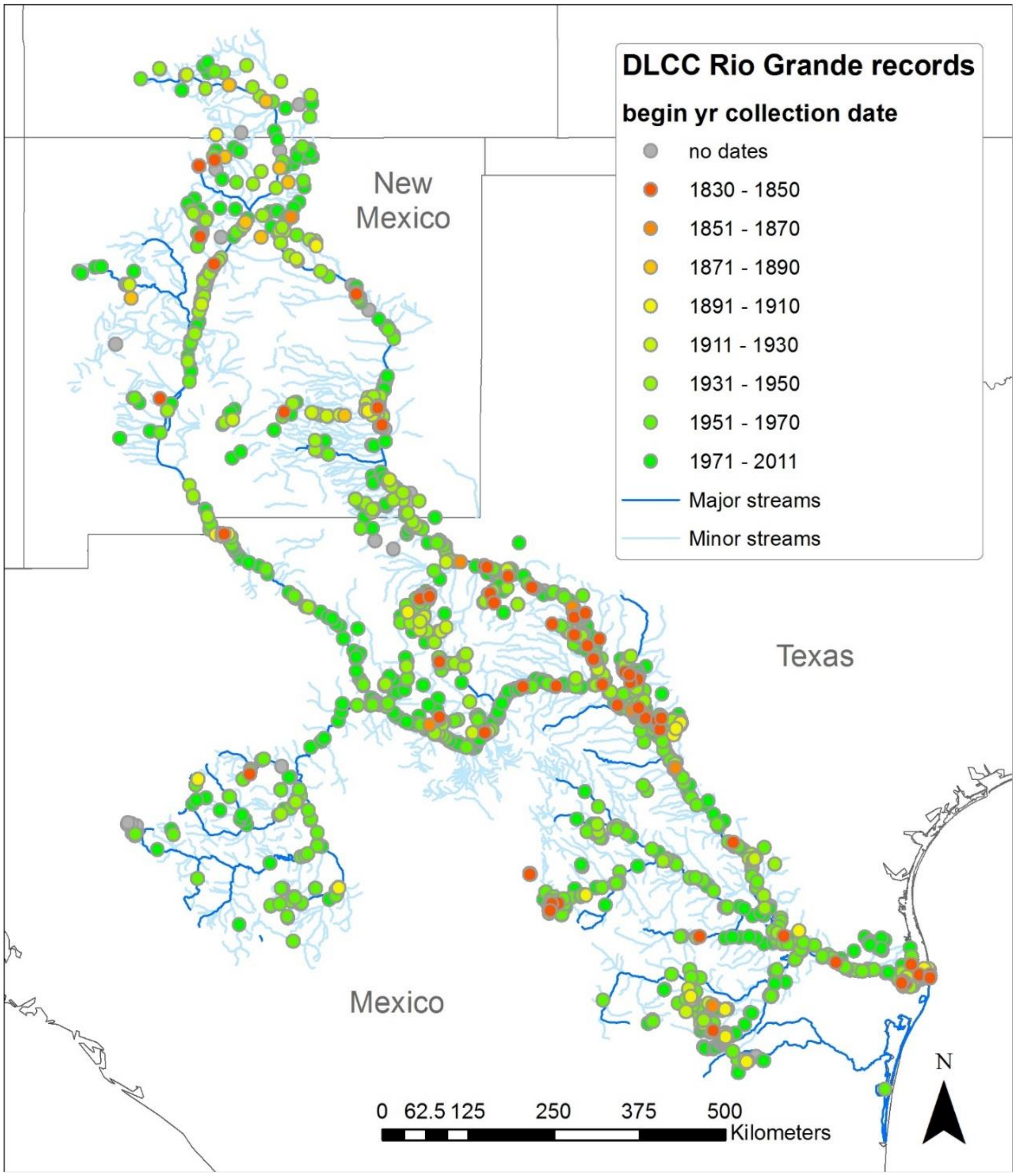

Figure 2. Georeferenced records within the Rio Grande basin.

Our georeferencing protocols are the same as those used in other large georeferencing projects such as HerpNet (http://herpnet2.org/) and MaNIS (http://manisnet.org/). All locations receive coordinates with an associated error radius calculated using an online calculator (http://manisnet.org/gci2.html). In addition to our own georeferences, we were able to extract additional georeferences from a concurrent multi-institutional project funded by the National Science Foundation and managed by the developers of FishNet2 that is georeferencing a much larger global fish occurrence dataset using Geolocate's collaborative and partially automated web-based georeferencing tools (http://www.museum.tulane.edu/ geolocate/community/default.html).

The dataset provided here includes 1,918 records from or near the Cuatro Ciénegas Basin (Coahuila, Mexico), primarily from our internally derived database which includes our own field collections as well as historic records going back to 1939. This is clearly the most complete source of fish occurrence data for this important National Protected Area. Most of this data was never before available, or if available was not georeferenced. Georeferencing legacy records from this area of high conservation interest has long been delayed since there are no definitive gazetteers or sources that tie locality names within the Protected Area to geographic coordinates. Therefore, georeferencing can only be done by someone with knowledge of the valley and who's aware of the many synonyms applied to the various pools, marshes and streams of the valley. Two of the authors of this report (Hendrickson and Cohen) have sampled in the valley extensively and have such knowledge. Hendrickson's multiple explorations of the valley in the 1990s with W. L. Minckley (one of the most prolific collectors working in the valley in the 1960's and 70's) allowed him to learn many of the locations that Minckley sampled and the names he applied to them. One of Minckley's publications (1969) maps most of his collecting locations and we were able to scan and overlay that map on Google Earth imagery (http://www.google.com/earth/) to allow us to precisely apply coordinates to many of his old collection locations.

After georeferencing, records that received coordinates were examined in a GIS environment species by species, and occurrences that were geographically disjunct and in conflict with distributions published by Page and Burr (2011) and Miller et al. (2006) were flagged as suspect (with a "1" in the "suspect flag" field of the dataset) and not used in modeling. Those 939 flagged records, however, are provided in this project's final dataset, which also includes all records that were not georeferenced (see "Supplemental data").

2 SPECIES DISTRIBUTION MODELS (SDMS) & CLIMATE PROJECTIONS

2.1 SDM BACKGROUND

Species distribution models (SDMs) are an increasingly popular tool for conversion of point occurrence data into range-wide continuous probability coverages useful for a great diversity of management-relevant applications (Guisan et al. 2013). This transformation is achieved through powerful software packages that evaluate statistical relationships between species occurrences and environmental variables. Here we produced SDMs for select priority fishes within the Rio Grande basin, and project them onto various future climate scenarios to determine potential shifts in climate-based habitat suitability. Figure 3 provides a conceptual guide for how SDMs (and other spatial products such as those provided in this report) should be incorporated into conservation planning and decision support (Guisan et al. 2013).

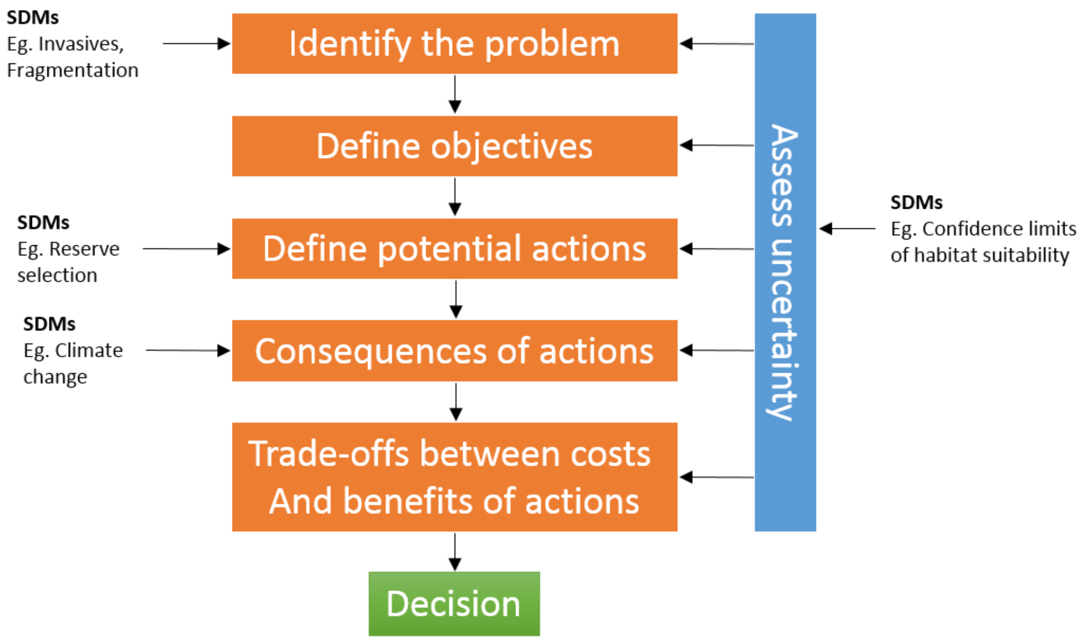

Figure 3. A decision-making process with indication of potential entry points for the use of SDMs in influencing conservation planning work. Adapted from Guisan et al., 2013.

2.2 Environmental variables

The environmental variables used in SDM construction (Table 2) were selected in part on the basis of expert evaluation of models created from subsets of variables for a set of species with well-known distributions (see Labay et al. 2011 for a detailed description). Climatic variables were obtained from http://www.worldclim.org (Hijmans et al. 2005). These data were constructed through interpolation of average monthly climate data from worldwide weather stations, and included databases compiled by the Global Historical Climatology Network (GHCN), the FAO, the WMO, the International Center for Tropical Agriculture (CIAT), R-HYdronet, and a number of additional sources for various parts of the globe using methods detailed at http://www.worldclim.org/methods. The climate variables used in the models are analogs of bioclimatic variables under future conditions (IPPC 4: see 2.5 SDM climate change projections emission scenario variables).

Table 2. Environmental variables used to train and project models

Layer category	***Description***	***Source***
Topological	aspect	2.5 minute DEM
Topological	slope	2.5 minute DEM
Topological	compound topological index (ln(acc.flow/tan[slope]))	2.5 minute DEM
Topological	altitude	www.ccafs-climate.org
Climate	annual mean temperature	www.worldclim.org
Climate	mean diurnal range (mean of monthly (max temp - min temp))	www.worldclim.org

Climate	isothermality (P2/P7)(*100)	www.worldclim.org
Climate	(temperature seasonality (sd *100)	www.worldclim.org
Climate	max temperature of warmest month	www.worldclim.org
Climate	min temperature of coldest month	www.worldclim.org
Climate	temperature annual range (P5-P6)	www.worldclim.org
Climate	annual precipitation	www.worldclim.org
Climate	precipitation of wettest month	www.worldclim.org
Climate	precipitation of driest month	www.worldclim.org
Climate	precipitation seasonality (coefficient of variation)	www.worldclim.org
Climate	precipitation of wettest quarter	www.worldclim.org
Climate	precipitation of driest quarter	www.worldclim.org
Climate	precipitation of warmest quarter	www.worldclim.org
Climate	precipitation of coldest quarter	www.worldclim.org

2.3 SDM CONSTRUCTION AND EVALUATION

To best match the resolution and time of the environmental layers used in modeling (2.5 minute resolution), occurrence data used were restricted to locations having error radii less than six km and observation dates after 1950. Records previously flagged as suspicious (see Georeferencing) were not used in modeling. Species distribution models were constructed using the maximum entropy algorithm encoded in the Maxent software package (Version 3.3.4; S. J Phillips, Anderson, and Schapire 2006), known to be robust for species distribution modeling with presence-only records (Elith et al. 2006). We implemented Maxent following default parameterization recommendations (Steven J. Phillips and Dudík 2008), with models cross-validated with 10 replicates (Elith et al. 2011). Individual species' model performance was evaluated using a receiver operating characteristic (ROC) analysis. The ROC analysis characterizes model performance at all possible thresholds using the area under the curve (AUC). An optimal model with perfect discrimination would have an AUC of one while a model that predicted species occurrences at random would have an AUC of 0.5 (Hanley and McNeil 1982).

2.4 SDM PRODUCTS

We modeled a total of 36 priority species from the Rio Grande basin (Table 3) and provide results in various formats. Model outputs for each species are provided (Appendix 3; Figure 4b) together with a map of occurrence records used in modeling (Figure 4a). These maps are useful for visual inspection and comparison. Model images are displayed as symbolized rasters layered over a shapefile of major streams within the Rio Grande basin. Only modeled probabilities > 0.5 are highlighted to aid in visual interpretation and to illustrate what we suggest be interpreted as prime suitable habitat based on the high quality occupancy data used. Complete raw model outputs are provided in supporting documents as GIS-ready grid data layers. This format provides continuous probability estimates over species' ranges (unlike point occurrence data) that can be deployed in a great diversity of mathematical and GIS analyses that are of considerable utility to managers attempting to understand factors affecting distributions and suitability over broad scales.

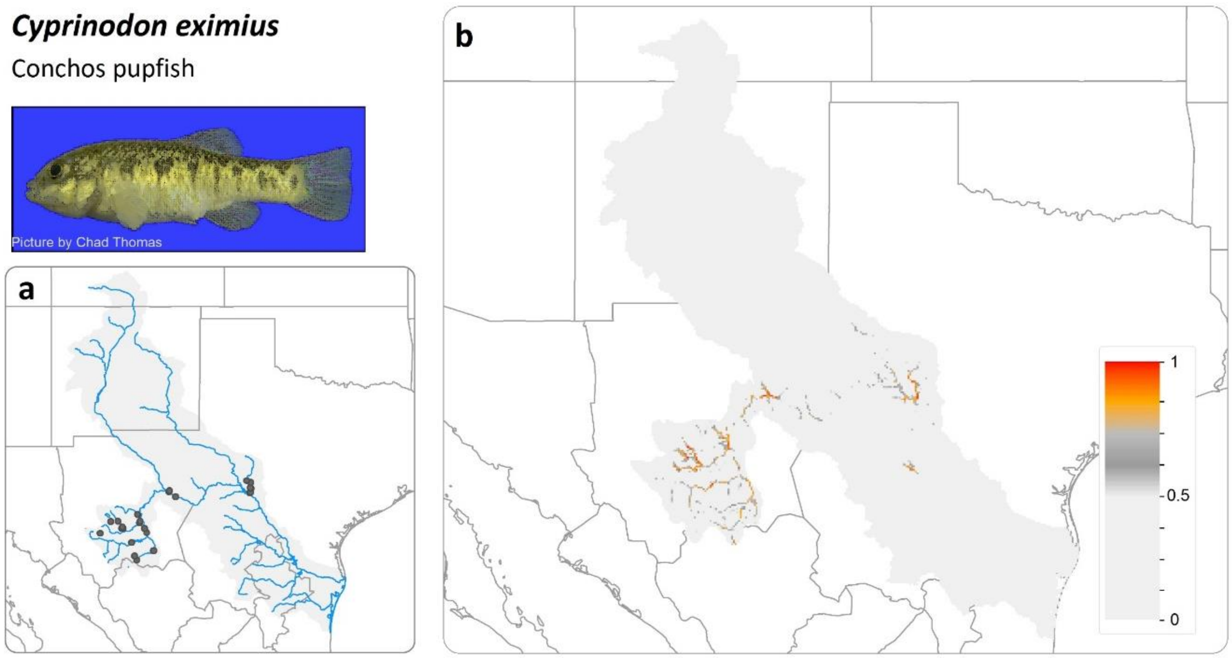

Figure 4. Example species distribution map product. Subfigure "a" shows occurrence records that were used in modeling for the respective species. Subfigure "b" indicates the "current" distribution of each respective species with the projected climate-based habitat suitability indicated by the grey-orange-red stretched color scale.

Additionally we provide, in supporting documents, the Maxent results log, containing model parameterization and result details, and html files of each model's Maxent model summary for the individual 10 replicates (e.g., Astyanax_mexicanus_1.html, Astyanax_mexicanus_2.html, etc.) as well as the average run (e.g., Astyanax_mexicanus.html). The summary includes plots of individual variable importance. Note that models do not directly account for anthropogenic influences such as dams or land use, and should thus be considered to estimate a species' potential, not necessarily actual, distribution. These data and models can thus serve as a benchmark for the species' distribution based on the best available occurrence data.

Table 3. Rio Grande priority species with indication of whether species was modeled or not.

Genus species subspecies	Common name	Nature Serve Global Status	Nature Serve Lowest State-level Status	N records in model (>1950, <6kmError, unique grid cell)	Test AUC
Anguilla rostrata	American eel	G4	NM-SX	-	-
Astyanax mexicanus	Mexican tetra	G5	NM-S2	286	0.95
Atractosteus spatula	Alligator gar	G3G4	TX-S4	-	-
Awaous banana	River goby	G5	TX-S1	-	-
Catostomus plebeius	Río Grande sucker	G3G4	CO-S1	15	0.94
Ctenogobius claytonii	Mexican goby	GNR	TX-S1	-	-
Cycleptus elongatus	Blue sucker	G3G4	NM-S1	65	0.99
Cyprinella lutrensis blairi	Maravillas red shiner	G5TX	TX-X	-	-
Cyprinella proserpina	Proserpine shiner	G3	TX-S2	59	0.96
Cyprinodon bovinus	Leon Springs pupfish	G1	TX-S1	-	-
Cyprinodon elegans	Comanche Springs pupfish	G1	TX-S1	-	-
Cyprinodon eximius	Conchos pupfish	G3G4	TX-S1	26	0.96
Cyprinodon pecosensis	Pecos pupfish	G1	TX,NM-S1	34	0.98
Cyprinus carpio	Common carp	Non-native	Non-native	100	0.96
Dionda argentosa	Manantial roundnose minnow	G2	TX-S2	39	0.99
Dionda diaboli	Devils river minnow	G1	TX-S1	16	0.99
Dionda episcopa	Roundnose minnow	G5	NM-S3	88	0.92
Etheostoma grahami	Río Grande darter	G2G3	TX-S2	48	0.97
Etheostoma lepidum	Greenthroat darter	G3G4	NM-S2	-	-
Gambusia clarkhubbsi	San Felipe gambusia	G1	TX-S1	-	-
Gambusia gaigei	Big Bend gambusia	G1	TX-S1	-	-
Gambusia nobilis	Pecos gambusia	G2	NM-S1	12	0.96
Gambusia senilis	Blotched gambusia	G3G4	TX-SX	29	0.97
Gambusia speciosa	Tex-Mex gambusia	G3Q	TX-S3	33	0.93
Gila pandora	Río Grande chub	G3	TX-S1	22	0.92
Hybognathus amarus	Río Grande silvery minnow	G1	TX-SX	35	0.98
Hybognathus placitus	Plains minnow	G4	CO-SH	10	0.92
Hypostomus sp.	Armored catfish	Non-native	Non-native	-	-
Ictalurus furcatus	Blue catfish	G5	NM-S2S3	63	0.98
Ictalurus lupus	Headwater catfish	G3	NM-S1	52	0.91
Ictalurus sp.	Chihuahua catfish	G1G2	TX-S1S2	-	-
Ictiobus bubalus	Smallmouth buffalo	G5	NM-S3	25	0.95

Lepisosteus osseus	Longnose gar	G5	NM-S2	43	0.96
Lepomis auritus	Redbreast sunfish	Non-native	Non-native	36	0.96
Lucania parva	Rainwater killifish	G5	NM-S3	42	0.97
Macrhybopsis aestivalis	Speckled chub	G3G4	NM-S2	130	0.96
Micropterus dolomieu	Smallmouth bass	Non-native	Non-native	10	0.99
Morone chrysops	White bass	Non-native	Non-native	18	0.92
Morone saxatilis	Striped bass	Non-native	Non-native	-	-
Moxostoma albidum	Longlip jumprock	n/a	n/a	40	0.97
Moxostoma austrinum	Mexican redhorse	G3	TX-S1	29	0.99
Moxostoma congestum	Gray redhorse	G4	NM-S1	81	0.95
Notropis amabilis	Texas shiner	G4	NM-SX	95	0.96
Notropis braytoni	Tamaulipas shiner	G4	TX-S4	143	0.97
Notropis chihuahua	Chihuahua shiner	G3	TX-S2	65	0.97
Notropis jemezanus	Río Grande shiner	G3	NM-S2	116	0.97
Notropis orca	Phantom shiner	GXQ	TX-SX	-	-
Notropis simus pecosensis	Pecos bluntnose shiner	G2T2	NM-S2	-	-
Notropis simus simus	Bluntnose shiner	G2TX	NM-SX	-	-
Oncorhynchus clarki virginalis	Río Grande cutthroat trout	G4T3	NM-S2	-	-
Oreochromis aureus	Blue tilapia	Non-native	Non-native	57	0.97
Percina macrolepida	Bigscale logperch	G5	NM-S2	-	-
Phenacobius mirabilis	Suckermouth minnow	G5	NM,CO-S2	-	-
Platygobio gracilis	Flathead chub	G5	NM-S4	14	0.98
Rhinichthys cataractae	Longnose dace	G5	TX-S2	106	0.96
Scaphirhynchus platorynchus	Shovelnose sturgeon	G4	NM-SX	-	-
Semotilus atromaculatus	Creek chub	G5	NM,TX-S3	-	-

2.5 SDM CLIMATE CHANGE PROJECTIONS

For the 36 species modeled (Table 3), we projected each species' model onto future climate data to predict shifts in climate-based habitat suitability within the Rio Grande basin. Climate variables used for projecting (Table 2) were downloaded from the Research Program on Climate Change, Agriculture, and Food Security (CGIAR) website (http://www.ccafs-climate.org/), and represent downscaled global climate model (GCM) 2.5 minute resolution data from the Intergovernmental Panel on Climate Change (IPPC, Fourth Assessment). Note that the IPCC Fifth Assessment (AR5) was recently published (September 2013; http://www.climatechange2013.org/) and could be used to update our projections, but that was not possible in the time frame of this project

We used the Commonwealth Scientific and Industrial Research Organization's (CSIRO-mk3) future (averages 2020s, 2050s, and 2080s) climatic model under A2, A1B, and B1 emission scenarios for model projections. These future scenarios encompass the low (B1), intermediate (A1B), and high (A2) projected emission and temperature, increases expected this century (Figure 6).

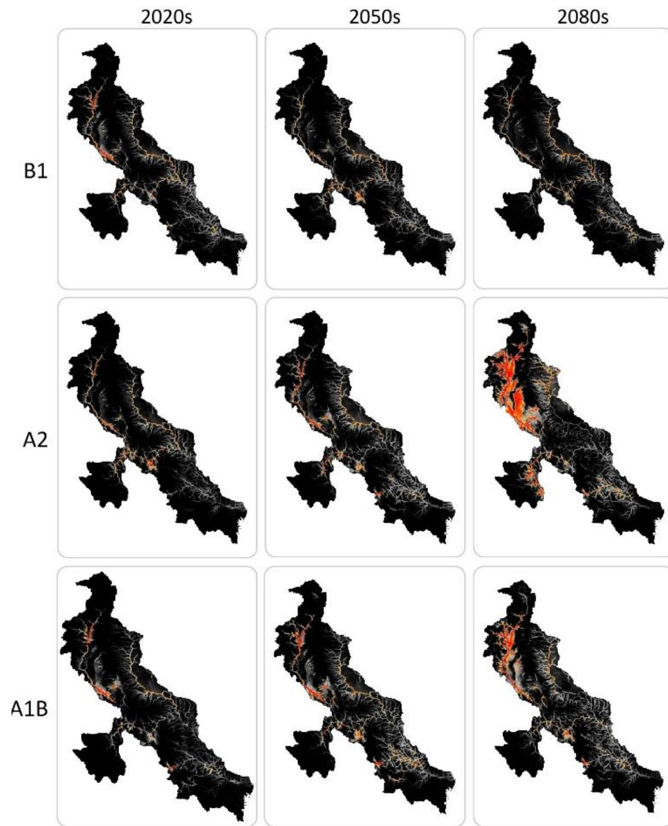

Figure 5. Example SDM projection within the Rio Grande basin based on 3 time periods (2020s, 2050s, 2080s) and 3 emission scenarios (B1-conservative, A2-extreme, A1B-intermediate). Highest projected climate-based habitat suitability is highlighted in red.

Rio Grande extents of these datasets are distributed as part of this project, and are provided in ARC GRID, and ASCII formats in the Supporting Documents directories provided as part of the grant deliverables. Mainstreamed map figures representing projections across time periods and emission scenarios are provided for each species (Appendix 3; Figure 6). These maps are useful for visual inspection and interpretation of results.

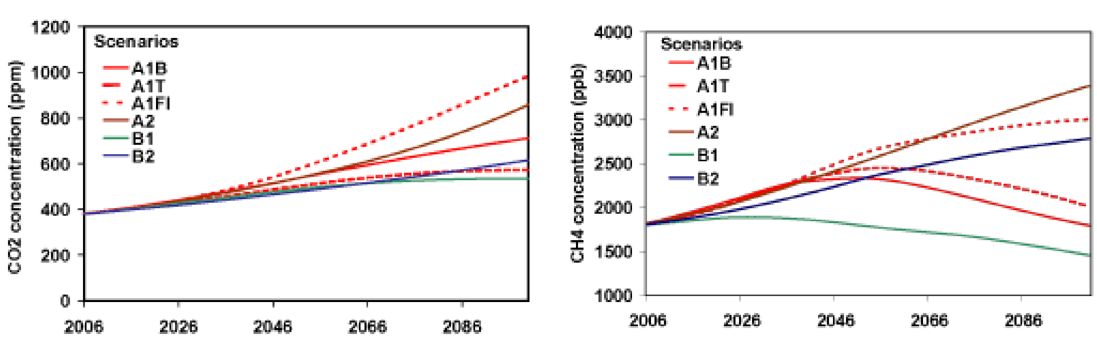

Figure 6. Projected changes over the 21st century in the atmospheric concentrations of carbon dioxide and methane. These projections by the United States Environmental Protection Agency are based on emission scenarios contained in the Special Report on Emission Scenarios (SRES) from the Intergovernmental Panel on Climate Change (IPCC). Figure source: http://goo.gl/9yWR5e

3 CONCLUSIONS AND DISCUSSION

3.1 DATA MINING AND PROCESSING

The dataset provided here is, to our knowledge, the most comprehensive single dataset available for historic fish occurrence records from throughout the entire Rio Grande drainage. We feel we have captured the majority of existing museum-based data, and that little additional historic data are likely to be available, although we did not include here a small database of trout records that includes some still uncataloged specimens from the Conchos basin, and we know of a small number of other collections not yet cataloged in institutional collections, but that eventually will be. Since the delivered data are primarily specimen-based (although the basis of the record is not always clearly indicated by some data sources) they offer a largely verifiable data source with great potential value to researchers wanting to understand historical (as early as mid-1800's) fish biogeography in the Rio Grande drainage, or for those trying to assess historical conservation status of species and local fish communities anywhere in the drainage. Our re-formatting makes these data searchable as a single resource and our meticulous georeferencing allows them to be used in geographic Information system (GIS) projects for the first time.

However, it is important to understand, before working with these data, issues relating to our compilation and processing methods that could lead users to draw erroneous conclusions when extrapolating from them. Since these data are derived from many institutions having unique management conventions, data sharing practices, and regional foci, it is expected that regions may be differentially represented in various ways. For example, we know that the data contain near-duplicate records extracted from different sources that differ in subtle and often inconsequential ways, yet we know that each record documents the exact same occurrence in time and space. This is often the result of data sharing. For example, an institution may have shared a record with our Fishes of Texas Project, GBIF, and FishNet2, and we may have also mined its original database, so that same record would appear 4 times in this dataset. We know that our dataset has high redundancy for some institutions and very low redundancy for others. The Museum of Southwestern Biology (MSB), for example, which has a focus in New Mexico and is the dominant record holder for this state, has not shared its data broadly and so its records are not highly duplicated in this data set. Thus, to the naïve user using record counts as an indicator of thoroughness of sampling, it would appear that the Río Grande drainage in New Mexico is under-sampled relative to other areas, when in fact that is anything but the case. It is not impossible to eliminate or at least greatly reduce duplicate records, but it is easy to lose potentially valuable data unique to single copies in the process, and we chose here not to risk such losses.

Similarly, a variety of issues led to our georeferences being applied to records differentially across the dataset. First, our ability to georeference any record depends on our ability to find the location in gazetteers and maps. Since many Mexican places (especially streams) are known by numerous names, and field workers often use names provided by local residents instead of from national standardized place names databases, it is often not possible to georeference such records without considerable research. Consequently many records in the data set here remain un-georeferenced and when the georeferenced records provided here are analyzed apart from the non-georeferenced records, such as via any mapping dependent on coordinates, the result may tend to be interpreted as significant differences among regions in density or thoroughness of sampling, when in fact such differences may be explained by methodological artifacts. For example, it appears from our mapping of the georeferenced data (Figure 2), that many records from small Mexican tributaries of the Rio Grande may have not been georeferenced due this issue. Employing georeferencers with intimate knowledge of the area, and additional resources (such as field notes), may allow us to apply coordinates to some of these still un-georeferenced records, and we hope to continue working on these data.

Another issue affecting database compilation and interpretation relates to the fact that our georeferencing effort was concurrent with a collaborative georeferencing project funded by the National Science Foundation and managed by the developers of FishNet2. As collaborators in that project we are aware that it utilized a rigorous georeferencing methodology very similar to our own, and knowing that it was georeferencing MSB's records, we focused our georeferencing efforts for this project elsewhere. However, at the time when we had to harvest data to move forward with other aspects of this project, relatively few MSB records had been processed by the NSF project. Consequently many MSB records remain ungeoreferenced in our dataset and since MSB is by far the largest single source of New Mexico fish occurrence records, mapping of the data provided here may give users the impression that New Mexico is less thoroughly sampled than is actually the case. We suggest that users of this data should independently assess adequacy of MSB's verbatim georeference data (included in the data set provided by this project) for their applications.

Despite all of these issues, mapping these occurrences (Figure 7) makes it reasonably clear that vast areas of the Rio Grande drainage, including the Conchos drainage and many of the smaller tributaries in Mexico have never been sampled or only barely been sampled for fishes, and provides a strong argument for the need for a targeted sampling effort.

The data query and compilation process conducted for this project was designed to be comprehensive for the scope of this project, while at the same time allowing us to produce a dataset that would expand our Fishes of Texas project's geographic scope beyond the political boundaries of Texas into neighboring states. Those neighbor state records were compiled along with the Rio Grande records provided here, but since they are outside the scope of this project they are not delivered as part of this project. As part of our Fishes of Texas project we intend, pending funding, to fully process and georeference these neighboring state records as we've done here for the Rio Grande records. At the same time we will also further process the Rio Grande records and apply our complete quality control methods. Much of that work will involve verifying specimen identifications, and eventually publishing them on our website (www.fishesoftexas.org). We will also continue to pursue funding that will allow us to continue our work georeferencing these records, collecting new specimens and acquiring additional historic data from the Rio Grande basin.

3.2 PRACTICAL VALUE OF THE DATABASE PROVIDED

The data here provided for the first time ever provide "one-stop-shopping" for scientifically sound species occurrence information on the fishes of the entire Río Grande basin. While much of this information for the U.S. sub-basins and the mainstream along the border was available before, relatively little of it was georeferenced and much of it was otherwise limited in ways that decreased its value for research and management. The processing done as part of this project has addressed many of those limitations.

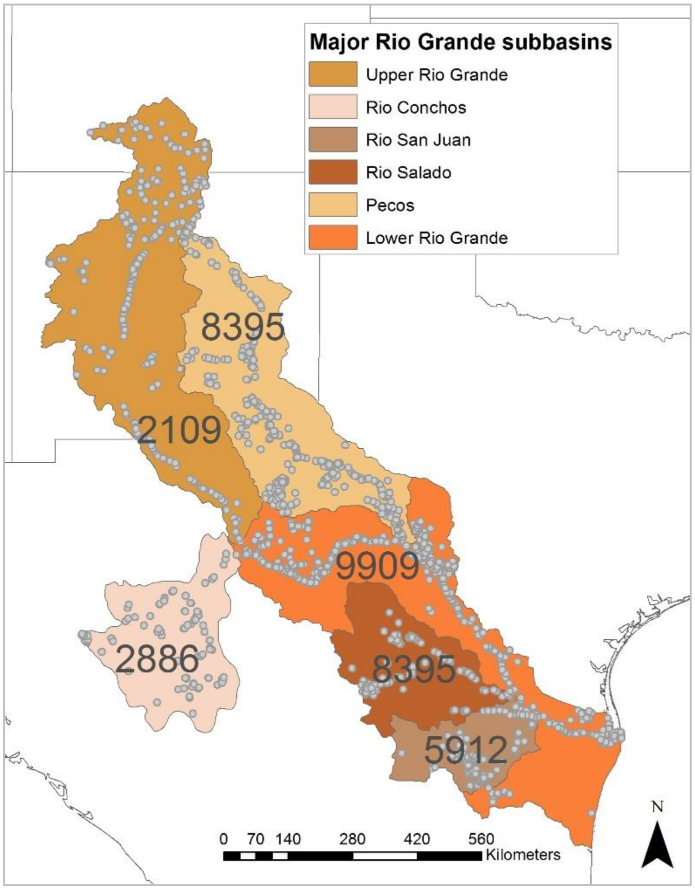

Figure 7. Counts of georeferenced records per sub-basin. See text for discussion of record duplications and possible effects on interpretation of numbers in this map.

In particular, the Conchos basin has long been one of the more under-sampled Rio Grande sub-basins, and much of the historic data available from it has long been inaccessible and scattered. Here we largely rectify that situation by providing this compilation of normalized and georeferenced records. This sub-basin is particularly important for its high endemism, numerous threatened and endangered species, high rate of endemism, and many known, but still undescribed species. Two trout species are being described (Camarena-Rosales et al. 2006), Chihuahua catfish is thought most likely to still persist in the Conchos (Hendrickson, unpublished data), what is now known as *Moxostoma austrinum* in the Conchos is likely an undescribed species (Clements, Bart, and Hurley 2012) and the Río Grande blue sucker (*Cycleptus* sp.) is being described as new as well (R. L. Mayden, pers. comm, 2013). It is clear that much of the Conchos' unique fauna is critically endangered by now extensive fragmentation and hydrological alterations caused by dams, contamination and severe groundwater depletion by agriculture (most recently reviewed by de la Maza 2009).

The Cuatro Ciénegas data included here also brings formerly scattered and previous un-georeferenced documentation of the fauna of this world class, but highly endangered, Protected Area together in one place.

The considerable value of this now easily accessed information for conservation and sustainable resource management is what largely motivates us to be committed to continued work on the data set provided here, verifying determinations and otherwise continuing to clarify the status of this important fauna to facilitate its conservation.

3.3 Species distribution models and climate projections

Government scientists and resource managers are increasingly looking to modeled projections of species' distribution shifts under future climates, such as provided in this report, to inform conservation strategy. It is important to understand how to properly interpret results of such studies. Predicted shifts in climate-suitability, as depicted on the maps provided here, do not necessarily imply that those shifts will or can take place. They simply represent the potential change in distribution of those climatic habitat conditions included in the models that are preferred by the target species. Whether the species can actually occupy those habits is uncertain since these models do not incorporate the many biotic and physical factors that influence distributions, such as interspecific competition, dispersal, habitat connectivity, behavioral adaptations, ecological equilibria, or evolution (Sinclair, White, and Newell 2010), nor do they incorporate man-made structures such as dams, diversions or other barriers. We suggest that primary interpretation of our analyses be restricted to understanding the relative magnitudes of shifts across species, and directions of climate change impact.

Our models of habitat condition shifts for the 35 target species, derived from climate change predictions, suggest that adequate conditions for most species will persist or even expand in the study region, however, some species may experience a reduction in suitable conditions. Five species appear to be expected to have appropriate conditions shift upward in elevation (*Catostomus plebeius, Gila pandora*, *Platygobio gracilis and Cyprinodon pecosensis)* or disappear in instances where higher elevations are not available (*Dionda episcopa)*. All of these species except *C. pecosensis* are predicted to have reduced suitable habitat under the climate change scenarios analyzed. Elevational shifts in response to climate change have been documented across numerous taxa (Walther et al. 2002, Hickling et al. 2006, Parmesan 2006, Colwell et al. 2008), so our results here are in line with that body of work.

Also notable are projected expansions of suitable conditions for three introduced species: *Cyprinus carpio, Morone chrysops*, and *Oreochromis aureus*. Models for *Lepomis auritus* and *Micropterus dolomieu* are inconclusive. Models for *Hypostoma sp*. and *Morone saxatilis* could not be completed with available data.

Species occurring in the lower Rio Grande basin (including Rio Salado and Rio San Juan), in most cases, appear to be little affected by climatic change forecasts. In contrast, species restricted to the middle Rio Grande around the Devils River appear potentially greatly affected as their preferred habitat is not predicted to be replaced elsewhere within the basin. This is evident for species such as *Etheostoma grahami, Cyprinella proserpina, Dionda argentosa, Dionda diaboli*, and *Lepomis auritus*, which lose much of their 'current' predicted suitability habitat without noticeable vertical shifts in projected suitability up- or down-basin.

Table 4 provides a list of ways in which SDMs can be used to address conservation decision making tasks under the threat of climate change and Table 5 provides a selection of recent (post 2010) peer-reviewed studies that incorporate climate projection results, such as provided here, into conservation assessments and planning. We suggest that one of the primary uses of these projections be a multi-species conservation assessment that could identify priority areas for long-term conservation of the Rio Grande fish community in the face of climatic pressures (*sensu* Levy and Ban 2013; Virkkala et al. 2013; Nakao et al. 2013).

Table 4. Classification of proposed climate change adaptation strategies along with proposed species distribution model utility for each. Table adapted from Schwartz 2012.

Decision Strategies	*SDM model utility*
(a) Habitat protection	
1. Increase the spatial extent of habitat protection.	Identify likely future occurrence opportunities
2. Increase landscape connectivity.	Identify current locations most likely to supply individuals for colonization of new locations
3. Improve representation and replication of protections within protected area networks.	Same as above
4. Design new natural areas and restoration sites to maximize resilience to climate change.	Same as above
5. Consider dynamic landscape conservation plans that allow protection zones to shift with climate changes.	Same as above
6. Develop a surveillance program to detect whether existing protections of habitats are adequate given changing climate.	Identify sites where target taxa should be more vulnerable to climate change in order to better understand climate change responsiveness
7. De-gazette reserves deemed to no longer protect valued resources in the future	Identify locations with high probability of loss of target taxa
(b) Habitat management	
1. Improve management and restoration of existing protected areas, and private land protection areas, to facilitate resilience to climate change.	Identify primary climatic attributes that predict sensitivity in order to foster monitoring responsiveness to climate
2. Monitor to detect problems associated with changing climate.	Identify primary climatic attributes that predict sensitivity in order to foster monitoring responsiveness to climate
3. Cease existing efforts to protect habitat for taxa perceived to be doomed to extirpation	Identify locations with high probability of loss of target taxa
(c) Species management	
1. Prioritize focal taxa at risk because of climate change.	Identify species most at risk of range shift
2. Translocate species at risk of extinction.	Identify likely future occurrence opportunities
3. Evaluate and enhance monitoring programs for focal taxa.	Identify primary climatic attributes that predict sensitivity in order to foster monitoring responsiveness to climate
4. Incorporate potential climate change impacts into species management plans.	Identify primary climatic attributes that predict sensitivity in order to foster monitoring responsiveness to climate
5. Monitor populations to determine if environmental change is driving a status change in a species.	Identify primary climatic attributes that predict sensitivity in order to foster monitoring responsiveness to climate

6. Cease efforts on behalf of taxa deemed destined for extinction under climate change	Identify locations with high probability of loss of target taxa

Table 5. Recent (post 2010) peer-reviewed studies that incorporate climate projection results, such as provided in this study, into conservation assessment, planning, or management strategy.

Study	*Methods*	*Citation*
Linking Climate Change and Fish Conservation Efforts Using Spatially Explicit Decision Support Tools	(1) strategic spatial prioritization of limited conservation resources and (2) deciding whether removing migration barriers would benefit a native fish also threatened with invasion by a nonnative competitor	(Peterson et al. 2013)
Conservation Planning with Uncertain Climate Change Projections	Account for several sources of uncertainty in conservation prioritization when using future projections of SDMs	(Kujala et al. 2013)
A method for incorporating climate change modelling into marine conservation planning: An Indo-west Pacific example	Incorporates climate change projections into the process of identifying priority areas for marine conservation	(Levy and Ban 2013)
Climate Change, Northern Birds of Conservation Concern and Matching the Hotspots of Habitat Suitability with the Reserve Network	Using bioclimatic envelope models and spatial data on habitats and conservation areas, we studied how efficient the reserve network will be in preserving bird species of conservation concern under three different climate scenarios.	(Virkkala et al. 2013)
Incorporating climate change adaptation into national conservation assessments	Describe three explicit strategies for climate change adaptation as part of national conservation assessments: conserving the geophysical stage, identifying and protecting climate refugia, and promoting cross-environment connectivity.	(Game et al. 2011)
Modeling climate change impacts on tidal marsh birds: Restoration and conservation planning in the face of uncertainty	Project the future distribution and abundance of five marsh bird species (through 2110) in response to changes in habitat availability and suitability as a result of projected sea-level rise, salinity, and sediment availability in the Estuary.	(Veloz et al. 2013)
Spatial conservation planning under climate change: Using species distribution modeling to assess priority for adaptive management of <u>Fagus crenata</u> in Japan	Assessed optimal actions (revision of protected areas or active management) in each geographical region to establish an effective spatial conservation plan in Japan	(Nakao et al. 2013)
Identifying priority areas for reducing species vulnerability to climate change	Quantified the vulnerability of 171 plant species in a fragmented yet biologically important agro-ecological landscape, typical of many temperate zones globally	(Crossman, Bryan, and Summers 2012)
Integrating ensemble species distribution modelling and statistical phylogeography to Inform projections of climate change impacts on species distributions	Integrating two independent but complementary methods, ensemble SDMs and statistical phylogeography, we Addressed key assumptions and created robust assessments of climate change impacts on species distributions while improving the conservation value of these projections.	(Forester, DeChaine, and Bunn 2013)

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7 Appendix 1. Query metadata for initial data gathering of target species occurrence data

Direct Data Source	url	N Records Received	Date Accessed	Query Specifications	Database Description
FishNet2	http://www.fishnet2.net/	4471	Nov 9, 2010	Unbounded by geography; for 6 target species (*Notropis girardi, Hybognathus amarus, Platygobio gracilis, Macrhybopsis tetranema, Pteronotropis hubbsi, Percina maculata*)	Includes global data on fish occurrences from numerous data sources.
FishBase	http://www.fishbase.org/search.php	201	Nov 2010	Unbounded by geography and limited only by target species names (including historical synonyms)	Includes global data on fish occurrences from numerous data sources.
Global Biodiversity Information Facility (GBIF)	http://www.gbif.org/	8686	Nov 3-8, 2010	Unbounded by geography; for 6 target species (*Notropis girardi, Hybognathus amarus, Platygobio gracilis, Macrhybopsis tetranema, Pteronotropis hubbsi, Percina maculata*)	Includes global data on organism occurrences from numerous data sources.
Great Plains Landscape Conservation Cooperative (GPLCC) project database (Hendrickson et al. 2012)		41098	Aug, 31, 2010 (CSU); Sept 16, 2010 (MSB); June 28, 2010 (OMNH)	all fish data within the GPLCC area	Dataset includes occurrence data for various animal taxa within the GPLCC area; for fish it includes data from Colorado State Univ., Museum of Southwestern Bio., and Oklahoma Museum of Natural History
Fishes of Texas Project	www.fishesoftexas.org	46504	Feb 14, 2012	Query includes all out of TX records, but target species and Rio Grande records within TX	Includes fish specimen data from 44 institutions

Global Biodiversity Information Facility (GBIF)	http://www.gbif.org/	33469	July 2011	Request for fish data within DLCC area (donors often provided from larger geographic area)	Includes global data on organism occurrences from numerous data sources.
FishNet2	http://www.fishnet2.net/	63508	July 2011	Request for fish data within DLCC area (donors often provided from larger geographic area)	Includes global data on fish occurrences from numerous data sources.
SONO DB	NA	1948	July 2011	Request for fish data within DLCC area (donors often provided from larger geographic area)	Compiled by Peter Unmack includes unvouchered and specimen-vouchered records from northern Mexico via 18 institutions
University of Michigan Ichthyology Collection	http://www.lsa.umich.edu/ummz/fishes/	3826	July 2011	Request for fish data within DLCC area (donors often provided from larger geographic area)	
New Mexico Biodiversity Collections Consortium	http://nmbiodiversity.org/index.php	2690	Jan 19, 2012	all fish data	Database restricted to New Mexico records only
University of Alabama Ichthyology Collection	http://www.as.ua.edu/uaic/	212	Feb 14, 2012	Request for fish data within DLCC area (donors often provided from larger geographic area)	

Universidad Nacional Autónoma de México, Ichthyology Collection	http://www.ibiologia.unam.mx/zoologia/html_09/coleccion.php?nick=cnpe&titulo=Colecci%C3%B3n%20Nacional%20de%20Peces	793	Oct 12, 2012	Request for fish data within DLCC area (donors often provided from larger geographic area)	
Cuatro Ciénegas database	NA	2476	Feb 10, 2012	All data	Compiled by Dean Hendrickson and Adam Cohen; contains unvouchered and specimen-vouchered data from Cuatro Cienegas Basin and Rio Salado de los Nadadores in Coahuila Mexico; many of the records from 1999, 2000 and 2001 have been accessioned in November 2013 (Oficio No. IBIO-DIR/193/2013) at Universidad Nacional Autónoma de México, Ichthyology Collection and are not yet cataloged at the time of this writing; others from those years are cataloged at TNHC.
Global Biodiversity Information Facility (GBIF)	http://www.gbif.org/	184454	Jan 31, 2012	fish from Texas' neighbor states	Includes global data on organism occurrences from numerous data sources.

FishNet2	http://www.fishnet2.net/	118435	Jan 30, 2012	fish from Texas' neighbor states	Includes global data on fish occurrences from numerous data sources.

