**S1 Text Table A** Predictor variables of fish species presence probability used in the species distribution models, including justification for inclusion and data source. The range and average values of under current climate conditions are given for study area.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Predictor** | **Unit** | **Range** | **Average** | **Justification** | **Source** |
| Strahler (STR) | - | 1 - 8 | 1.6 | Stream size is an important predictor of habitat suitability for fish (Buisson et al., 2008; Dußling et al., 2018); the European catchments and Rivers network system gives the Strahler order as a measure of stream size and ranges from small headwaters to large rivers. | European Environment Agency: Ecrins, version 1, Jun. 2012, Denmark |
| Slope (SL) | ‰ | 0 - 22.9 | 1.7 | Terrain slope was used as surrogate predictor of stream slope in this region before (Chucholl, 2017). | (Hijmans et al., 2005),  WorldClim.org; derived from elevation data |
| Mean Diurnal Range  (M*DR, bio2*)  Isothermality  (*ISO, bio3*)  Temperature seasonality  (*TS, bio4*)  mean temperature of warmest quarter (Su*T, bio10*)  mean temperature of coldest quarter  (*WiT, bio11)* | °C  -  °C  °C  °C | 5.6 - 10.1  27 – 35  53.9 – 67.8  6.5 - 18.9  -7.0 - 2.4 | 8.6  32.2  64.4  16.7  0.3 | Temperature is known to affect physiology and life history of fish and temperature variables have been widely used to predict presence probability of aquatic species (Poulos et al., 2012; Capinha et al., 2013; Chucholl, 2017; Schmidt et al., 2020). Data are for air temperature, which is assumed to correlate with water temperature. | Hijmans *et al.* (2005),  WorldClim.org |
| Precipitation of warmest quarter  (*SuP, bio18)*  Precipitation of coldest quarter  (*WiP, bio19*) | mm  mm | 170 – 480  97 – 477 | 272  170 | Precipitation during summer can be considered as surrogate predictor of the risk of drying up of fish habitats, whereas winter precipitation in the region can be a value for flooding. Both has been previously shown to affect presence probability in aquatic ecosystems (Poulos et al., 2012; Gallardo & Aldridge, 2013; Chucholl, 2017). | Hijmans *et al*. (2005),  WorldClim.org |

**S1 Text Table B** Thirteen different climate change data sets were used to generate future predictions for fish species. All data were obtained from the Worldclim.org database website.

|  |  |  |
| --- | --- | --- |
| Abbreviation |  | General circulation model |
| *AC* | ACCESS1-0 | Australian Community Climate and Earth System Simulator |
| *BC* | BCC-CSM1-1 | Beijing Climate Center Climate System Model |
| *CC* | CCSM4 | Community Climate System Model, version 4 |
| *CN* | CNRM-CM5 | Earth system model by the National Centre for Meteorological Research |
| *GF* | GFDL-CM3 | Geophysical Fluid Dynamics Laboratory Coupled Model |
| *GI* | GISS-E2-R | Goddard Institute for Space Studies, ModelE |
| *HA* | HadGEM2-ES | Hadley Centre Global Environment Model Version 2 |
| *IN* | INMCM4 | Institute for Numerical Mathematics Climate Model version 4 |
| *IP* | IPSL-CM5A-LR | Institute Pierre Simon Laplace Climate Model version 5 |
| *MI* | MIROC5 | Model for Interdisciplinary Research On Climate |
| *MP* | MPI-ESM-LR | Max Planck Institute Earth System Model |
| *MR* | MRI-CGCM3 | Meteorological Research Institute Coupled Global Climate Model Version 3 |
| *NO* | NorESM1-M | Norwegian Earth System Model |

**S1 Text Table C** Estimates of relative contributions of the environmental variables to the Maxent model for different fish species under current conditions in Baden-Württemberg.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | STR | SL | MDR | ISO | TS | SuT | WiT | SuP | WiP |
| S. trutta | 63 | 3 | 1 | 1 | 1 | 1 | 23 | 2 | 5 |
| T. thymallus | 36 | 2 | 5 | 2 | 2 | 1 | 30 | 20 | 2 |
| B. barbatula | 42 | 3 | 15 | 5 | 5 | 3 | 6 | 6 | 17 |
| P. fluviatilis | 43 | 17 | 5 | 4 | 10 | 7 | 9 | 4 | 2 |
| R. rutilus | 14 | 9 | 4 | 20 | 10 | 6 | 9 | 26 | 3 |
| S. glanis | 61 | 2 | 5 | 4 | 13 | 5 | 4 | 3 | 3 |

**S1 Text Table D** Elevation range of Maxent model for fish species under current and future conditions in Baden-Württemberg (average median and interquartile range, 25%-75%, 10th percentile cut off).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Species** | **elevation range [m]** | | | | |
|  | **Current** | **2050** | | **2070** | |
|  |  | ***RCP4.5*** | ***RCP8.5*** | ***RCP4.5*** | ***RCP8.5*** |
| S. trutta | 489  (383-627) | 653  (535-814) | 645  (521-817) | 668  (540-823) | 649  (498-792) |
| T. thymallus | 493  (392-590) | 503  (404-598) | 498  (378-603) | 517  (421-606) | 474  (394-559) |
| B. barbatula | 330  (224-443) | 373  (242-498) | 364  (240-494) | 360  (234-484) | 339  (221-466) |
| P. fluviatilis | 368  (209-509) | 384  (250-509) | 393  (257-527) | 400  (261-534) | 410  (267-553) |
| R. rutilus | 333  (218-470) | 340  (228-446) | 352  (240-461) | 365  (245-479) | 379  (252-507) |
| S. glanis | 277  (161-410) | 327  (207-436) | 326  (214-436) | 321  (213-442) | 337  (222-472) |