8 Appendix 2. All entities contributing data to initial dataset and their accepted codons

Institution code	Institution/Collection Name
OZCAM	Online Zoological Collections of Australian Museums
AMNH	American Museum of Natural History, New York; see also F:AM (paleo)
ANSP	Academy of Natural Sciences, Philadelphia, Pennsylvania; current for fishes, herps and vertebrate paleontology as three separately cataloged collections
ARC	Atlantic Reference Centre, St. Andrews, New Brunswick
ASU	Arizona State University
AZGF	Arizona Game and Fish Department
BMNH	Natural History Museum [formerly British Museum (Natural History)], London; also as NHM
BPBM	Bernice P. Bishop Museum, Department of Zoology, Honolulu, Hawaii
BYU	Brigham Young University, Monte L. Bean Life Science Museum, Provo, Utah
CAS	California Academy of Sciences, San Francisco, California; also as CAS-GVF, CAS-IU, CAS-SU
CIAD	Centro de Investigación en Alimentación y Desarrollo, A.C., Hermosillo, Sonora; current for fishes; also as CES (herps).
CICIMAR	Centro Interdisciplinario de Ciencias Marinas, Instituto Politécnico Nacional, La Paz, Baja California Sur; also as CI (Colección Ictiológica del CICIMAR), CICIMAR-CI (for non-ictioplancton vs. CICIMAR for ictioplancton)
CMNFI	Canadian Museum of Nature Fish Collection, Ottawa; also as NMC, National Museums of Canada; Includes VMMB collection
FMNH	Field Museum of Natural History, Zoology Department, Chicago, Illinois [obsolete as CNHM, Chicago Natural History Museum]; includes fishes from IU.
CSIRO	Commonwealth Scientific & Industrial Research Organisation, Division of Marine & Atmospheric Research, Hobart, Tasmania; formerly Division of Fisheries & Oceanography at Cronulla, NSW; includes specimens from Marine Lab, Sydney
CU	Cornell University Museum of Vertebrates, Ithaca, New York; also as CUMV
DEDSZC	Comisión Nacional para el Conocimiento y Uso de la Biodiversidad

DGR	Arctos - DGR Fishes Specimens
ENCB-IPN	Escuela Nacional de Ciencias Biológicas, Instituto Politécnico Nacional, Mexico City; current for fishes; also as IPN, IPN-ENCB (both obsolete for fishes).
ENMU	Eastern New Mexico University, Portales, New Mexico
CPUM	Universidad Michoacana de San Nicolás de Hidalgo, Facultad de Biologia, Laboratory de Biologia Acuática, Morelia, Michoacán; current for fishes; also as UMSNH (herps)
UANL	Universidad Autónoma de Nuevo León, Facultad de Ciencias Biológicas, Departamento de Zoología de Vertebrados, San Nicolás de los Garza [also as Monterrey], Nuevo León; also as FCB (obsolete)
GCRL	Gulf Coast Research Laboratory, The University of Southern Mississippi, Ocean Springs, Mississippi; also as GCRLM; Some specimens moved to USM
GNM	Göteborgs Naturhistoriska Museum, Göteborg; replaces NHMG (sensu Leviton et al. 1985), also as GNHM, NMG
HU	unknown "HU"
CNP-IBUNAM	Colección Nacional de Peces, Instituto de Biología, Universidad Nacional Autónoma de México (UNAM), Mexico City; also as IBUNAM, UNAM, UNAM-CNPE (all obsolete for fishes)

IIPB	Instituto de Ciencias del Mar [formerly Instituto de Investigaciones Pesqueras], Departament de Biologia Marina i Oceanografia, Barcelona; also as ICM
ITESM	Inventario y monitoreo del Canal de Infiernillo para el comanejo de los recursos marinos en el territorio Seri, Golfo de California
IGFA	unknown "IGFA"
ITESM-OTO	Consolidacion y sistematizacion de las colecciones de referencia de peces y mamiferos marinos del ITESM Campus Guaymas
ITLM	Genetica y taxonomia de los robalos (Centropomus spp) del golfo de California, Mexico
JFBM	[James Ford] Bell Museum of Natural History, University of Minnesota, Minneapolis, Minnesota
KU	University of Kansas Natural History Museum, Lawrence, Kansas; current for Recent fishes and herps; see KUVP for paleo collection
LACM	Natural History Museum of Los Angeles County, Los Angeles, California
LBM	National Museum of Nature and Science, Japan, Freshwater Fish Specimens of Lake Biwa Museum
LEMA	Inventario de la biota marina (invertebrados, peces y macroalgas bentonicos) del parque nacional Isla Isabel
LSUMZ	Louisiana Museum of Natural History [formerly Louisiana State University, Museum of Zoology (-1999)], Baton Rouge, Louisiana

MDUG	Museo Alfredo Dugès, Universidad de Guanajuato, Guanajuato; contains many herp types of Dugès; also as MADUG
MCNB	Museu de Ciencies Naturals de Barcelona: MCNB-Cord
MCZ	Museum of Comparative Zoology, Harvard University, Cambridge, Massachusetts; also as MCZH
MNHP	Národní muzeum [National Museum], Prague; also as MHP, NMP6V (both herps)
MMNS	Mississippi Museum of Natural Science [formerly Fannye A. Cook Memorial Museum], Jackson, Mississippi; some Cook fish specimens at FMNH, USNM, AMNH
MNCN	Museo Nacional de Ciencias Naturales, Madrid
MHNM	Museo Nacional de Historia Natural y Antropología (MUNHINA) [formerly Museo de Historia Natural de Montevideo], Montevideo; suggested replacement for MNHN
MNHN A	Museo Nacional de Historia Natural y Antropología (MUNHINA) [formerly Museo de Historia Natural de Montevideo], Montevideo; suggested replacement for MNHN
MNHN BE	Museo Nacional de Historia Natural y Antropología (MUNHINA) [formerly Museo de Historia Natural de Montevideo], Montevideo; suggested replacement for MNHN
MSB	Museum of Southwestern Biology, Department of Biology, University of New Mexico, Albuquerque; also as UNM
MSU	Mississippi State University, Mississippi
MSUM	Michigan State University Museum, East Lansing, Michigan; also as MSU (obsolete)
MTKD	Museum für Tierkunde, Senckenberg Naturhistorische Sammlungen [Staatliche Naturhistorische Sammlungen], Dresden; also as MTD
MVZ	Museum of Vertebrate Zoology, University of California at Berkeley, California; also as BNHM (obsolete); most of fish collection now at CAS
MZUS	Musée Zoologique de la ville de Strasbourg, Université de Strasbourg [includes formerly independent Université Louis-Pasteur], Strasbourg; also as MZS
NCSM	North Carolina Museum of Natural Sciences [formerly North Carolina State Museum], Raleigh, North Carolina
ND	Especies de peces introducidas en aguas continentales de Mexico. Catilogo y manuscrito
No proporcionado	Diversidad dinamica y patrones reproductivos en la comunidad de peces demersales del Golfo de Tehuantepec
not recorded	not recorded
NRM	Naturhistoriska Riksmuseet, Department of Vertebrate Zoology, Stockholm; Replaces NHRM (sensu Leviton et al. 1985); also seen as SMNH, NRMS

NTSRV	NatureServ
NTUM	National Taiwan University, Institute of Zoology, Taipei
OMNH	University of Oklahoma, Sam Noble Oklahoma Museum of Natural History [formerly Stovall Museum], Norman, Oklahoma; currently used for cataloging fishes & herps (also as OMNH-N); previously proposed abbreviation UOMZ (Leviton et al. 1985) not adopted; alternative abbreviation OKMNH proposed by Leviton & Gibbs (1988) cited in publications for fishes
OSM	Ohio State University, Museum of Biological Diversity, Museum of Zoology, Columbus, Ohio; also as OSUM (obsolete)
OSUS	Oklahoma State University, Department of Zoology, Stillwater, Oklahoma; also as OAM, OSUMZ (both obsolete)
PBDB	Marine Science Institute, UCSB, Paleobiology Database
RMNH	Naturalis–Nationaal Natuurhistorisch Museum [formerly Rijksmuseum van Natuurlijke Historie], Leiden; dry fish collection preceded by "D"; museum officially includes collections of ZMA which ultimately will be transferred from Amsterdam to Leiden.
ROM	Royal Ontario Museum, Department of Natural History, Toronto, Ontario
ROM-CID	Royal Ontario Museum, Department of Natural History, Toronto, Ontario
RUSI	Rhodes University and the Council for Scientific and Industrial Research, J.L.B. Smith Institute of Ichthyology, Grahamstown; renamed SAIAB.
S	unknown "S"
SAIAB	South African Institute for Aquatic Biodiversity, [formerly Rhodes University, J.L.B. Smith Institute of Ichthyology (RUSI)], Grahamstown
SAMA	South Australian Museum, Adelaide, South Australia
SBMNH	Santa Barbara Museum of Natural History, Santa Barbara, California
SIO	Scripps Institution of Oceanography, Marine Vertebrate Collection, La Jolla, California
SMK	Sarawak Museum, Kuching; also as SM.
SM-AM	Registro de datos de peces del pacifico mexicano de la Coleccion Biologica de la Secretaria de Marina
SMF	Senckenberg Forschungsinstitut und Naturmuseum [alternatively Senckenberg Research Institute and Natural History Museum], Frankfurt
SMNS	Staatliches Museum für Naturkunde, Stuttgart; also as MNS
SU	Stanford University, Palo Alto, California; also as LSJUM; Fishes transferred to CAS (CAS-SU) with 100,000 added to each SU catalog numbers for computerization

TCWC	Texas Cooperative Wildlife Collection, Texas A&M University, College Station, Texas
TNHC	Texas Natural History Collections, Texas Natural Science Center, Texas Memorial Museum, University of Texas at Austin, Austin, Texas
TU	Tulane University Museum of Natural History [formerly F. Edward Hebert Riverside Research Laboratories (fishes)], Belle Chasse, Louisiana
UAMZ	University of Alberta, Museum of Zoology, Edmonton, Alberta; see also UALVP for paleo collections
UABC	Universidad Autónoma de Baja California, Ensenada, Baja California; also as CI-UABC (for fishes)
UAChi	Peces de la region de Norogachi, Alta Sierra Tarahumara, Chihuahua
ARK	University of Arkansas, Museum, Fayetteville
UAM	University of Alaska Museum of the North, Fairbanks, Alaska
UAZ	University of Arizona, Department of Ecology and Evolutionary Biology, Tucson, Arizona; also as UA
UBC	University of British Columbia, Cowan Vertebrate Museum [part of Beaty Biodiversity Museum], Vancouver, British Columbia
UCD	University of California, College of Biological Sciences, Davis, California
UCLA	University of California at Los Angeles, Department of Ecology and Evolutionary Biology [formerly Biology], Los Angeles, California; much of fish collection now at LACM
UCM	University of Colorado Museum of Natural History, Boulder, Colorado
UMZC	University Museum of Zoology, University of Cambridge, Cambridge, England; also as ZMC
UMMZ	University of Michigan Museum of Zoology, Ann Arbor, Michigan
UNSM	University of Nebraska State Museum, Lincoln; replaces UN (sensu Leviton et al. 1985)
USGS-NAS	United States Geological Survey, Nonindigenous Aquatic Species Database
USNM	National Museum of Natural History, Smithsonian Institution [formerly United States National Museum], Department of Vertebrate Zoology, Washington D.C.
USON	Coleccion de los peces nativos de Sonora
UW	University of Washington, College of Ocean and Fishery Sciences [formerly College of Fisheries], Seattle, Washington; also as MNHW, UWF
WNMU	Western New Mexico University
YPM	Yale University, Peabody Museum of Natural History, New Haven, Connecticut; also as BOC

ZMA	Zoölogisch Museum, Universiteit van Amsterdam [alternatively Zoological Museum Amsterdam], Amsterdam; collections now officially part of Naturalis Museum (RMNH) and ultimately to be transferred to Leiden
ZMH	Zoological Museum Hamburg [Biozentrum Grindel und Zoologisches Museum; formerly Zoologisches Institut und Museum], Universität Hamburg, Hamburg; also as NMH, ZIM
ZMO	unknown "ZMO"
ZMUC	Københavns Universitet, Zoologisk Museum [Zoological Museum, University of Copenhagen], Vertebrater, Fiskesamlingen, Copenhagen; also seen as UZMK
ZSM	Zoologische Staatssammlung München [alternatively as Bavarian State Collection of Zoology; previously as Zoologisches Sammlung des Bayerischen Staates], München
DMNH	Dallas Museum of Natural History, Dallas, Texas
NLU	University of Louisiana at Monroe [formerly Northeast Louisiana University], Museum of Natural History [formerly Zoology], Monroe, Louisiana; also as NLM
SIUC	Southern Illinois University, Department of Zoology, Carbondale, Illinois
SMBU	Strecker Museum [moved to Mayborn Museum Complex], Baylor University, Waco, Texas; replacement for BU (Baylor University)

SRSU	Sul Ross State University, Alpine, Texas
UF	University of Florida, Florida Museum of Natural History [formerly Florida State Museum (FSM)], Gainesville, Florida; also as FLMNH (obsolete for fishes & herps)
UT	University of Tennessee, Department of Zoology, Knoxville, Tennessee
AUM	Auburn University Natural History Museum, Auburn, Alabama (fishes and herps); also as AU and API (both obsolete)
INHS	Illinois Natural History Survey [descended in part from Illinois State Laboratory of Natural History], University of Illinois, Champaign, Illinois
UAIC	University of Alabama Ichthyological Collection, Tuscaloosa, Alabama; replacement for ALA (sensu Leviton et al. 1985)
UA	Arkansas State University Museum of Zoology – Fish Collection
USM	University of Southern Mississippi, Museum of Ichthyology, Department of Biological Sciences, Hatiesburg, Mississippi; also as USMS
UAFS	University of Arkansas at Fort Smith (formerly University of West Arkansas)
VPN	Vertebrate Paleontology Laboratory, University of Texas
SHVM	Sam Houston State University

9 APPENDIX 3. SPECIES DISTRIBUTION MODELS AND RESPONSE TO CLIMATE CHANGE

Each species successfully modeled (see Table 2 for list and Section 2 for methods) has two figures, a profile figure and a climate projection figure.

Species Profile Figures:

Subfigure "a" shows occurrence records that were used in modeling.

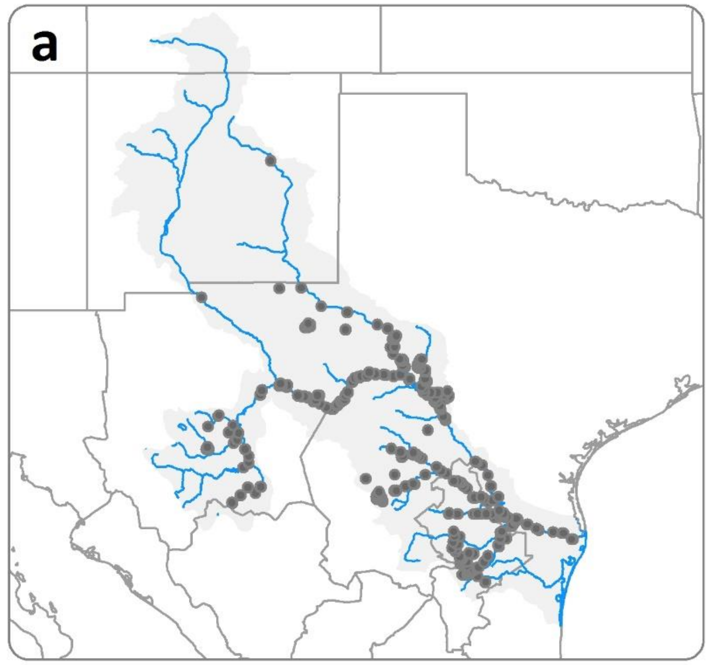
Subfigure "b" indicates the "current" distribution of the species. These models were trained on climate data averaged from 1950-2000, which represents temporal concordance with most of the occurrence data. The model figure ("b") is displayed as a symbolized grid raster. Probabilities > 0.5 are featured to better illustrate what we suggest be interpreted as prime suitable habitat considering occurrence records and environmental parameter space utilized (see Section 2). Complete raw model output can be found in supporting documents in ASCII grid layer format. Note that models do not directly account for anthropogenic influences such as dams or land use, and should thus be considered to estimate a species' potential, and not necessarily actual, distribution.

Climate Projection Figures:

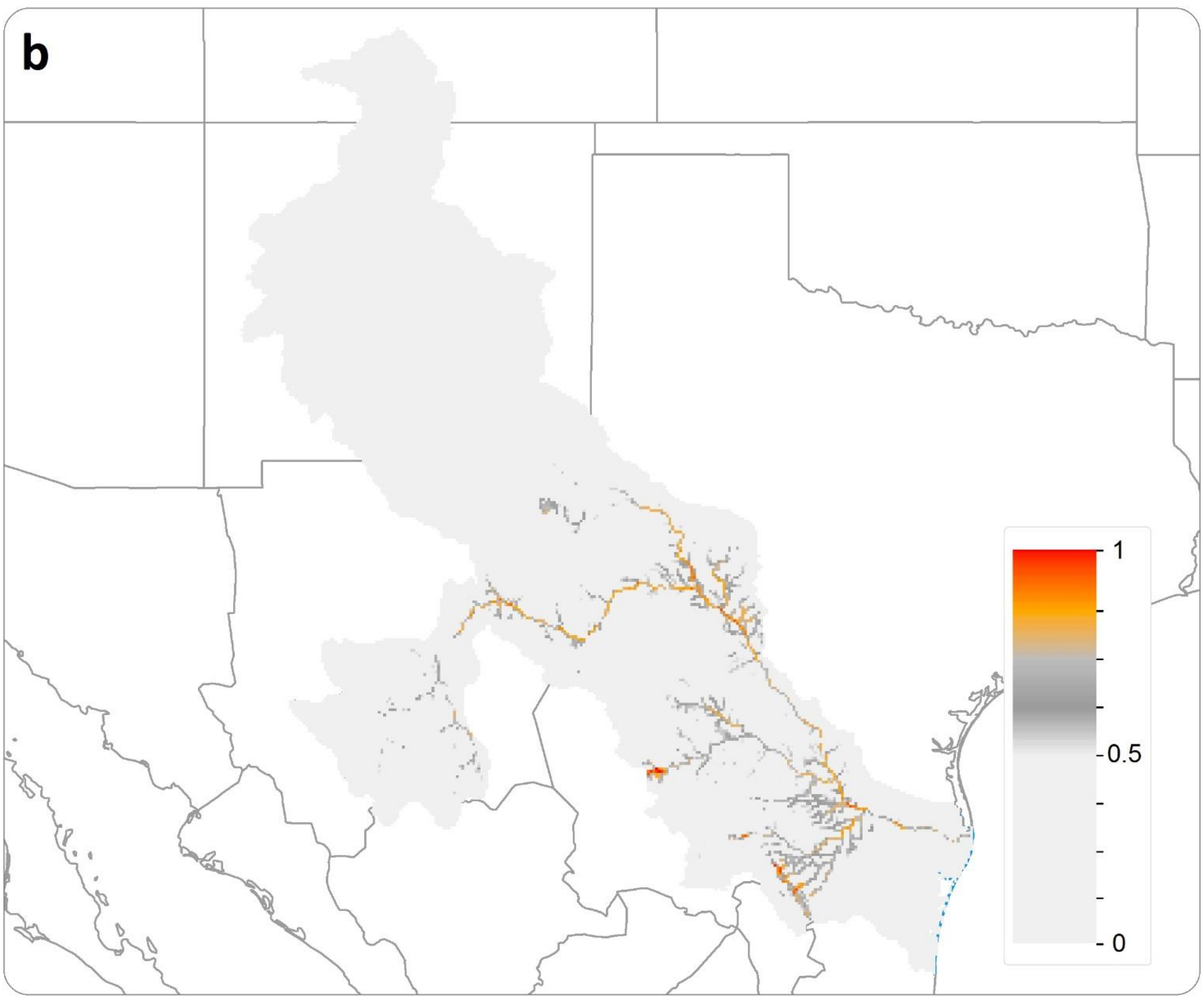
Subfigures represent projections onto climate variables resultant from three emission scenarios (A2-extreme, B1-conservative, A1B-intermediate) for three time periods: 2020s, 2050s and 2080s. These figures help to illustrate the direction and magnitude of climatic shift the species will experience. Complete raw model outputs can be found in supporting documents in ASCII grid layer format.

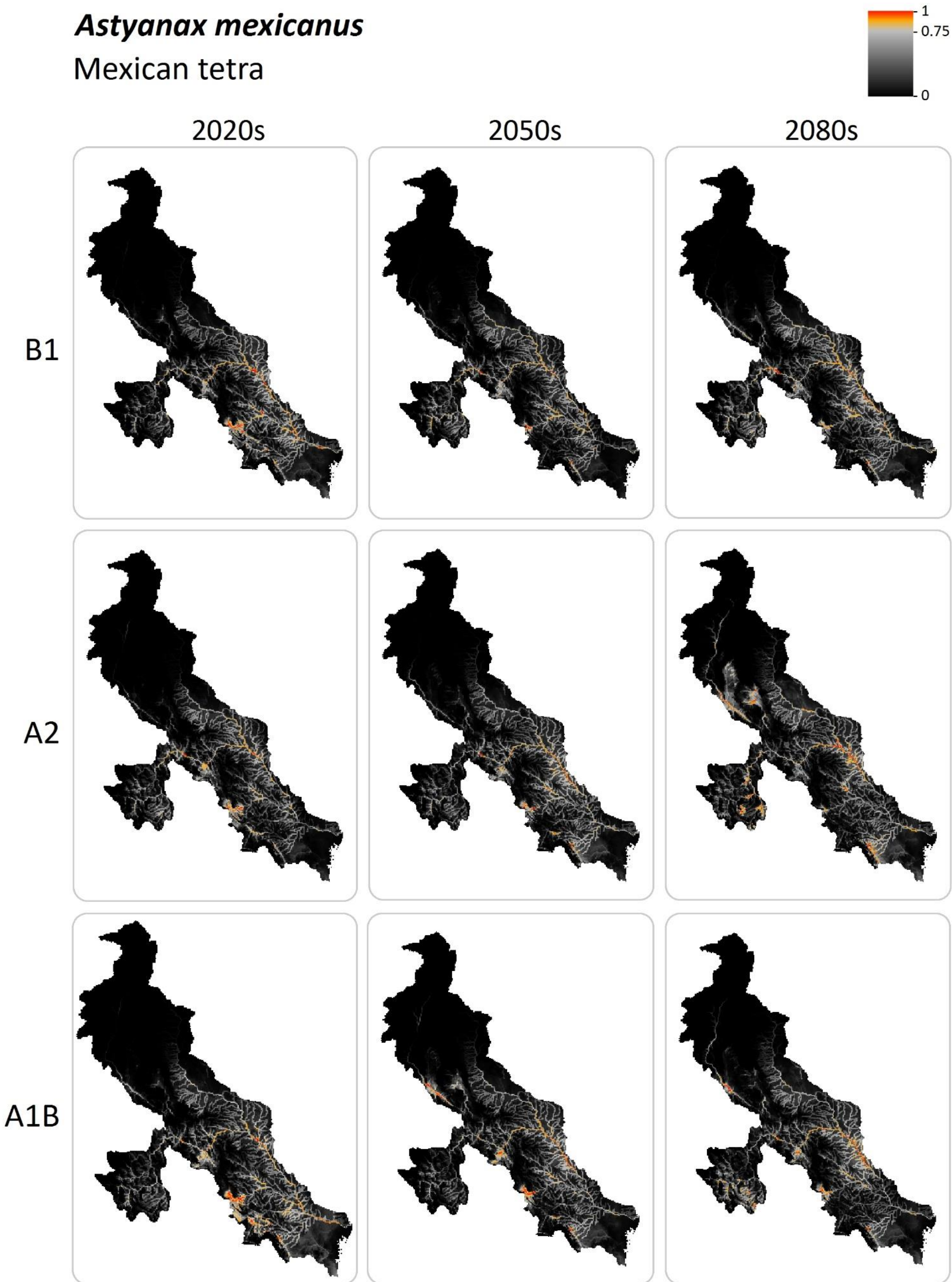
Astyanax mexicanus

Mexican tetra



a. Occurrence records used in model
b. "Current" distribution model

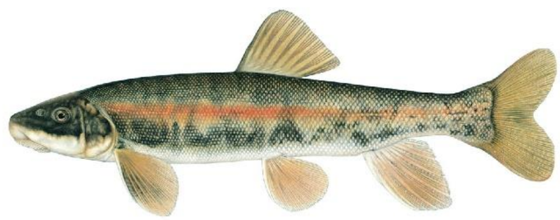


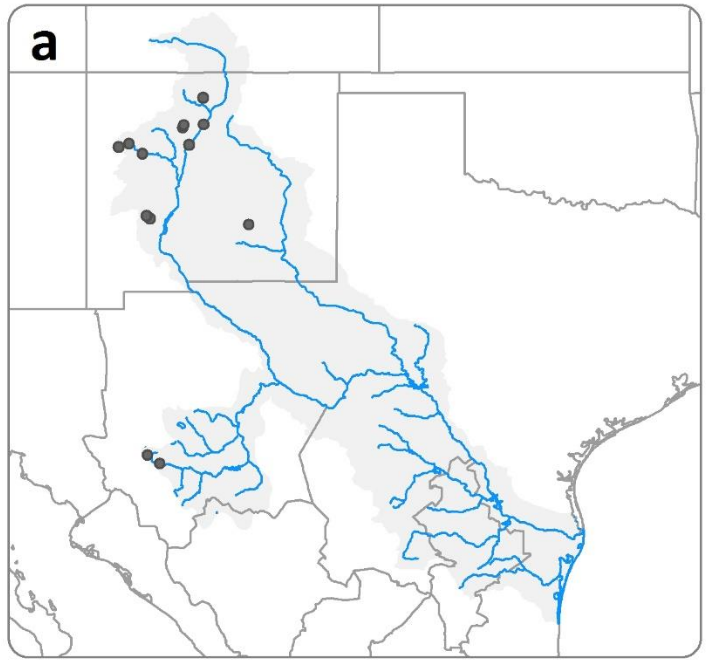


Astyanax mexicanus
Mexican tetra
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

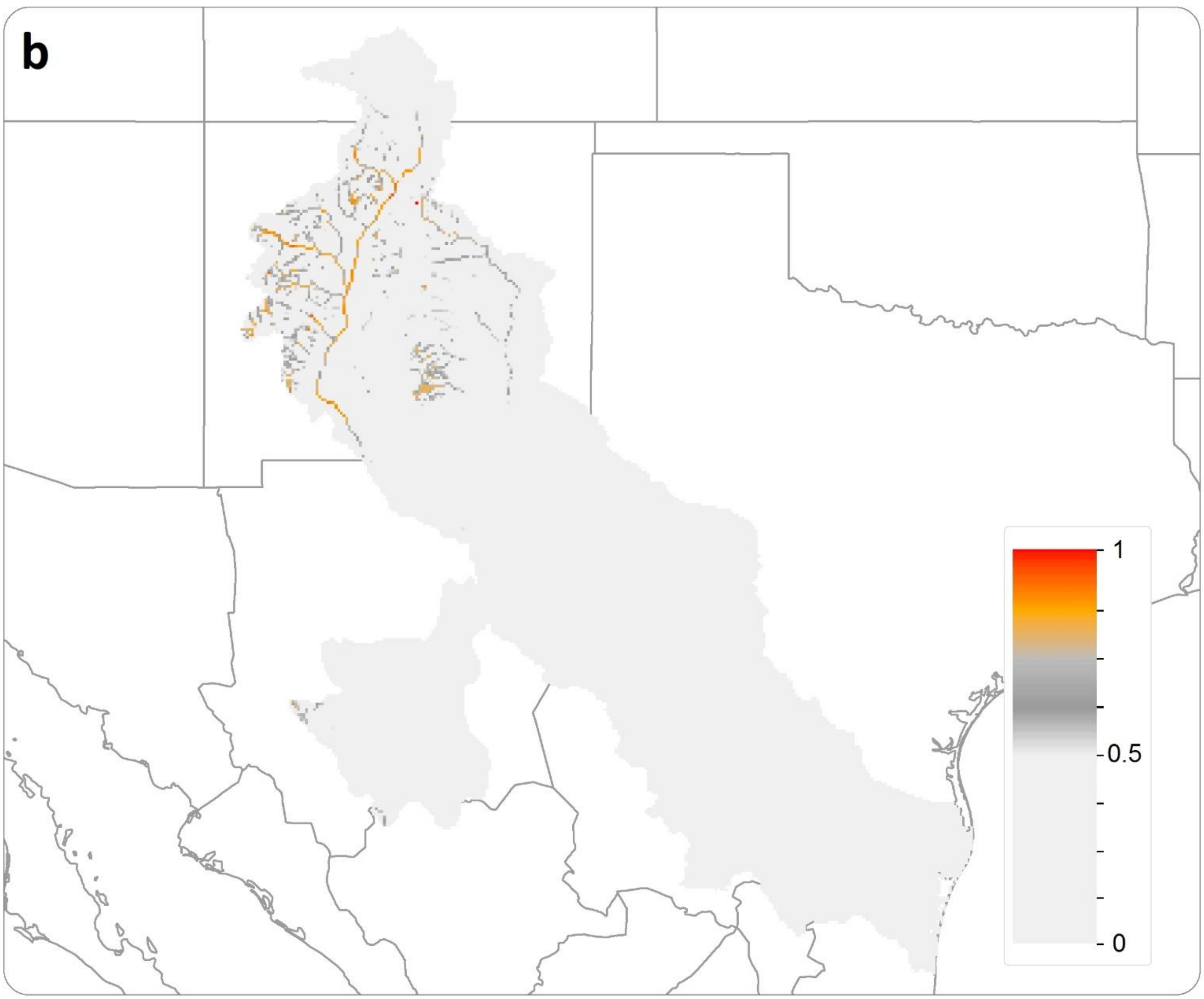
Catostomus plebeius

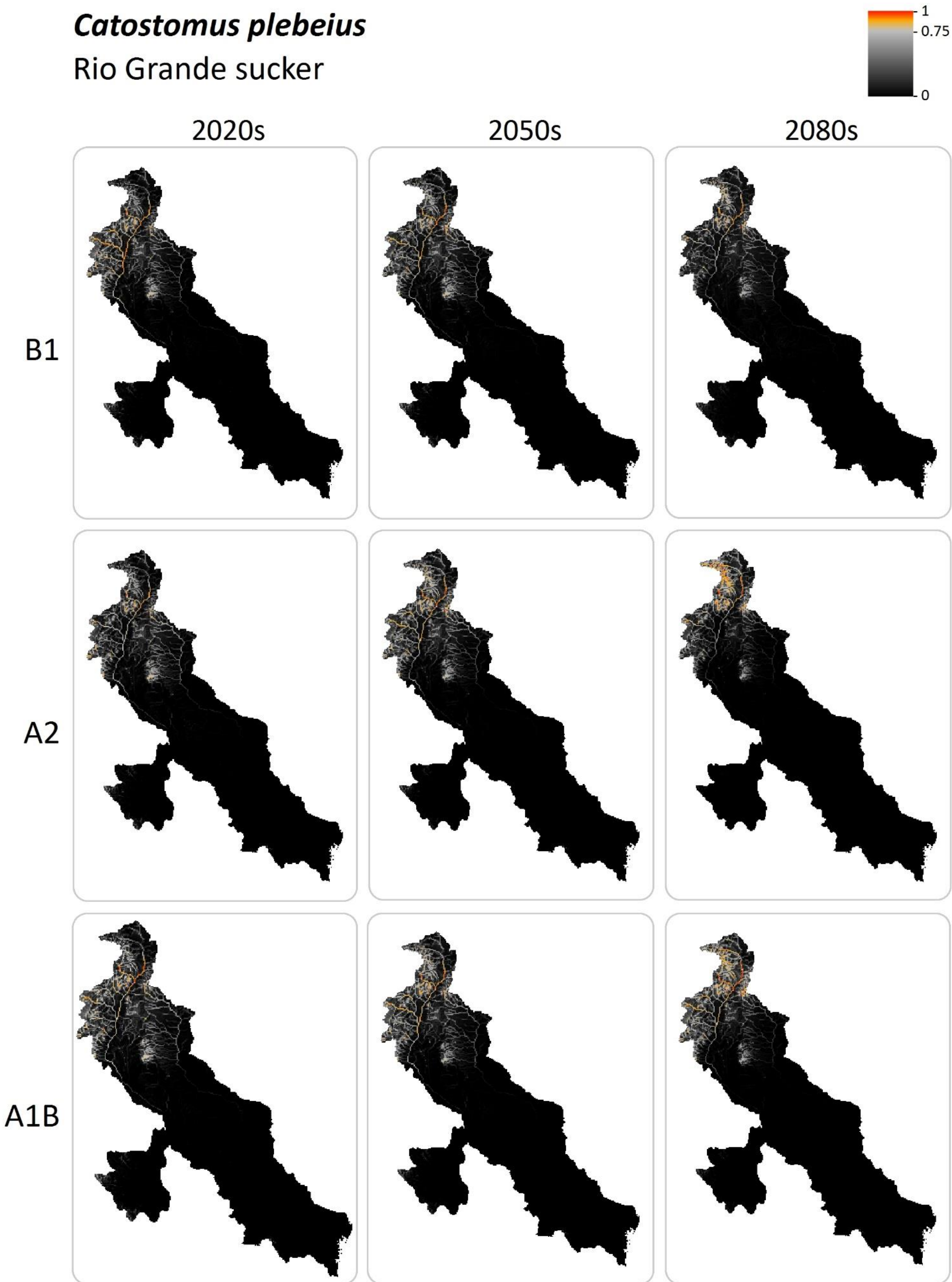
Rio Grande sucker





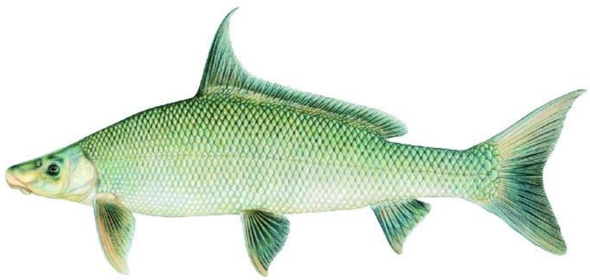
a. Occurrence records used in model
b. "Current" distribution model

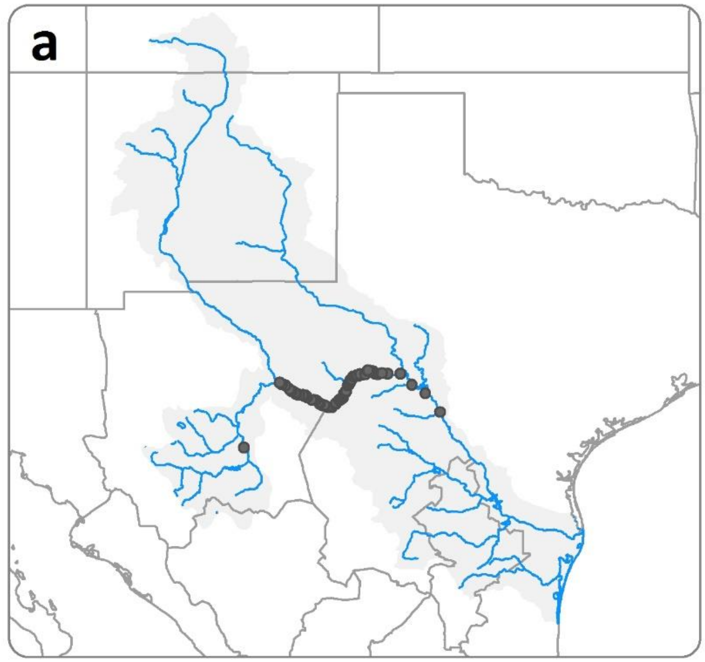



Catostomus plebeius
Rio Grande sucker
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

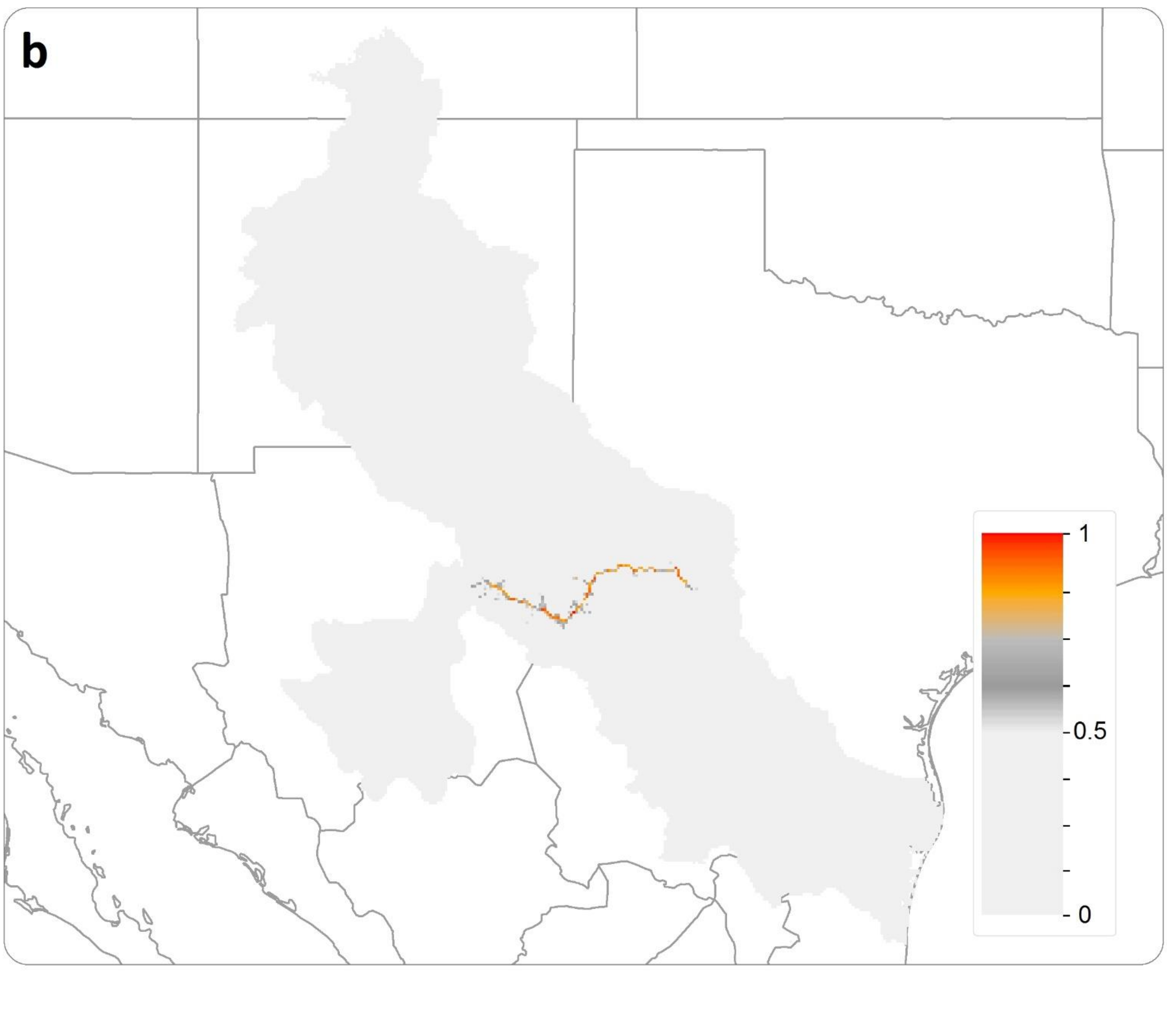
Cycleptus elongatus

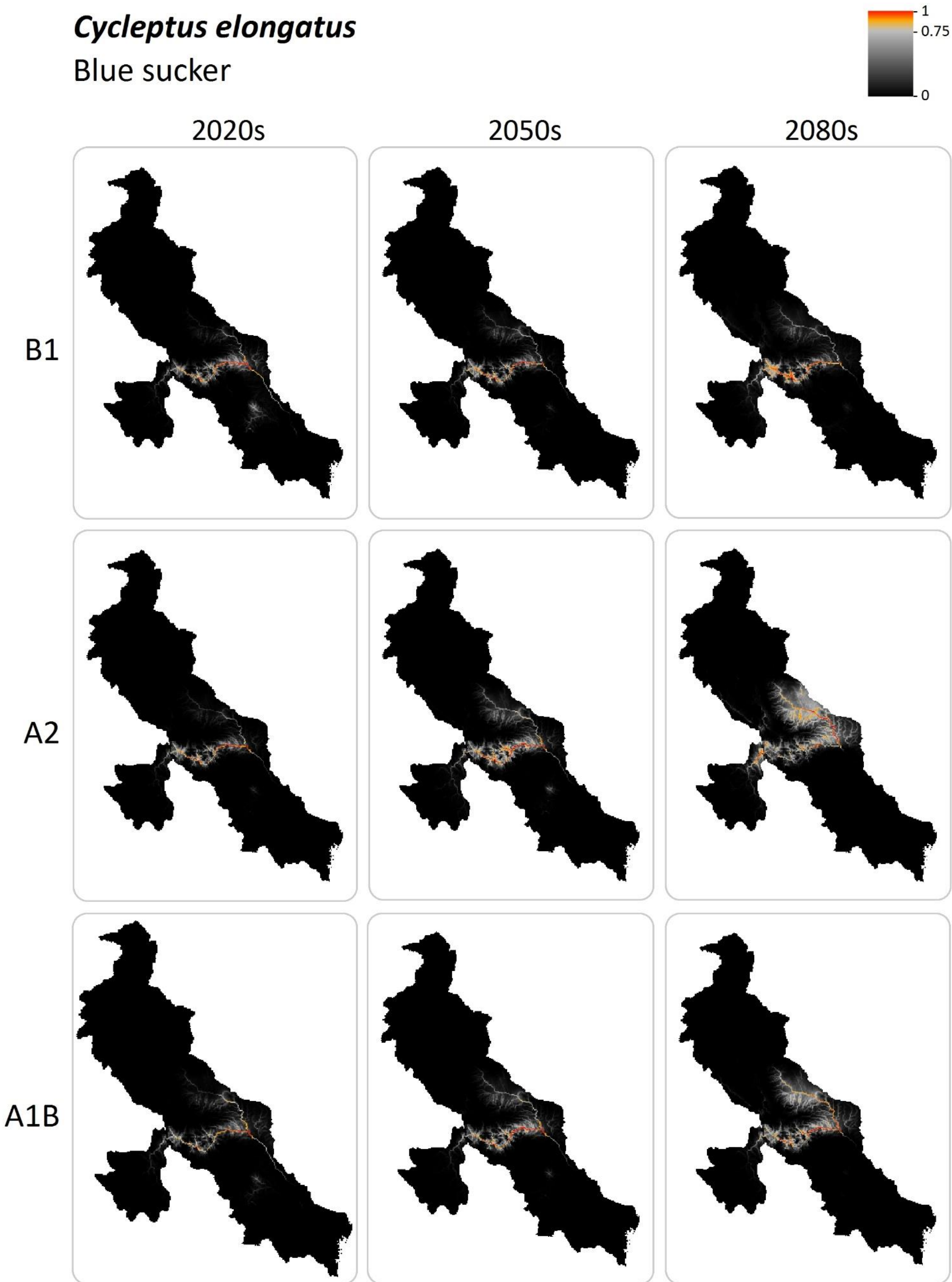
Blue sucker





a. Occurrence records used in model
b. "Current" distribution model

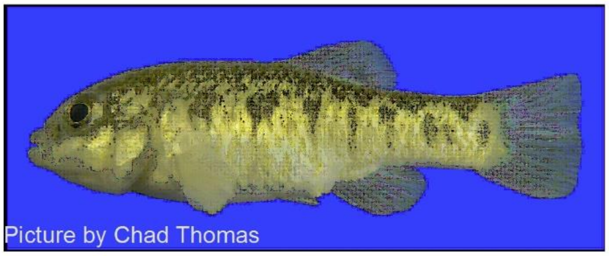


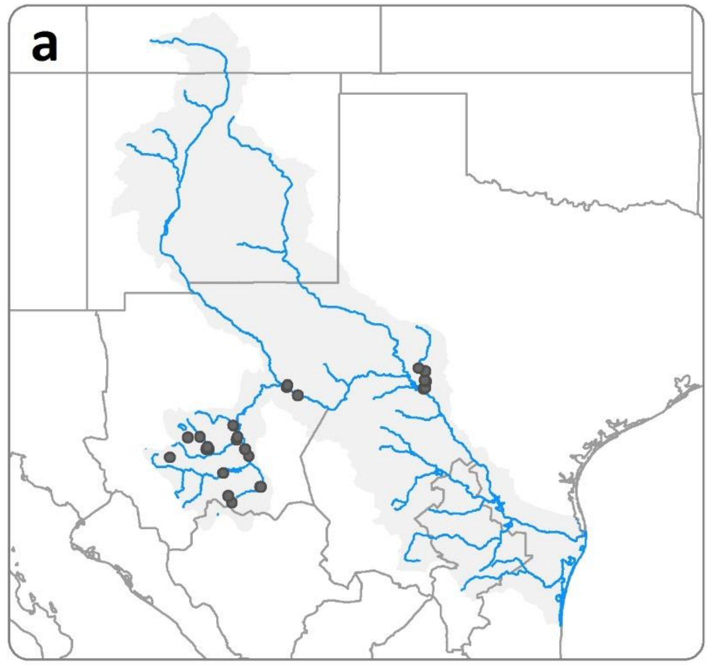


Cycleptus elongatus
Blue sucker
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

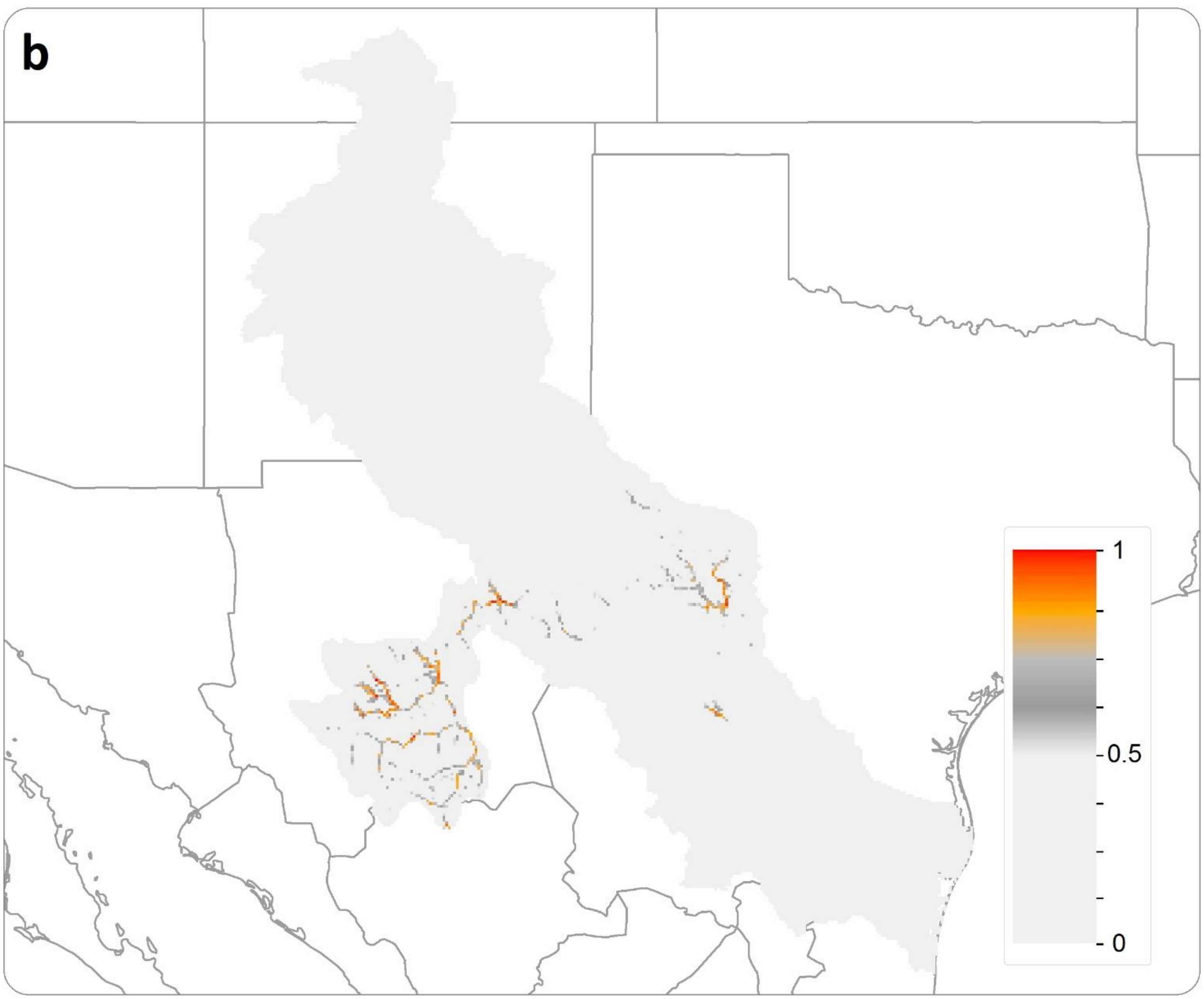
Cyprinodon eximius

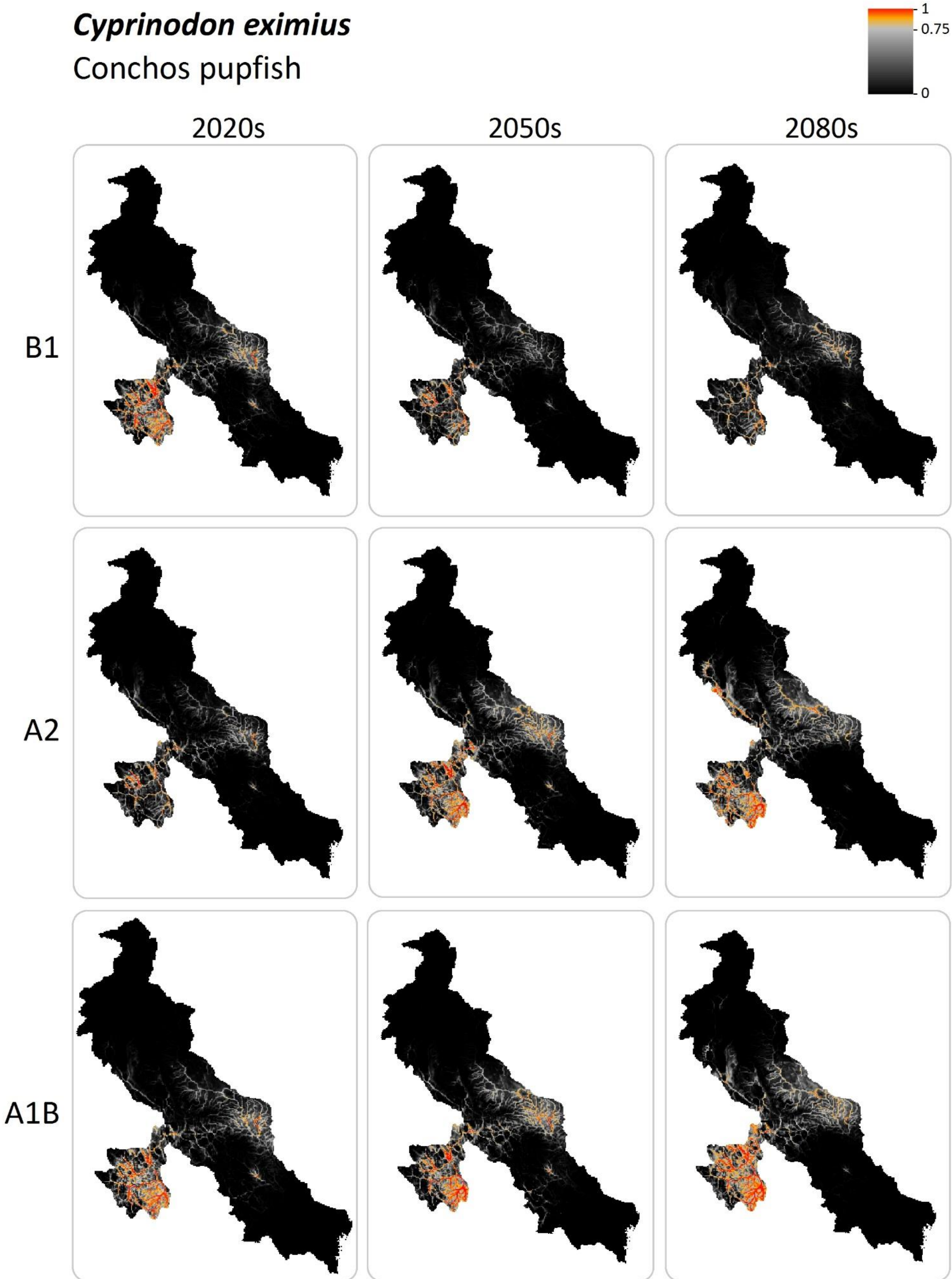
Conchos pupfish





a. Occurrence records used in model
b. "Current" distribution model

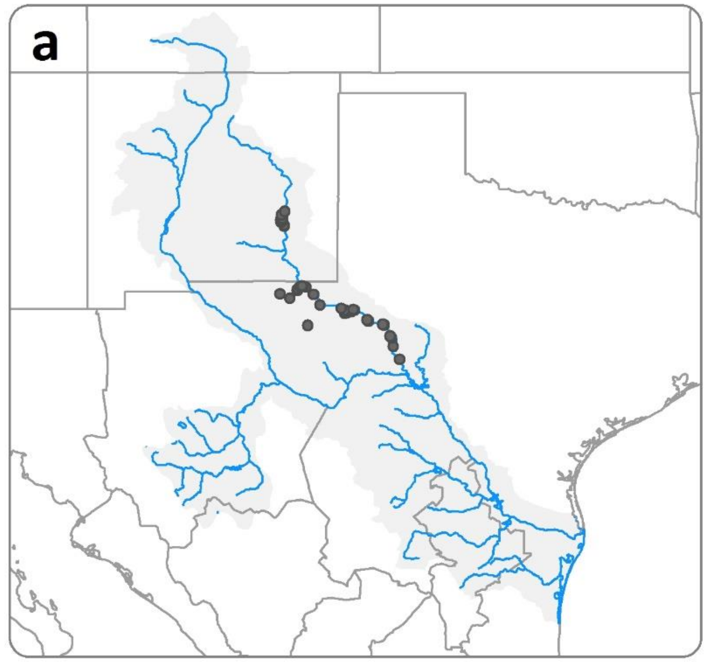


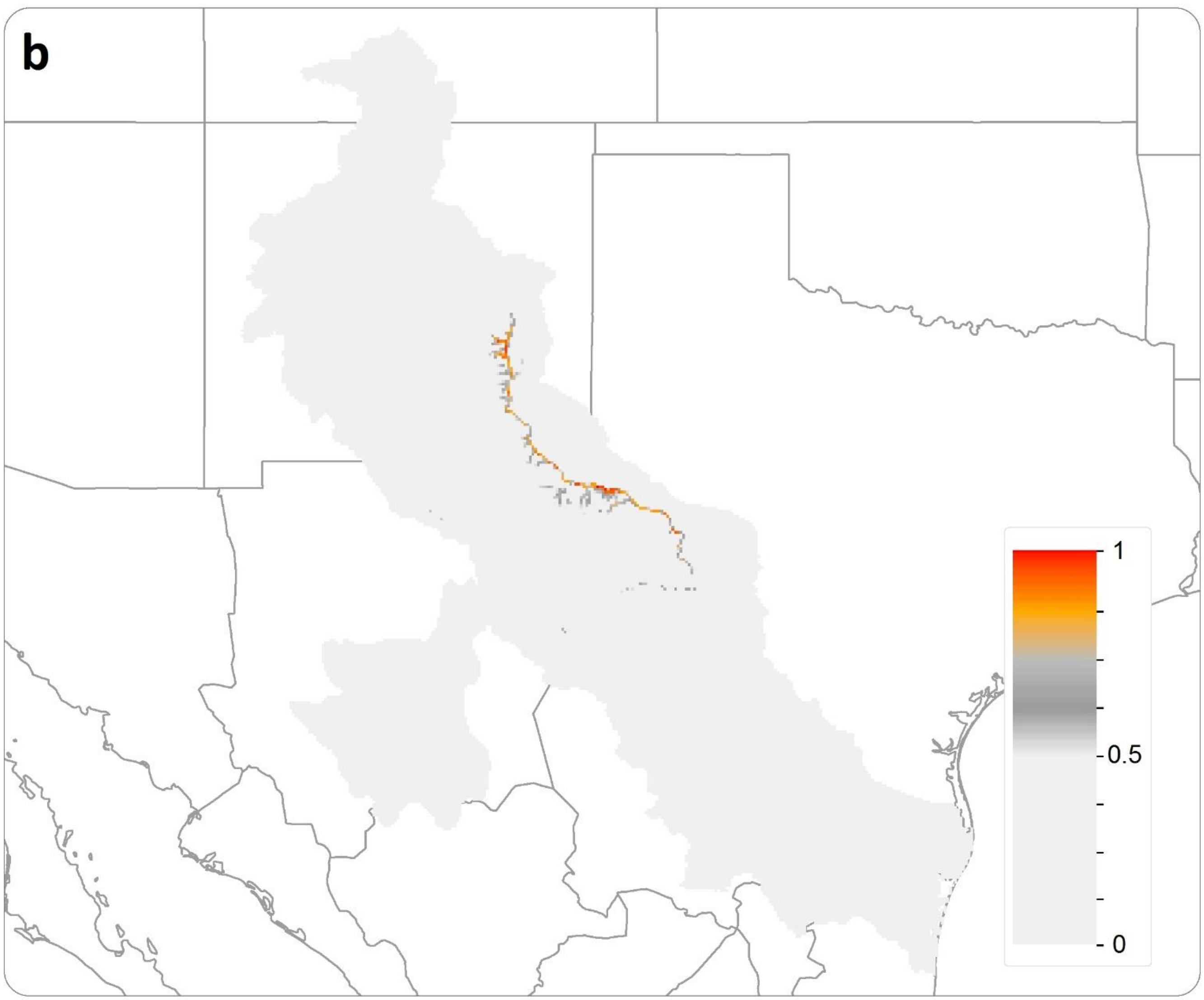

Cyprinodon eximius
Conchos pupfish
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

Cyprinodon pecosensis

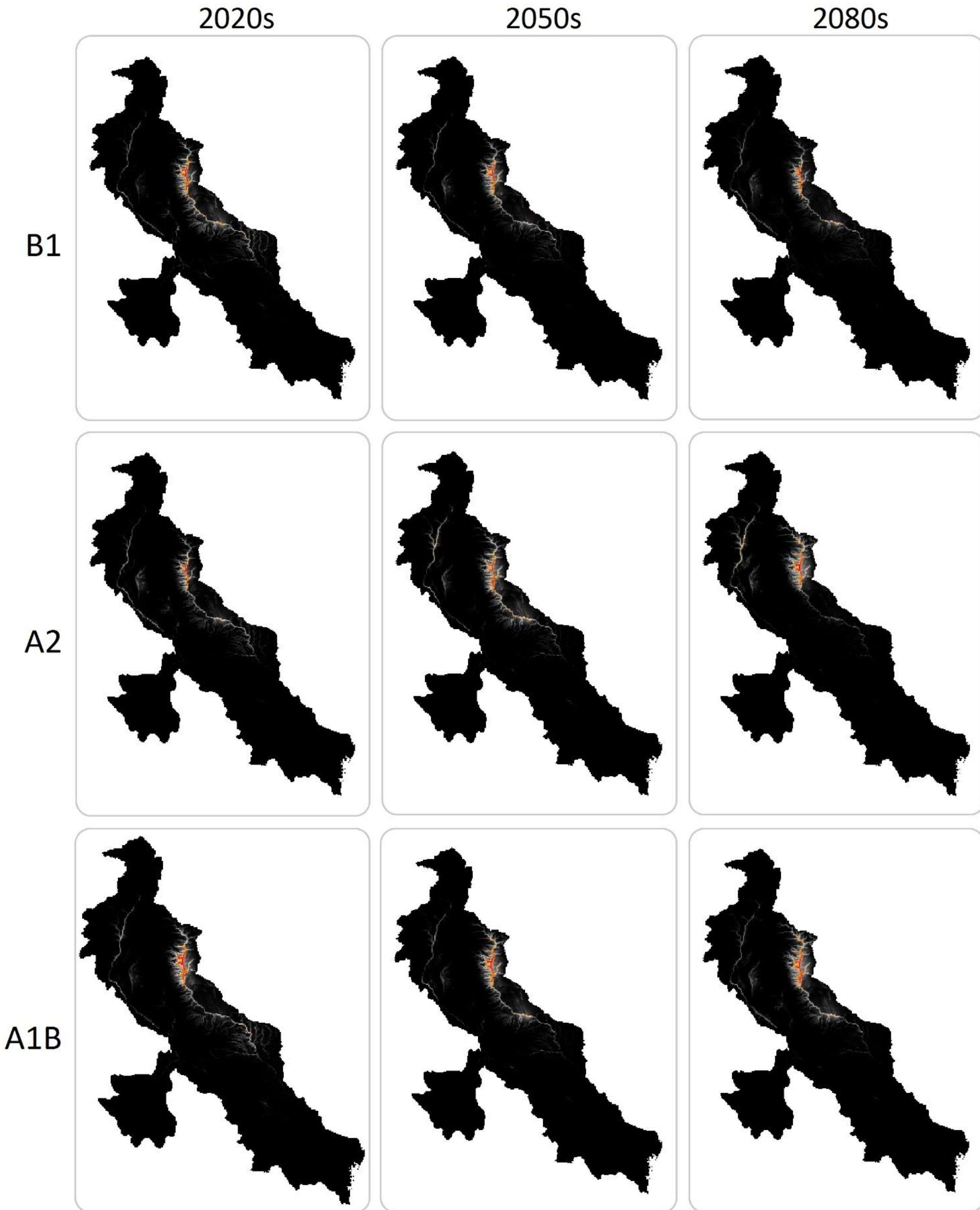
Pecos pupfish

a. Occurrence records used in model
b. "Current" distribution model



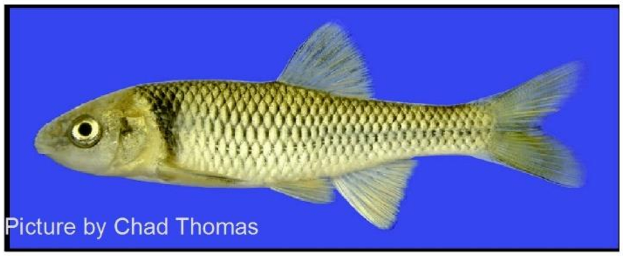


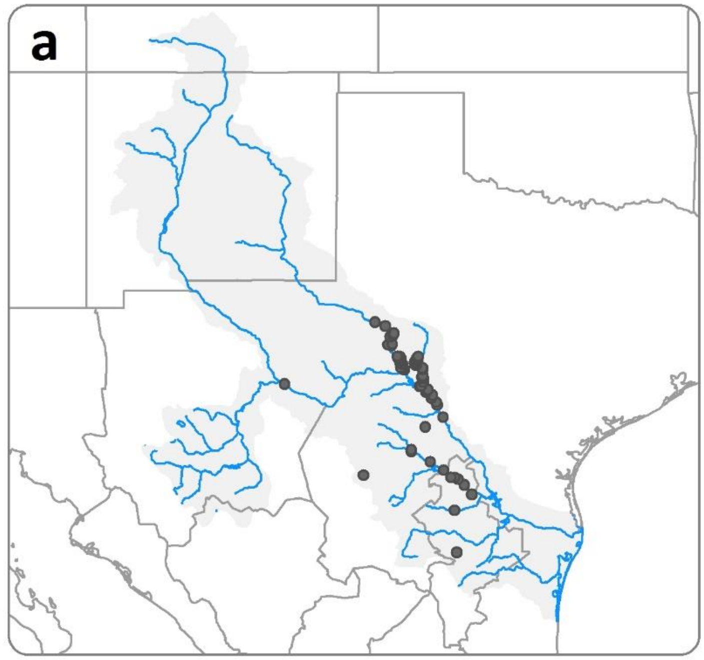
Cyprinodon pecosensis
Pecos pupfish



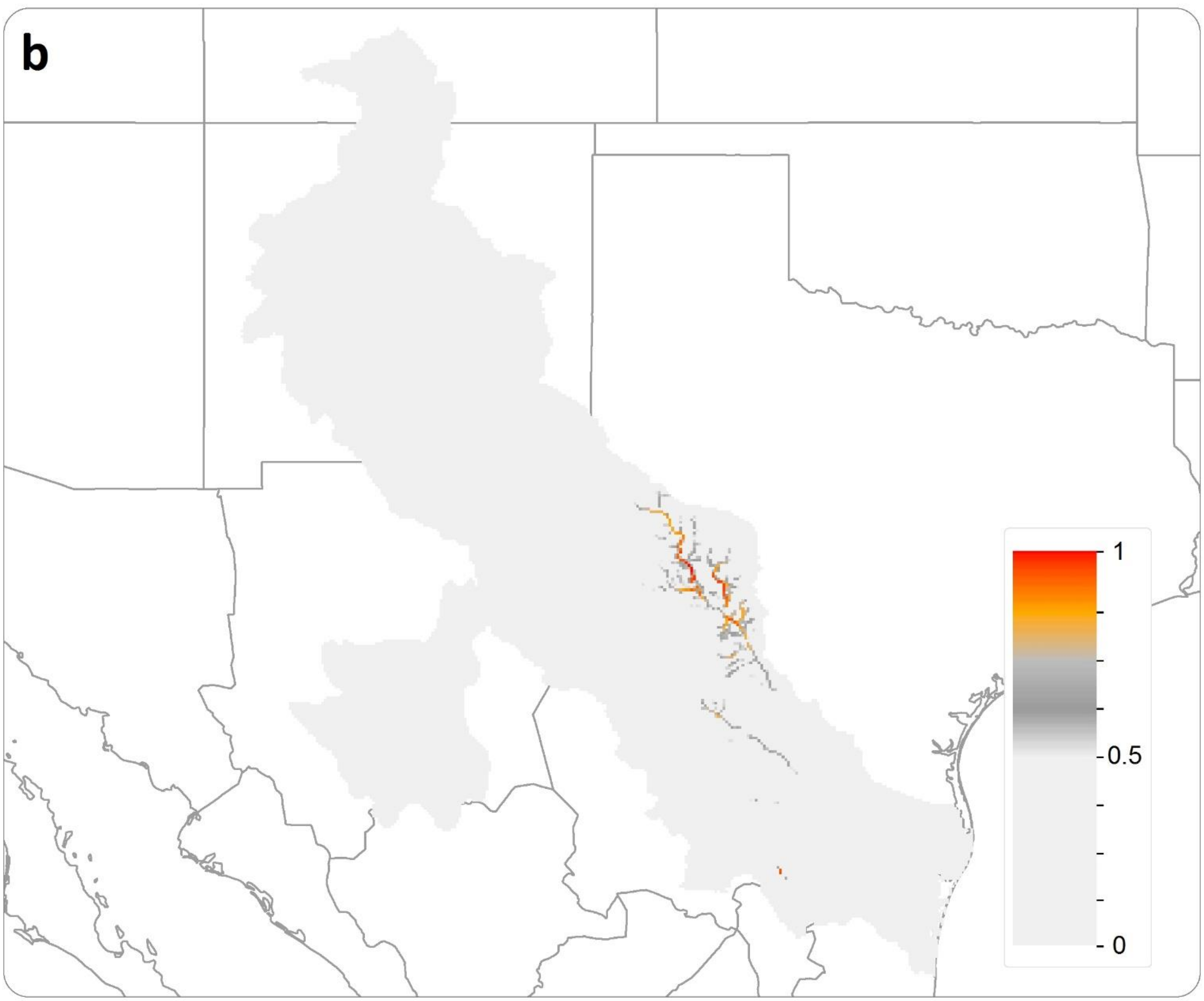
Cyprinella proserpina

Proserpine shiner

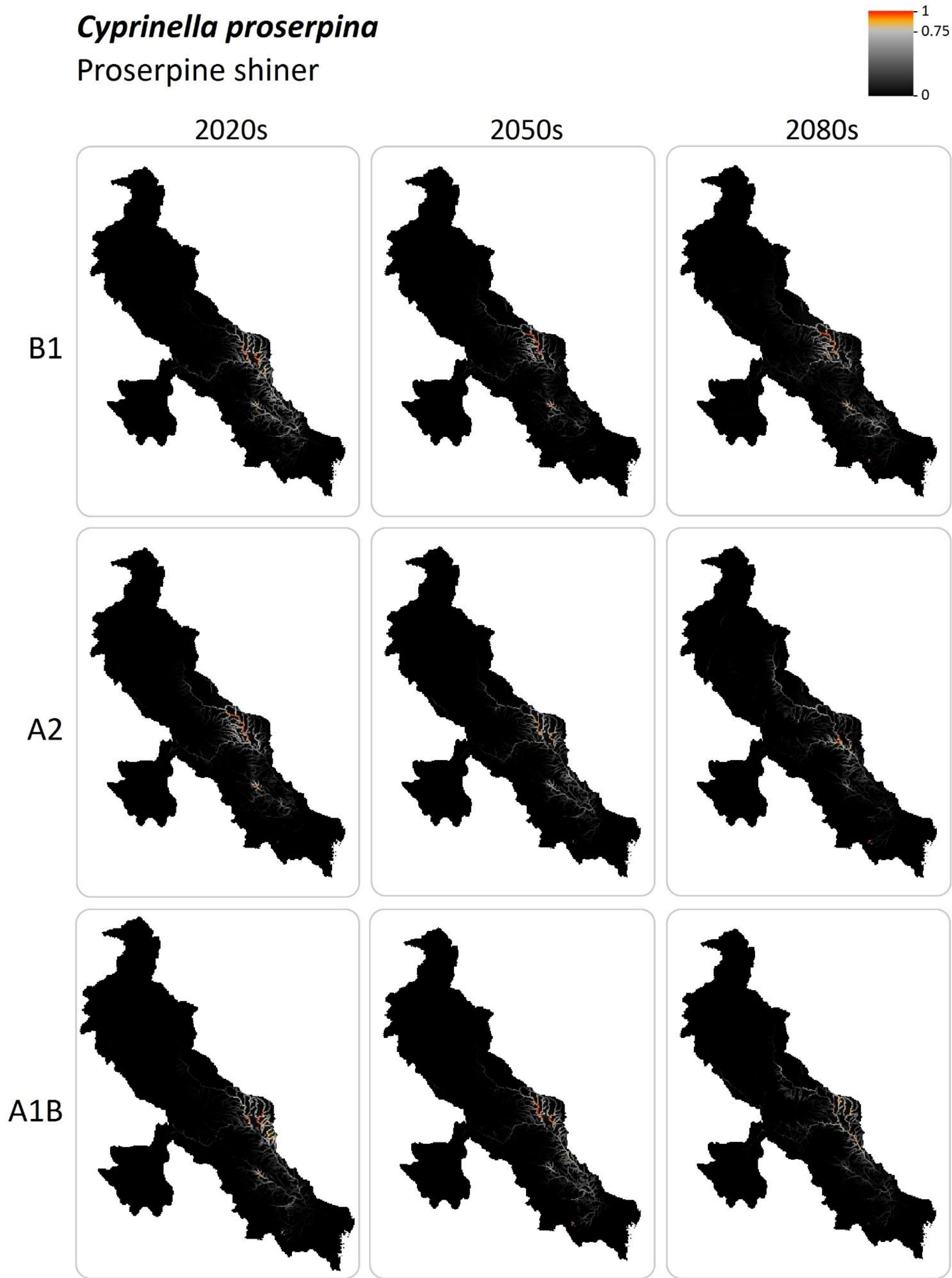




a. Occurrence records used in model
b. "Current" distribution model

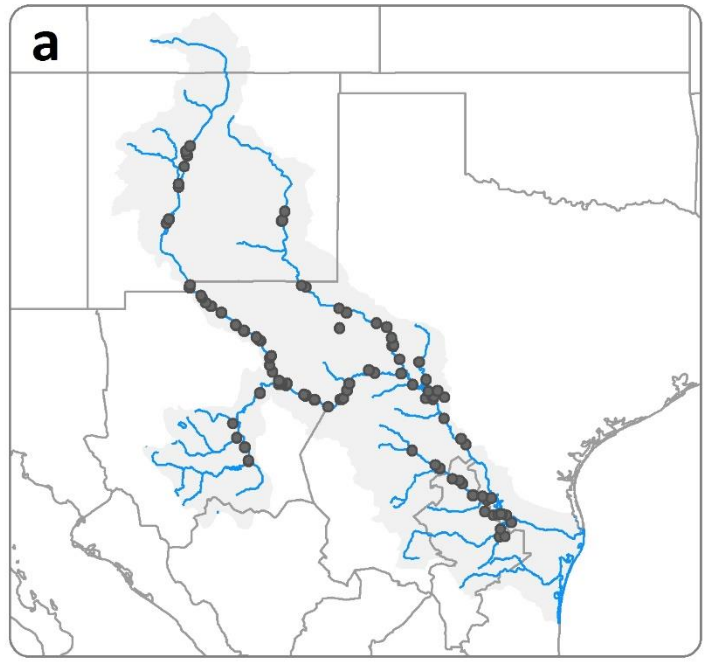


Cyprinella proserpina
Proserpine shiner

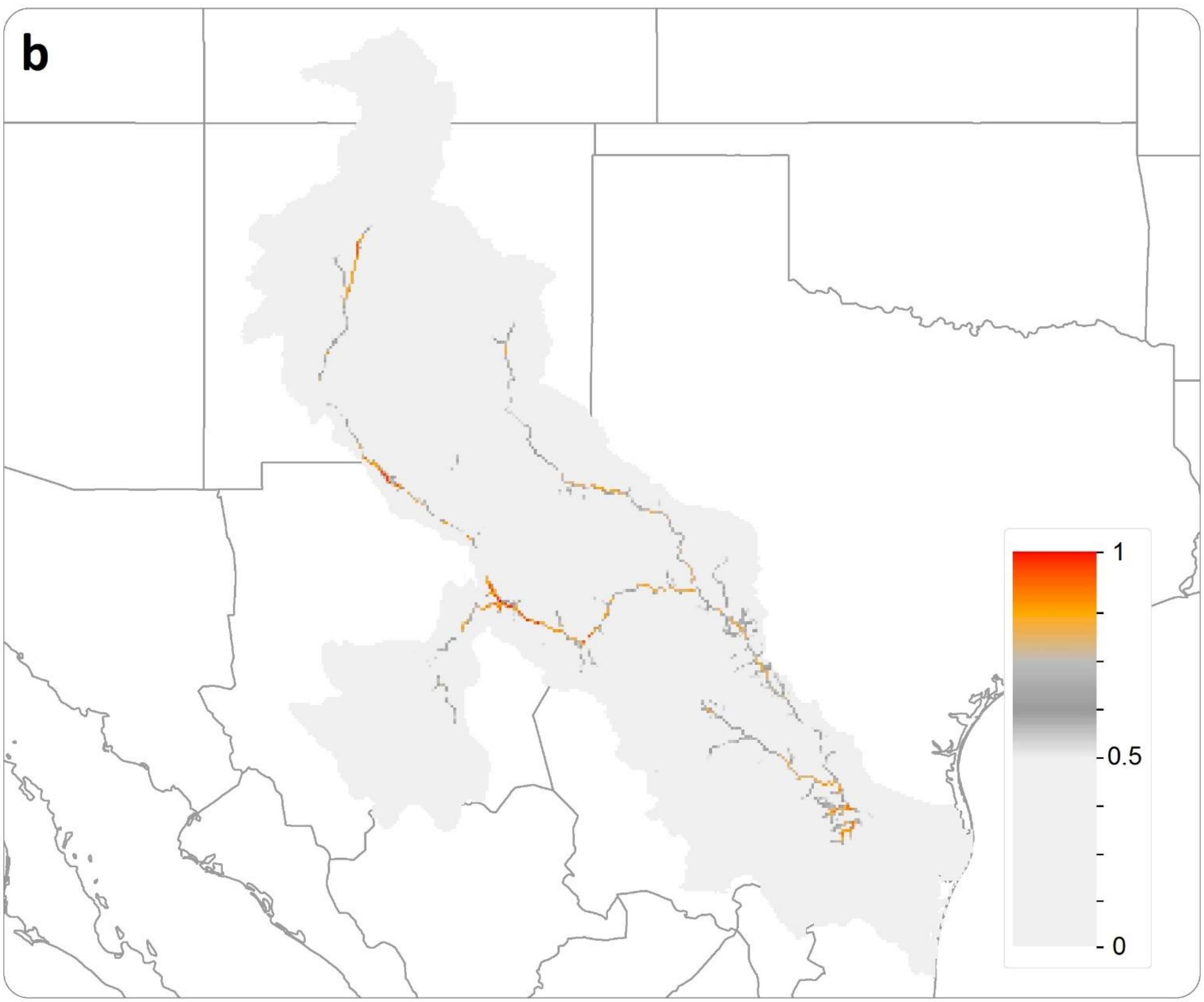


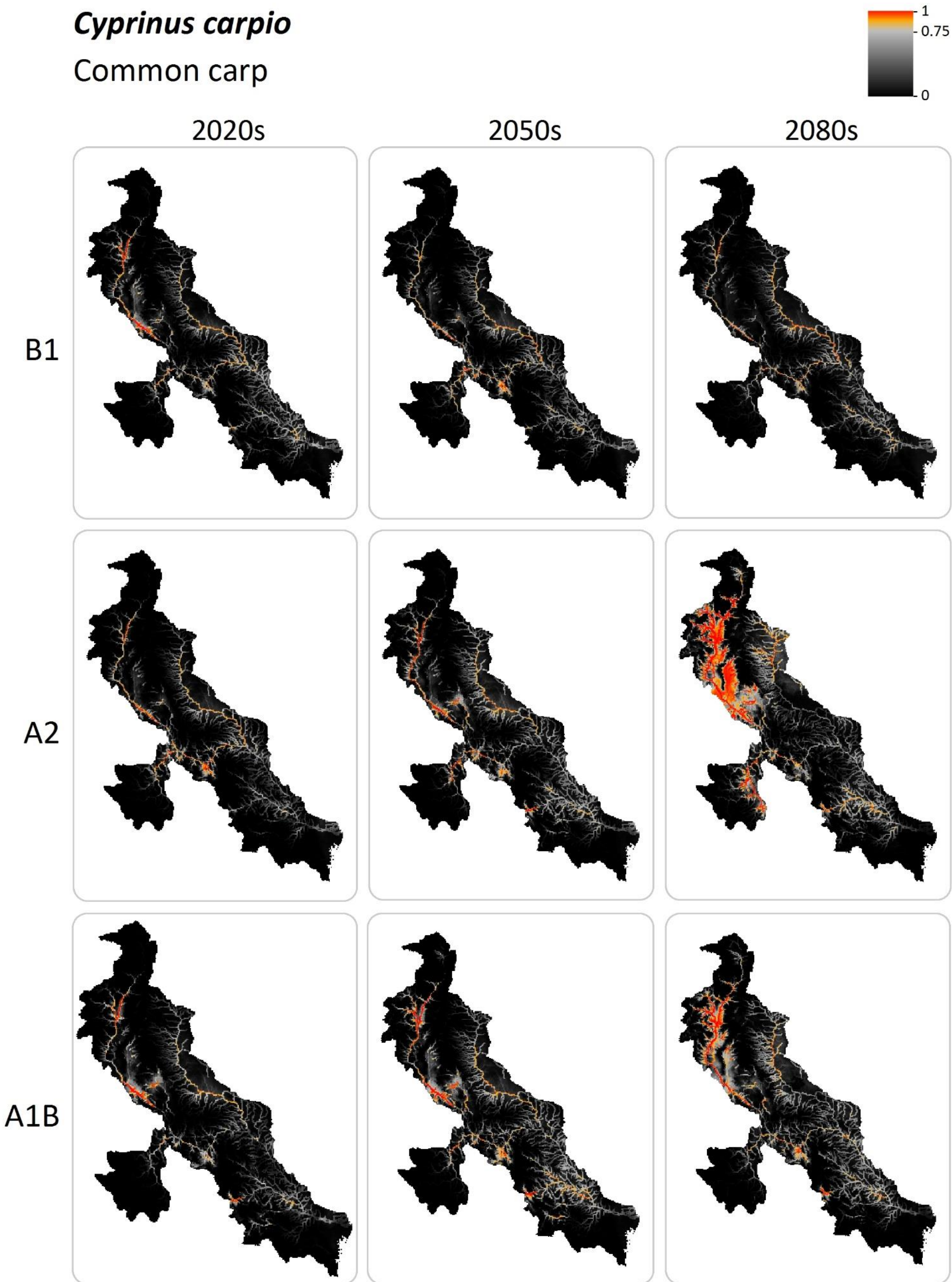
Cyprinus carpio

Common carp



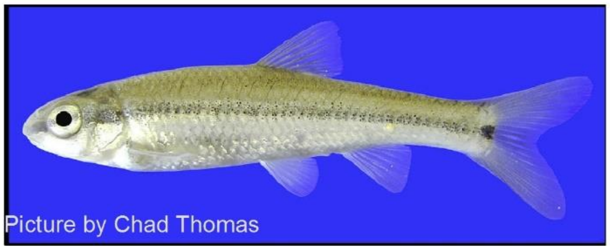
a. Occurrence records used in model
b. "Current" distribution model

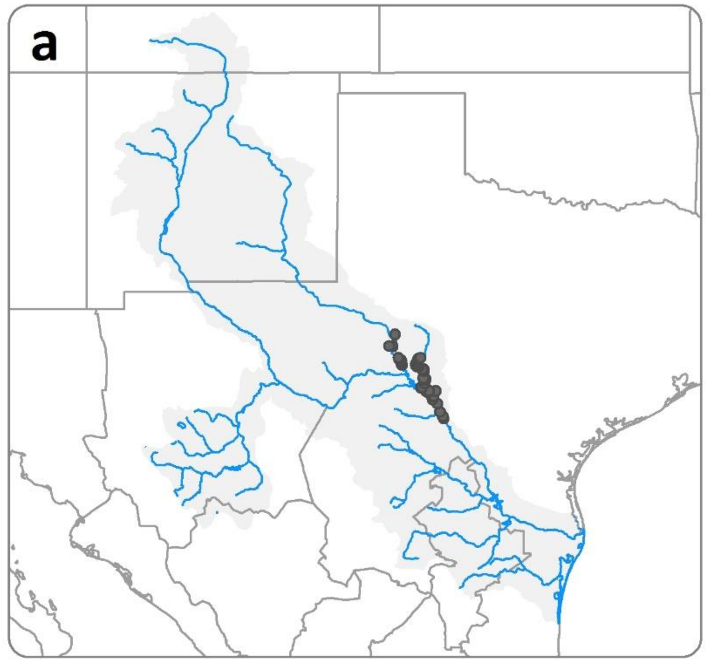



Cyprinus carpio
Common carp
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

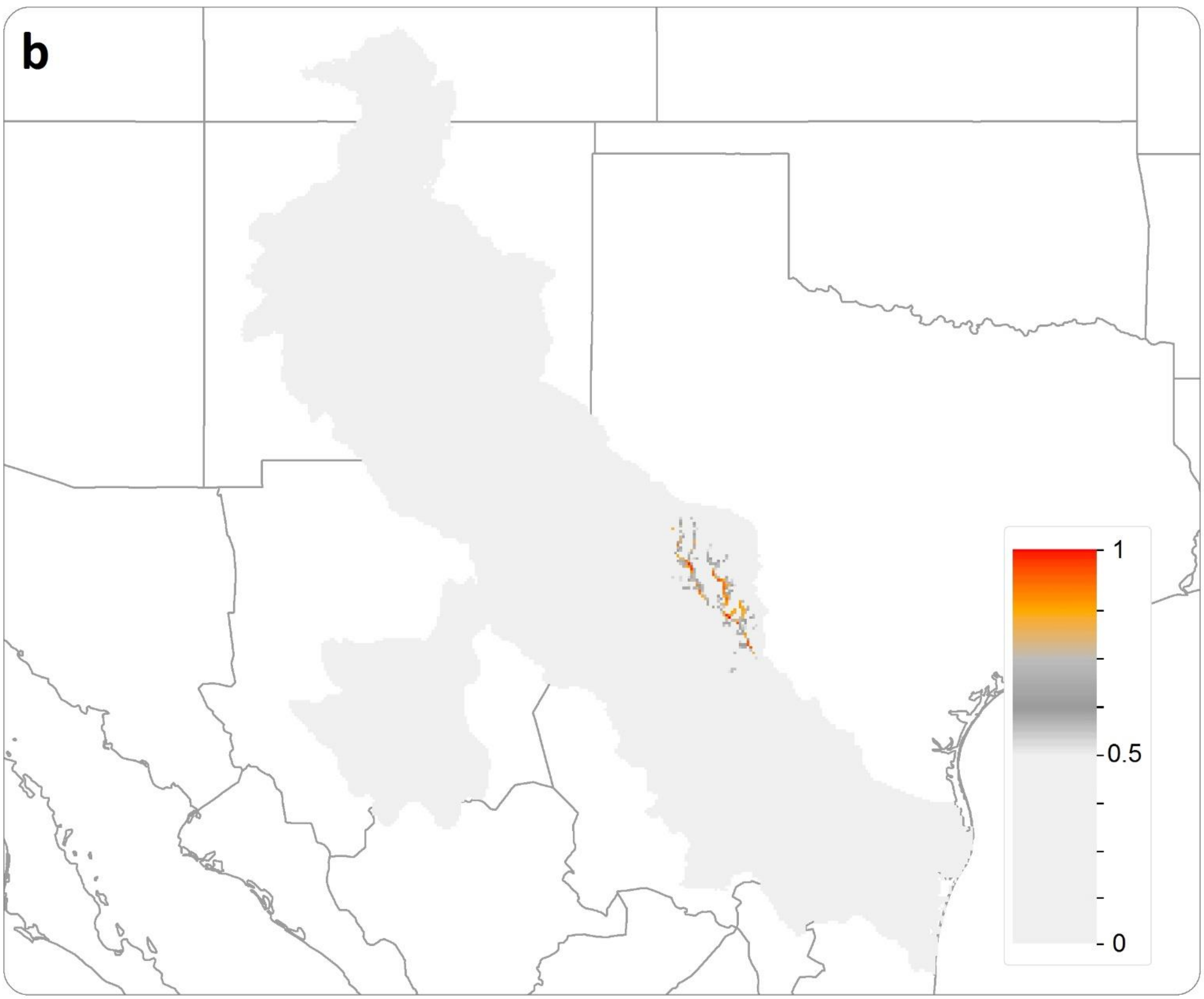
Dionda argentosa

Manantial roundnose minnow



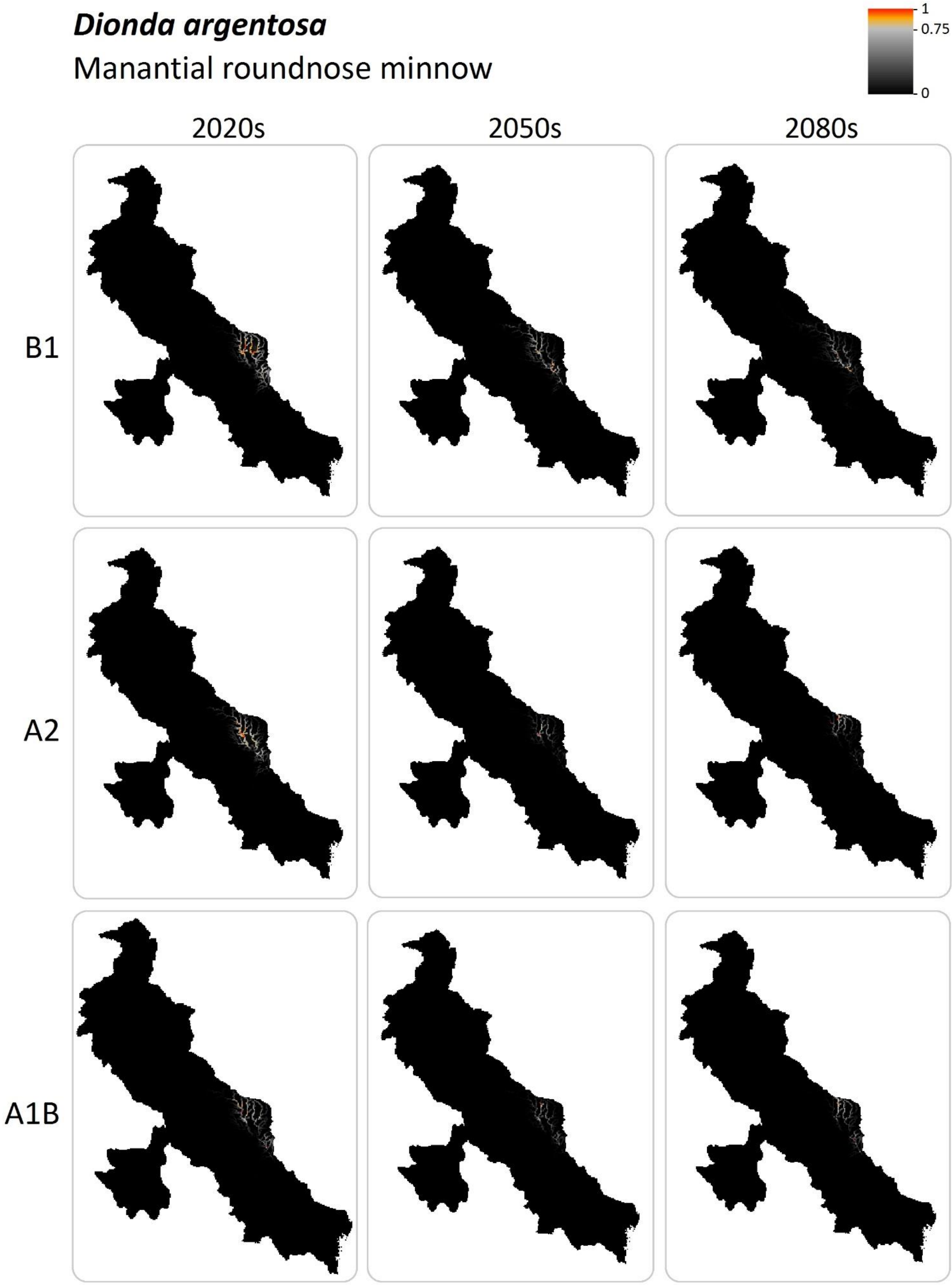


a. Occurrence records used in model
b. "Current" distribution model



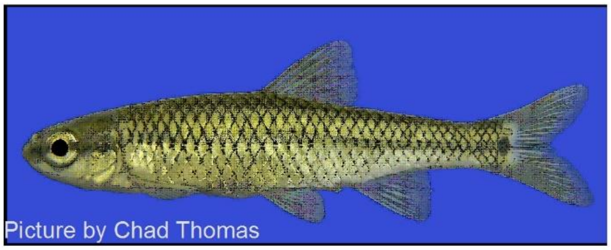
Dionda argentosa

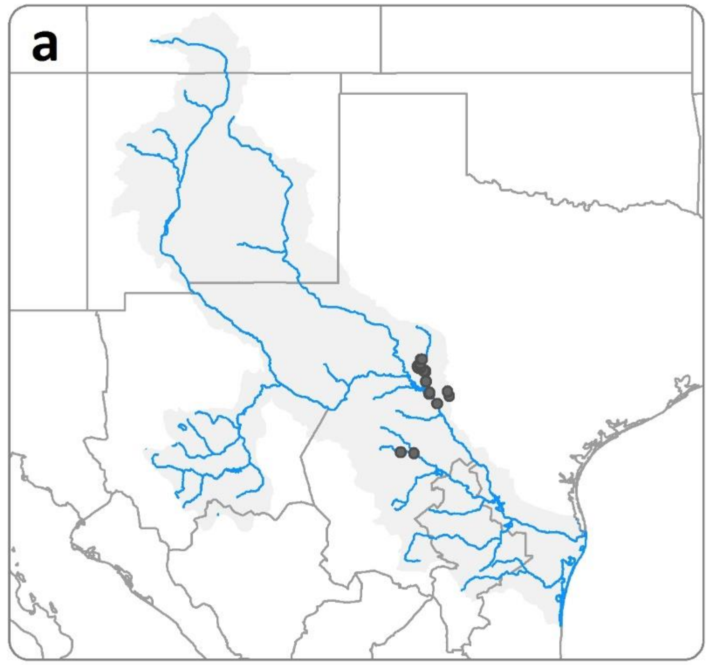
Manantial roundnose minnow



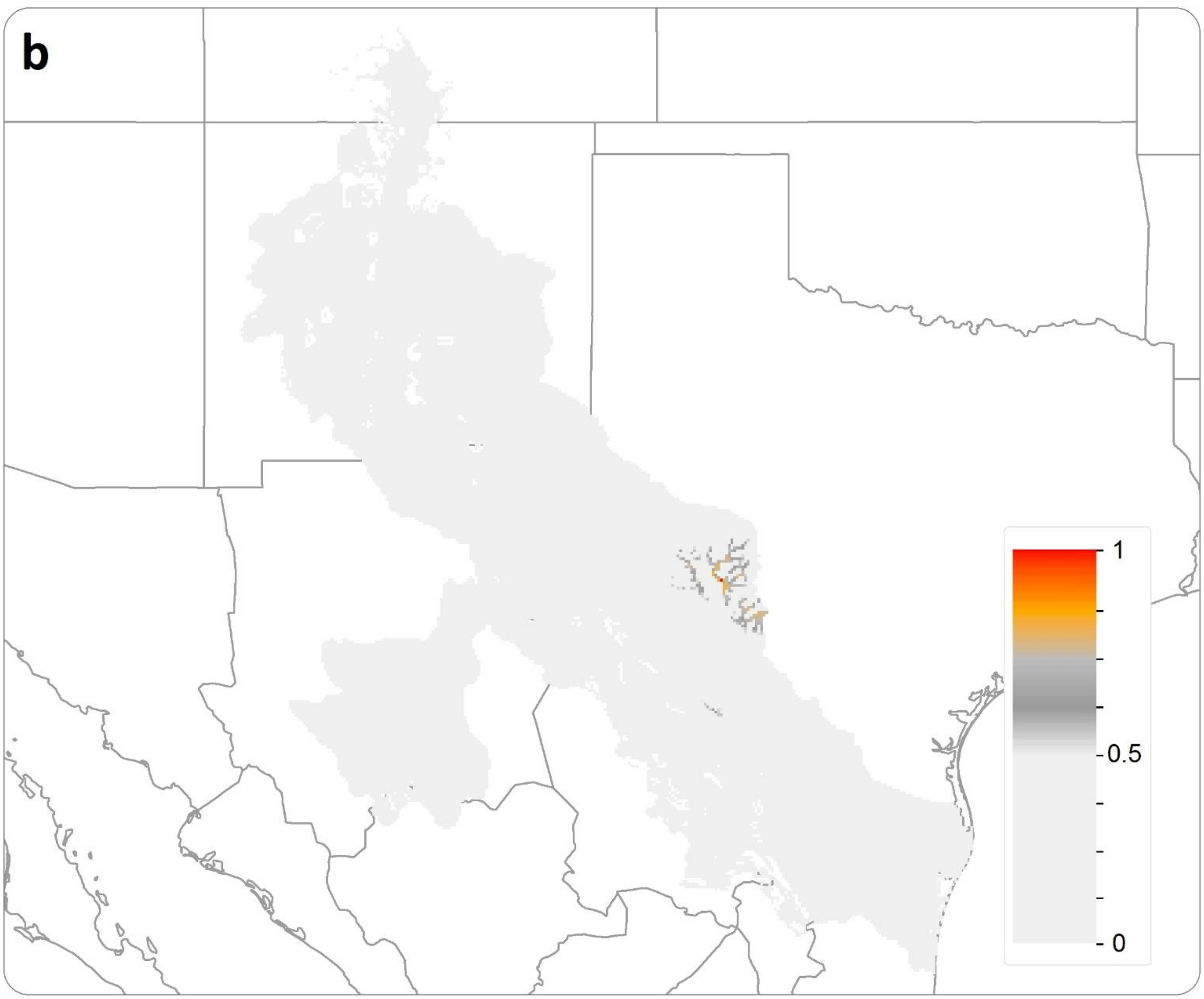
Dionda diaboli

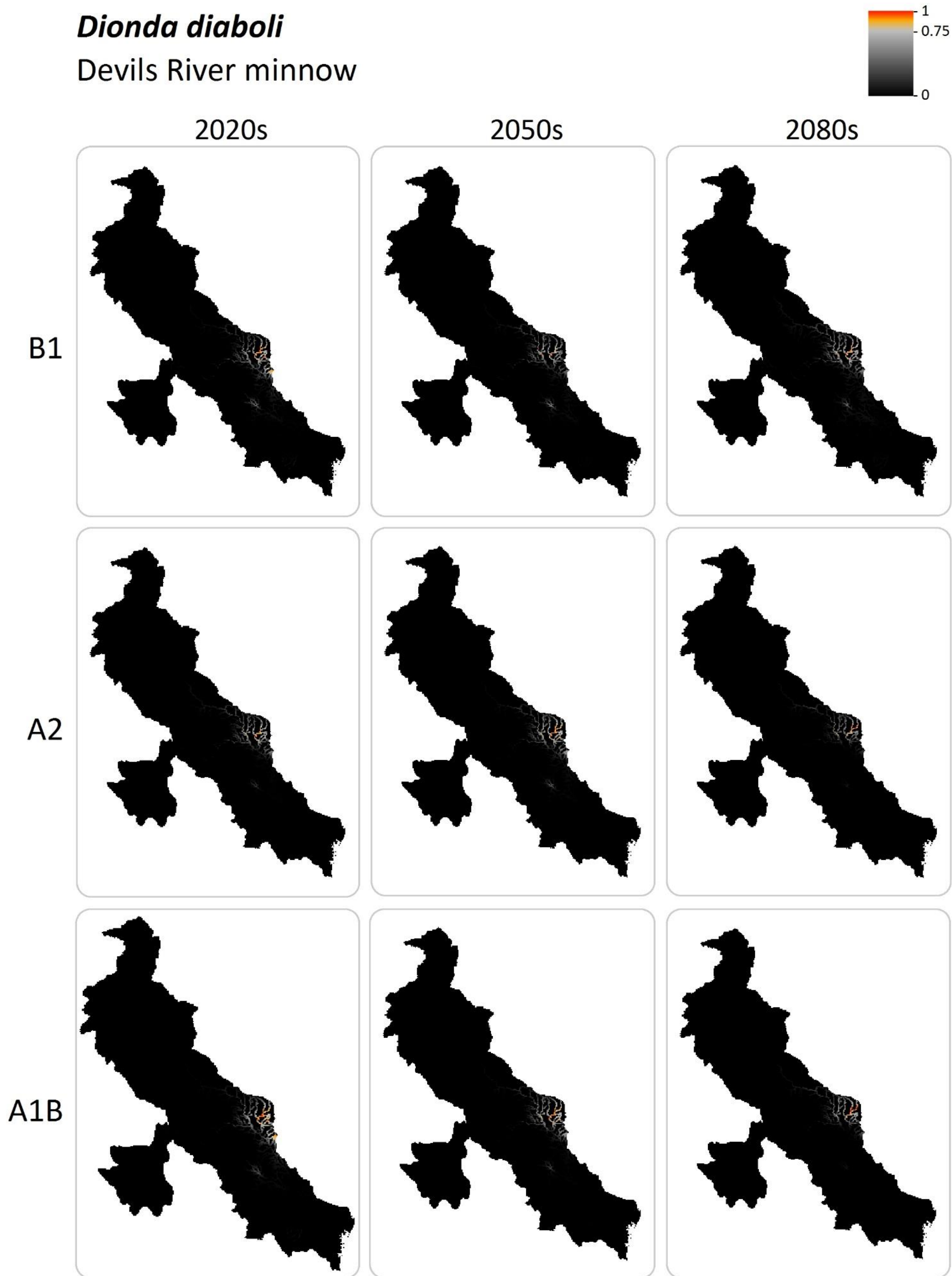
Devils River minnow





a. Occurrence records used in model
b. "Current" distribution model

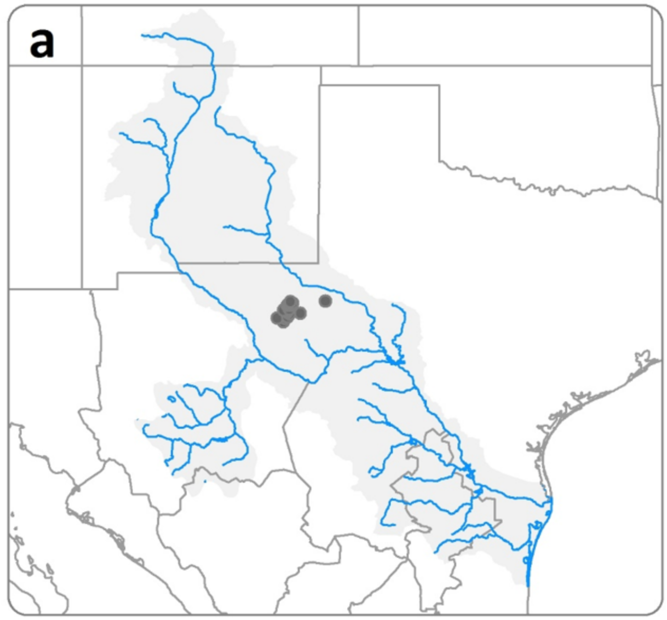


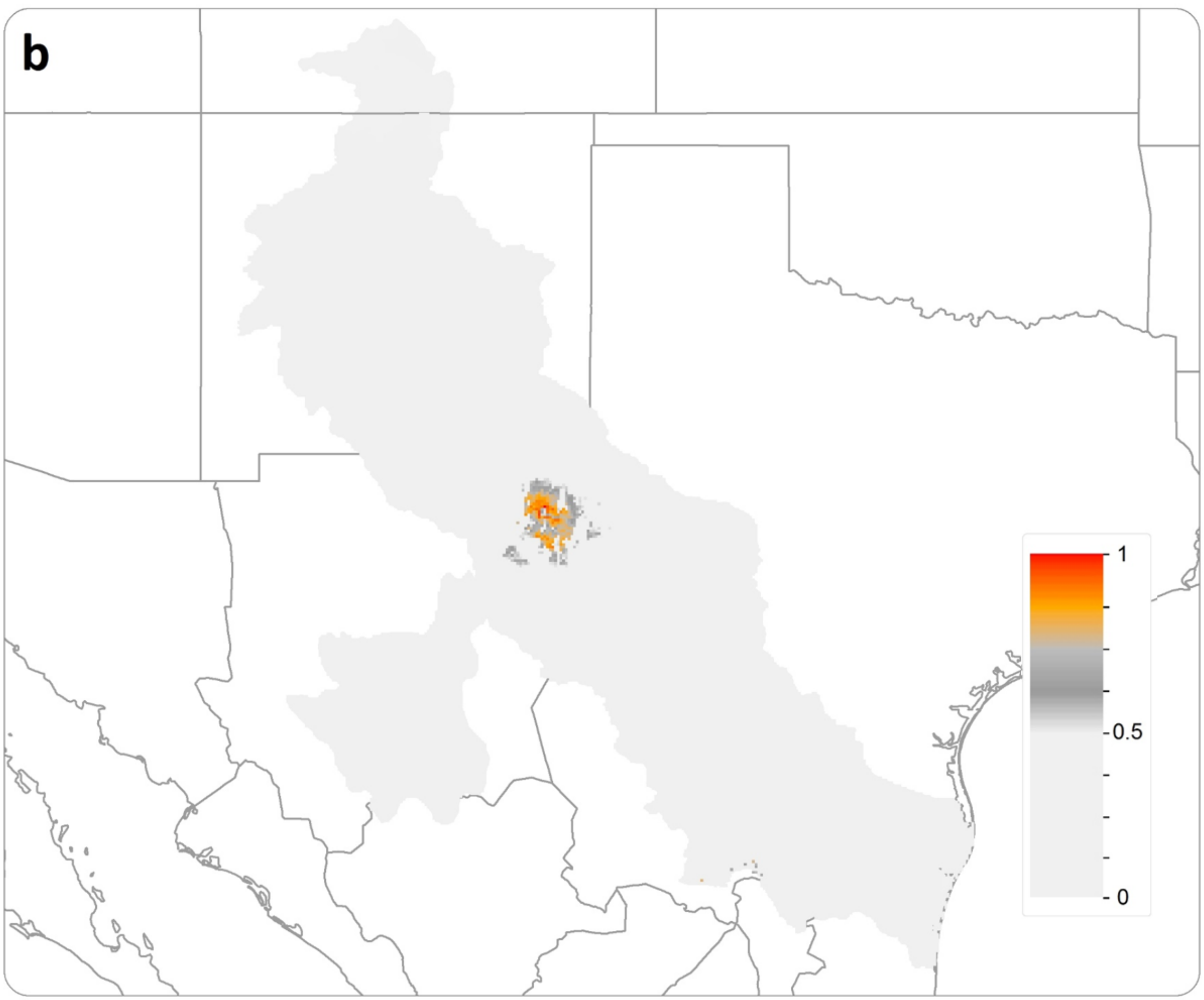

Dionda diaboli
Devils River minnow
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

Dionda episcopa

Roundnose minnow

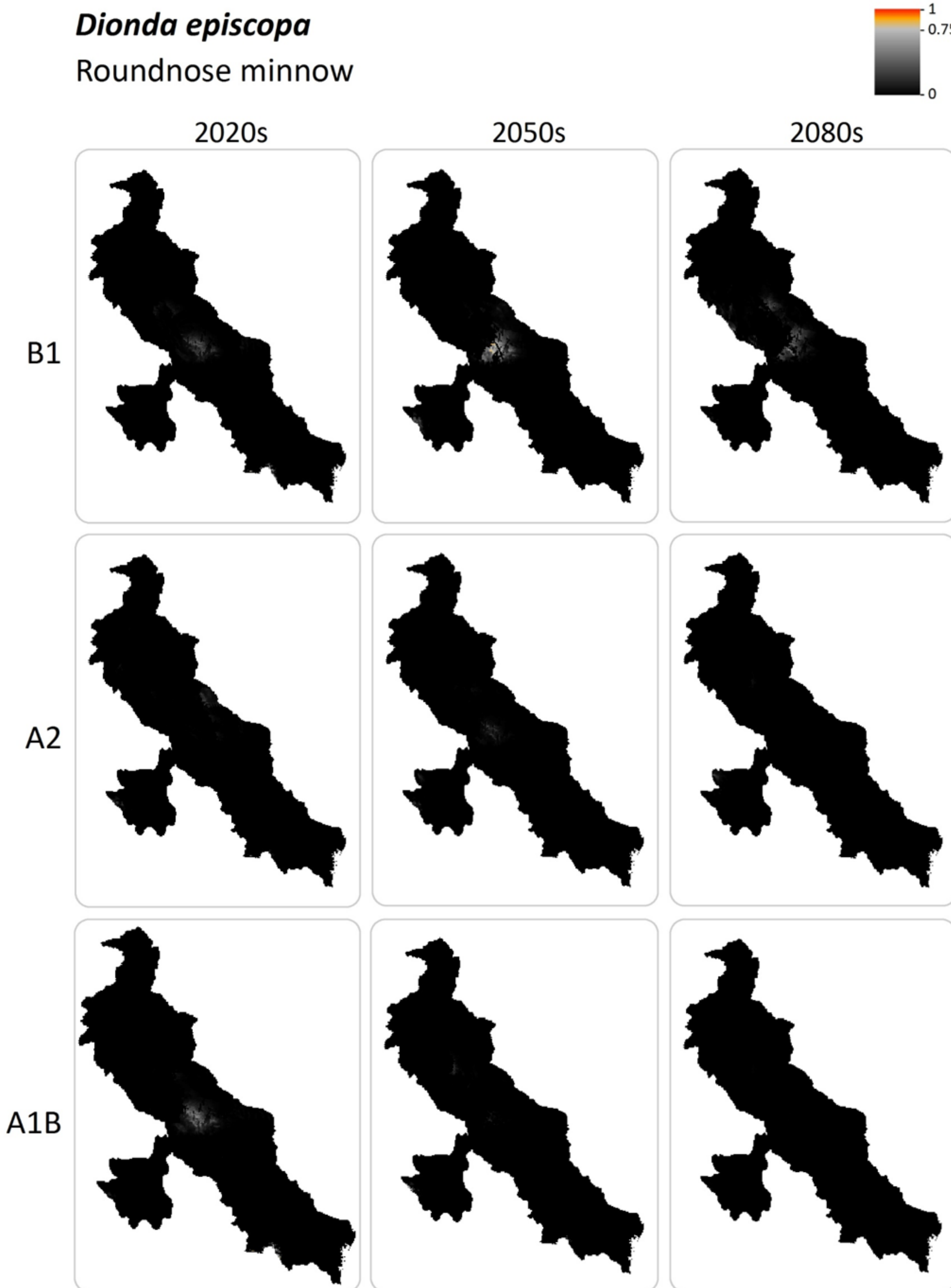
a. Occurrence records used in model
b. "Current" distribution model





Dionda episcopa

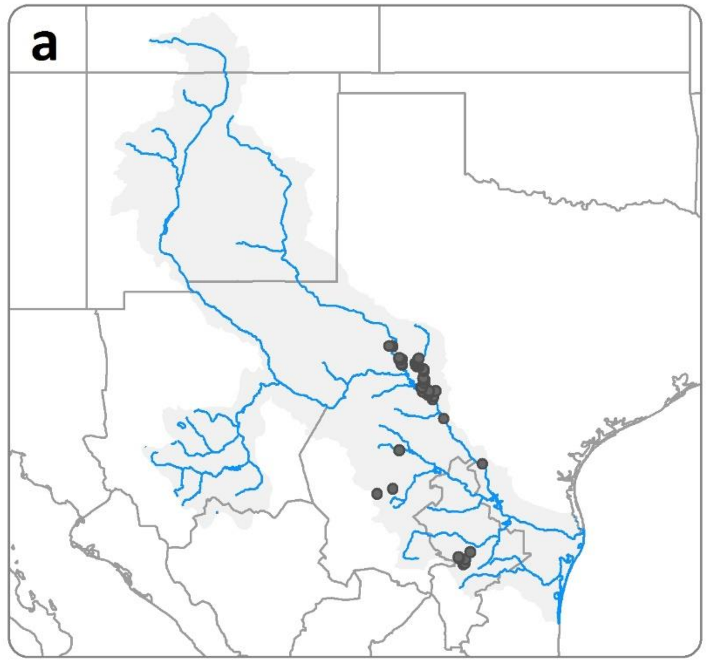
Roundnose minnow

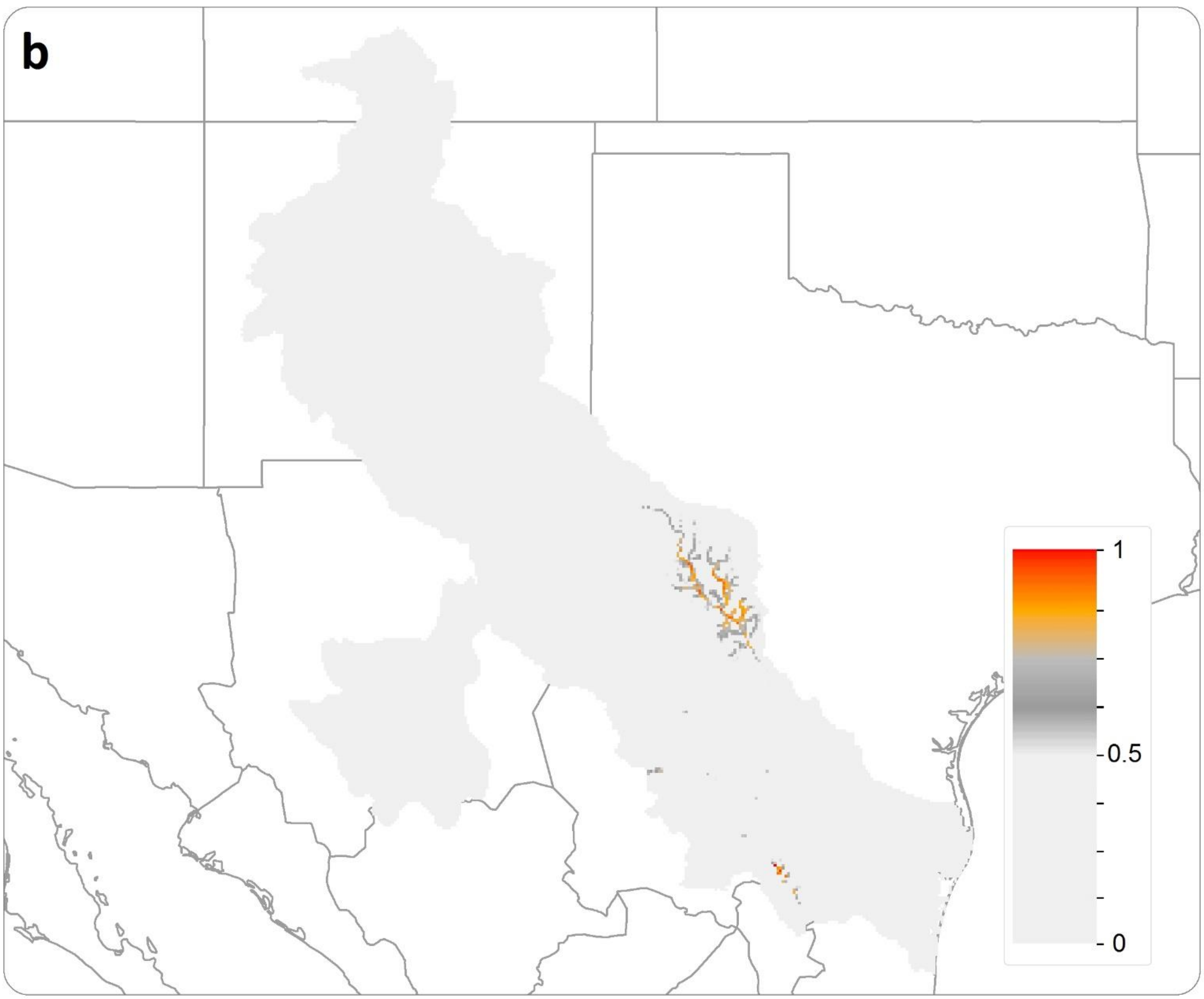


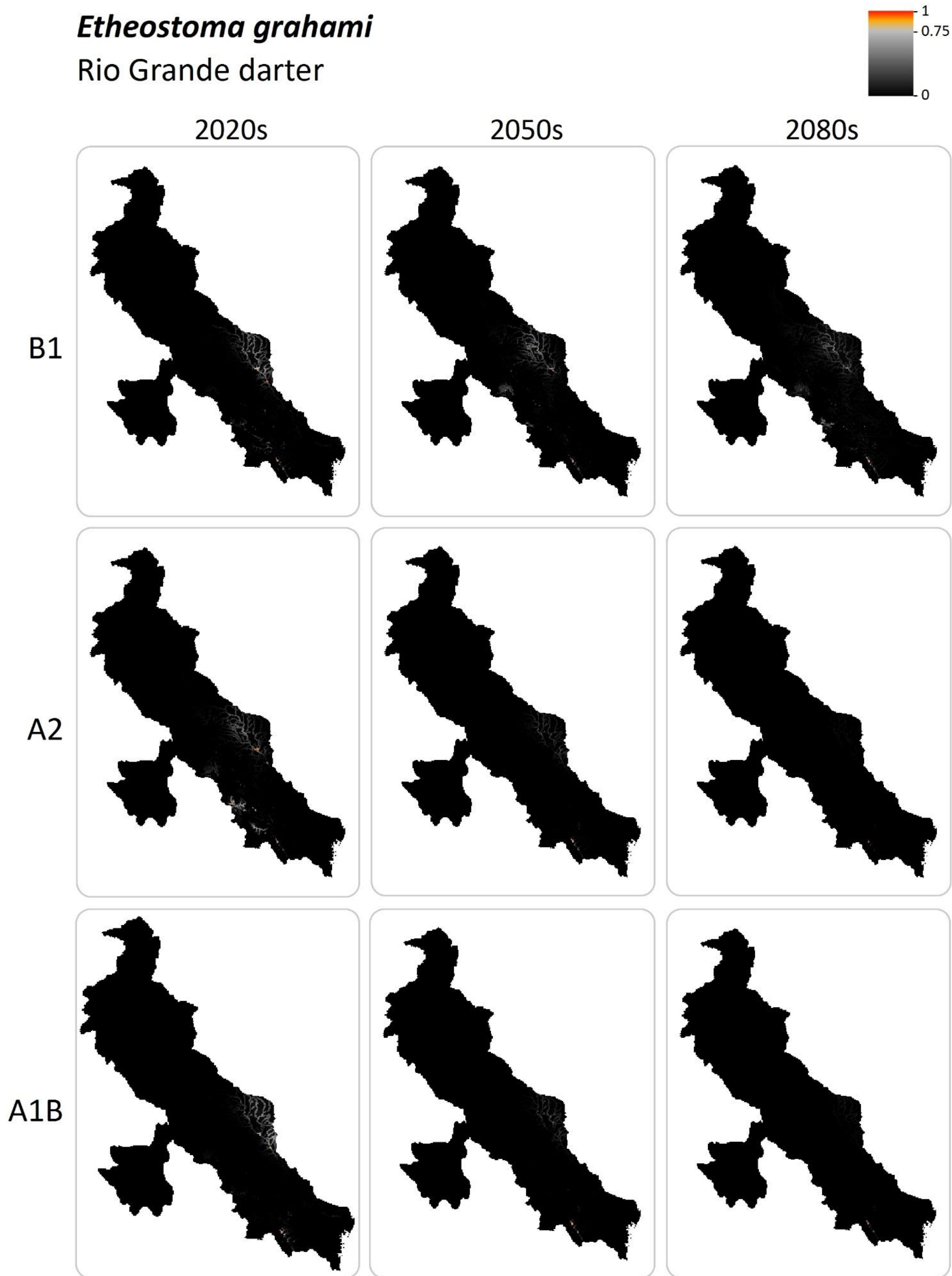
Etheostoma grahami

Rio Grande darter

a. Occurrence records used in model
b. "Current" distribution model

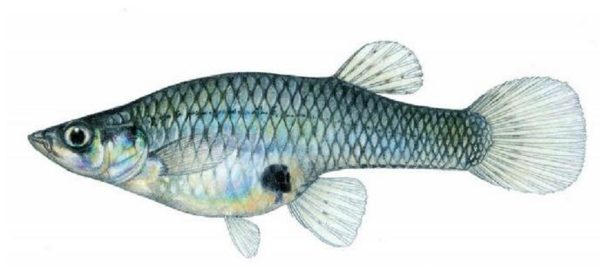




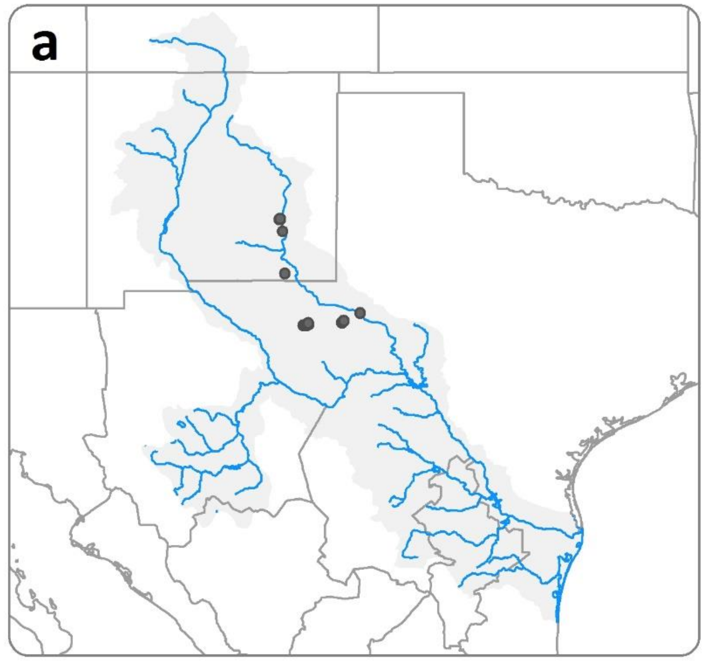

Etheostoma grahami
Rio Grande darter
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

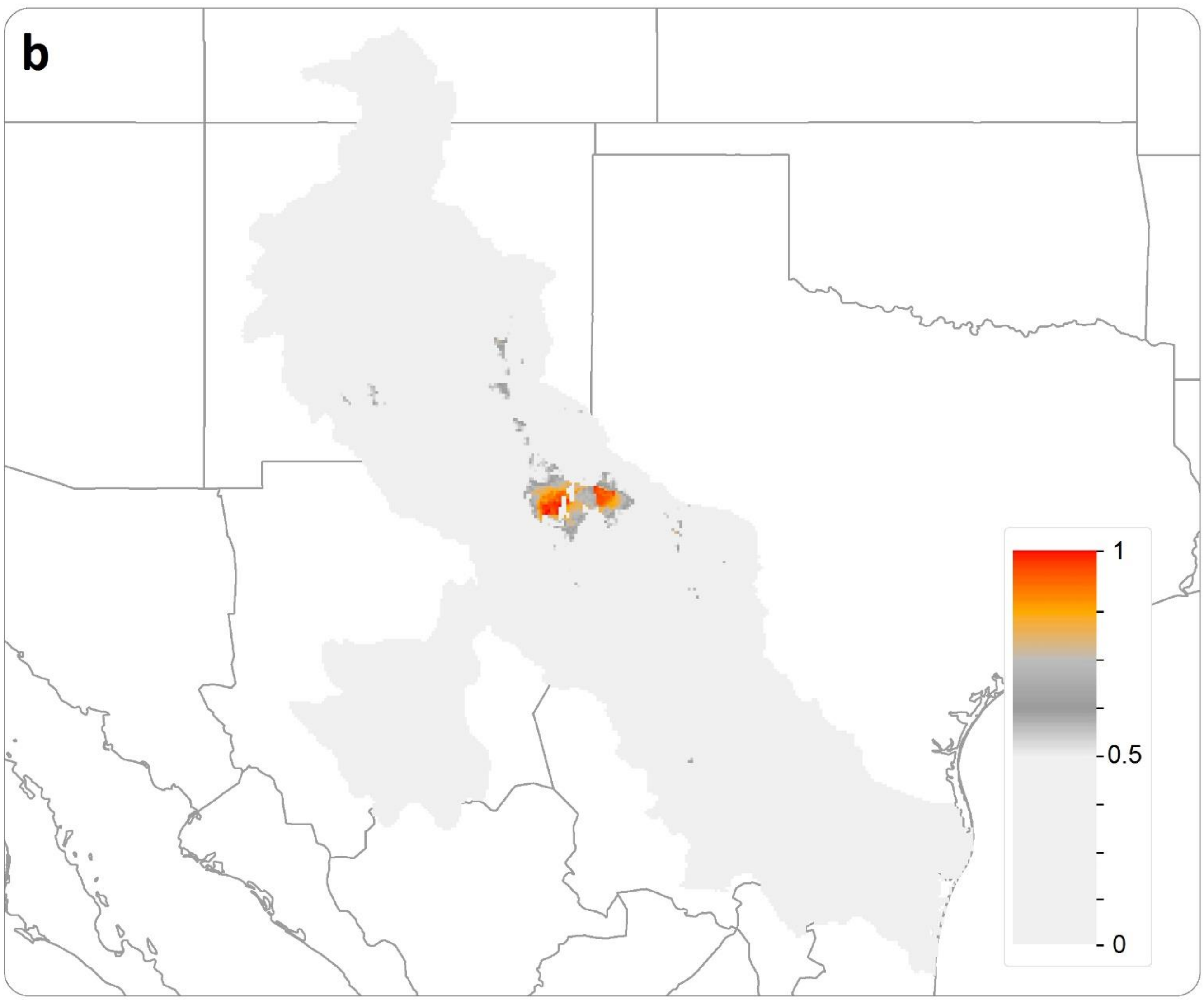
Gambusia nobilis

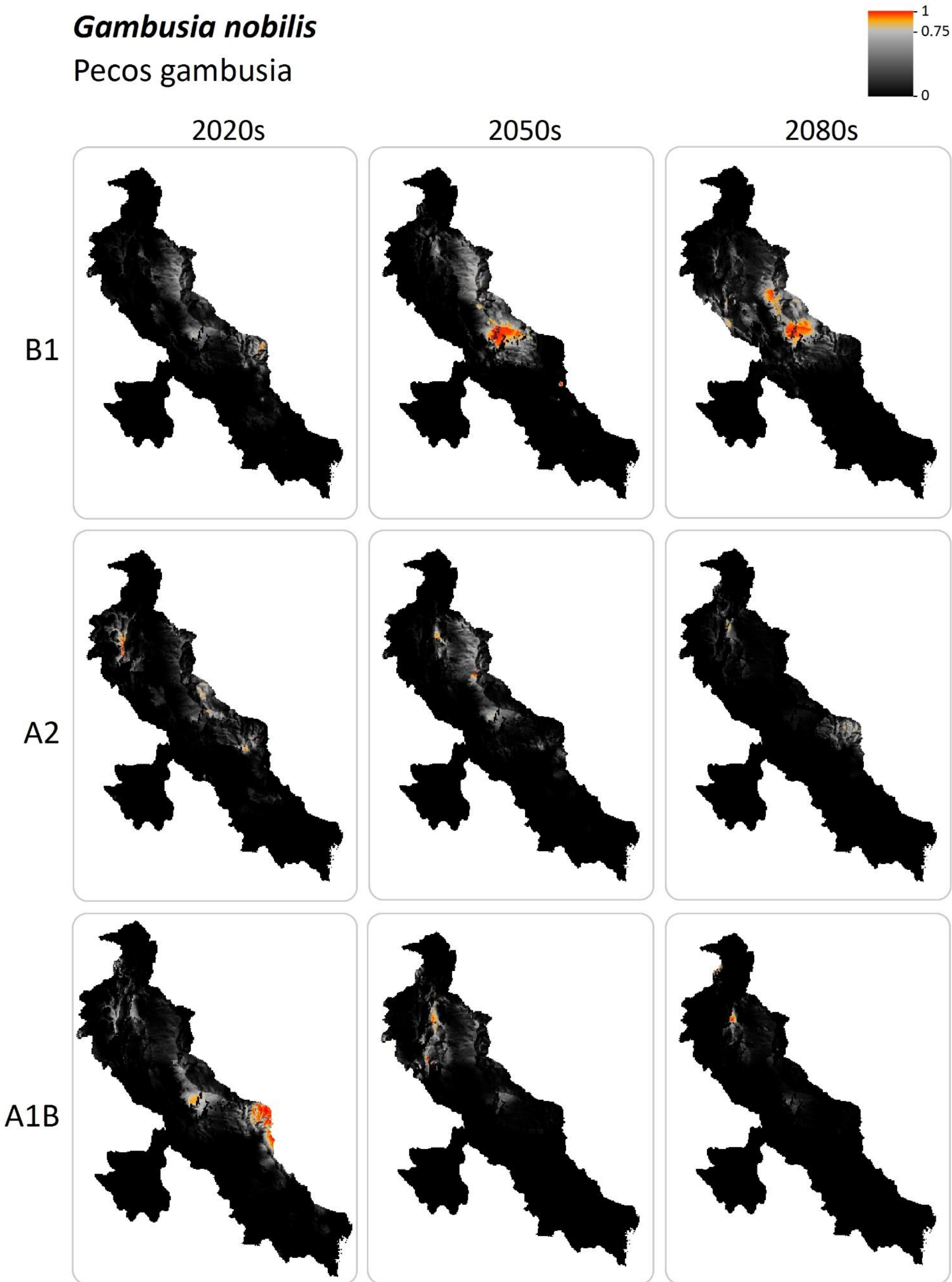
Pecos gambusia



a. Occurrence records used in model
b. "Current" distribution model



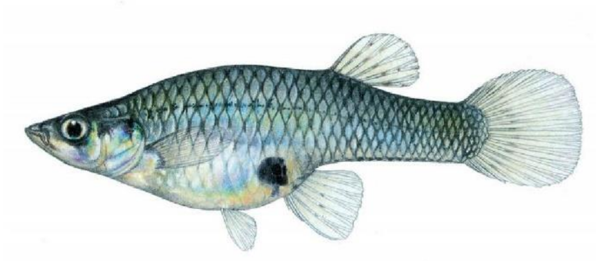


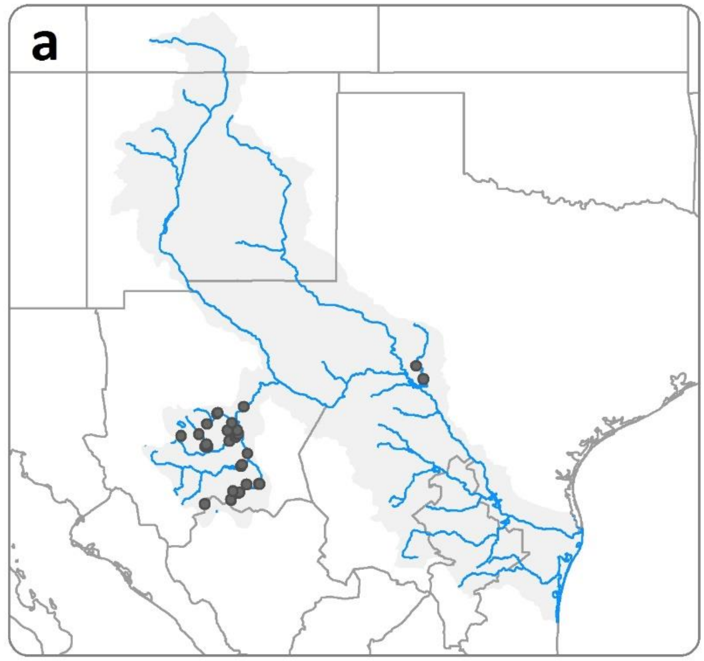


Gambusia nobilis
Pecos gambusia
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

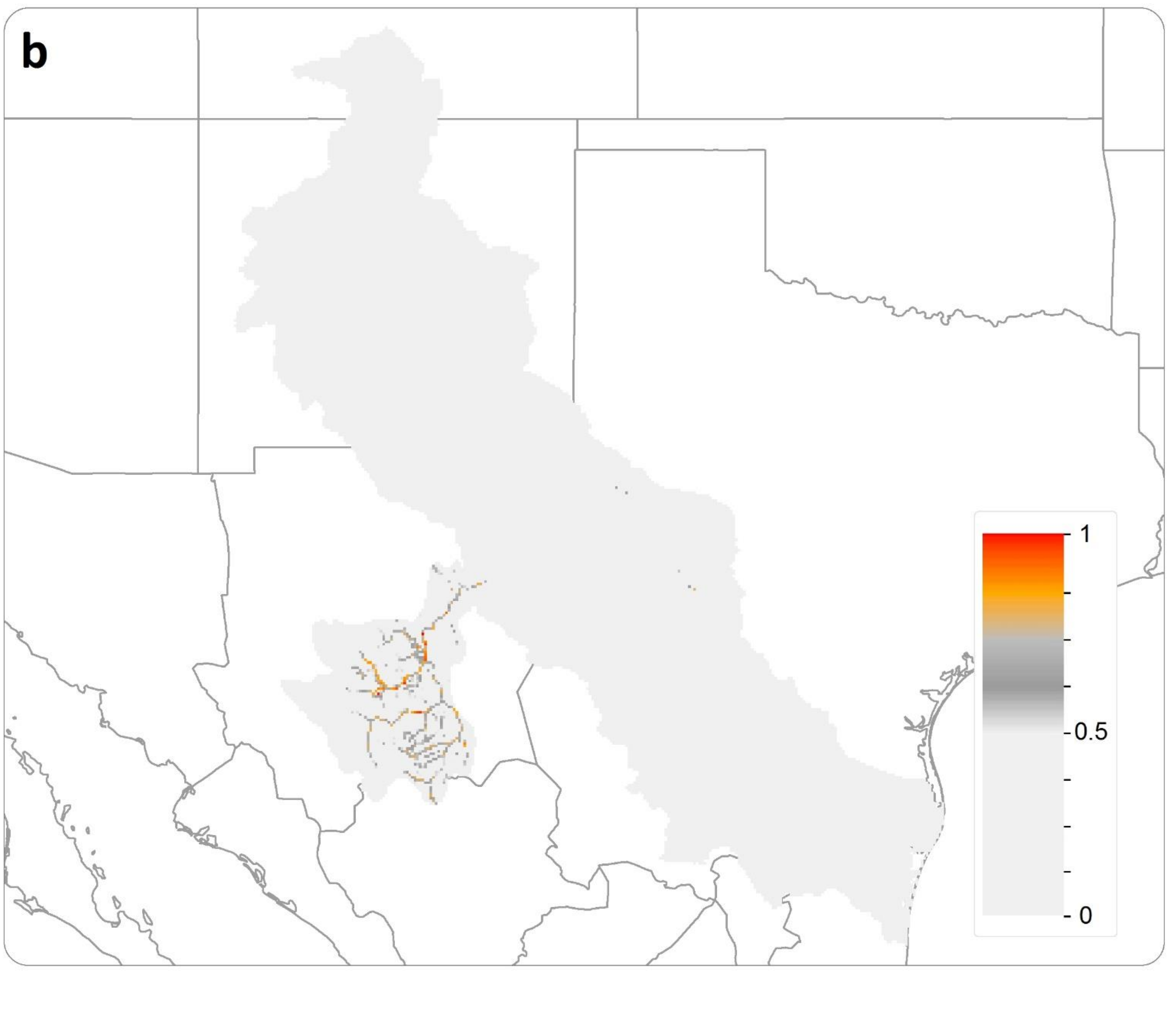
Gambusia senilis

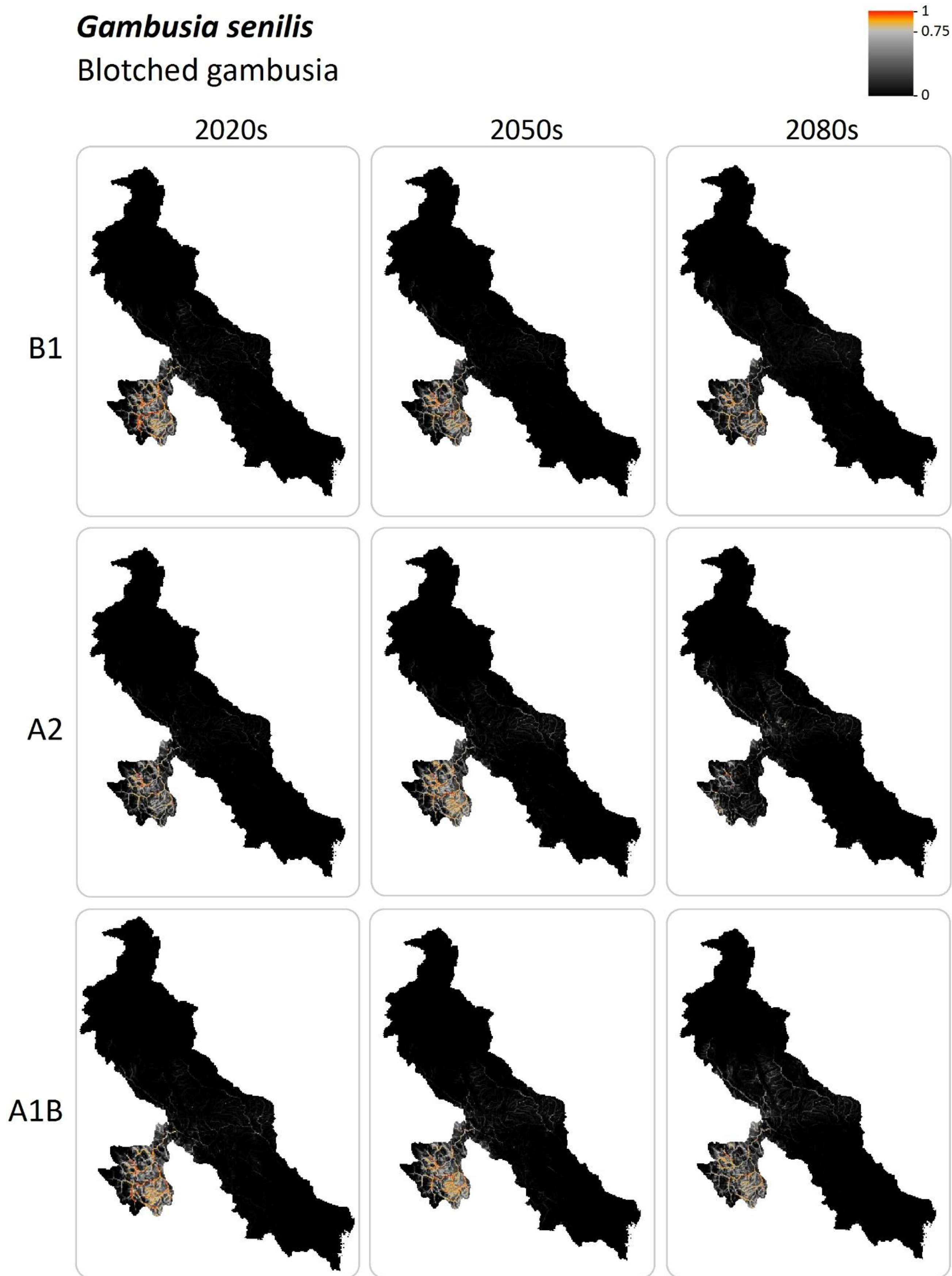
Blotched gambusia





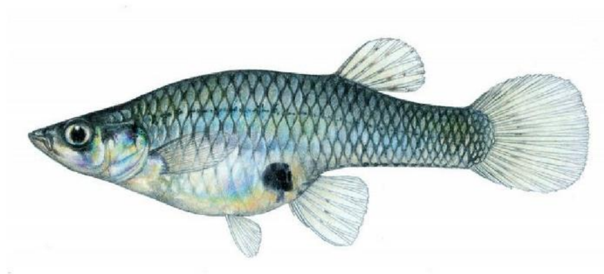
a. Occurrence records used in model
b. "Current" distribution model

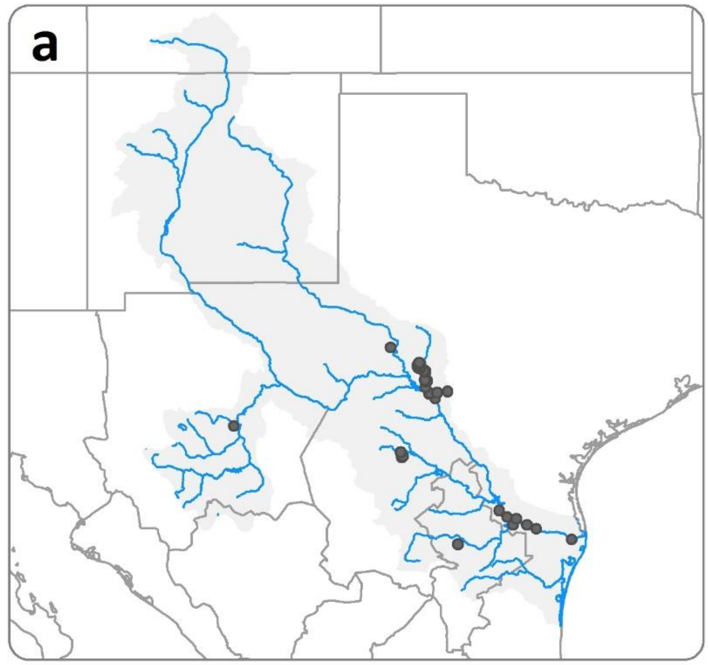



Gambusia senilis
Blotched gambusia
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

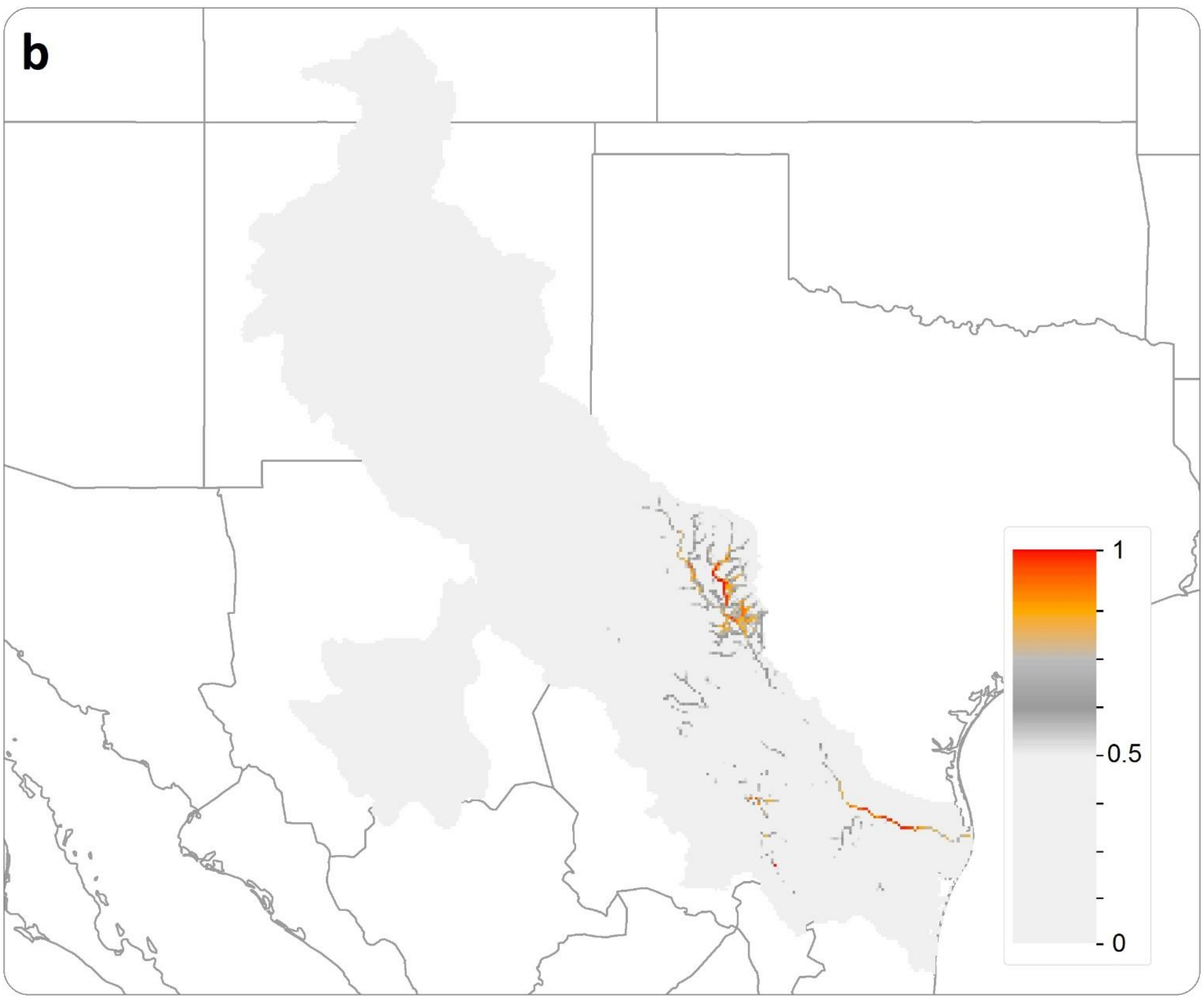
Gambusia speciosa

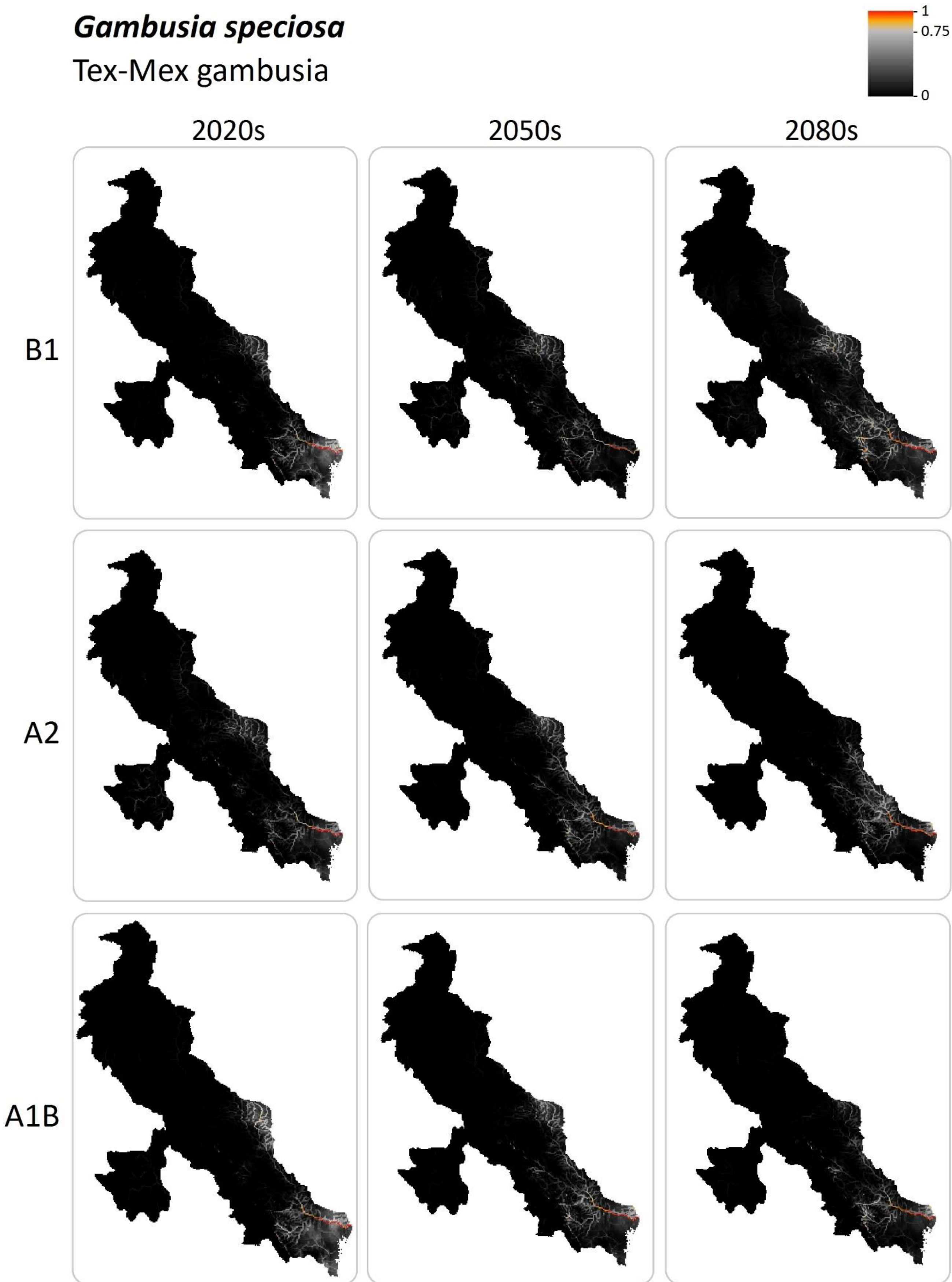
Tex-Mex gambusia





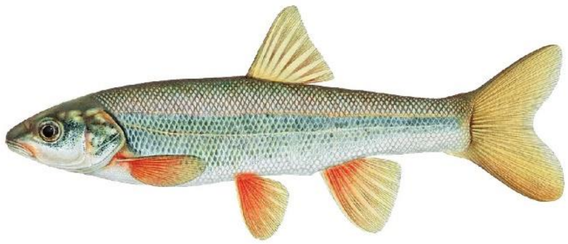
a. Occurrence records used in model
b. "Current" distribution model

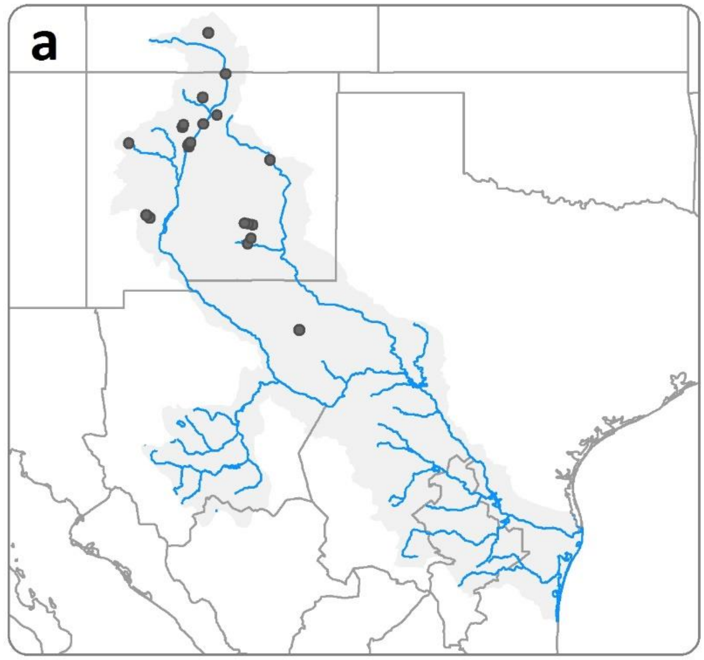



Gambusia speciosa
Tex-Mex gambusia
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

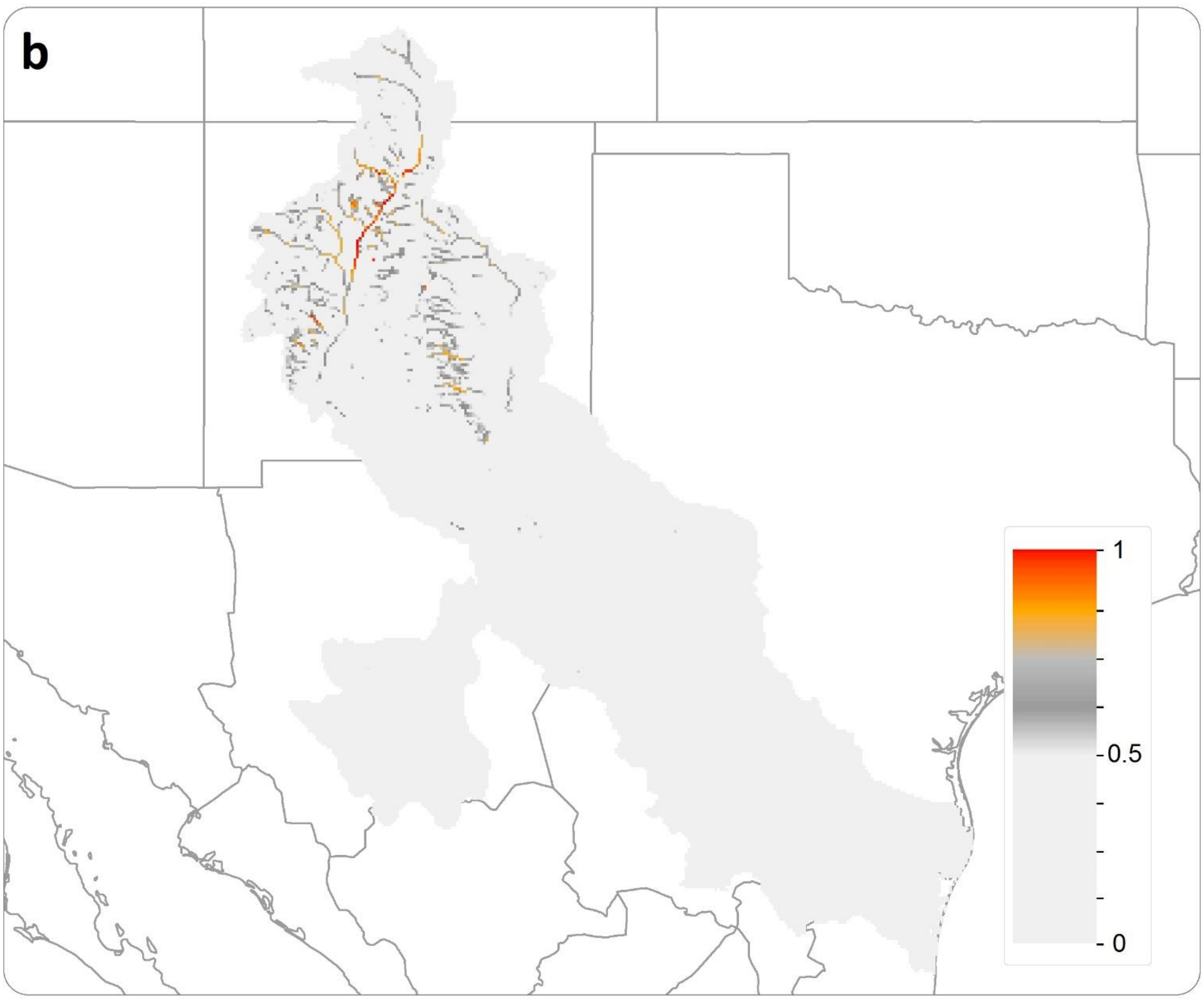
Gila pandora

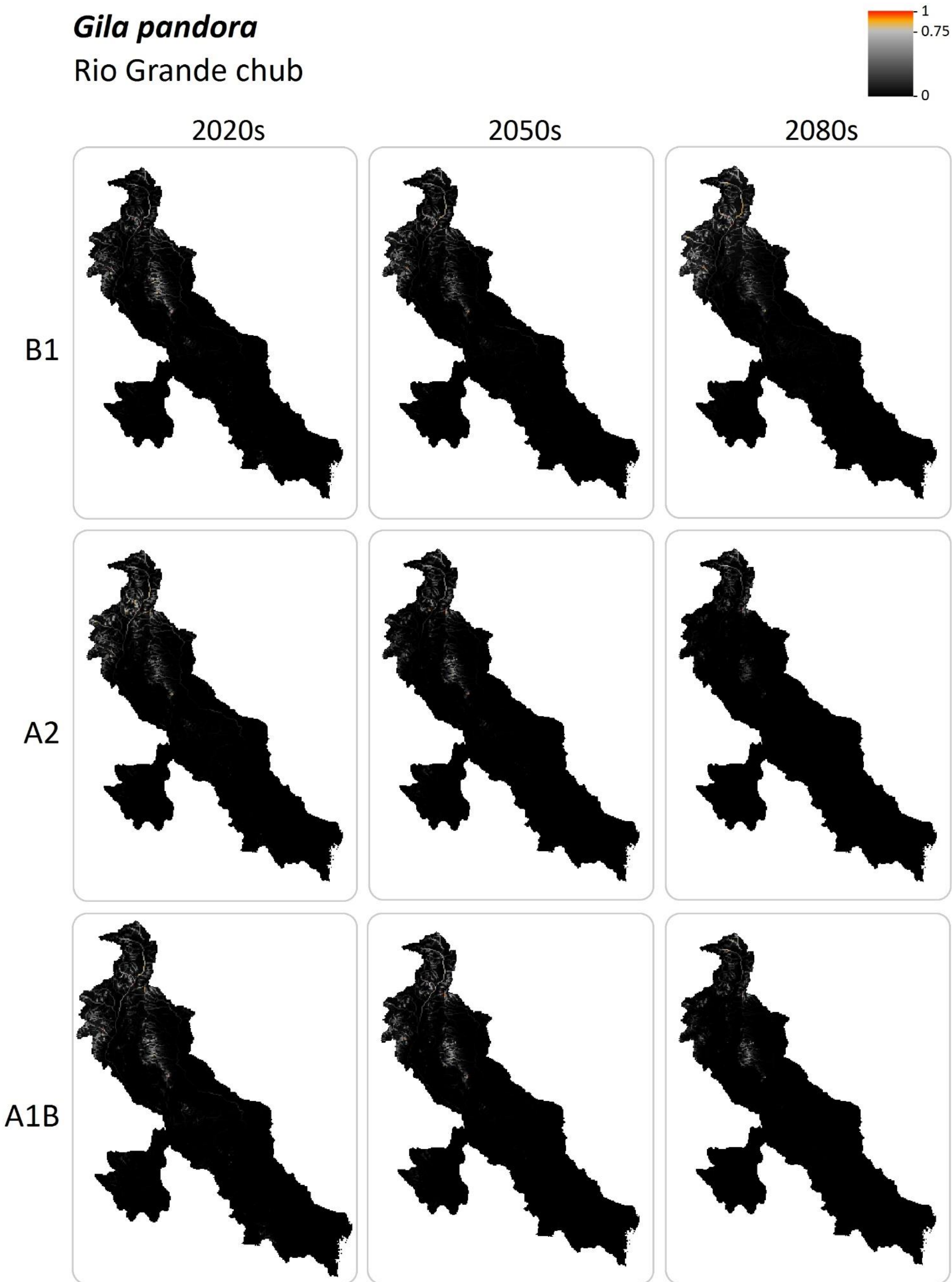
Rio Grande chub





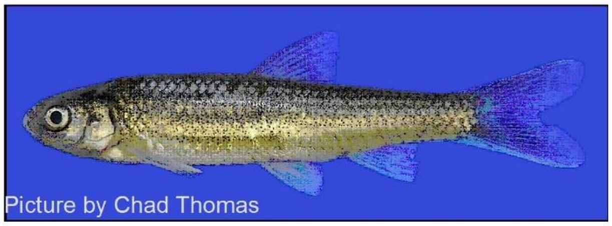
a. Occurrence records used in model
b. "Current" distribution model

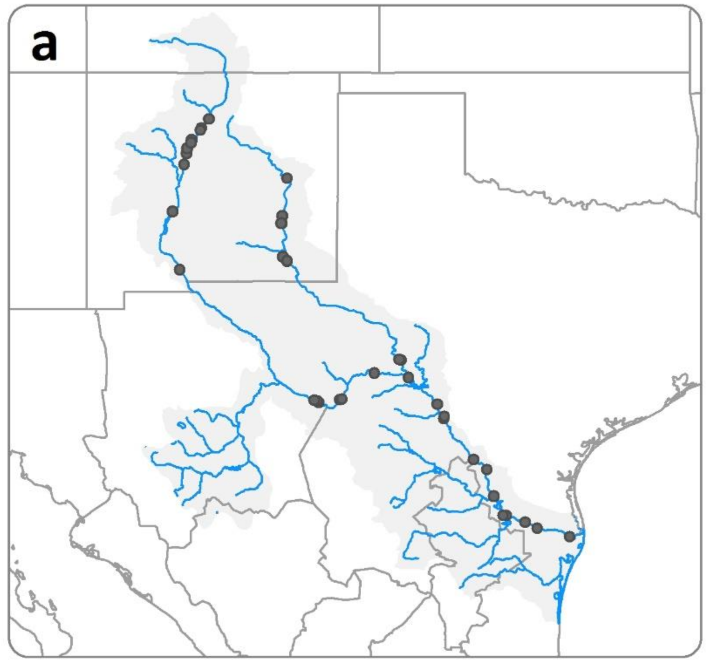



Gila pandora
Rio Grande chub
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

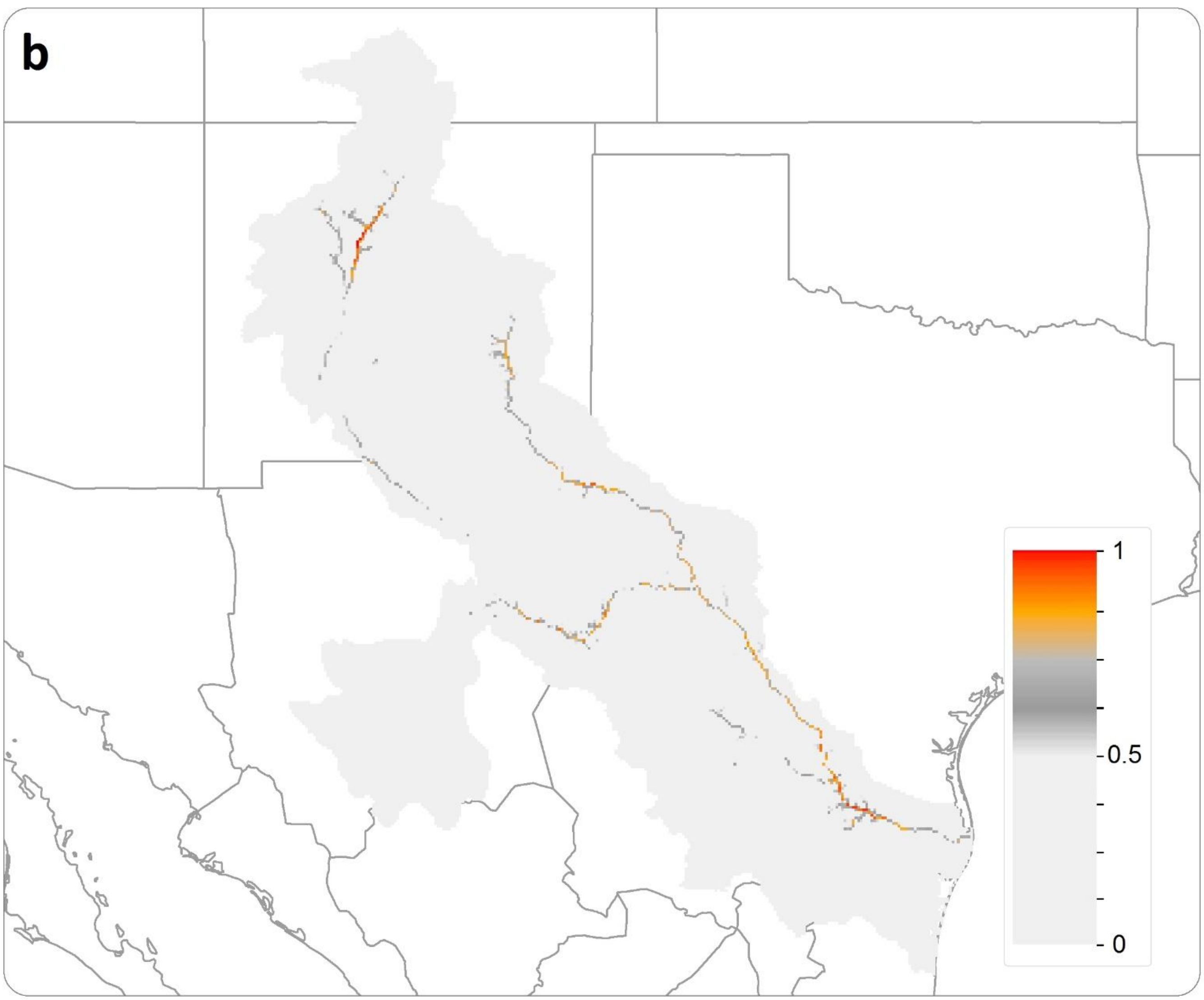
Hybognathus amarus

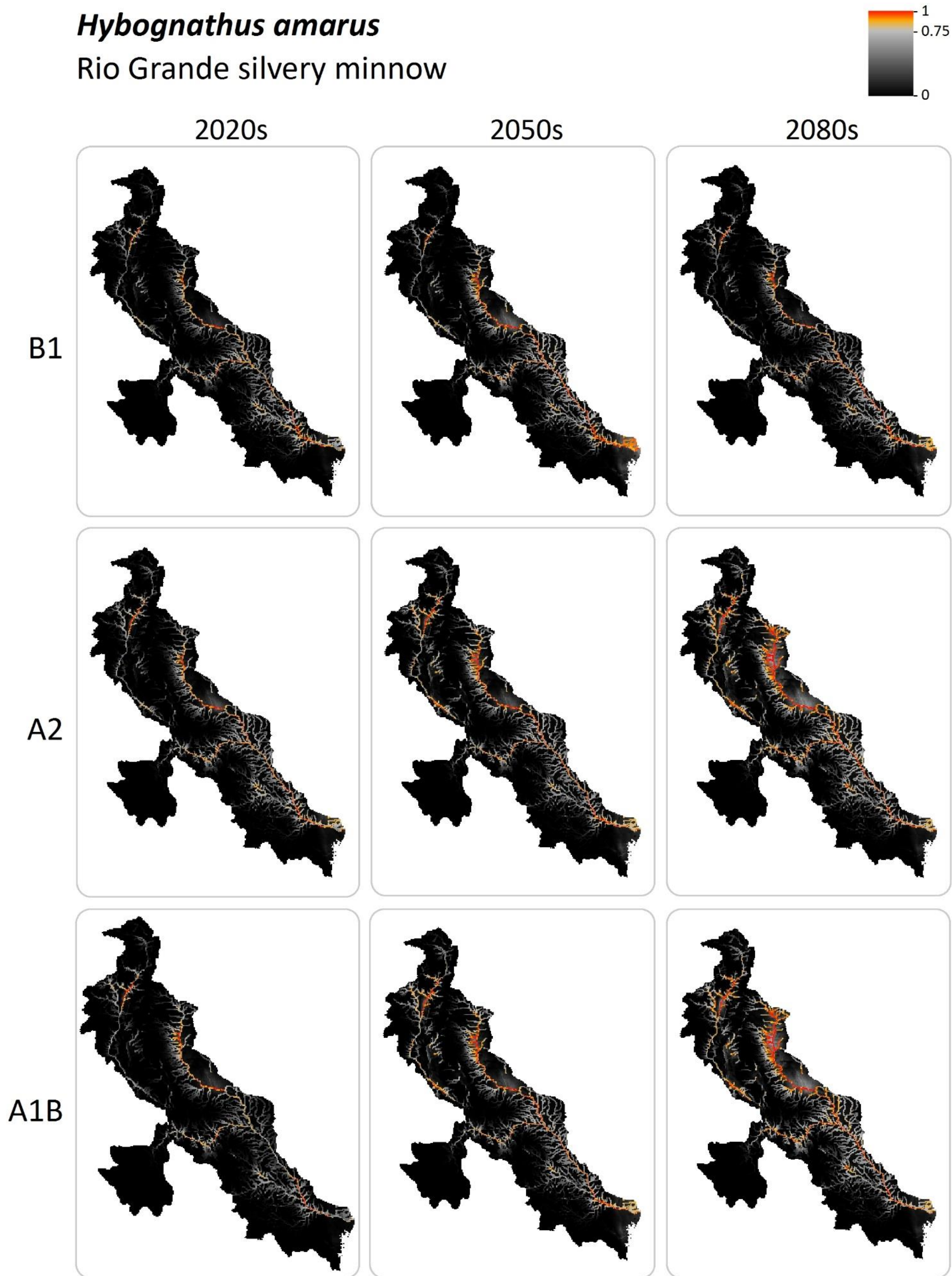
Rio Grande silvery minnow





a. Occurrence records used in model
b. "Current" distribution model

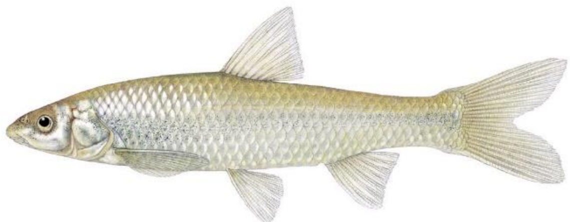


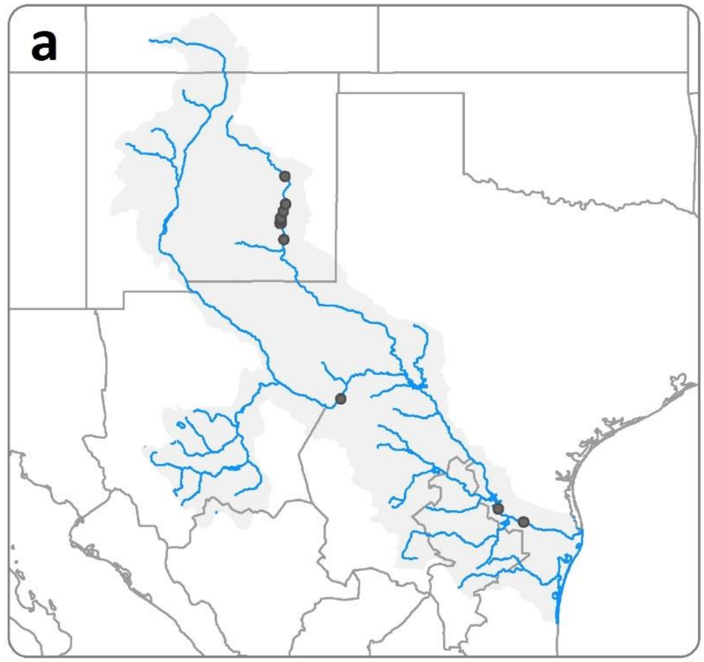


Hybognathus amarus
Rio Grande silvery minnow
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

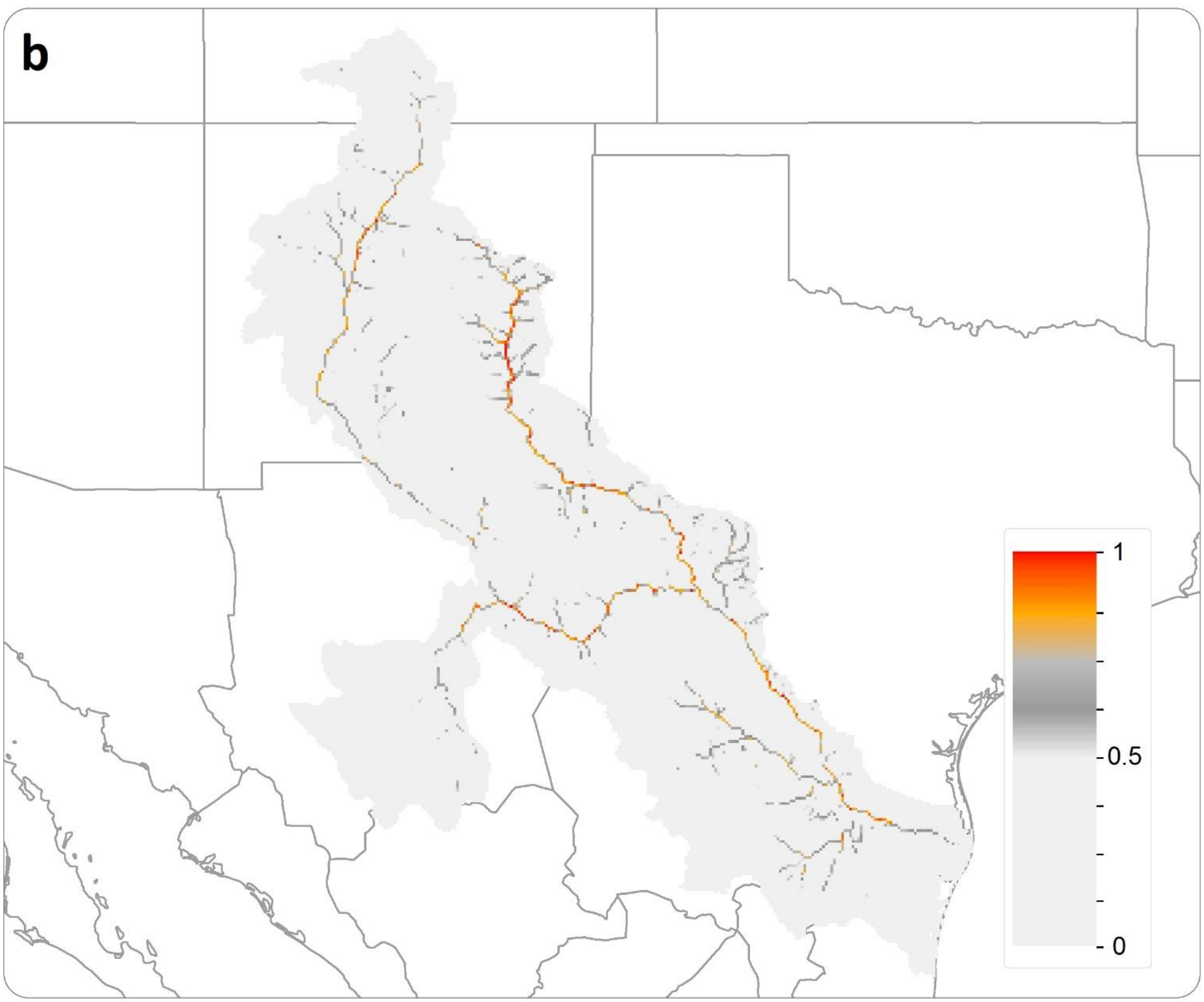
Hybognathus placitus

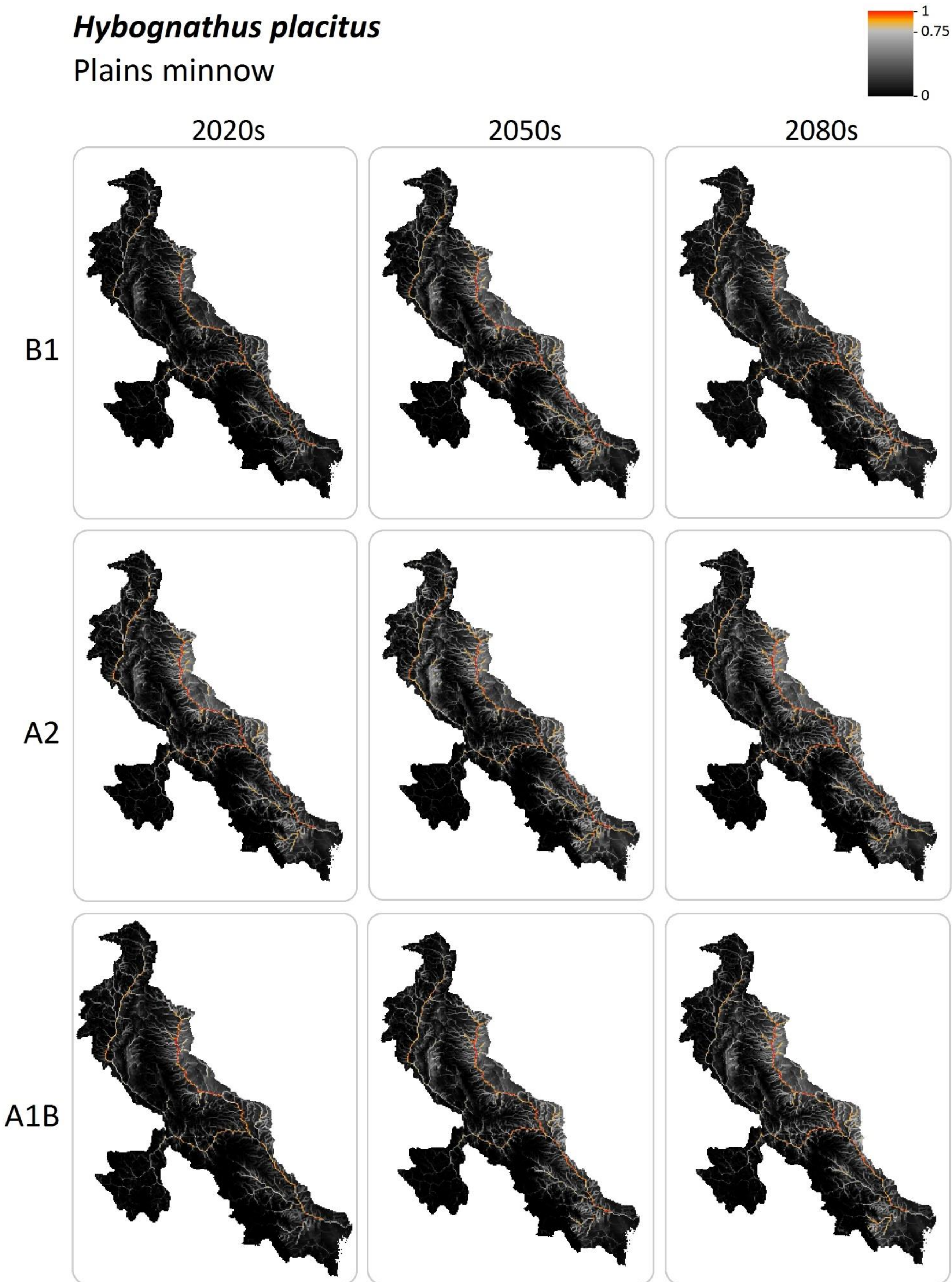
Plains minnow





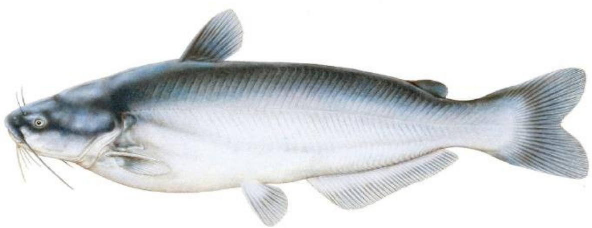
a. Occurrence records used in model
b. "Current" distribution model

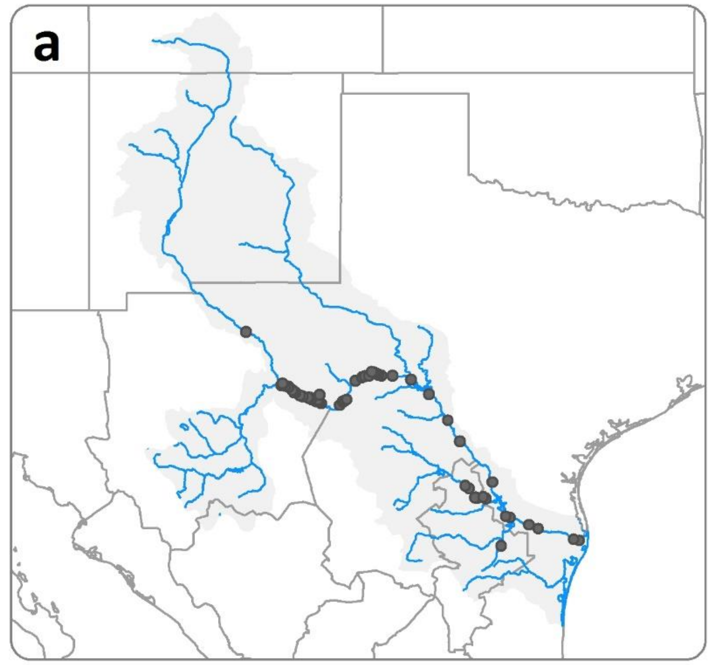



Hybognathus placitus
Plains minnow
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

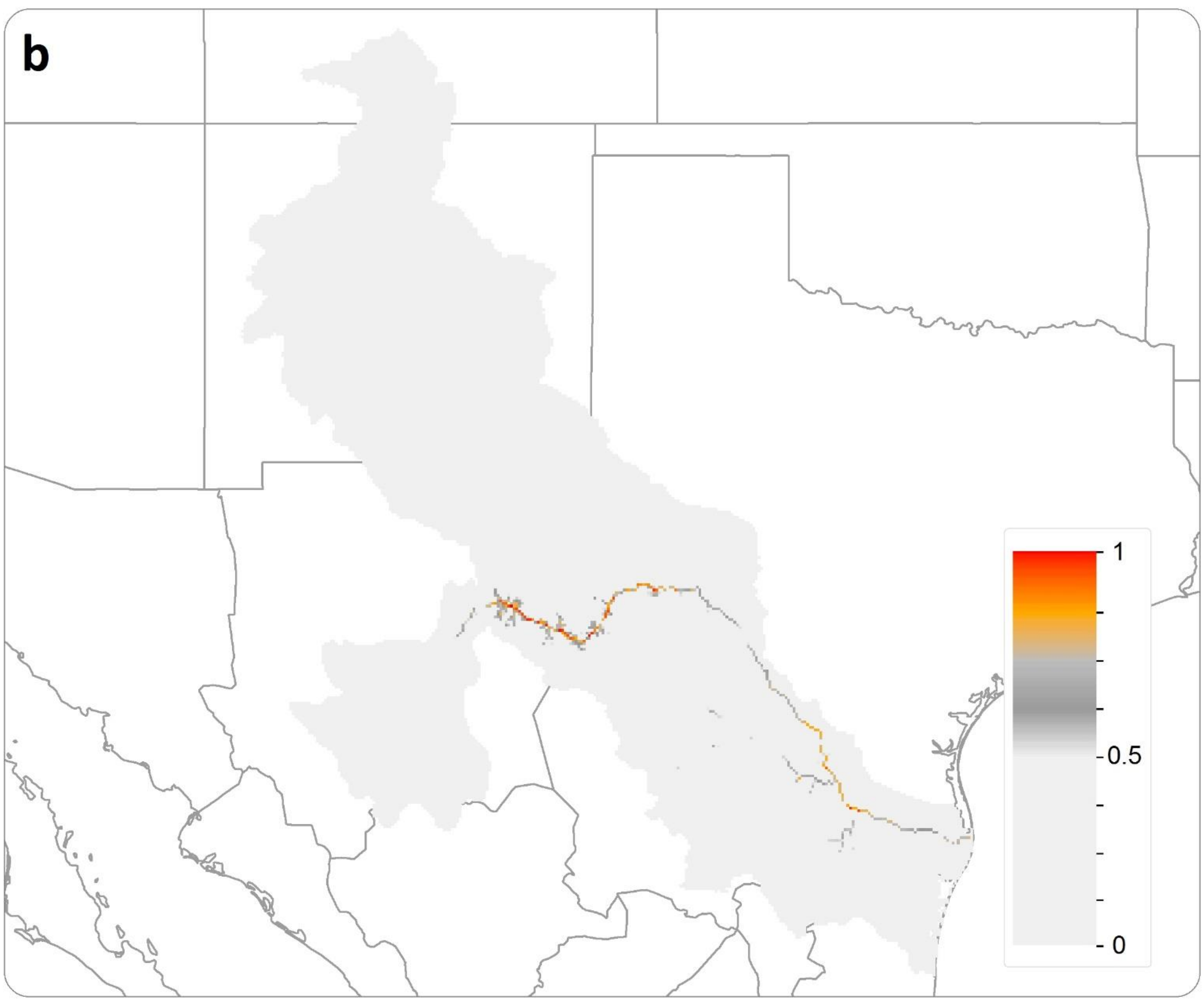
Ictalurus furcatus

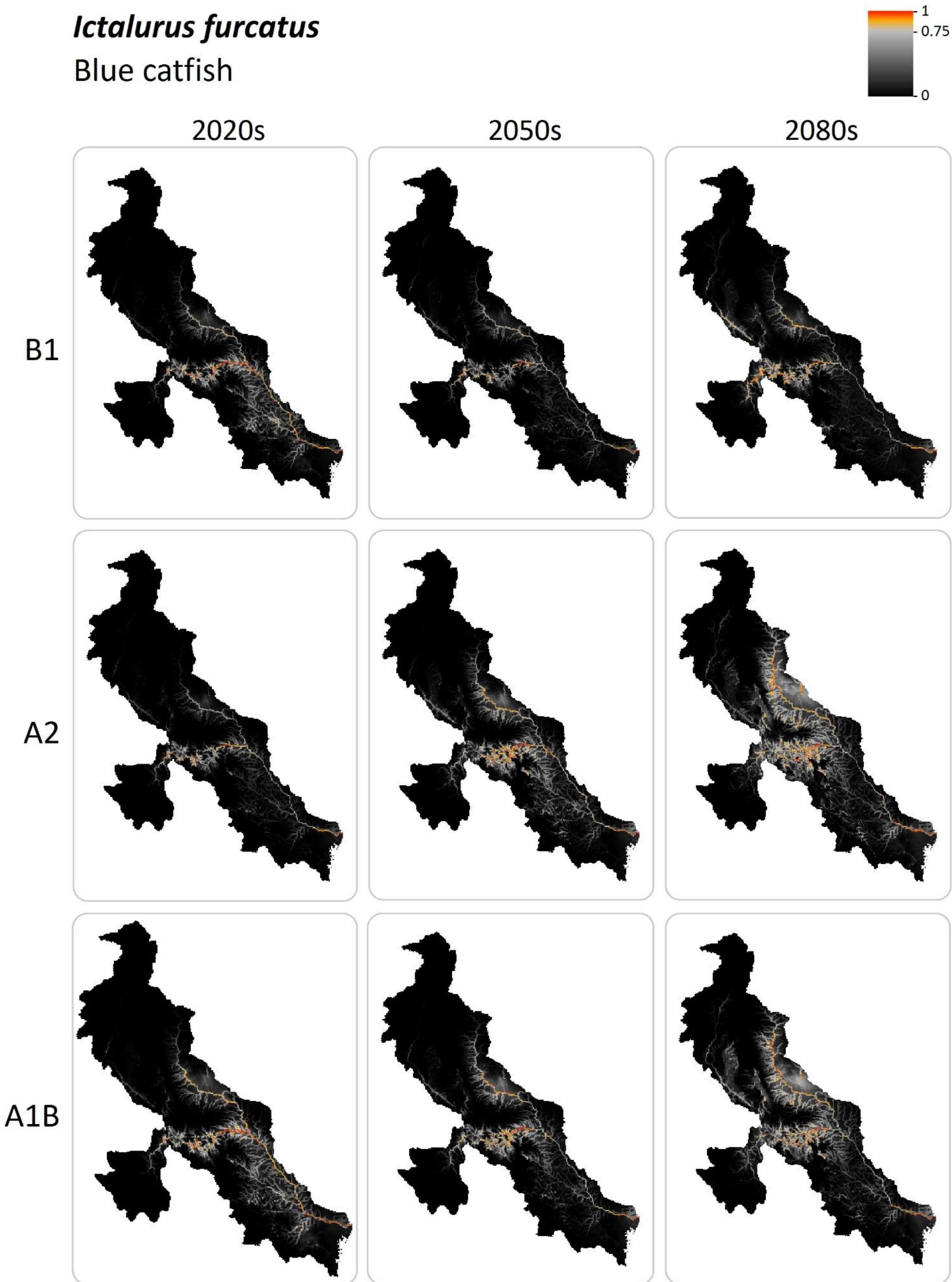
Blue catfish





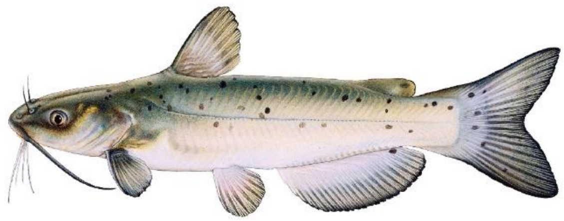
a. Occurrence records used in model
b. "Current" distribution model

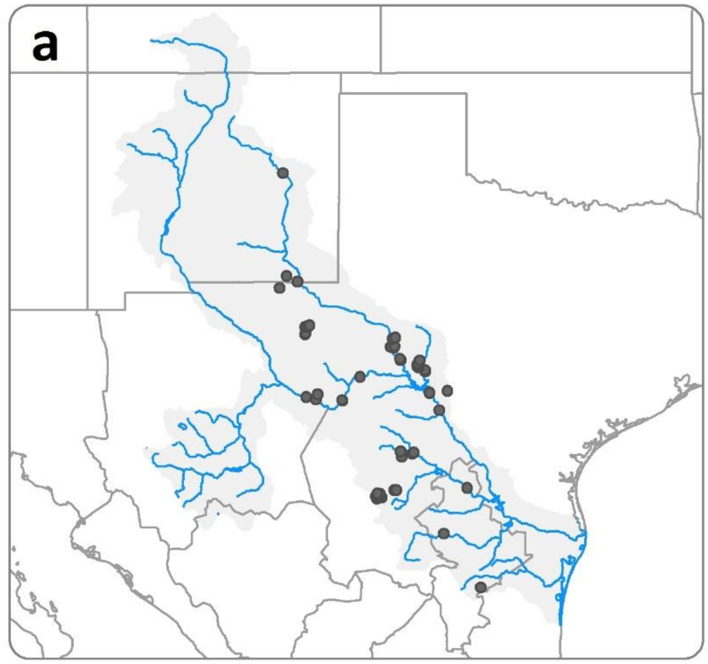



Ictalurus furcatus
Blue catfish
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

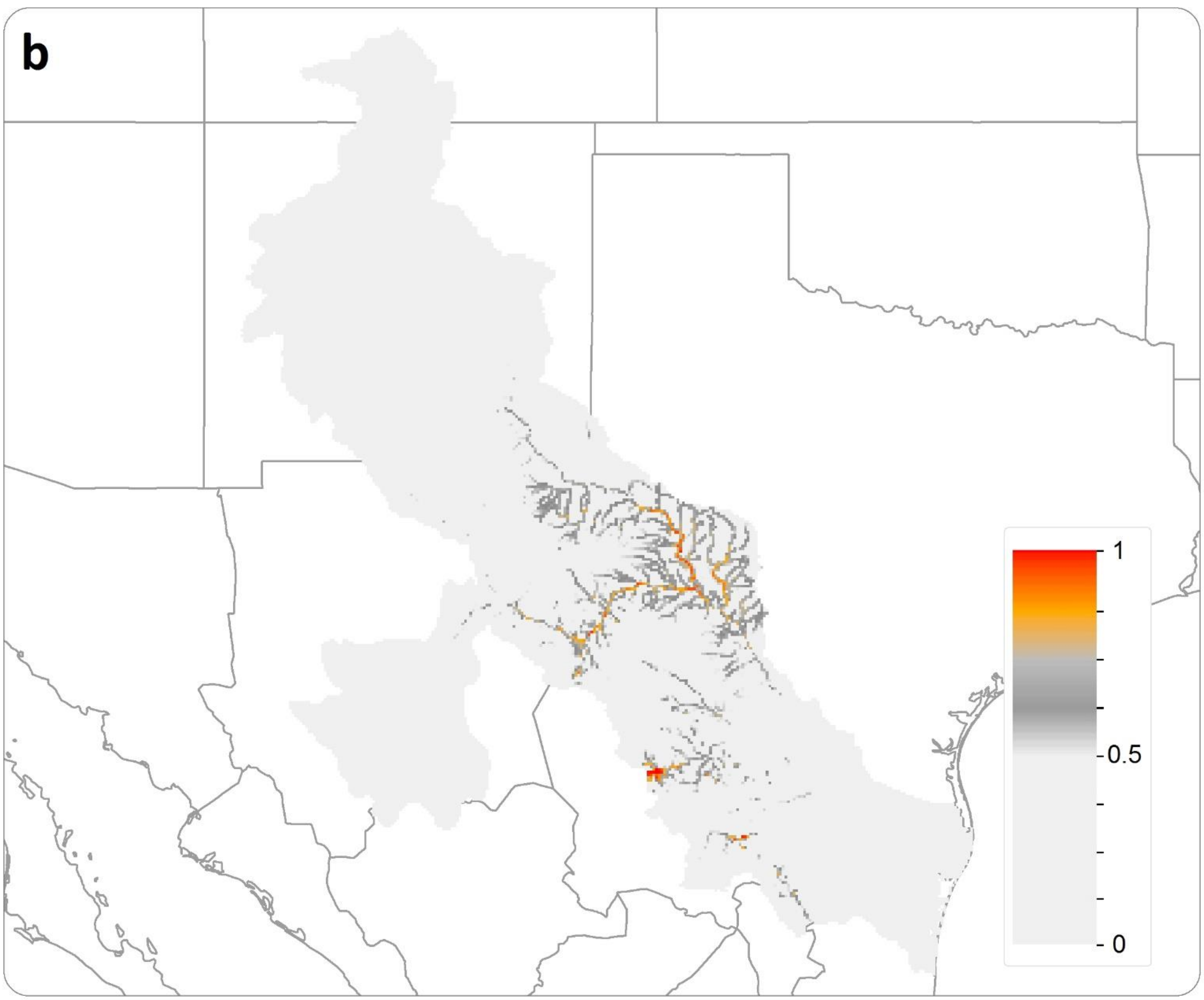
Ictalurus lupus

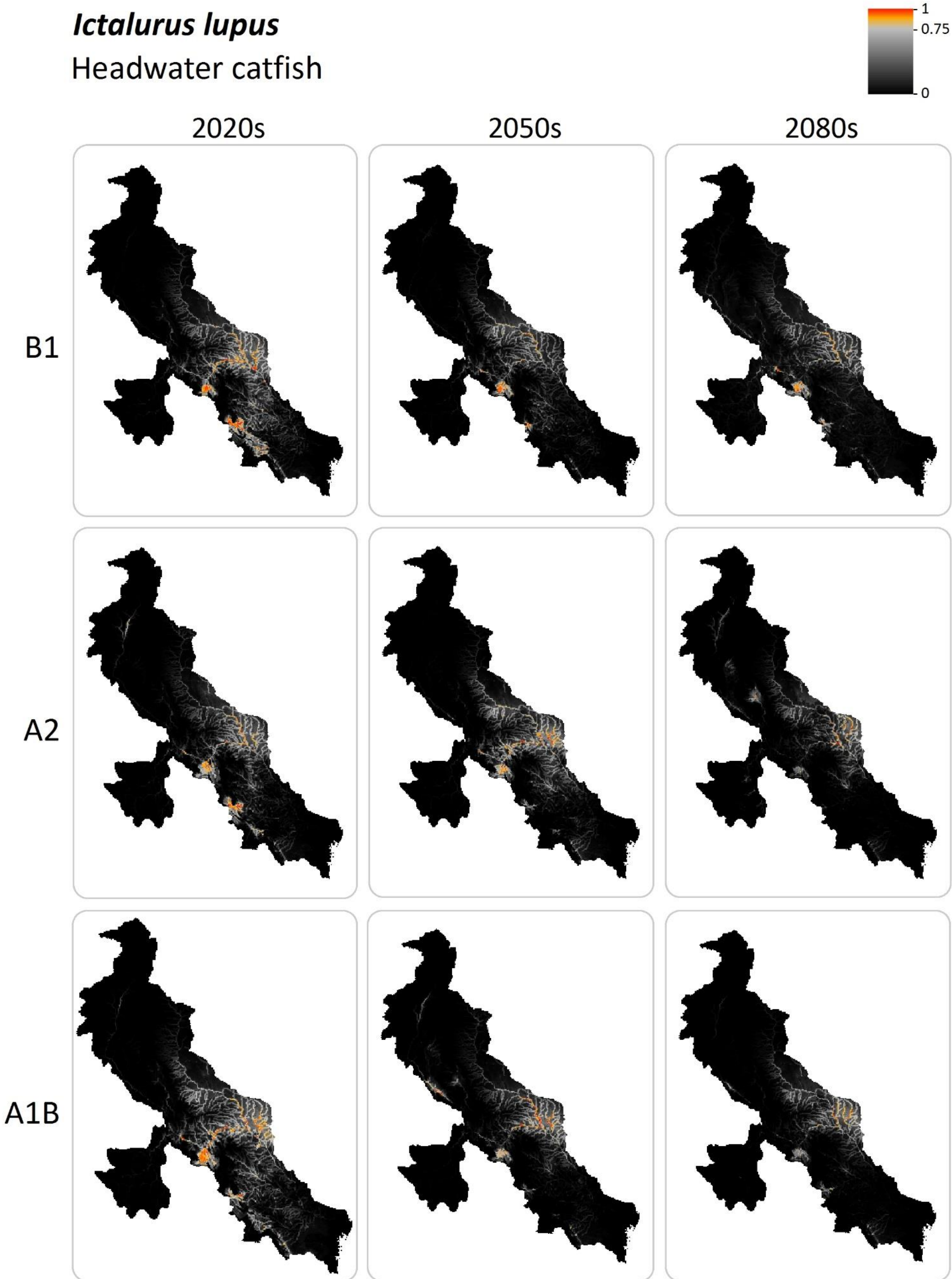
Headwater catfish





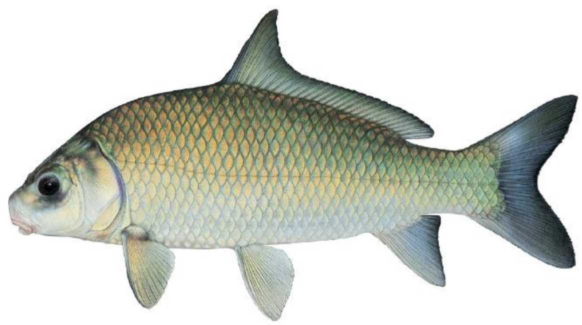
a. Occurrence records used in model
b. "Current" distribution model



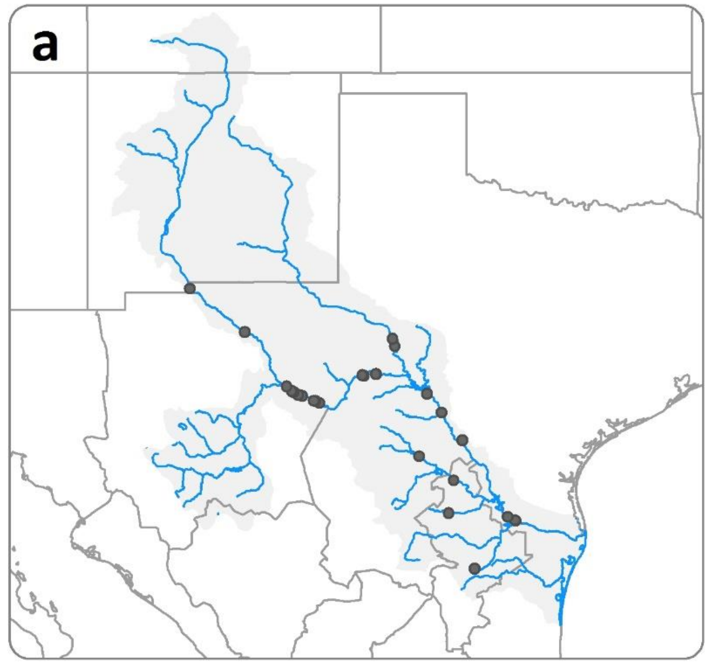

Ictalurus lupus
Headwater catfish
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

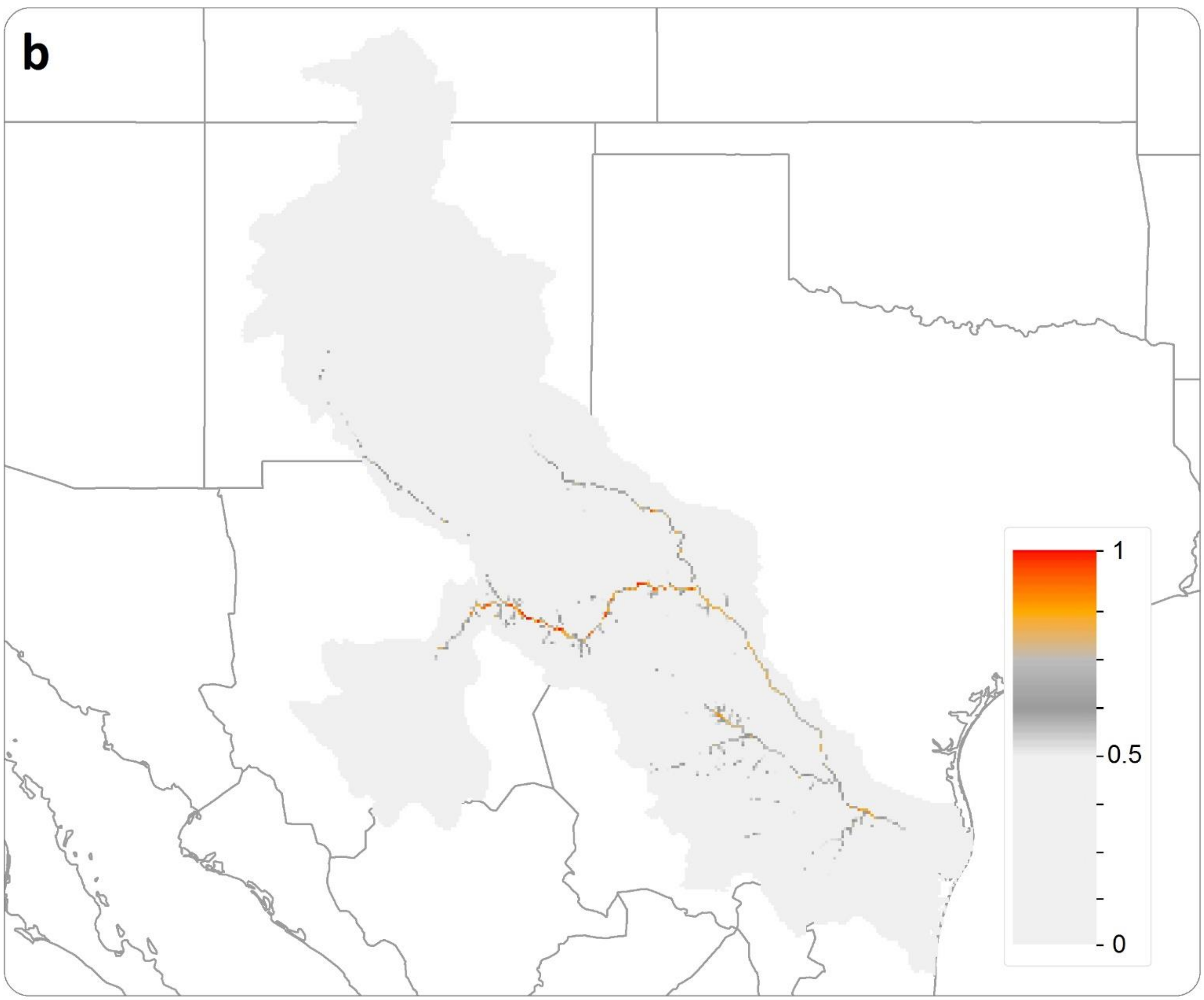
Ictiobus bubalus

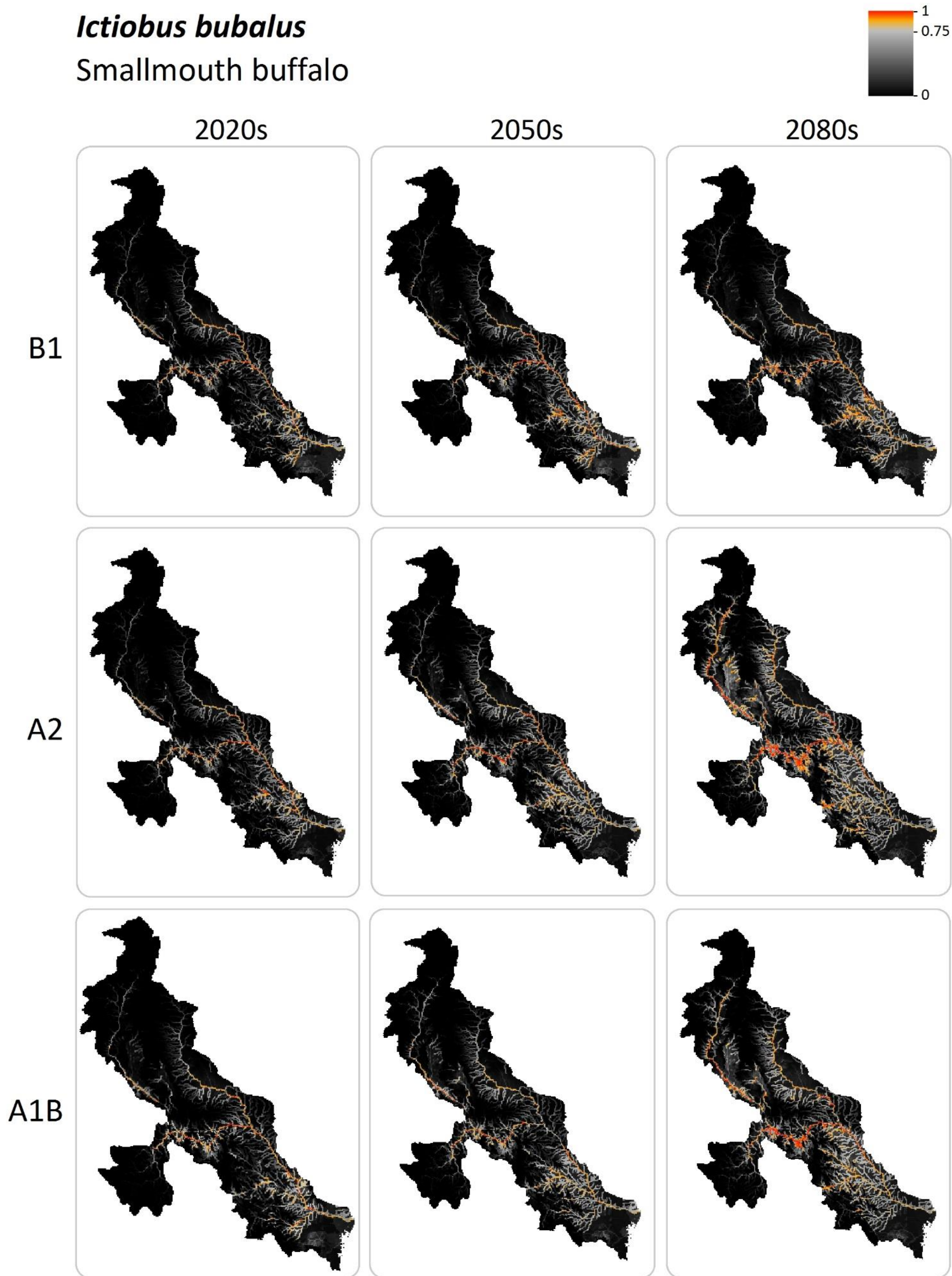
Smallmouth buffalo



a. Occurrence records used in model
b. "Current" distribution model

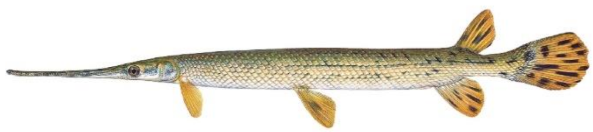




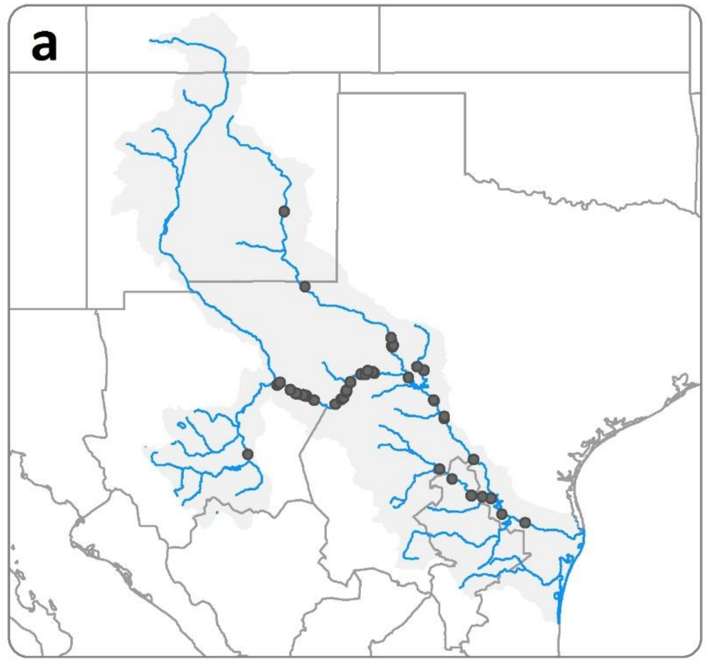

Ictiobus bubalus
Smallmouth buffalo
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

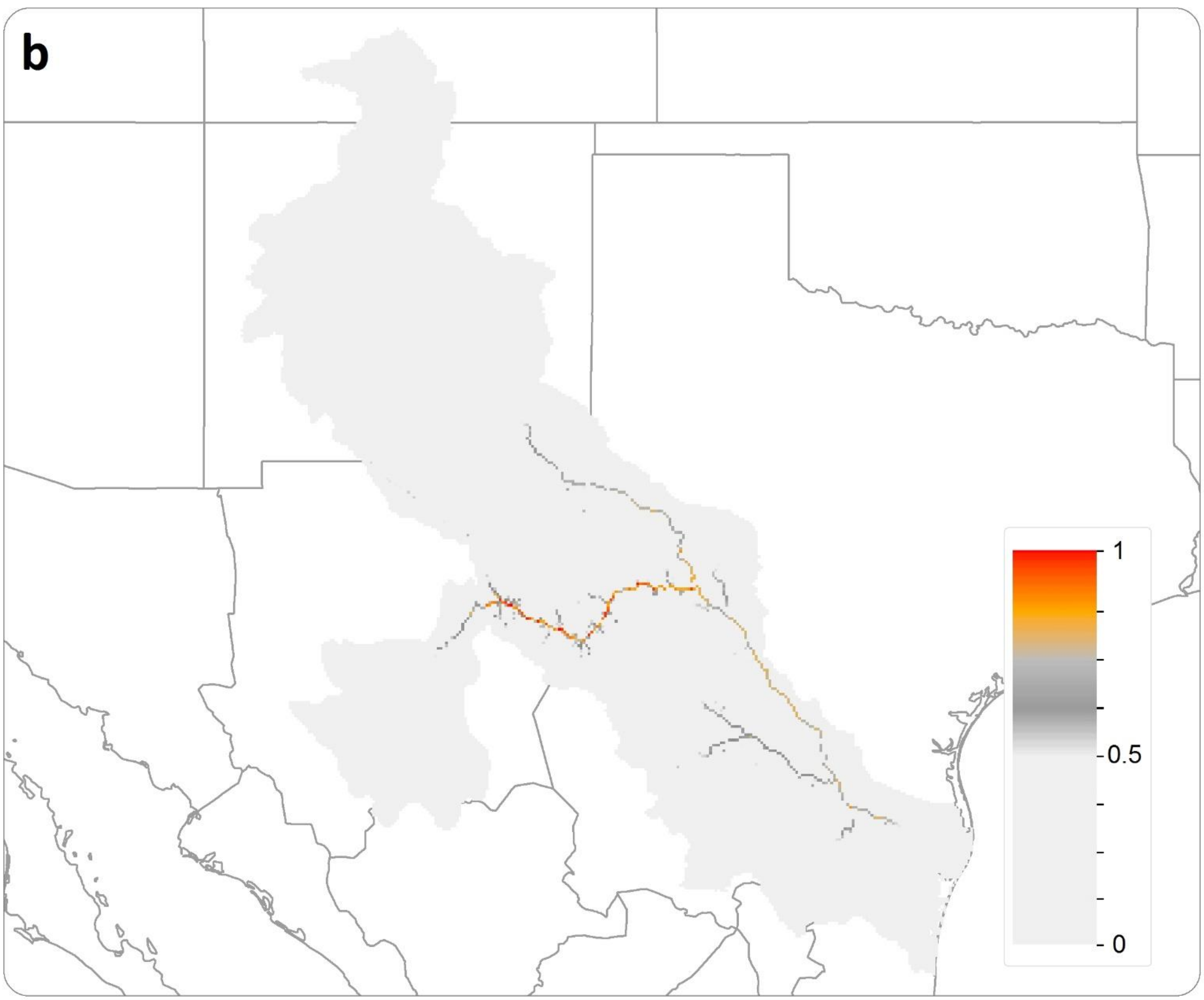
Lepisosteus osseus

Longnose gar



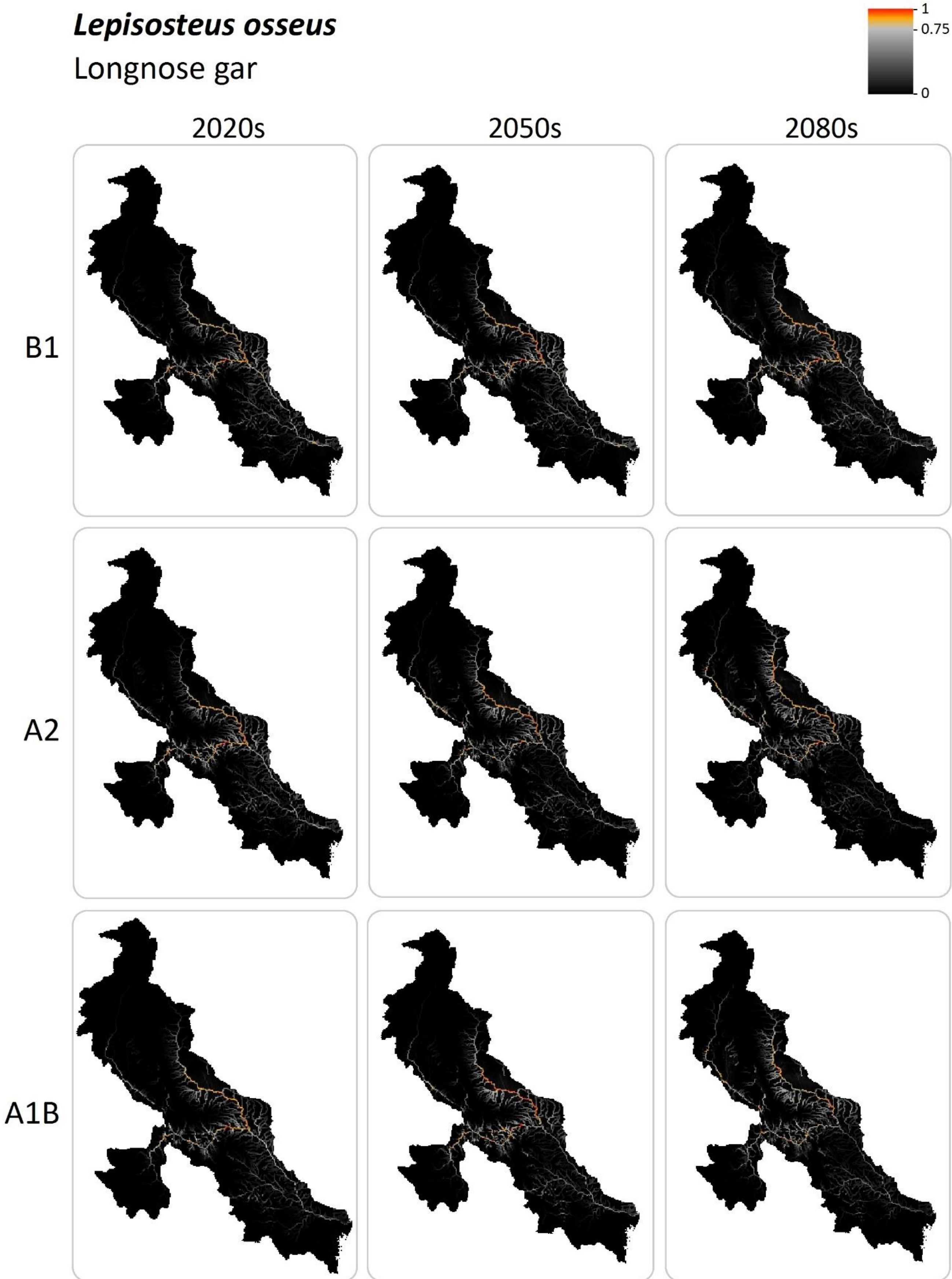
a. Occurrence records used in model
b. "Current" distribution model





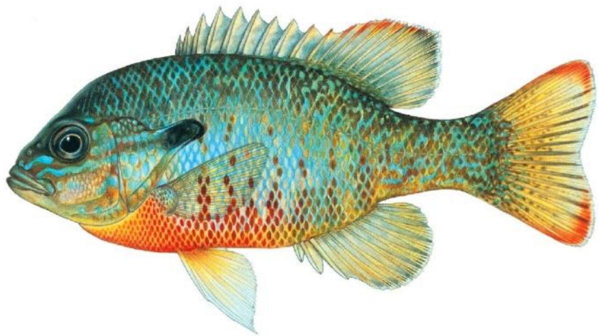
Lepisosteus osseus

Longnose gar

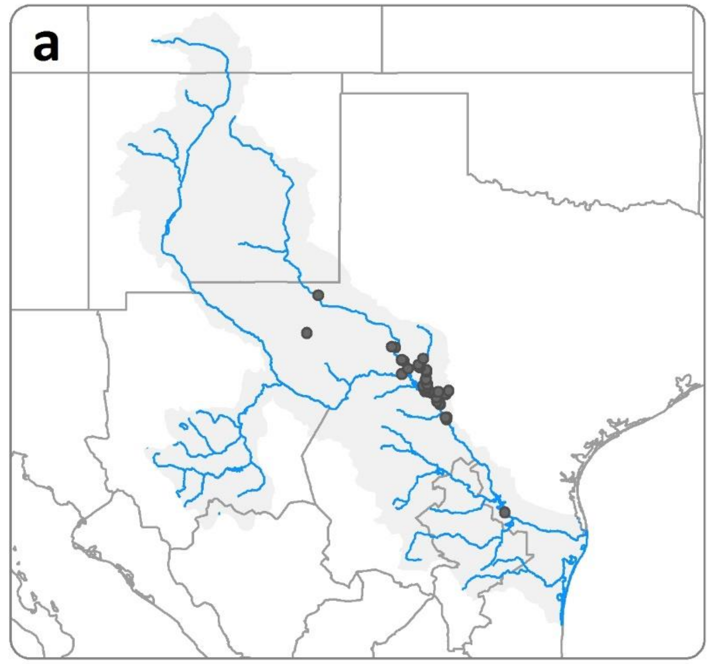


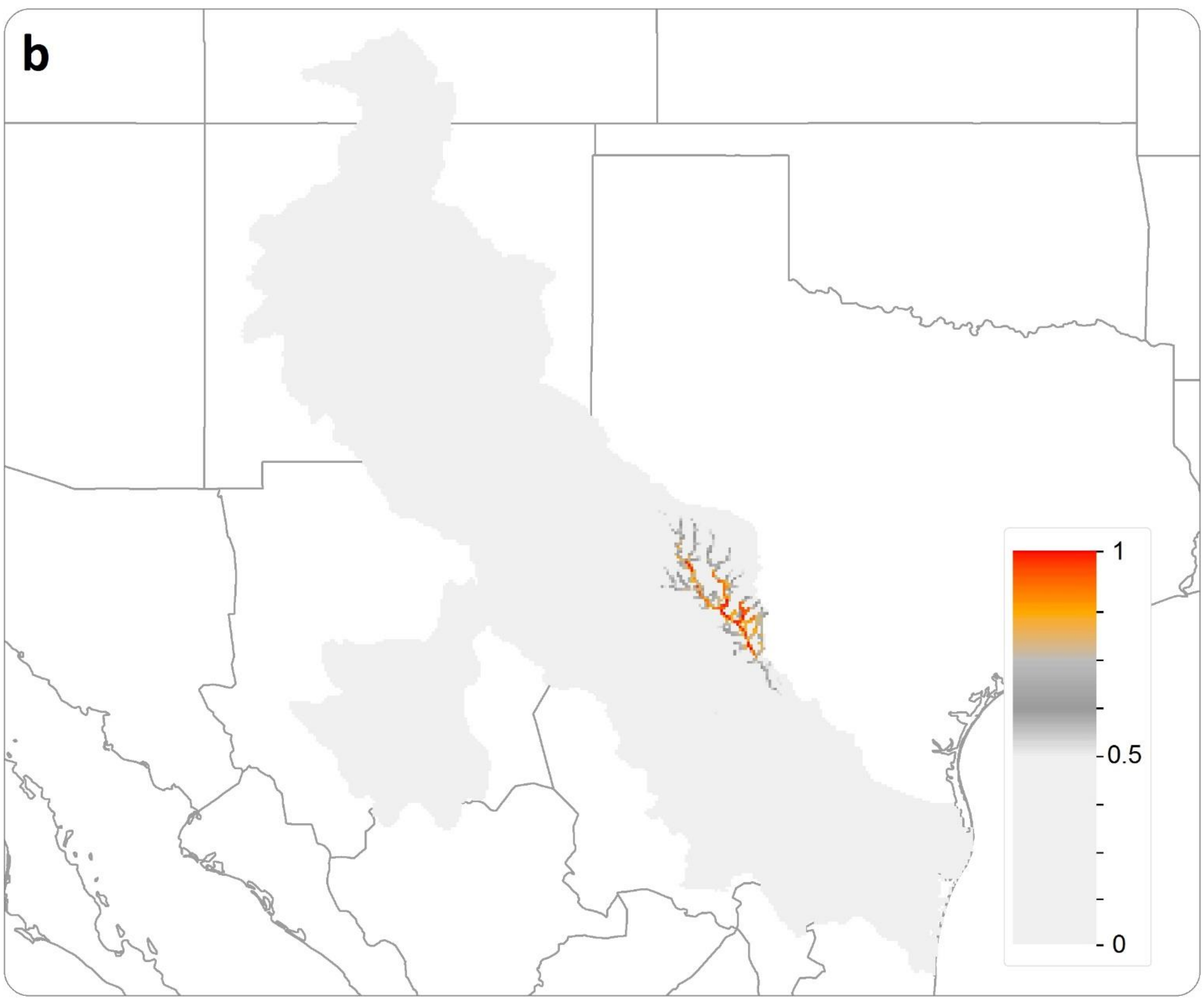
Lepomis auritus

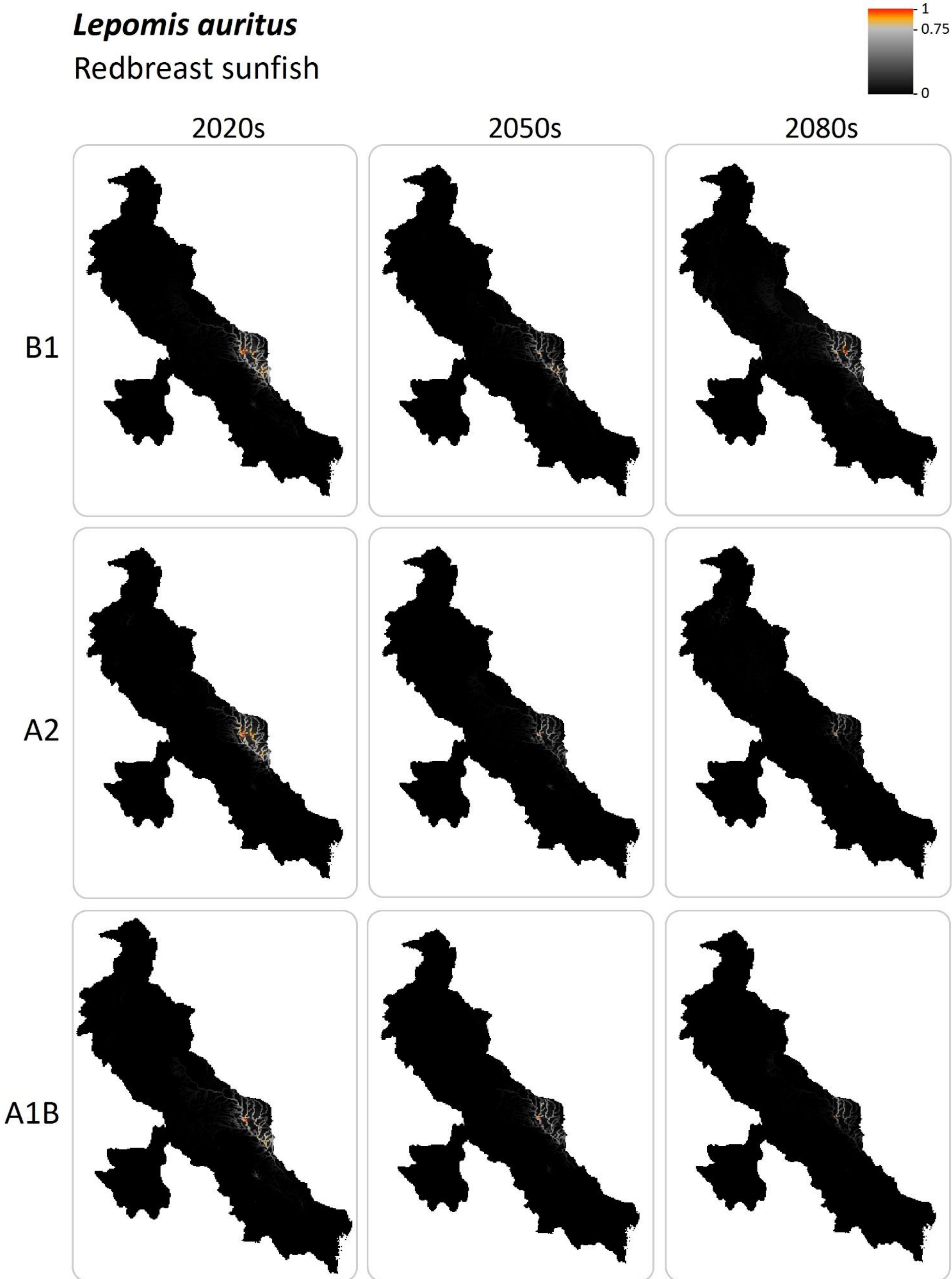
Redbreast sunfish



a. Occurrence records used in model
b. "Current" distribution model

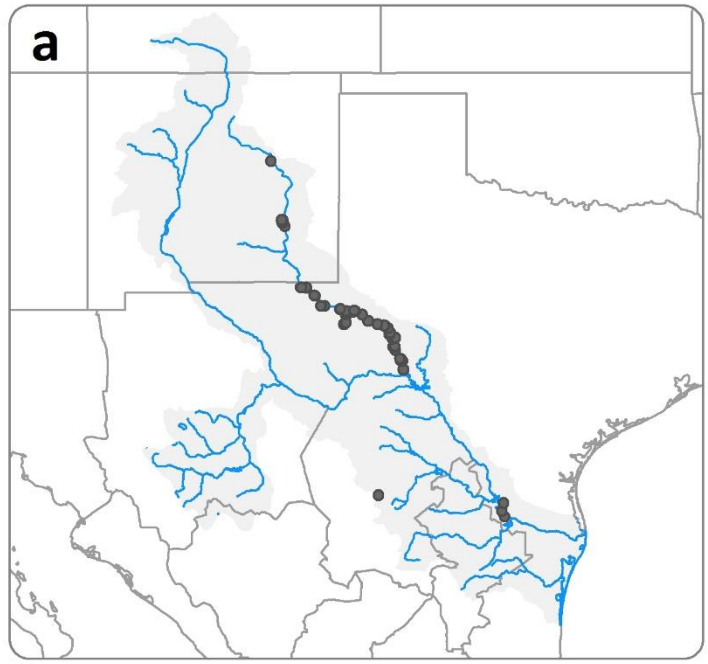




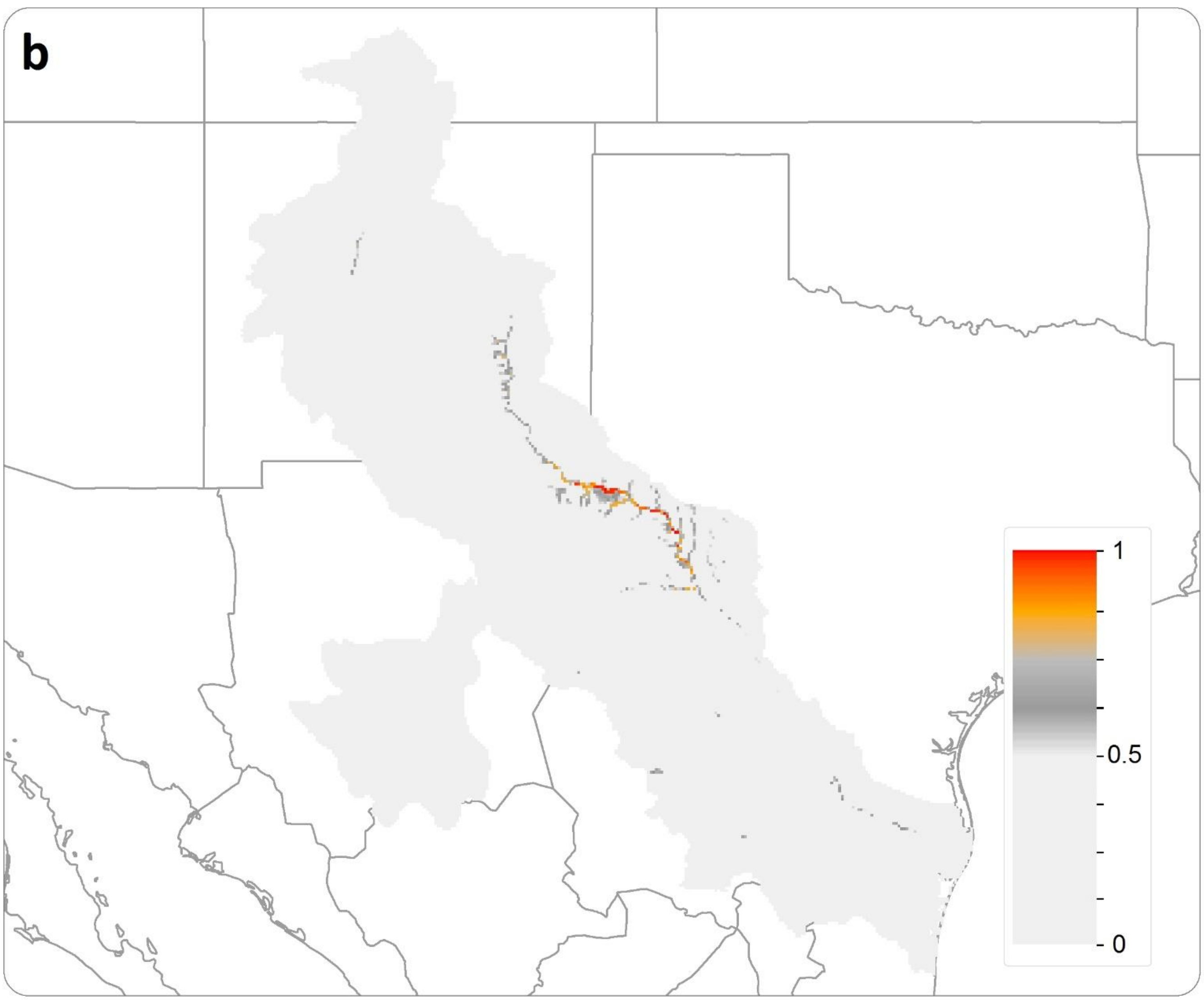

Lepomis auritus
Redbreast sunfish
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

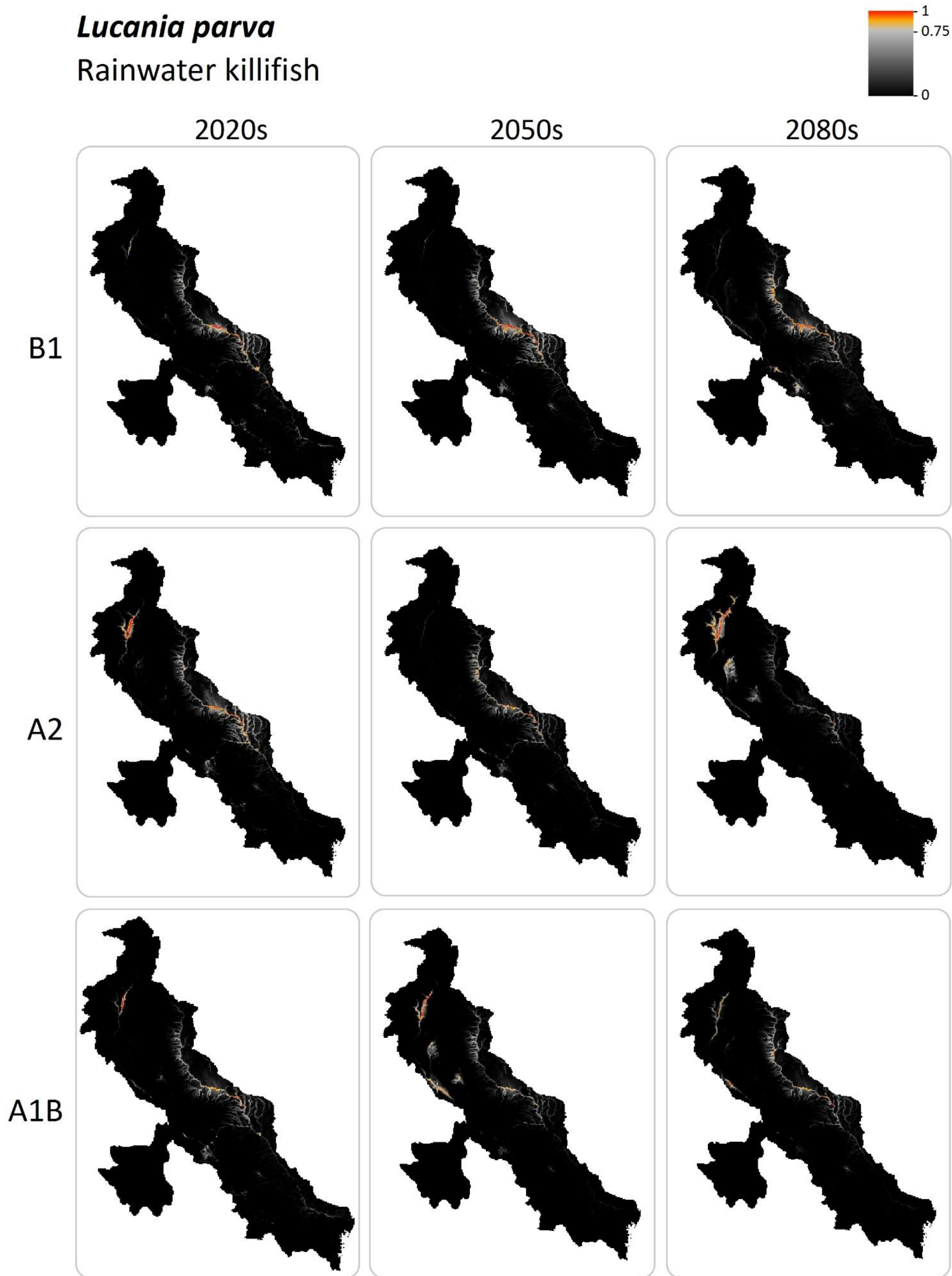
Lucania parva

Rainwater killifish



a. Occurrence records used in model
b. "Current" distribution model

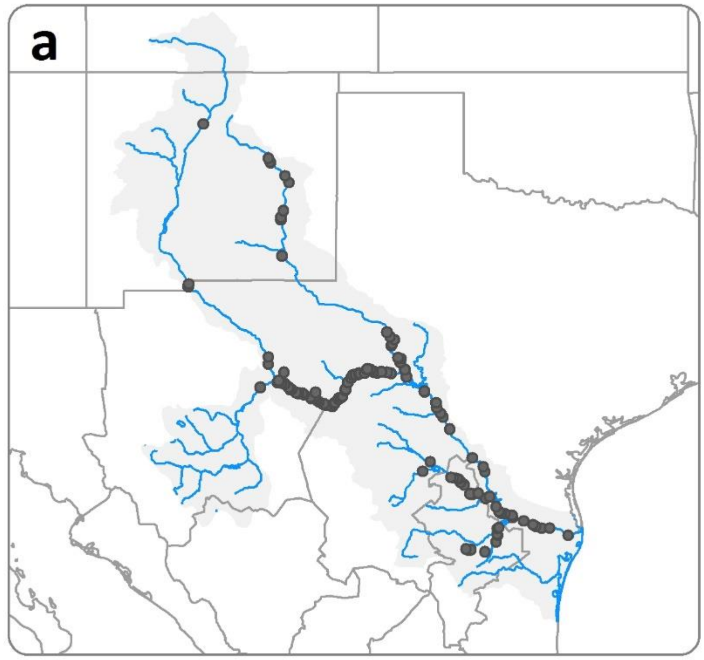




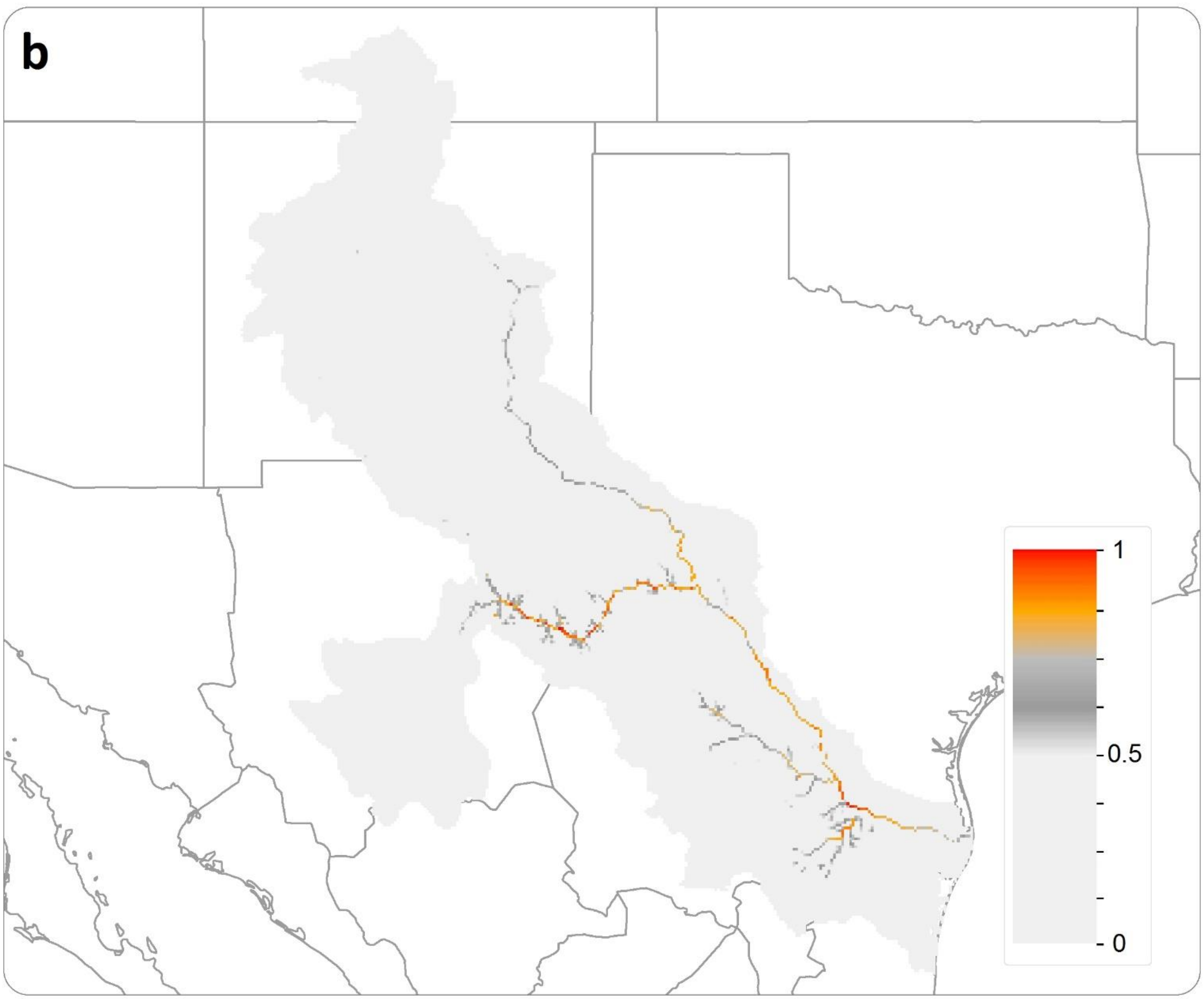
Lucania parva
Rainwater killifish
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

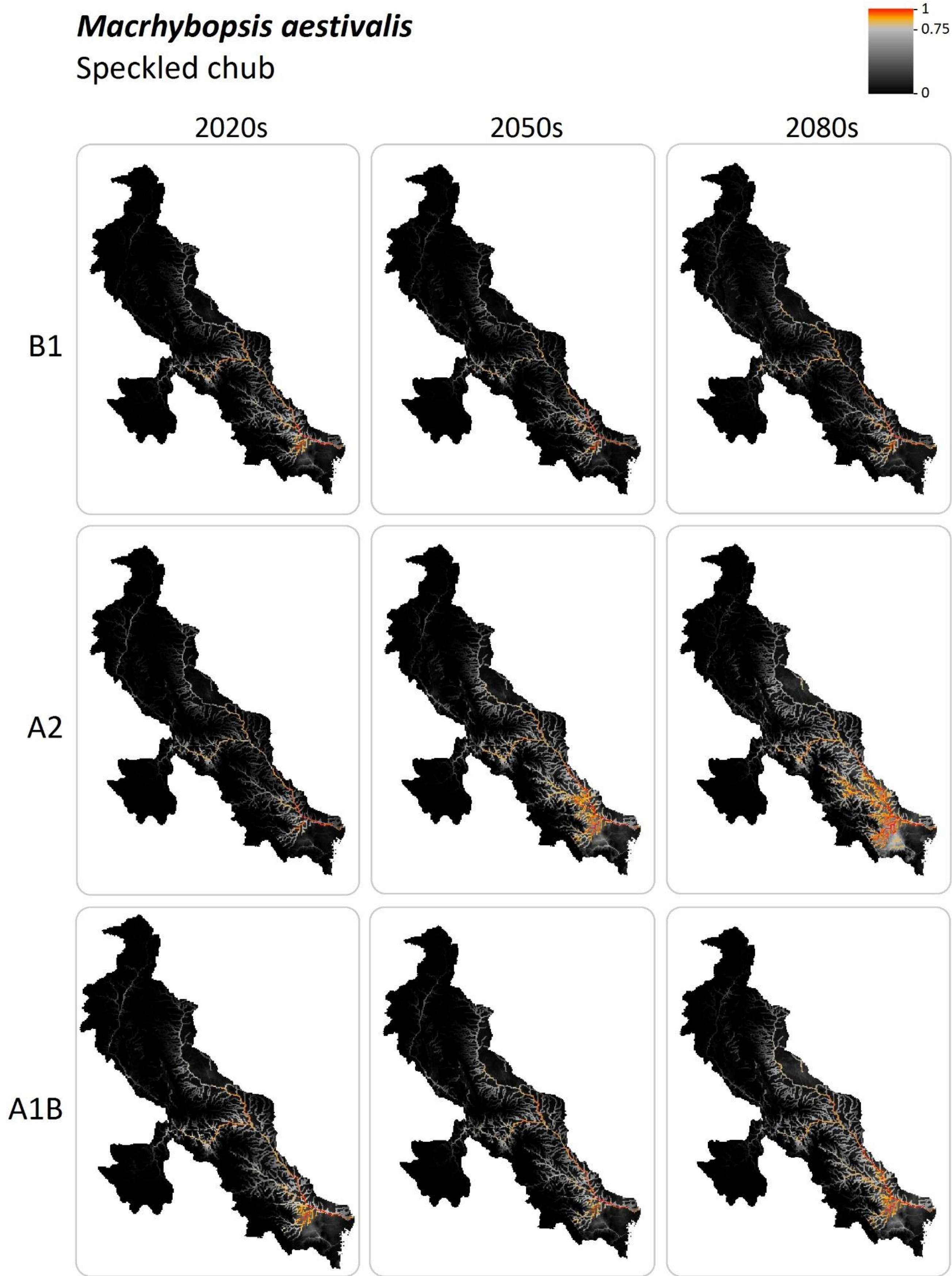
Macrhybopsis aestivalis

Speckled chub



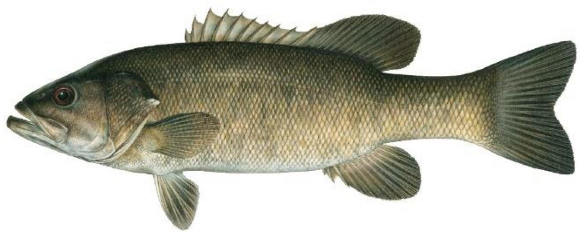
a. Occurrence records used in model
b. "Current" distribution model

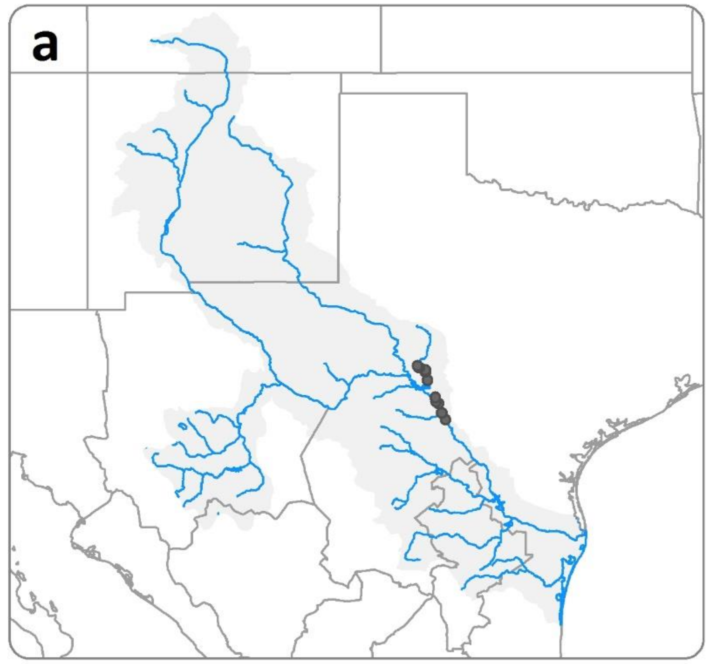



Macrhybopsis aestivalis
Speckled chub
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

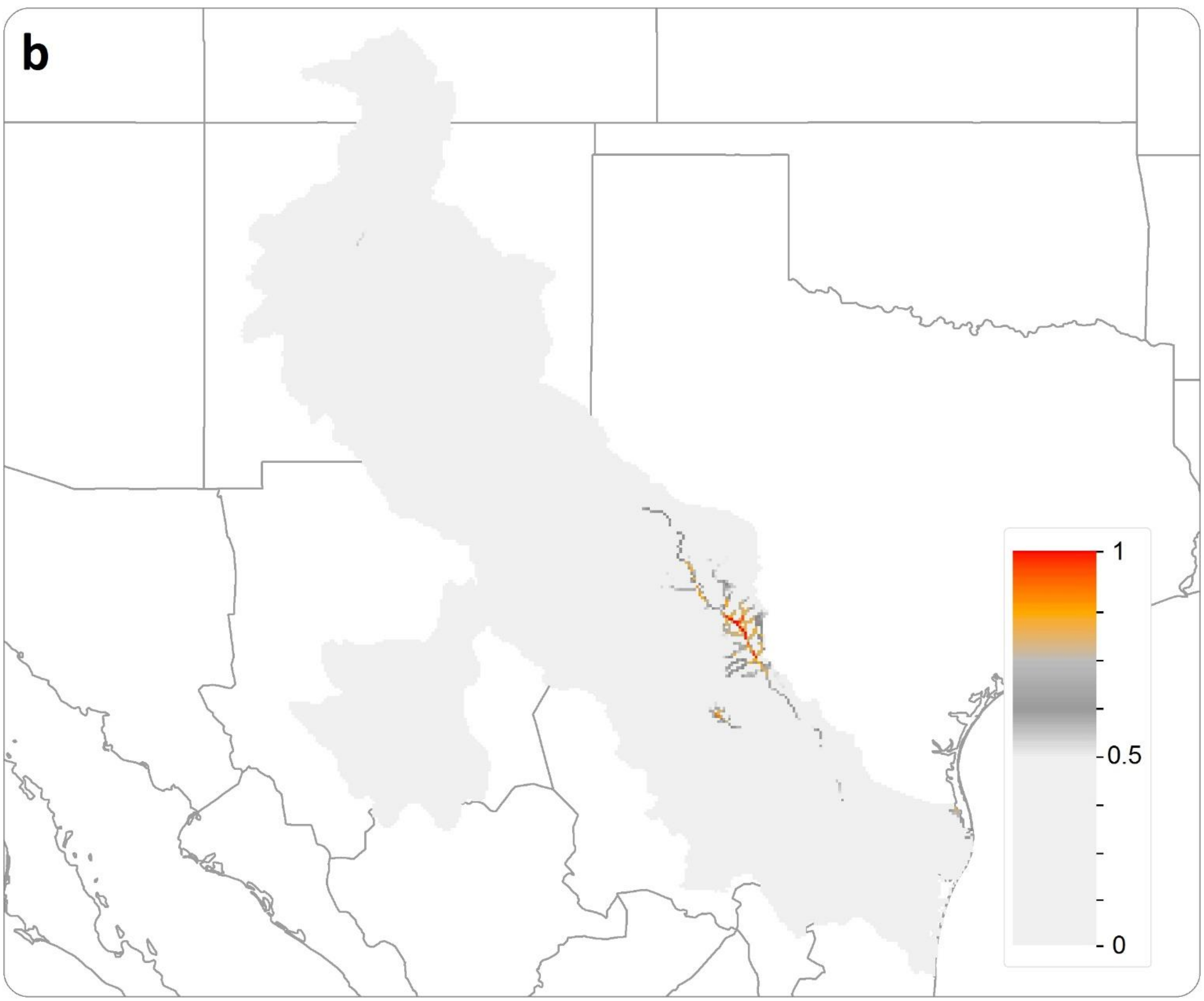
Micropterus dolomieu

Smallmouth bass

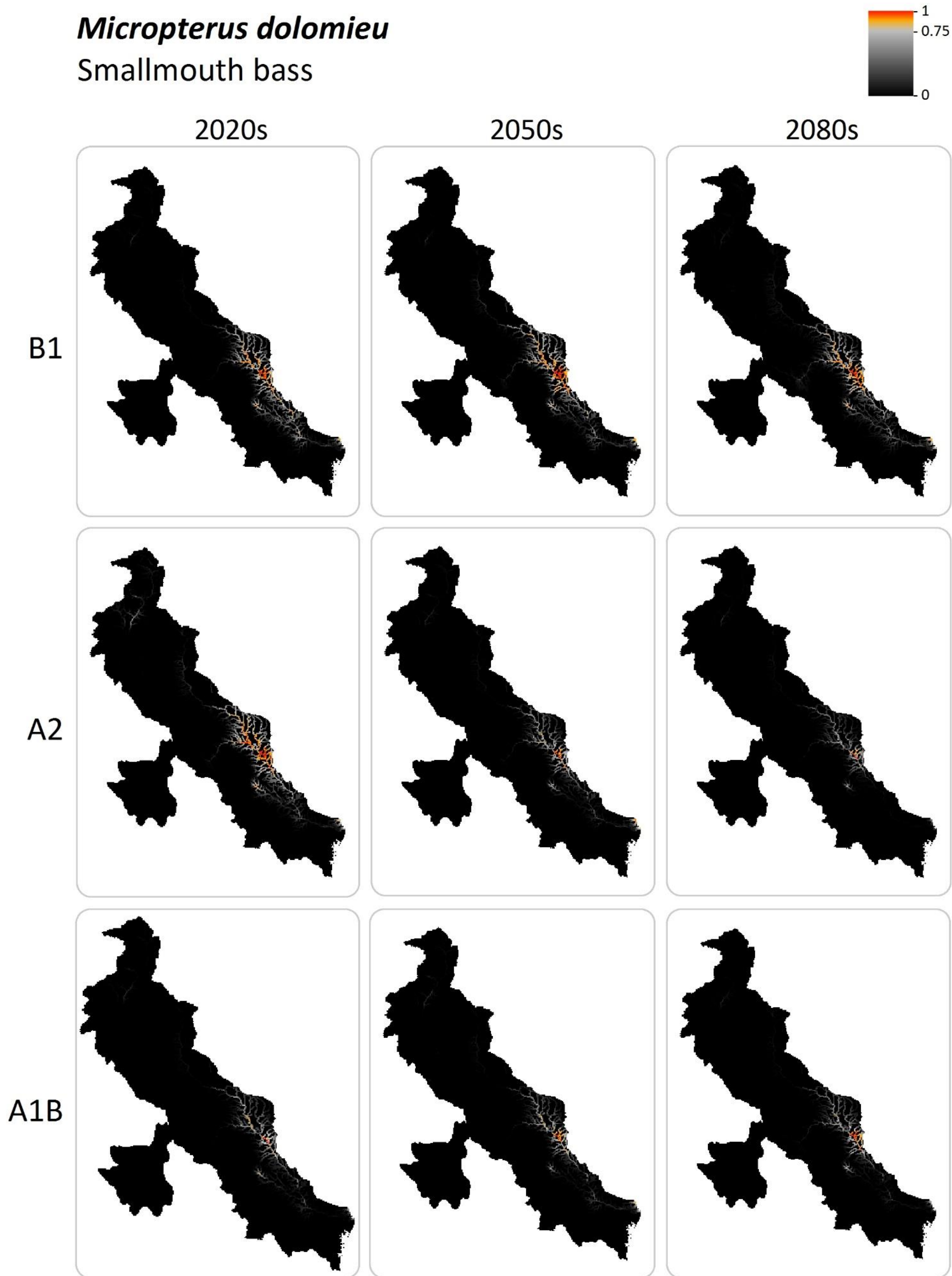




a. Occurrence records used in model
b. "Current" distribution model

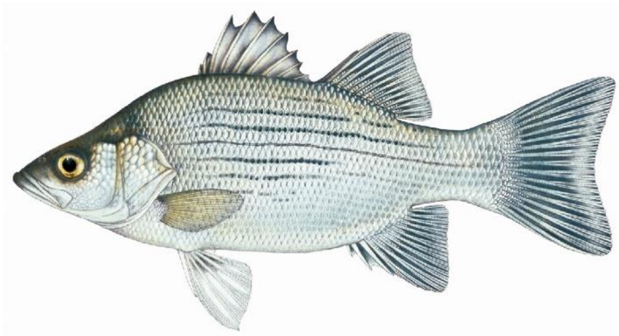


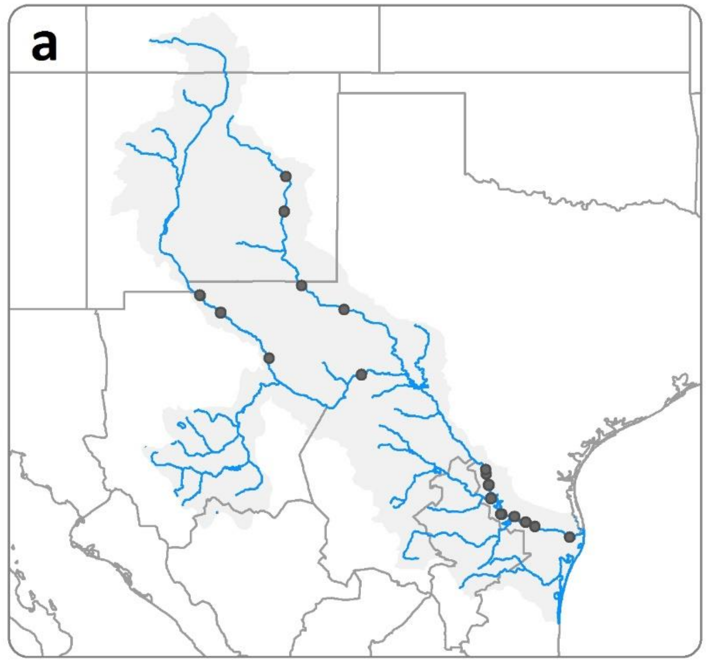
Micropterus dolomieu
Smallmouth bass



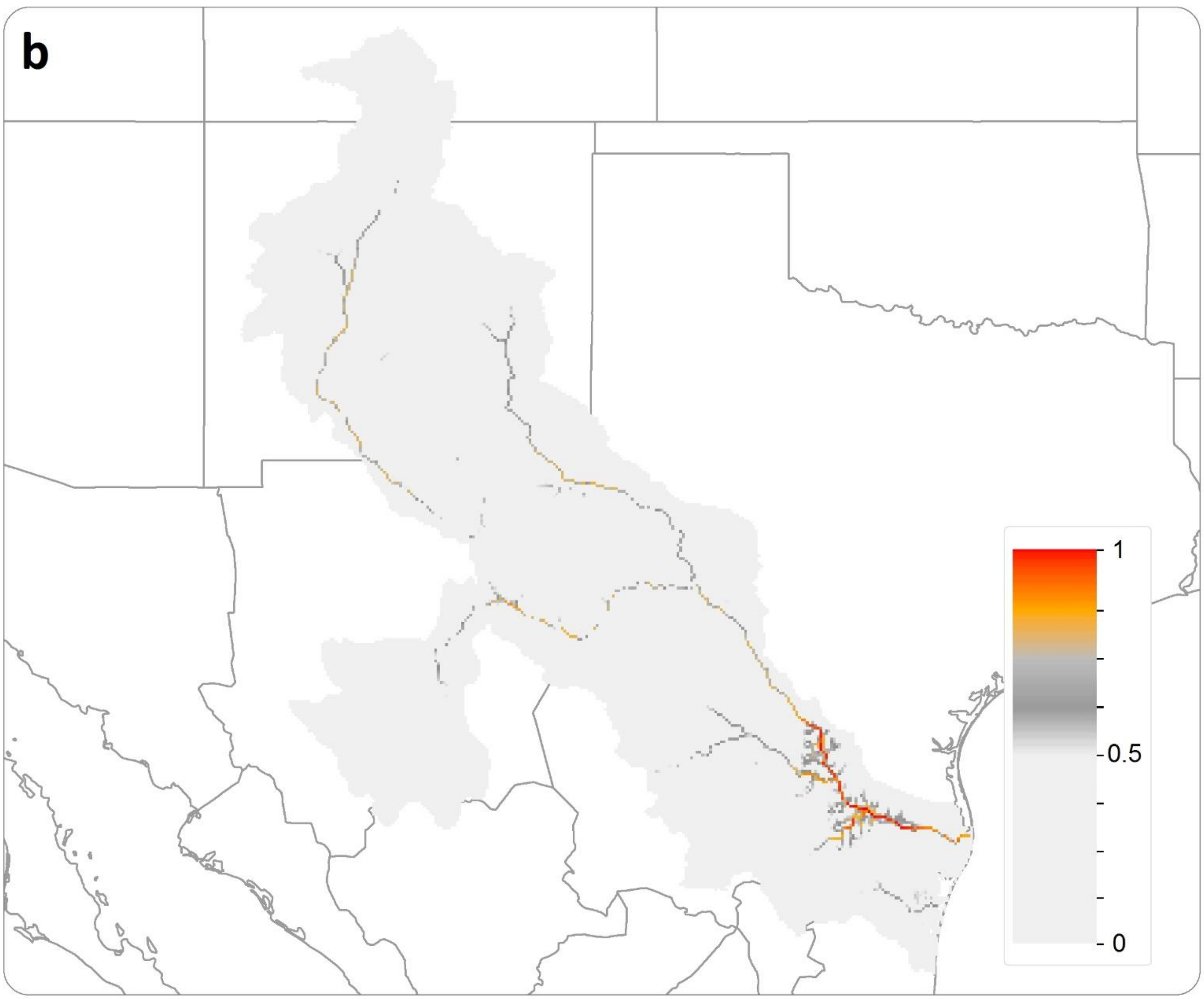
Morone chrysops

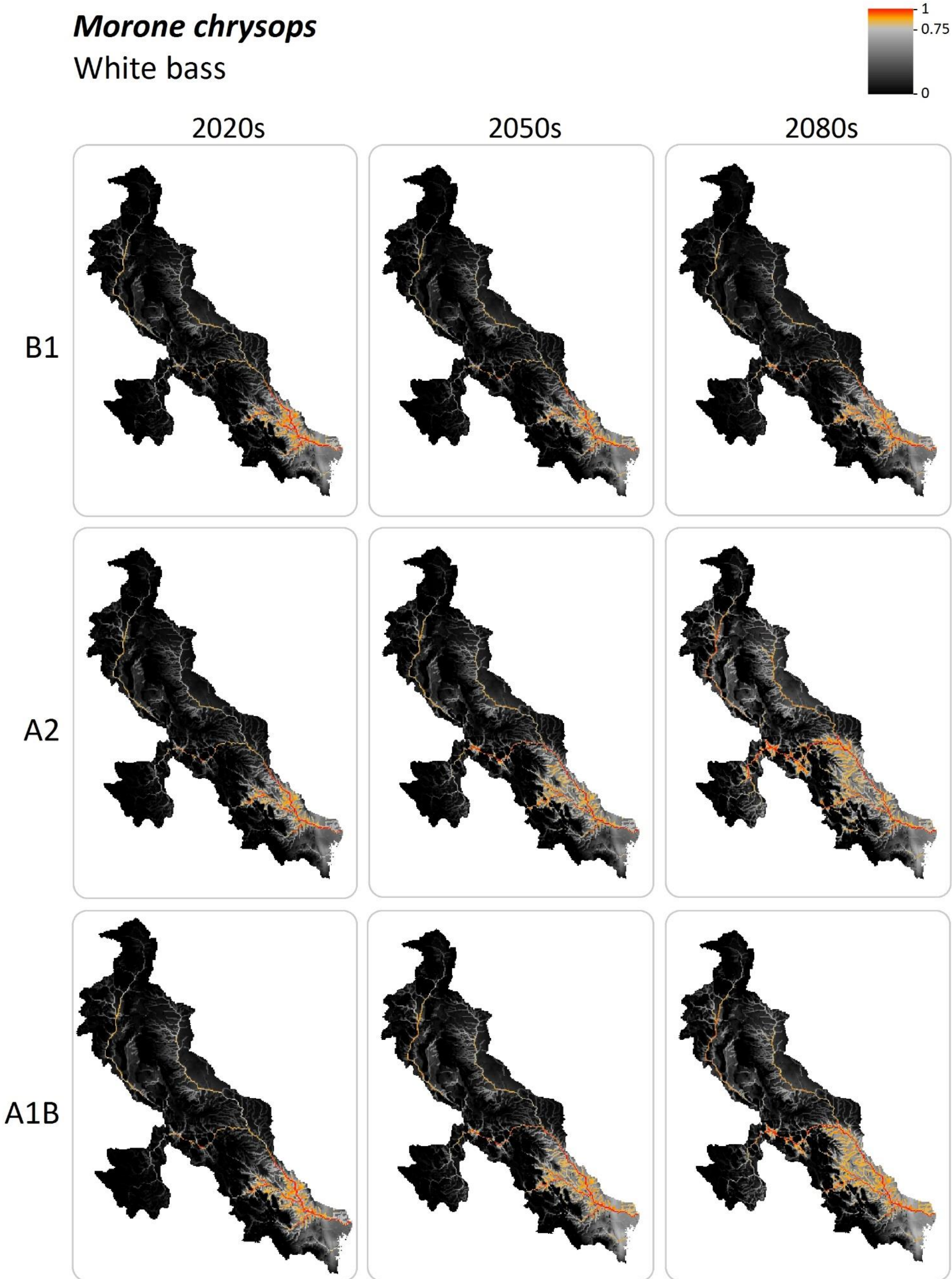
White bass





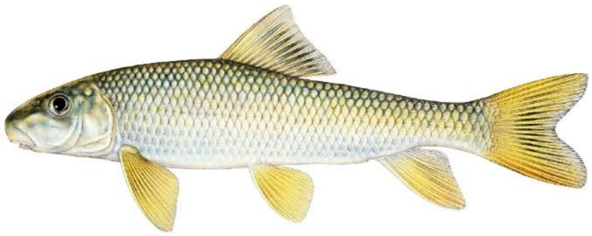
a. Occurrence records used in model
b. "Current" distribution model

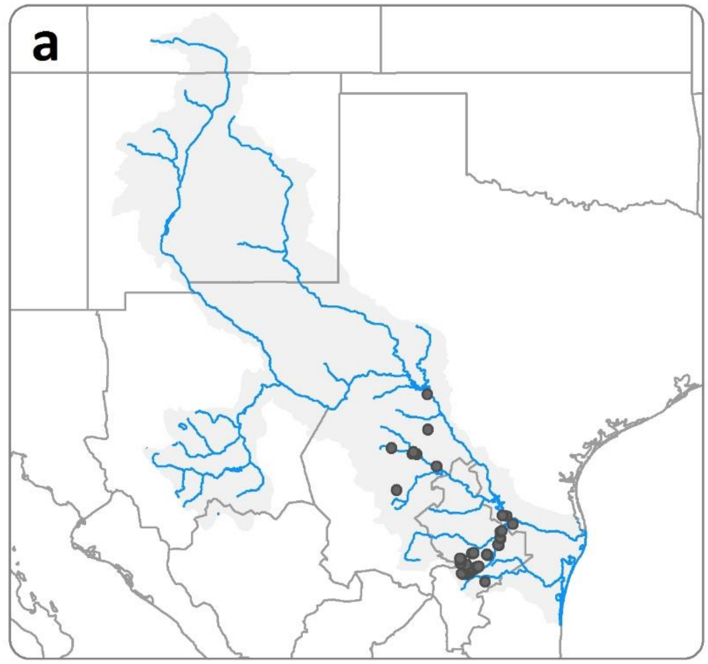



Morone chrysops
White bass
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

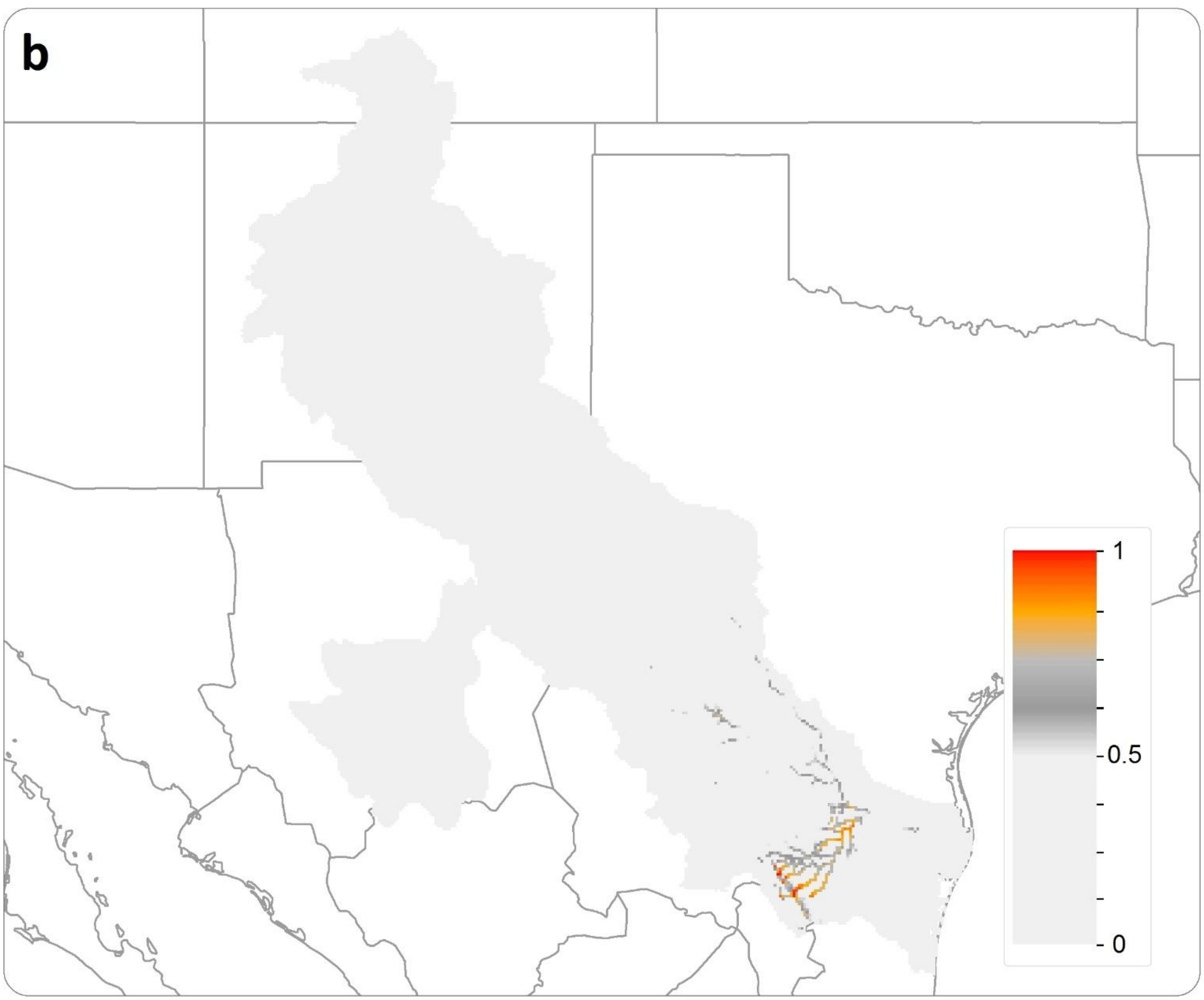
Moxostoma albidum

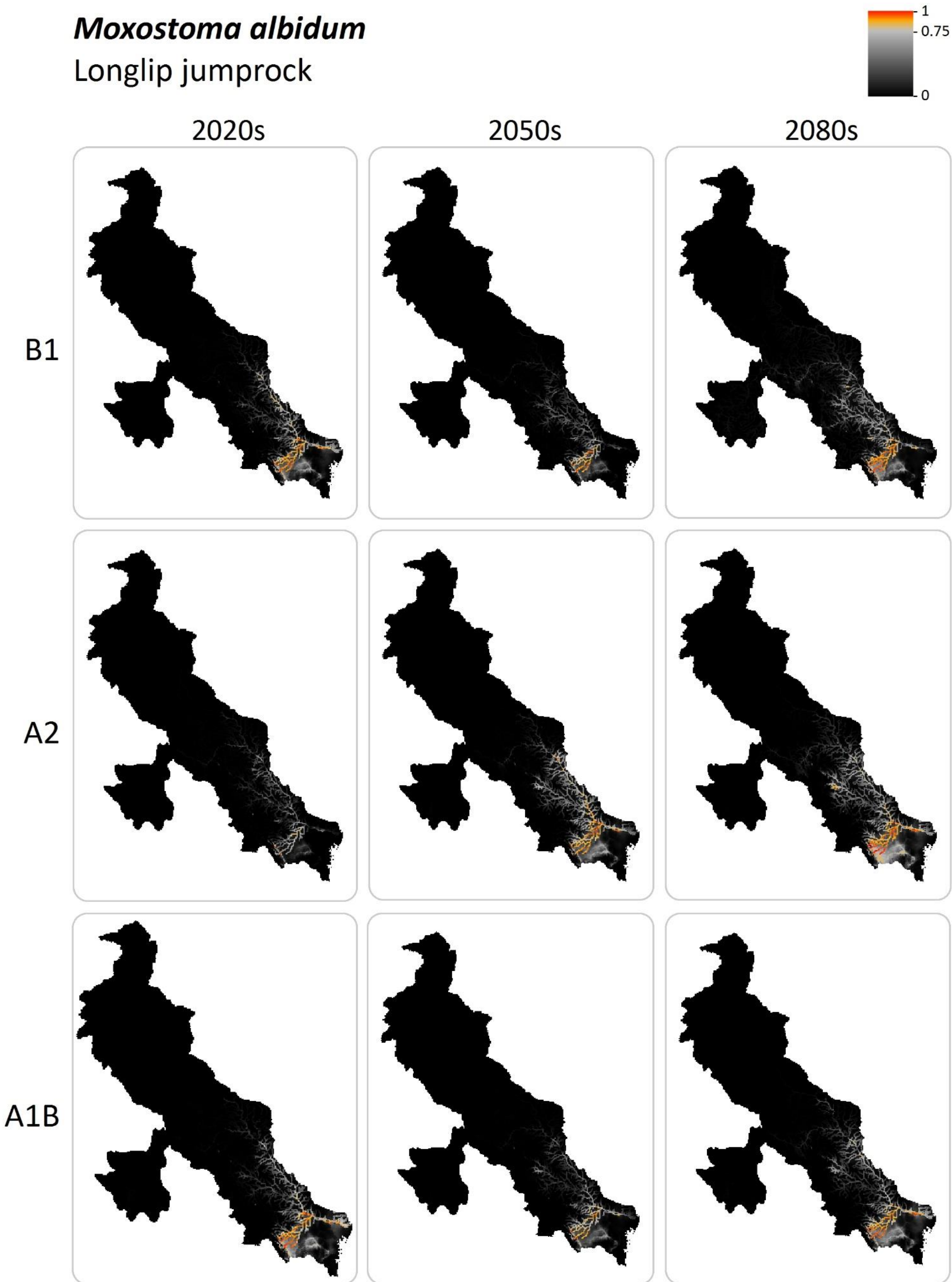
Longlip jumprock





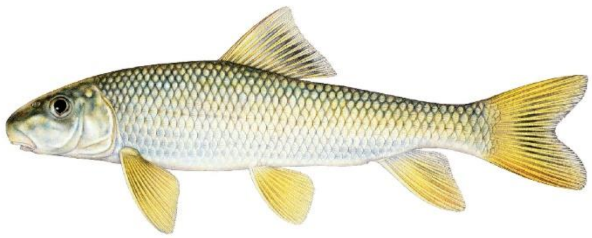
a. Occurrence records used in model
b. "Current" distribution model



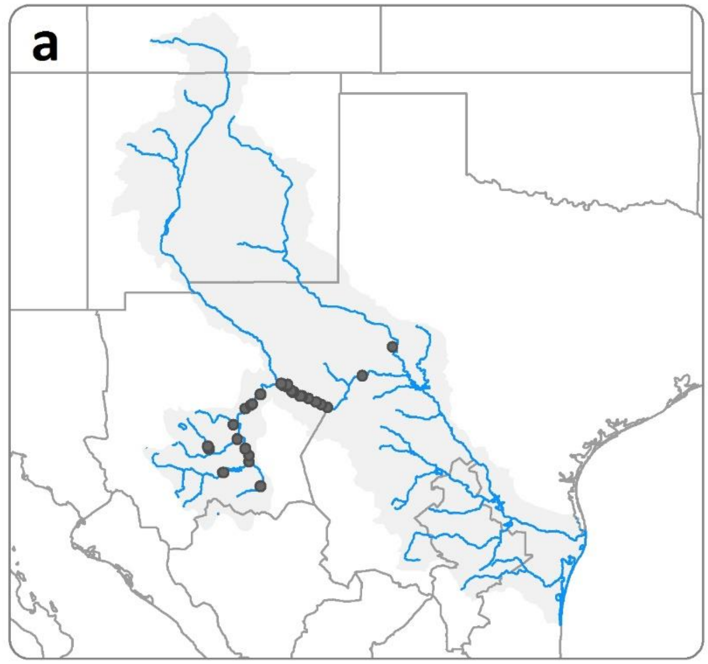

Moxostoma albidum
Longlip jumprock
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

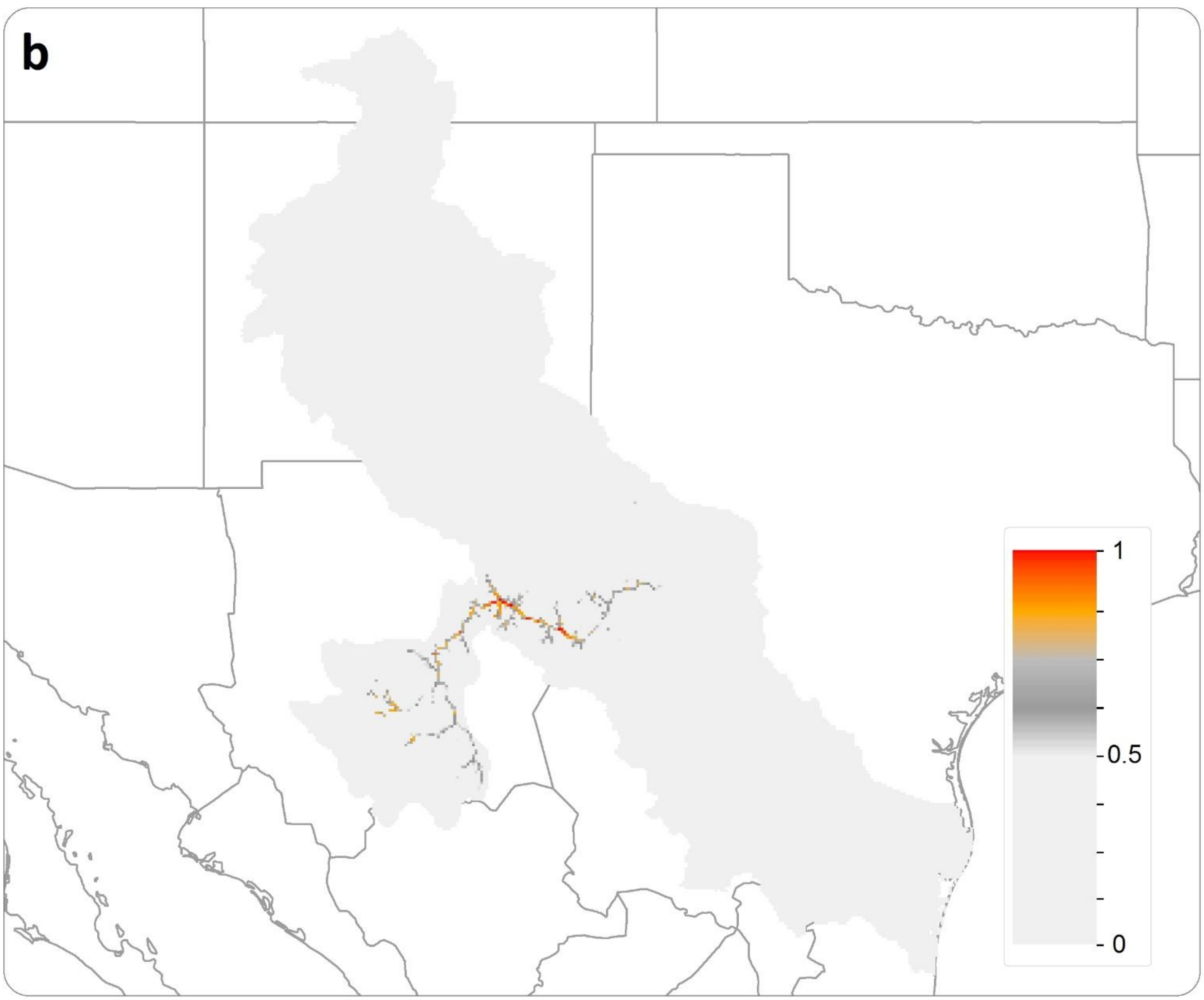
Moxostoma austrinum

Mexican redhorse

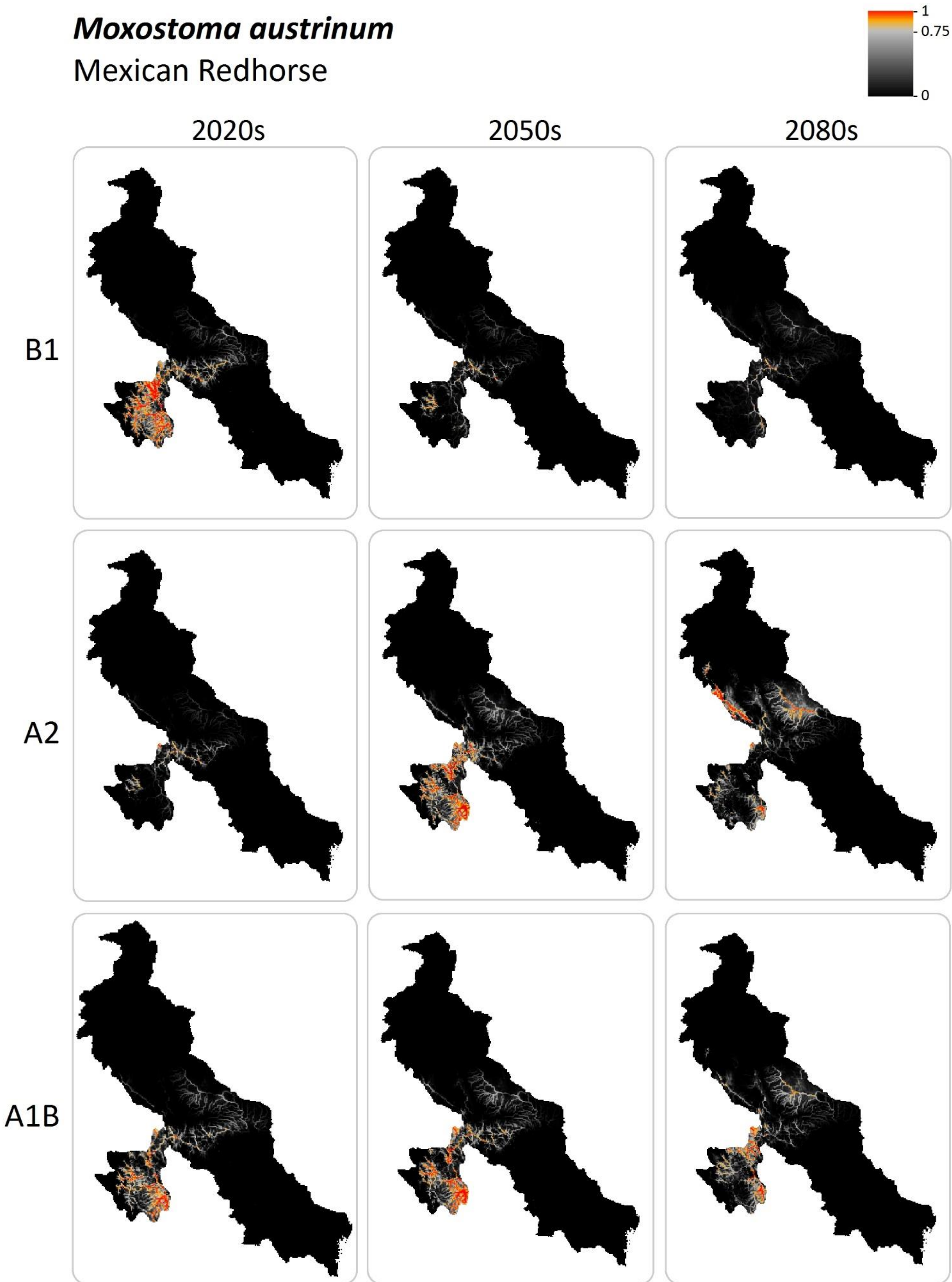


a. Occurrence records used in model
b. "Current" distribution model



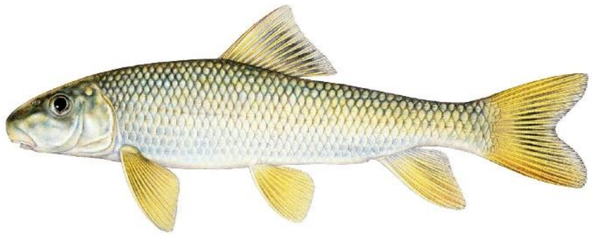


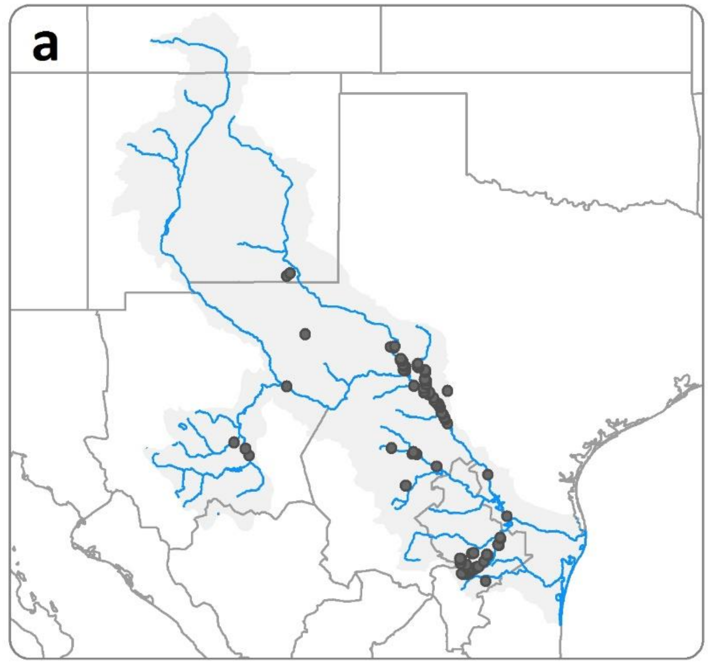
Moxostoma austrinum
Mexican Redhorse



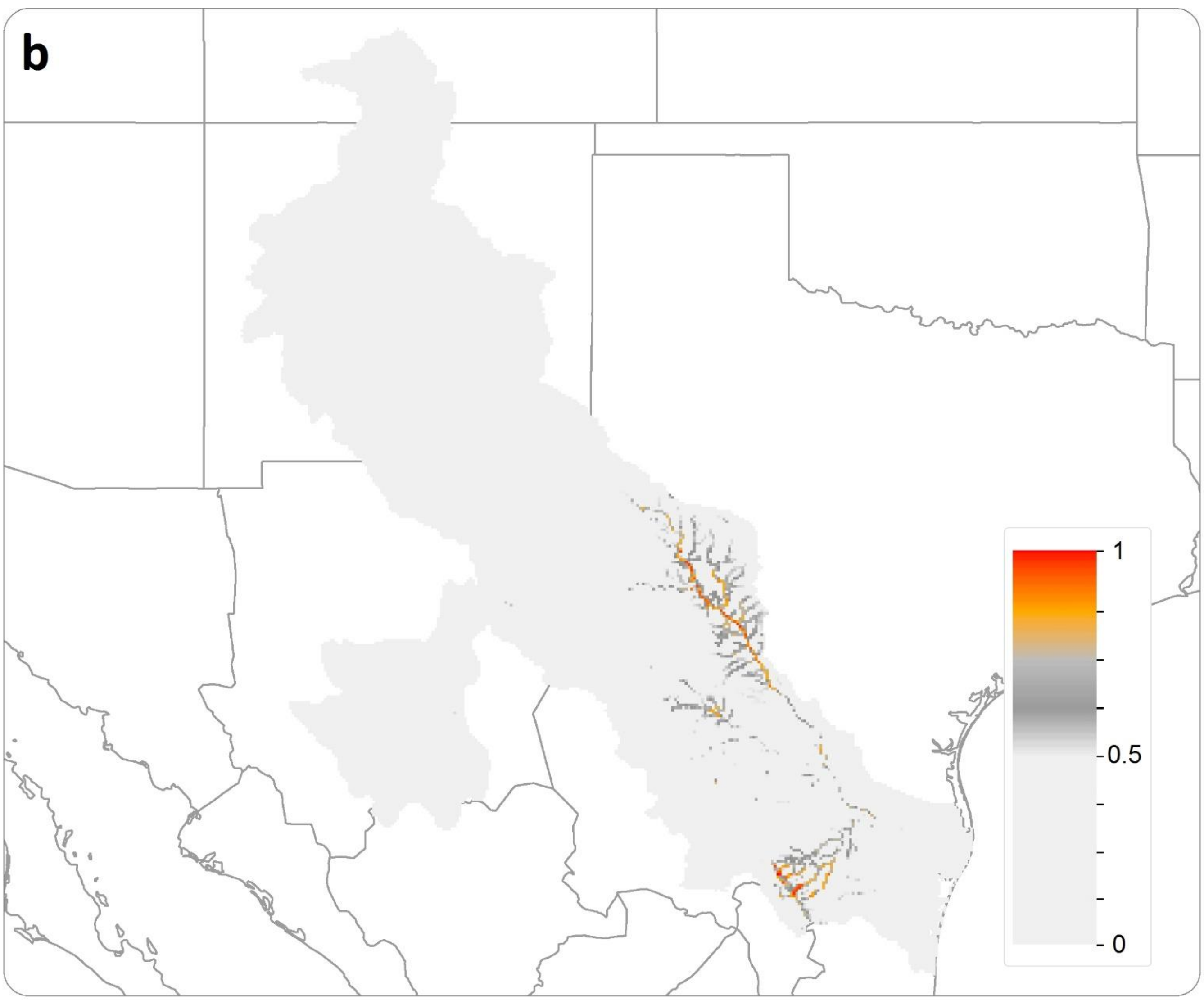
Moxostoma congestum

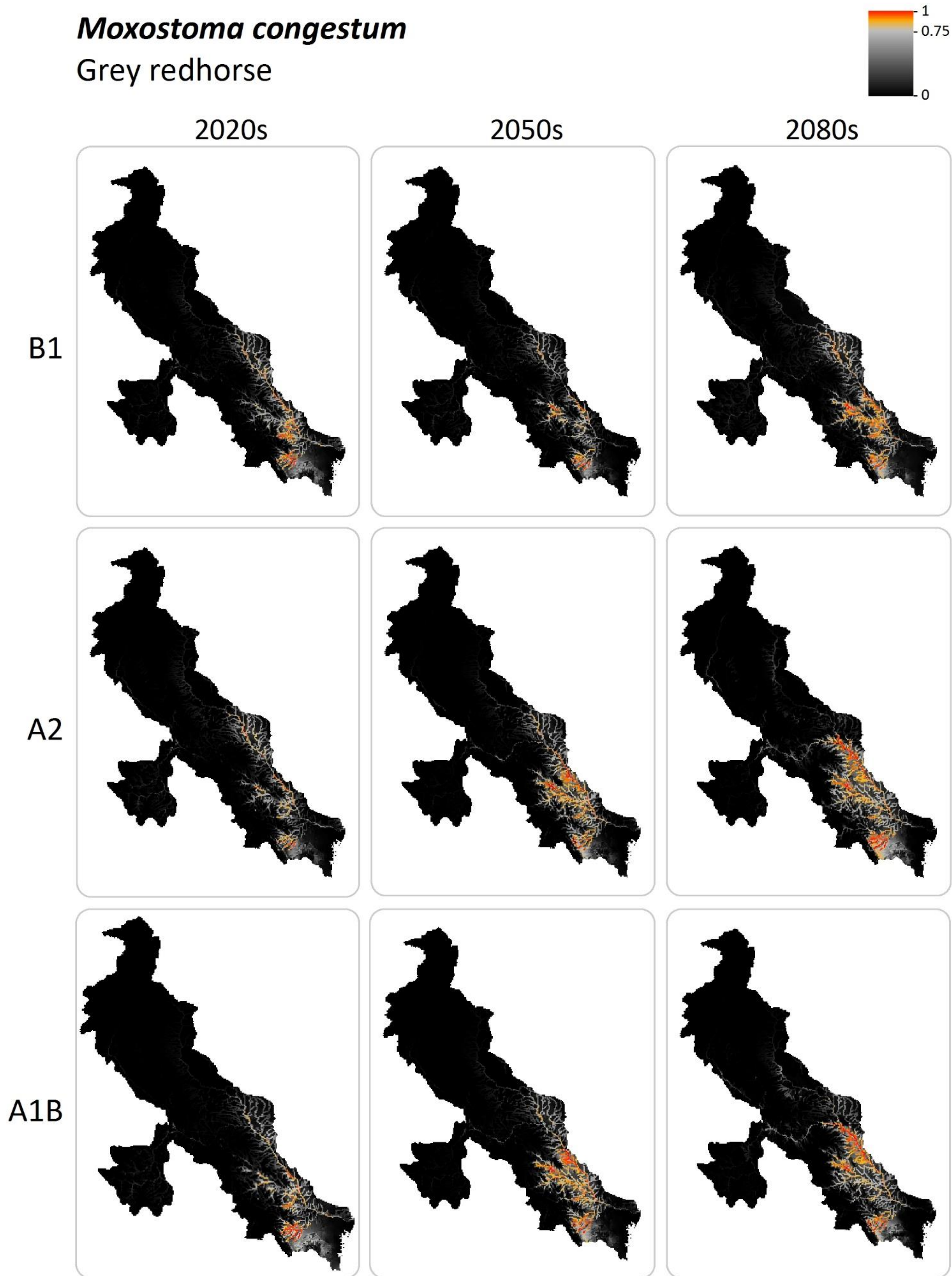
Gray redhorse





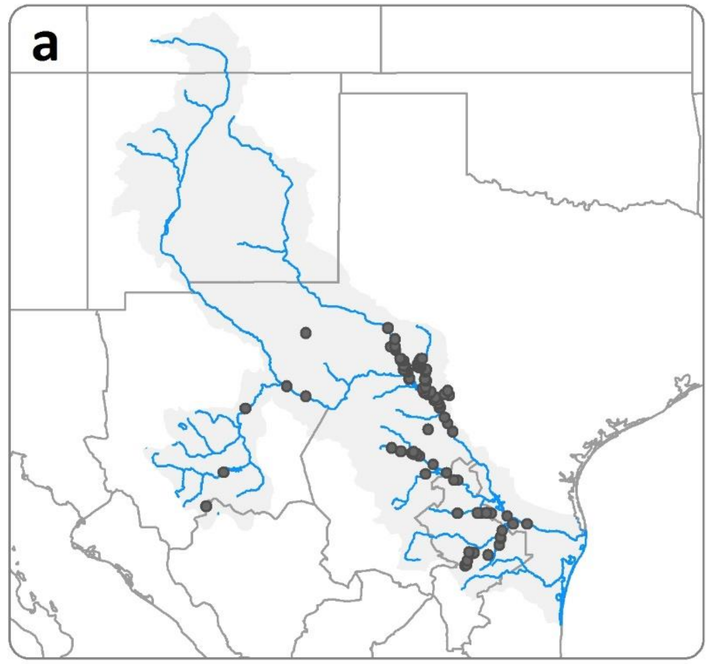
a. Occurrence records used in model
b. "Current" distribution model



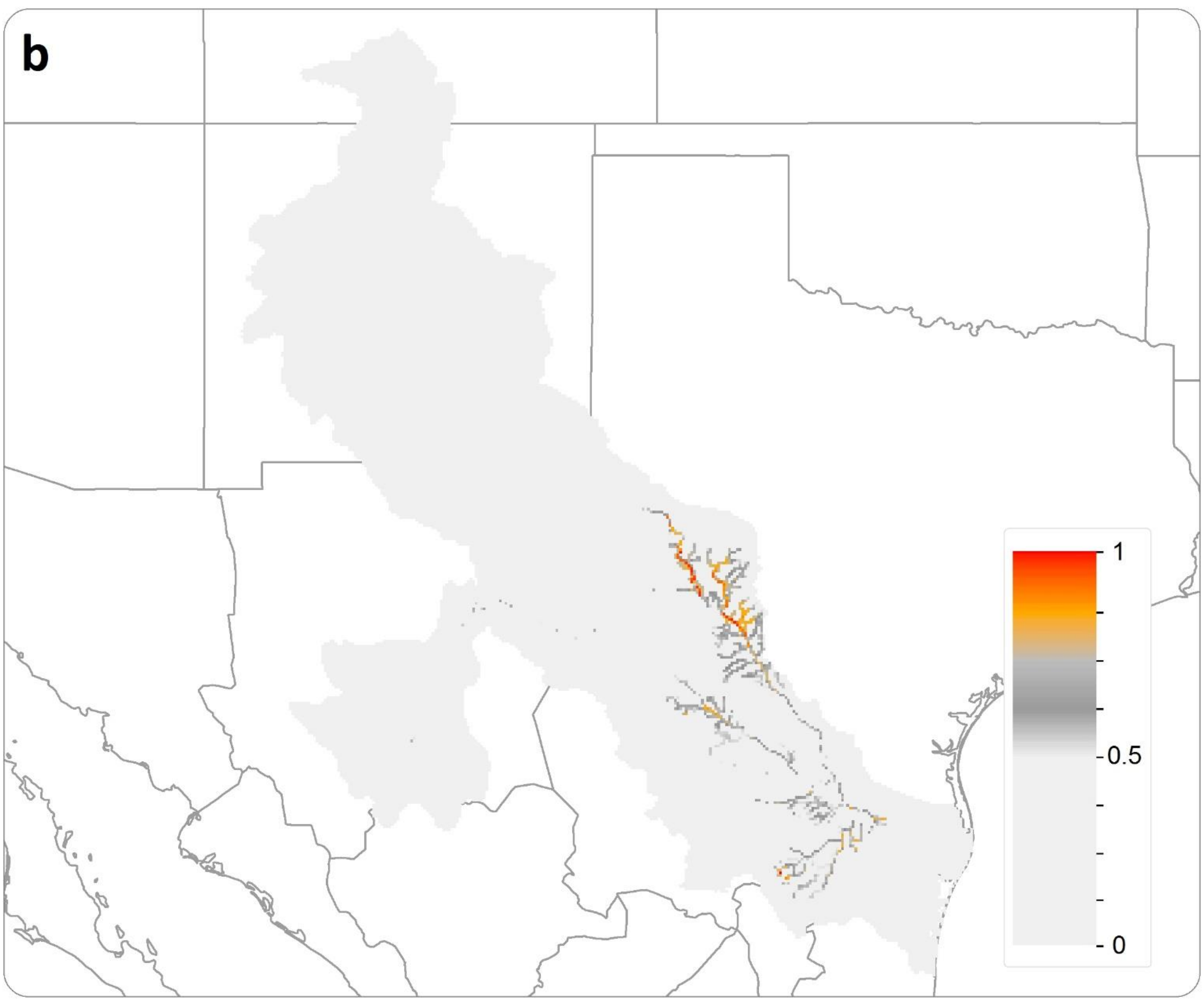

Moxostoma congestum
Grey redhorse
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

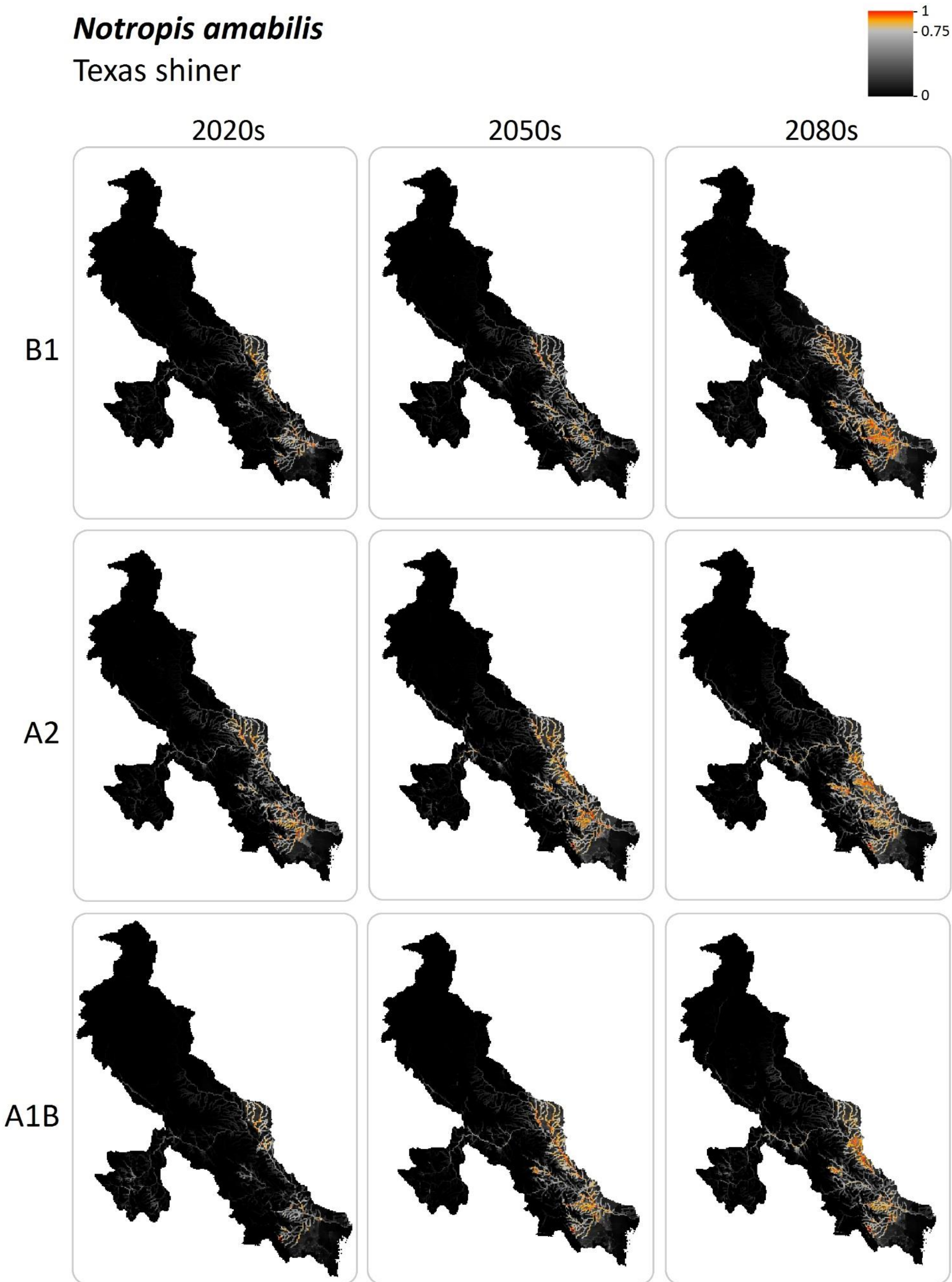
Notropis amabilis

Texas shiner



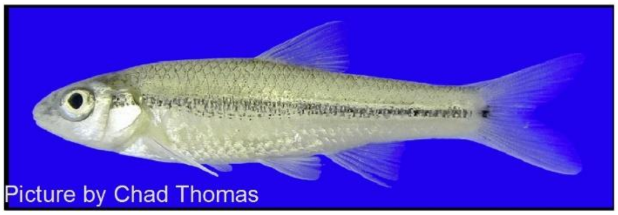
a. Occurrence records used in model
b. "Current" distribution model

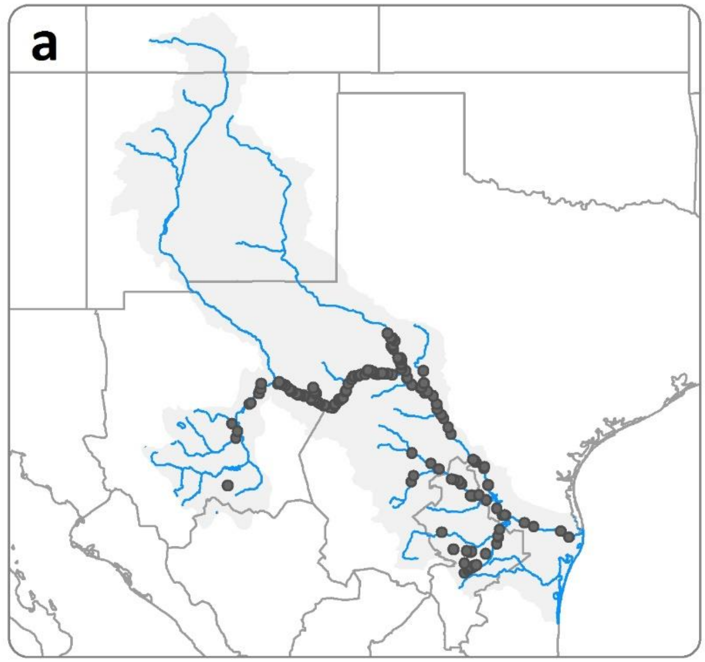



Notropis amabilis
Texas shiner
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

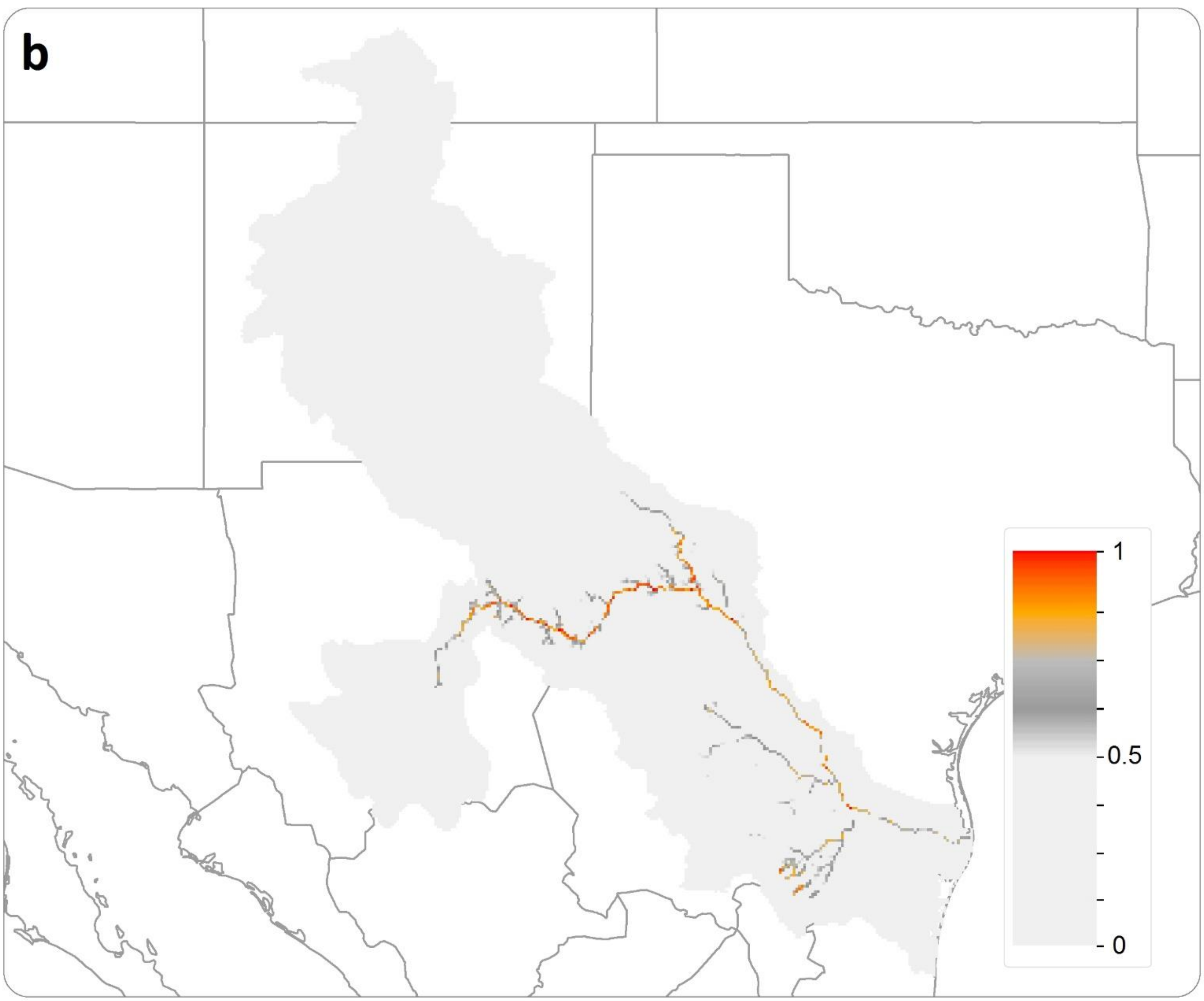
Notropis braytoni

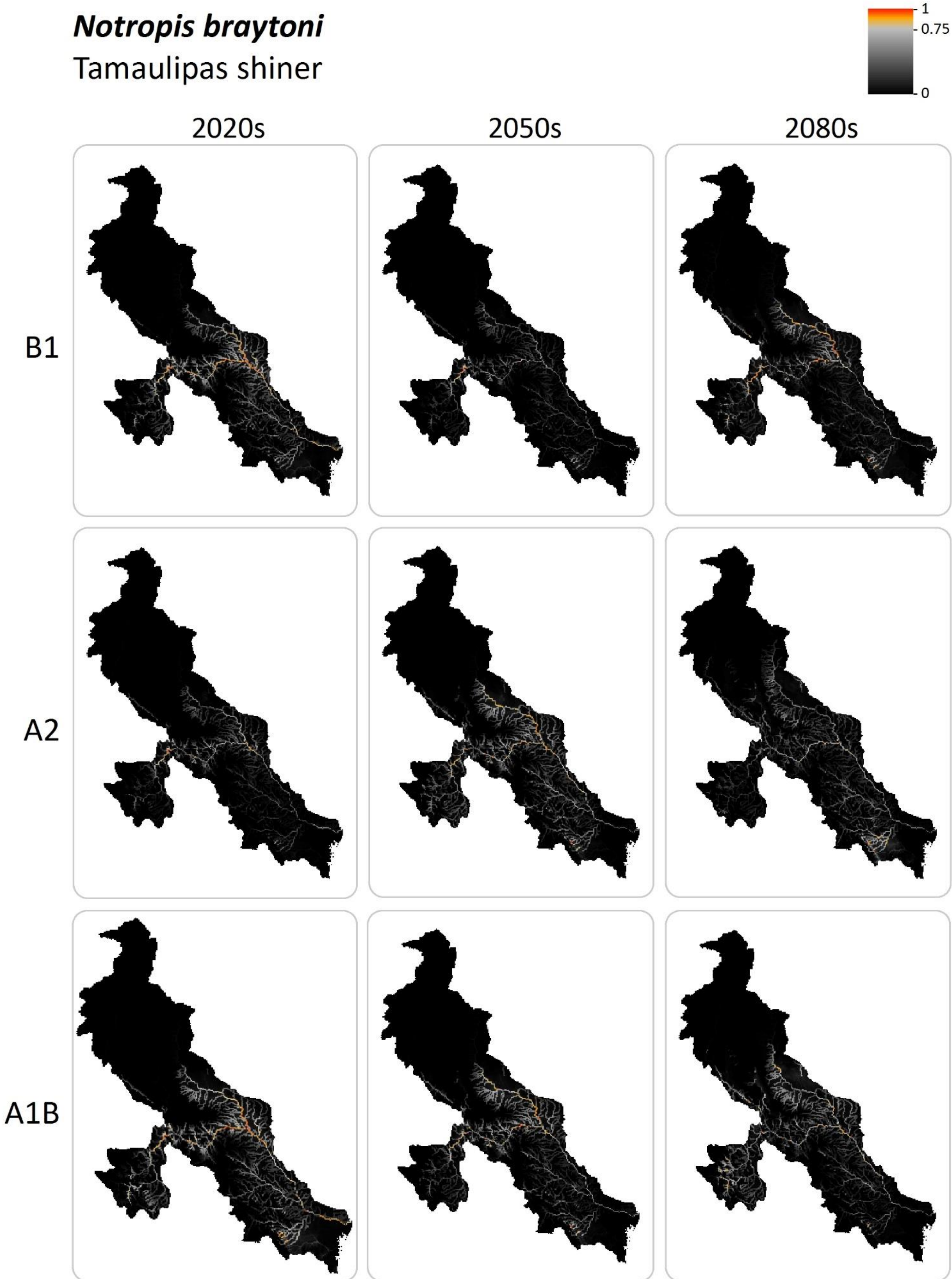
Tamaulipas shiner





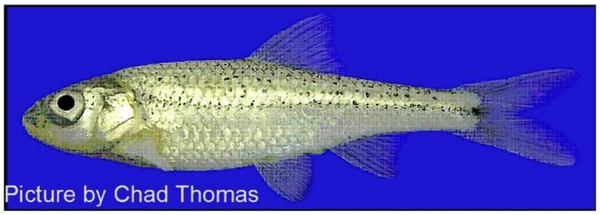
a. Occurrence records used in model
b. "Current" distribution model

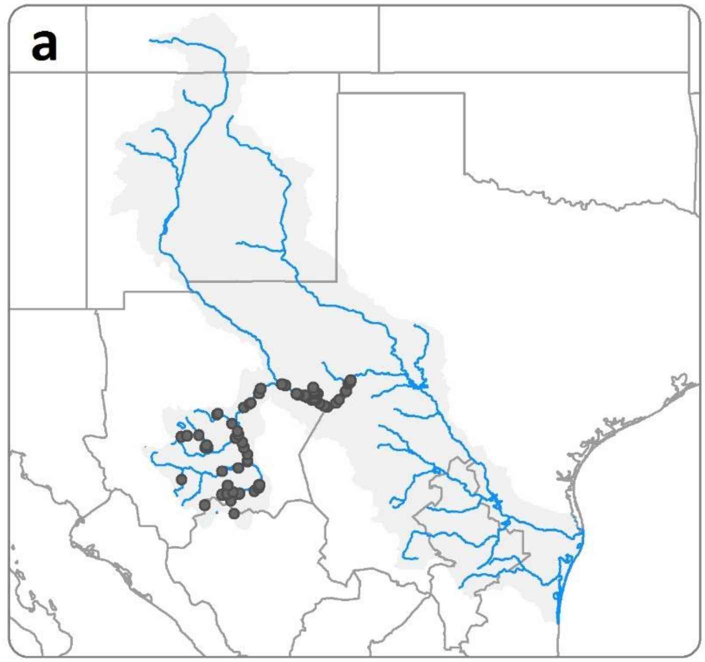



Notropis braytoni
Tamaulipas shiner
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

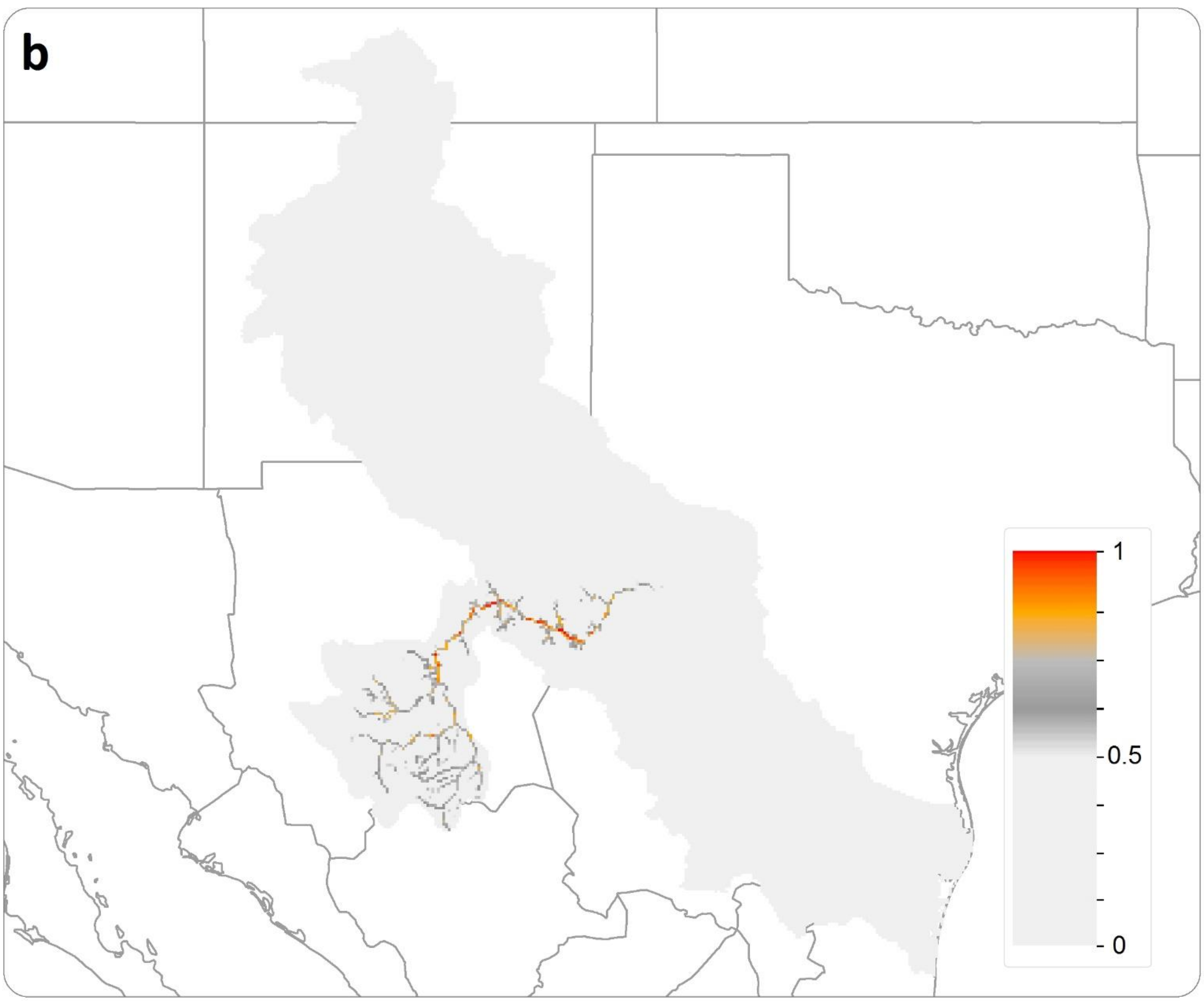
Notropis chihuahua

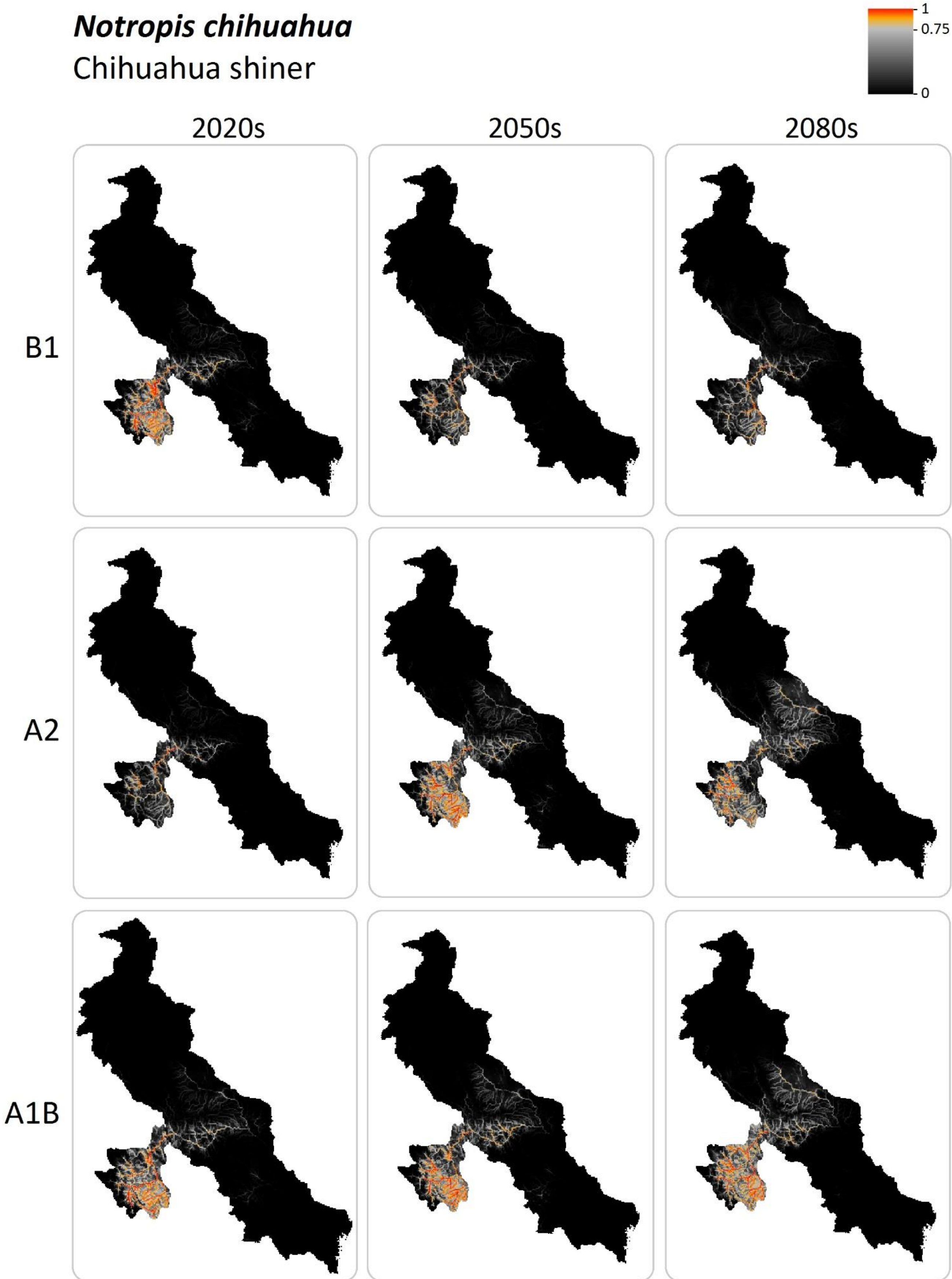
Chihuahua shiner





a. Occurrence records used in model
b. "Current" distribution model

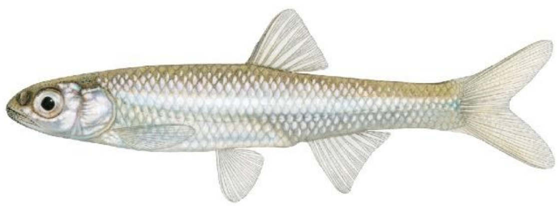


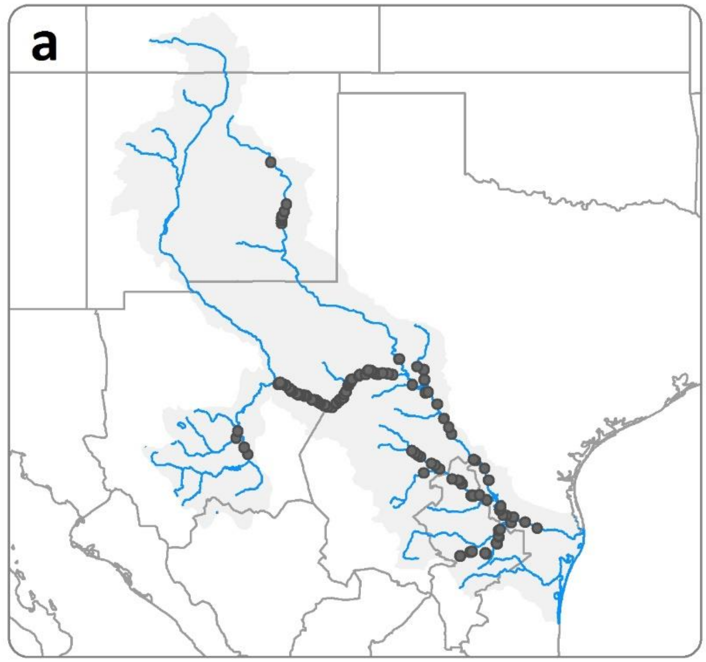


Notropis chihuahua
Chihuahua shiner
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

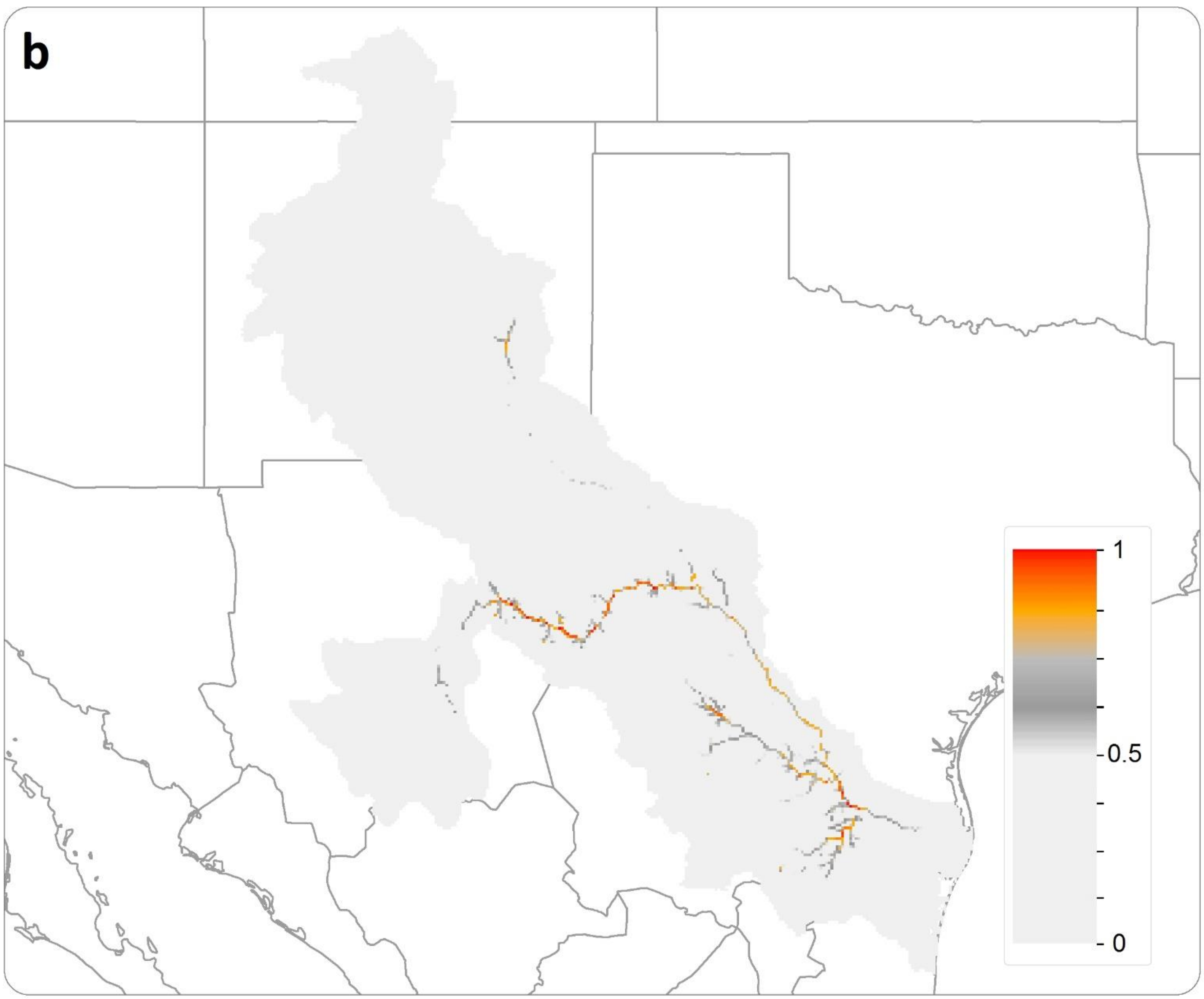
Notropis jemezanus

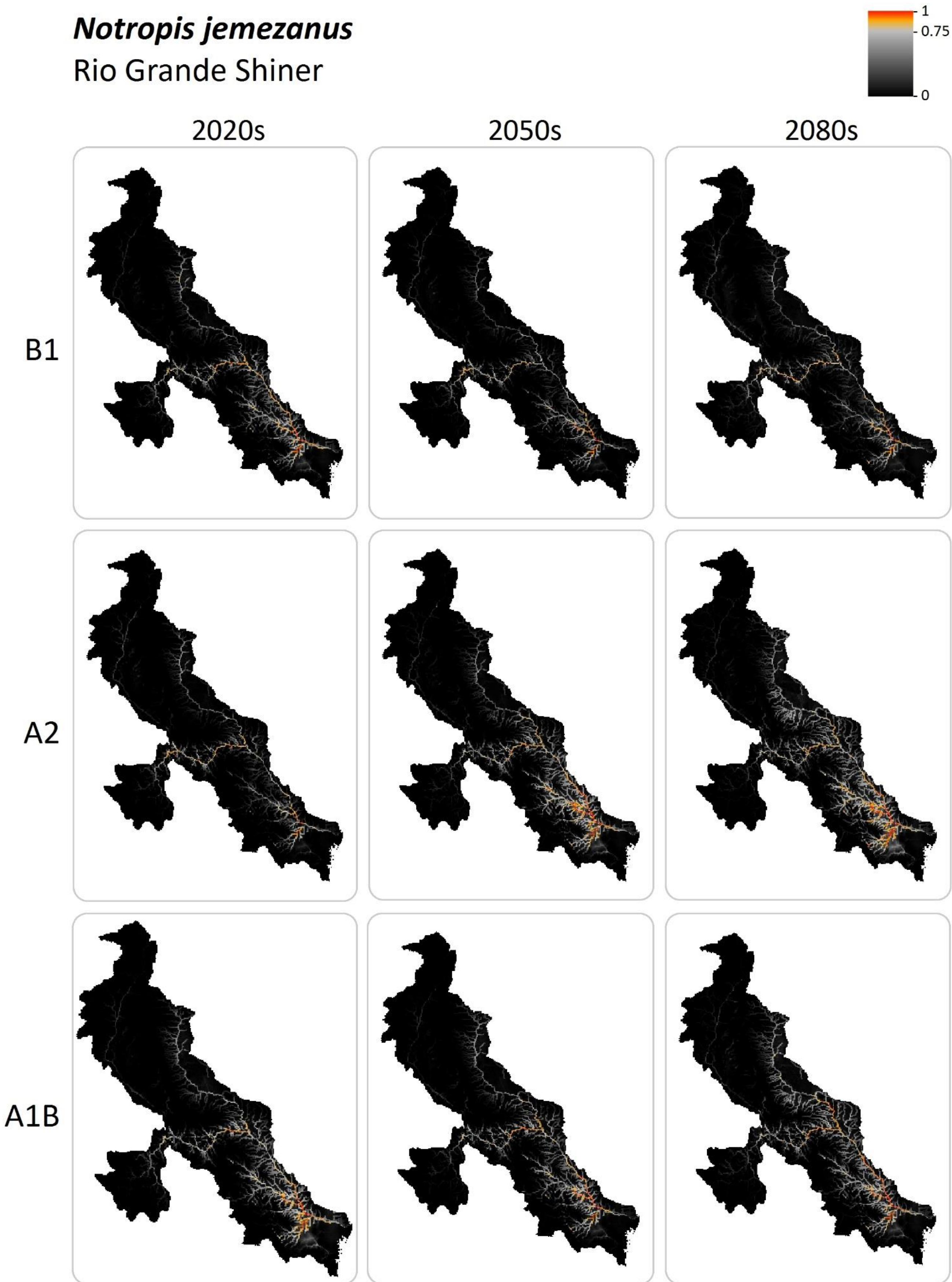
Rio Grande shiner





a. Occurrence records used in model
b. "Current" distribution model



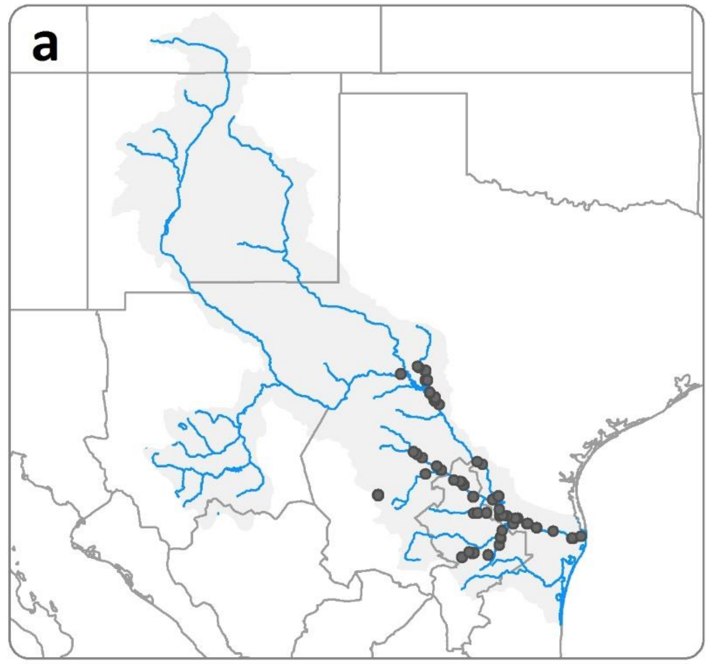


Notropis jemezanus
Rio Grande Shiner
1
0.75
0
2020s
2050s
2080s
B1
A2
A1B

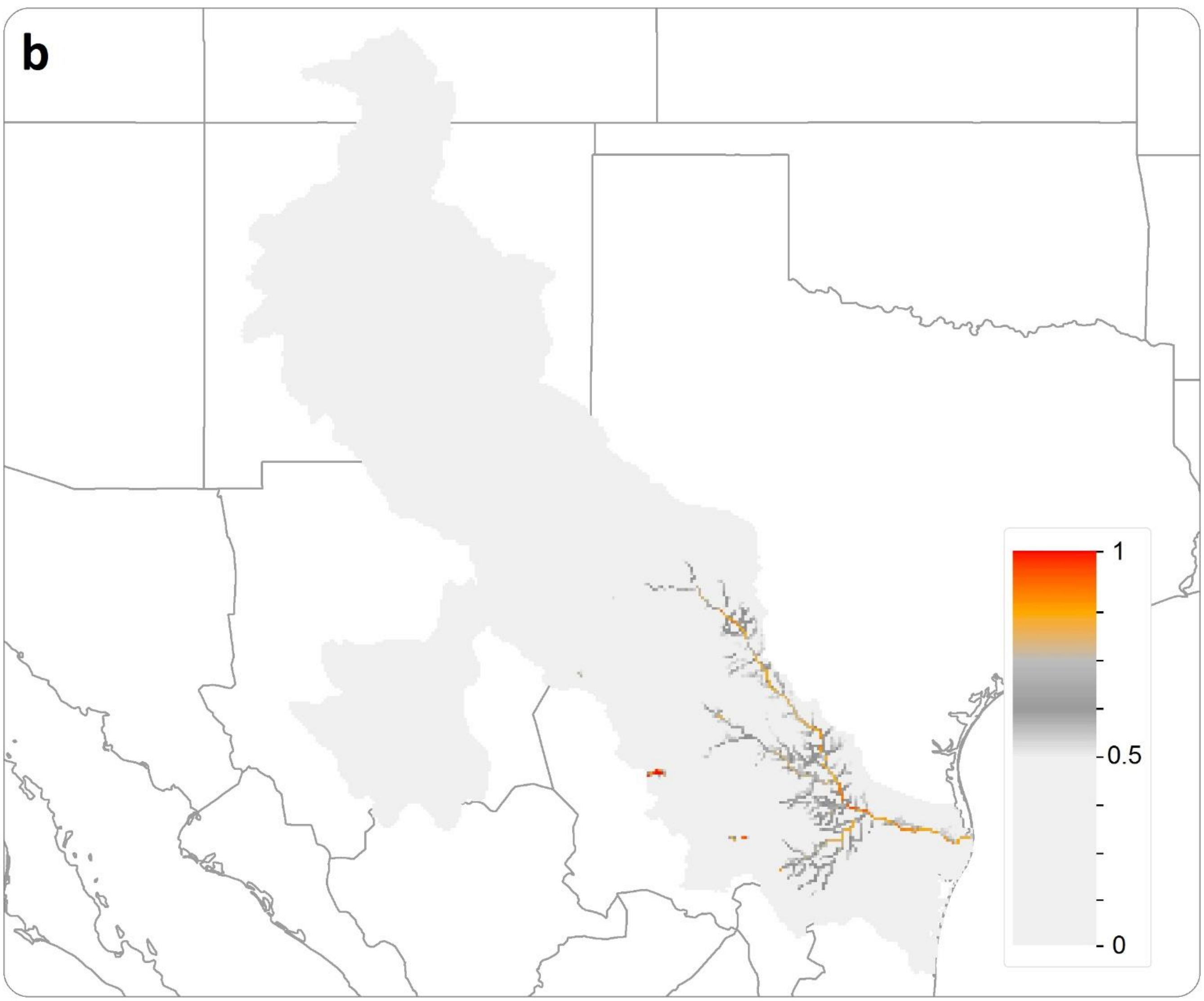
Oreochromis aureus

Blue tilapia

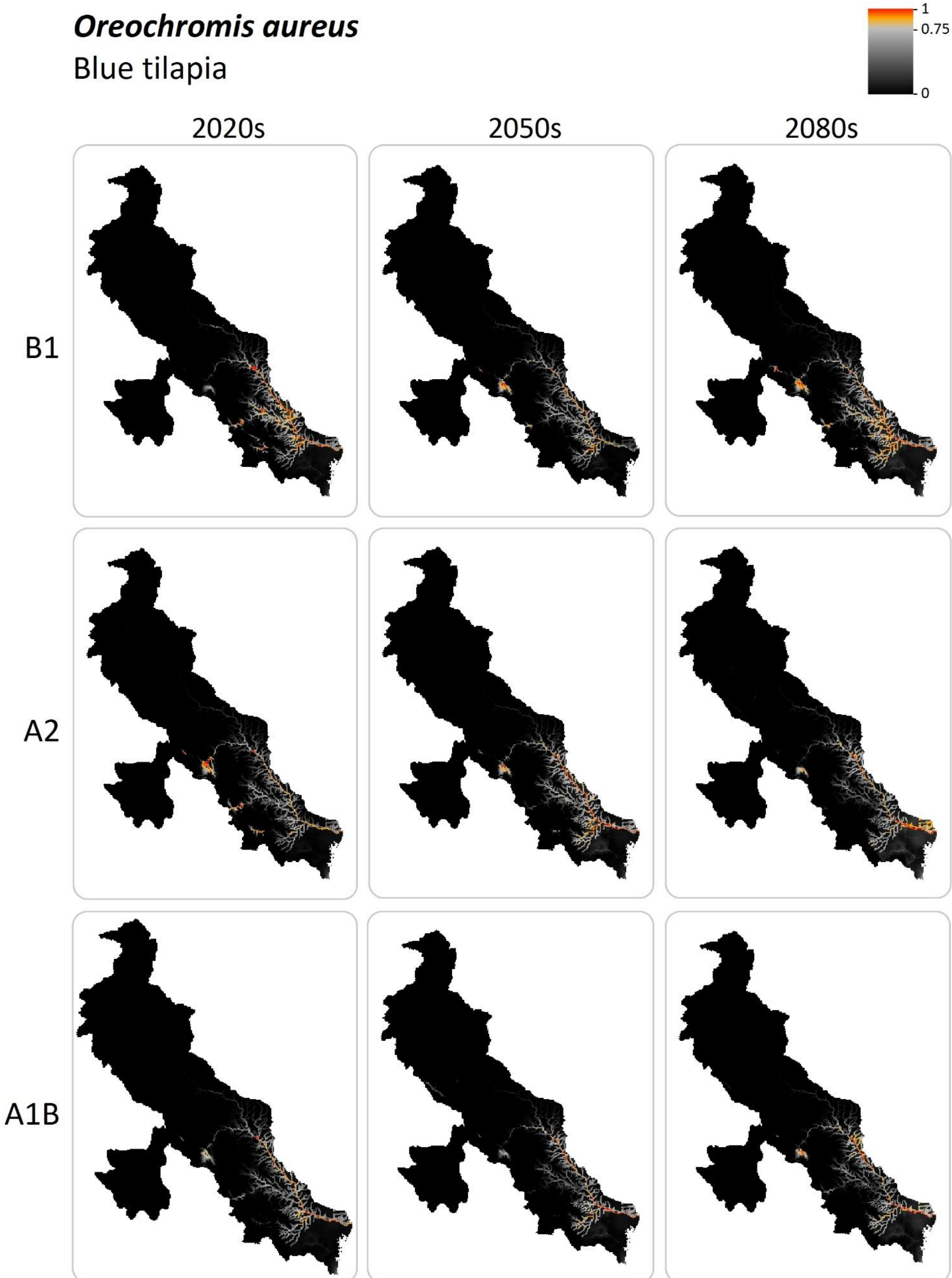

Picture by Chad Thomas



a. Occurrence records used in model
b. "Current" distribution model

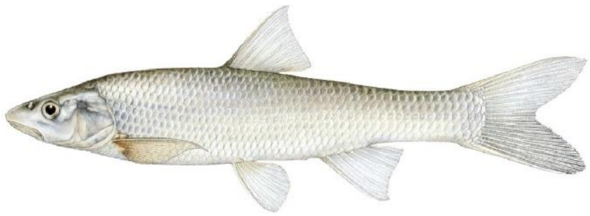


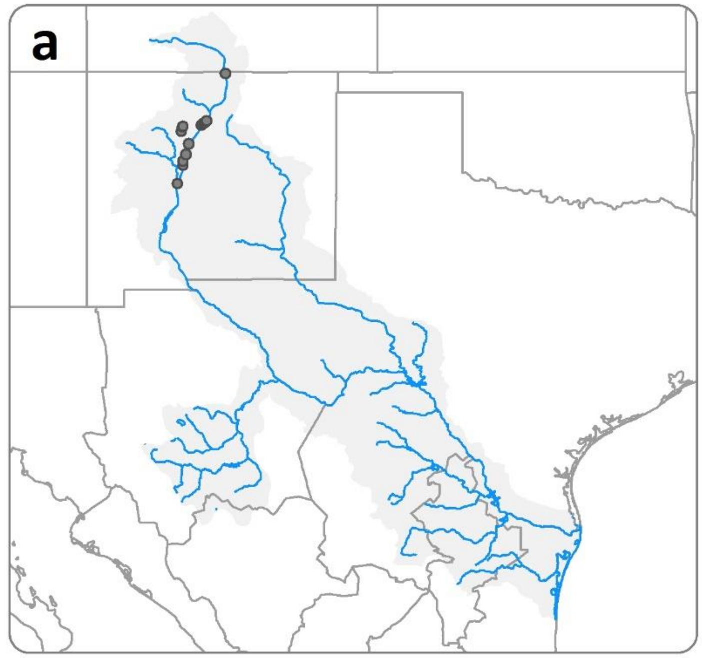
Oreochromis aureus
Blue tilapia



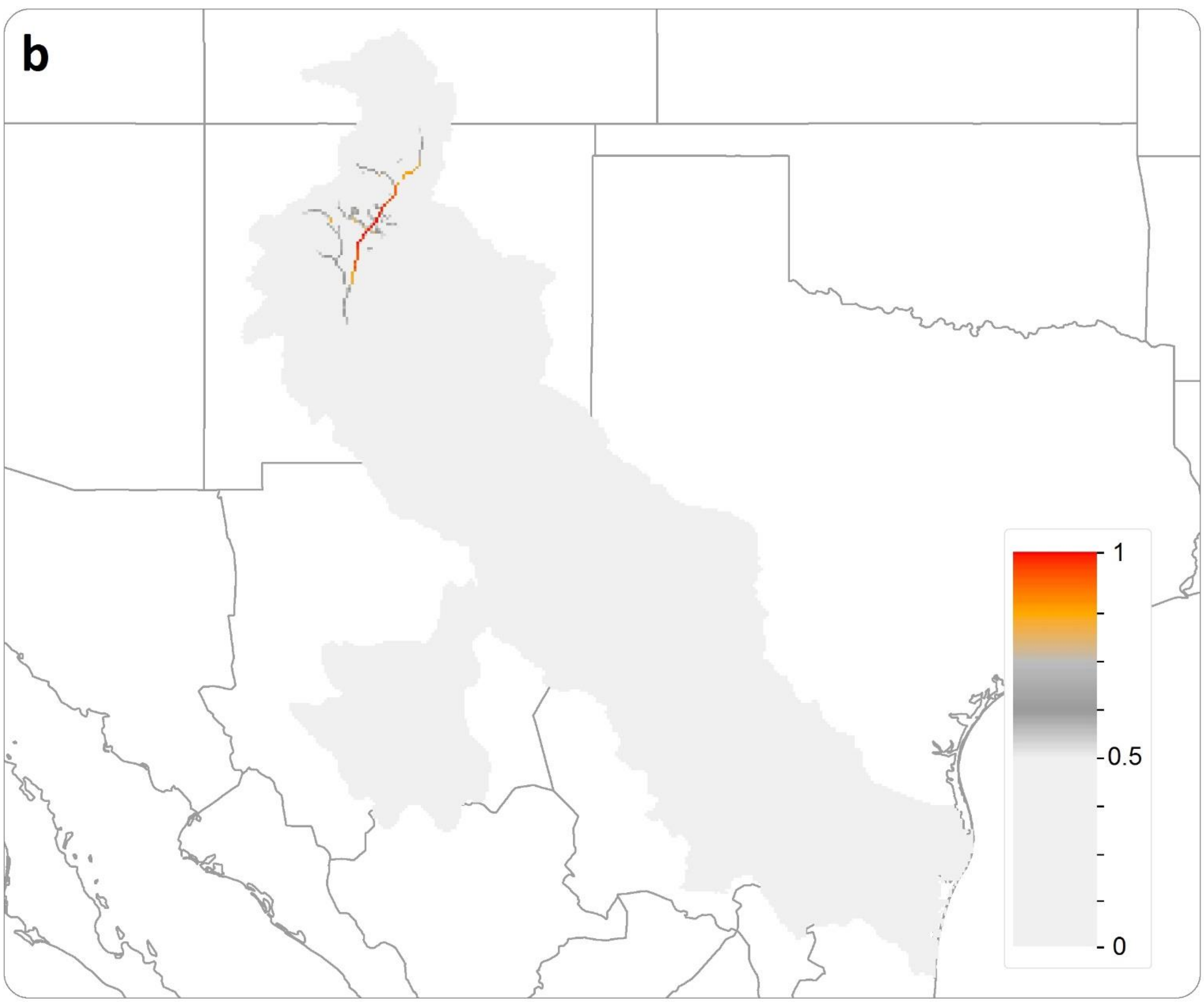
Platygobio gracilis

Flathead chub

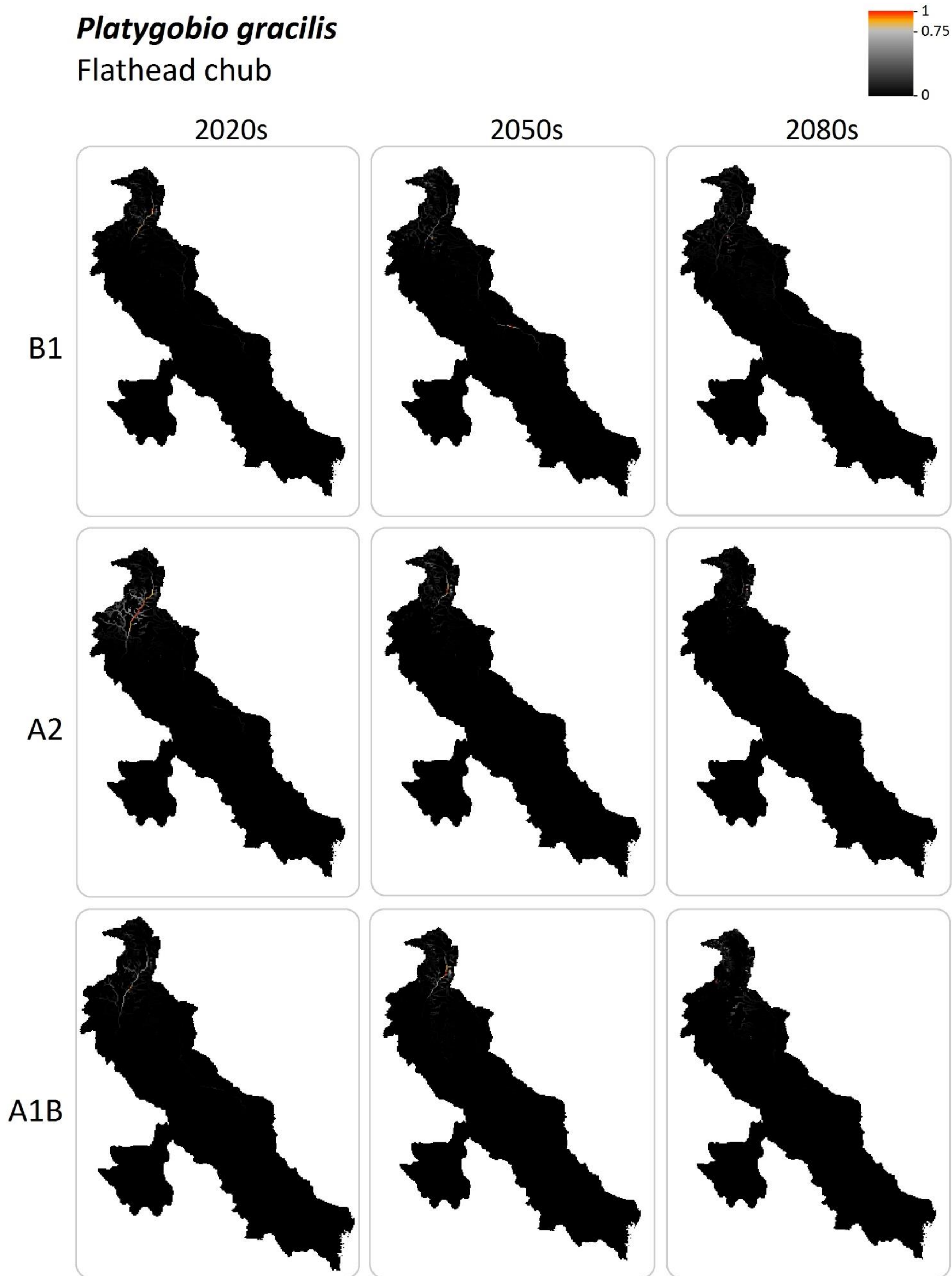




a. Occurrence records used in model
b. "Current" distribution model



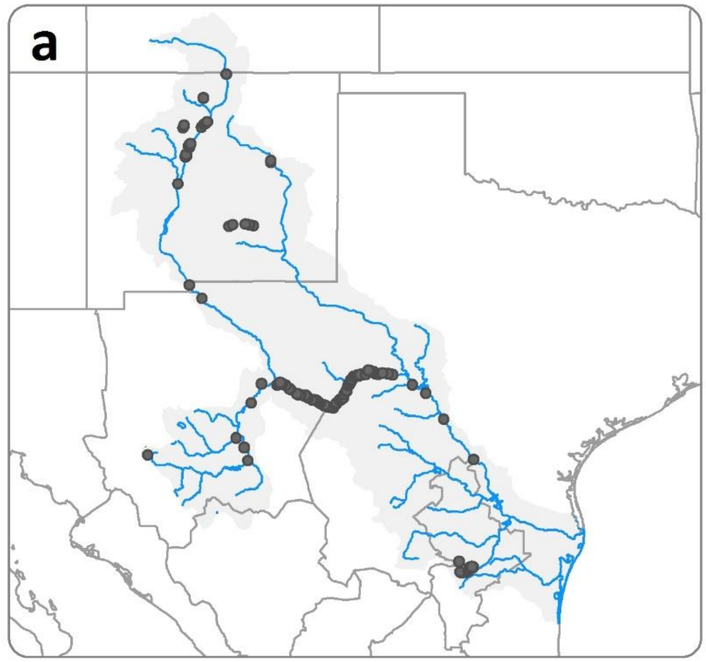
Platygobio gracilis
Flathead chub

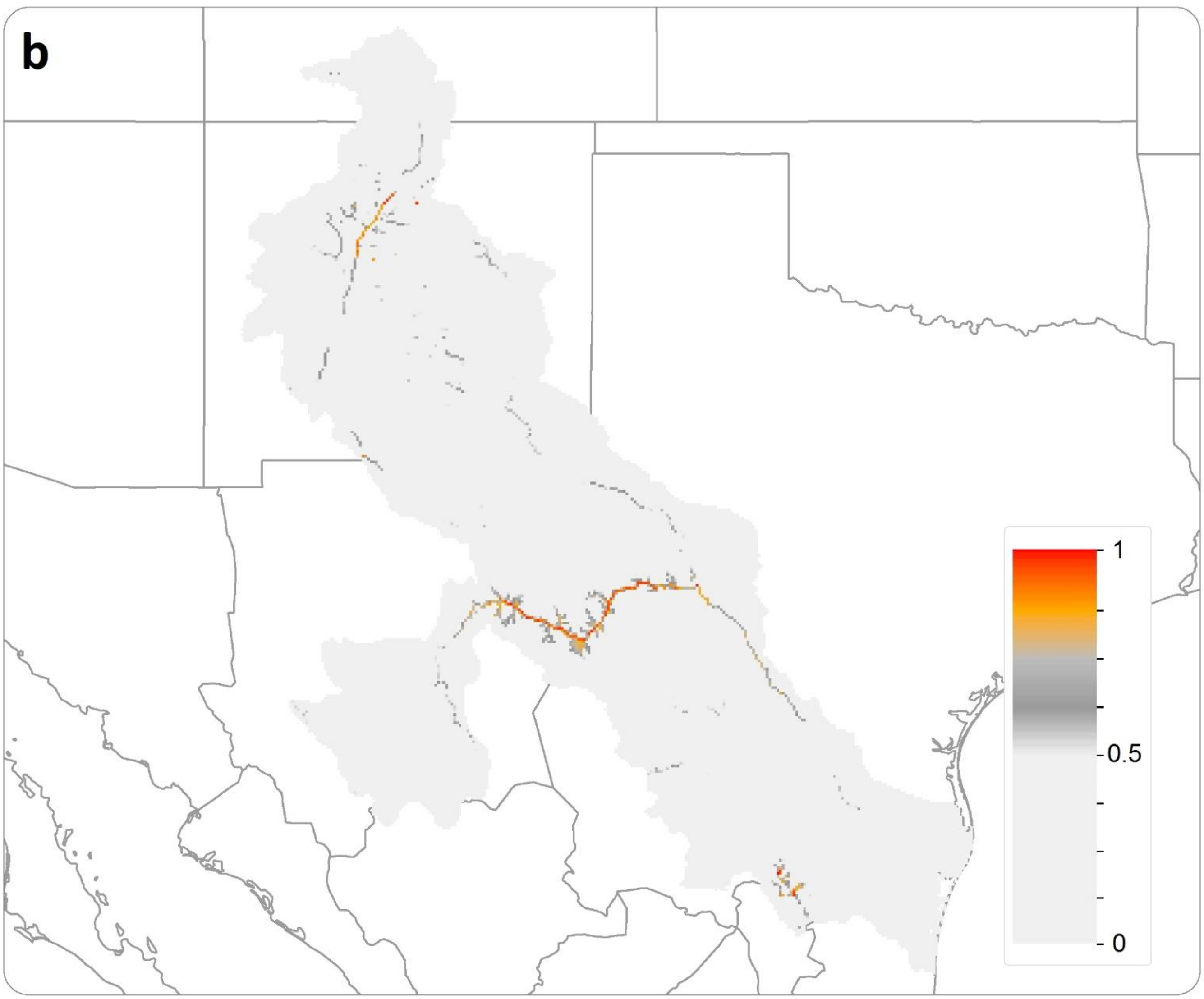


Rhinichthys cataractae

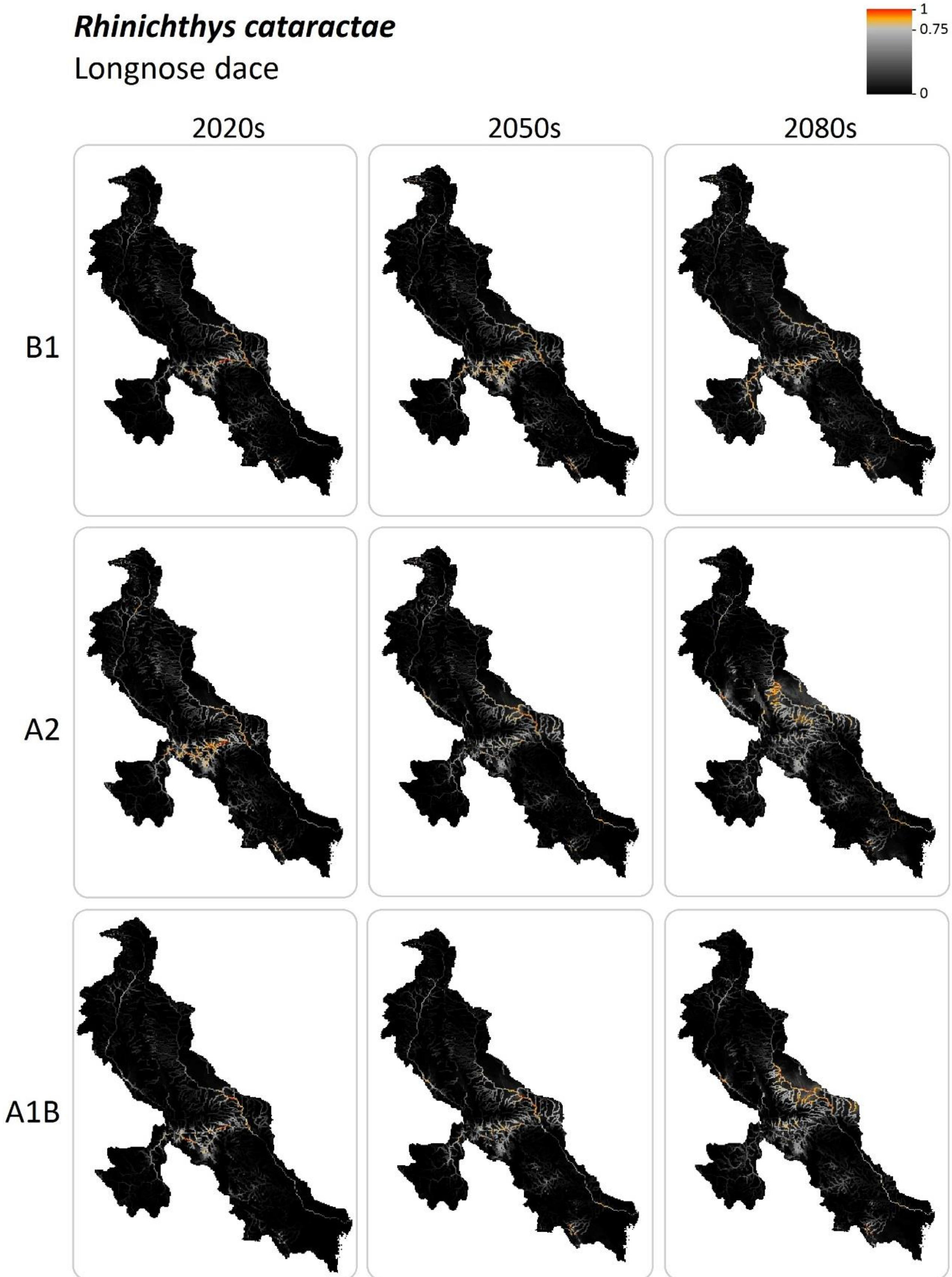
Longnose dace

a. Occurrence records used in model
b. "Current" distribution model





Rhinichthys cataractae
Longnose dace



10 SUPPLEMENTAL DATA

This report and the following supplemental data files will be permanently archived in the Digital Repository of the University of Texas Austin (http://repositories.lib.utexas.edu/). The archive contains this complete report and supplemental data files (total 1.18 GB in 58,819 files in 34 folders. The complete file structure is described as follows:

\data – Contains CSV (comma separated values) files: Data, Notes to data fields, Institution Codes, and Production and processing.

\SDMs&ClimateProjections\EnvironmentalVariables_forModelTraining – contains ASCII files for environmental variables used in training species distribution models. See section 2.2 for more details.

\SDMs&ClimateProjections\MaxentResults - contains Maxent summary model output for each species replicate and average over replicates. These summary results are for the 'current' species distribution model runs and provide i.) model run metadata, ii.) variable response curves, iii.) jackknife tests of variable importance, iv.) analyses if omission/commission (Receiver operating characteristic curves), v.) probability/suitability predictions of individual model replicates, and vi.) mean and standard deviation of replicate predictions.

\SDMs&ClimateProjections\ProjectionLayers_RioGrandeExtent – contains raw ASCII grid layers used to project current model results onto. Subdirectories within indicate emission scenario (A1B, A2, and B1) and time period (2020s, 2050s, 2080s). Final directories labels indicate exact model parameters selected for download from http://www.ccafs-climate.org/. For Example, "csiro_mk3_0_sres_a1b_2020s_bio_2_5min" indicates data from the CSIRO(mk3.0) climate model, with the emission scenario of SRES A1B, for the 2020s time period, at a 2.5 minute resolution.

\SDMs&ClimateProjections\RawModelAsciis – contains raw ASCII grid layer results from the current and future projected models. Future projected files are organized in the same file structure described above within \ProjectionLayers_Rio GrandeExtent