**S1 Text Table E** Analysis of Variance Model with Post Hoc Test (estimated marginal means/least square means) for elevation distribution of six different fish species in southwestern Germany under current and future climatic conditions. Significant differences to current distribution are highlighted in bold.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | year |  |  | **2050** | **2050** | **2070** | **2070** |
|  | *Sum Sq* | *F value* | *p* | ***RCP4.5*** | ***RCP8.5*** | ***RCP4.5*** | ***RCP8.5*** |
| S. trutta | 391873 | 28.66 | **<0.001** | **<0.001** | **<0.001** | **<0.001** | **<0.001** |
| T. thymallus | 15932 | 1.85 | 0.129 | 0.95 | 0.96 | 0.328 | 0.877 |
| B. barbatula | 22493 | 2.45 | 0.054 | 0.074 | 0.155 | 0.405 | 0.949 |
| P. fluviatilis | 16401 | 0.83 | 0.511 | 0.97 | 0.86 | 0.72 | 0.46 |
| R. rutilus | 18723 | 0.916 | 0.46 | 1 | 0.94 | 0.72 | 0.45 |
| S. glanis | 399994 | 1.73 | 0.153 | 0.45 | 0.38 | 0.32 | 0.19 |

**S1 Text Table F** Species distribution model parameters for fish species in Baden-Württemberg. Suitable range (median and interquartile range, 25%-75%, ‘equate entropy of thresholded and original distributions threshold’ cut off) is given for current and future climatic conditions for 13 different models (see Table B in S1 Text for details), two timespans and two different RCP pathways. The values correspond to percentage of total assessed area. Maxent AUC for training and test are given as mean ± SD. [Compare with Table 2 for 10th percentile cut off values for more conservative/restrict future estimations.]

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Suitable range** | | | | | | | | | | | | |
|  |  | **Current** | **2050** | | | | | | **2070** | | | | | |
|  | **AUC** |  | ***RCP4.5*** | | | ***RCP8.5*** | | | ***RCP4.5*** | | | ***RCP8.5*** | | |
| Species | Test |  | Stable | Loss | Gain | Stable | Loss | Gain | Stable | Loss | Gain | Stable | Loss | Gain |
| S. trutta | 0.62  (±0.03) | 95.3  (95.1-95.5) | 72.6  (61.2-81.4) | 22.7  (14.0-34.2) | 0.9  (0.9-1.1) | 57.9  (23.9-69.0) | 37.4  (26.3-71.4) | 1.0  (0.7-1.2) | 54.2  (28.8-74.4) | 41.2  (20.9-66.5) | 0.9  (0.1-1.6) | 30.7  (16.7-51.1) | 64.6  (44.2-78.6) | 1.0  (0.4-1.2) |
| T. thymallus | 0.88  (±0.04) | 15.3  (15.1-15.6) | 11.6  (9.9-13.5) | 3.5  (1.6-5.2) | 0.6  (0.3-1.1) | 10.5  (8.0-12.6) | 4.7  (2.6-7.1) | 0.6  (0.3-1.0) | 7.5  (5.6-11.5) | 7.6  (3.6-9.5) | 0.2  (0.1-1.6) | 7.1  (3.6-9.6) | 8.0  (5.5-11.5) | 0.2  (0.1-0.5) |
| B. barbatula | 0.71 (±0.03) | 76.8  (76.6-77.2) | 73.8  (70.7-76.5) | 3.0  (0.3-6.1) | 2.8  (1.6-5.3) | 69.6  (65.6-76.2) | 7.2  (0.6-11.2) | 2.2  (1.3-5.0) | 73.4  (64.0-76.3) | 3.5  (0.5-12.8) | 2.6  (0.9-4.5) | 64.4  (56.5-74.2) | 12.4  (2.7-20.4) | 0.7  (0.3-4.5) |
| P. fluviatilis | 0.83  (±0.04) | 58.3  (57.7-58.7) | 58.1  (54.9-58.1) | 0.2  (0.1-3.3) | 21.9  (10.5-30.8) | 57.8  (54.6-58.2) | 0.4  (0.0-3.7) | 28.9  (12.1-35.9) | 58.1  (50.5-58.2) | 0.1  (0.0-7.7) | 30.2  (9.0-35.2) | 58.2  (55.0-58.3) | 0.1  (0.0-3.3) | 34.2  (18.3-39.1) |
| R. rutilus | 0.79  (±0.04) | 63.9  (63.5-64.3) | 59.2  (52.9-59.8) | 4.7  (4.1-11.0) | 11.6  (4.3-14.7) | 59.8  (46.5-62.7) | 4.1  (1.2-17.4) | 15.9  (0.9-27.1) | 61.0  (51.2-63.9) | 3.0  (0.1-12.7) | 19.7  (2.9-30.4) | 62.0  (49.9-64.0) | 2.0  (0.0-14.1) | 22.1  (0.9-34.9) |
| S. glanis | 0.83 (±0.04) | 51.1  (50.7-51.9) | 51.1  (49.7-51.1) | 0.1  (0.1-1.4) | 23.6  (2.7-26.9) | 51.1  (29.4-51.2) | 0.1  (0.0-21.8) | 24.7  (0.1-31.6) | 51.1  (37.1-51.2) | 0.1  (0.0-14.1) | 20.6  0.1-31.5) | 51.2  (23.3-51.2) | 0.0  (0.0-27.9) | 32.6  (0.2-37.3) |



**S1 Text Fig A:** Triangle plot of theoretical species distribution changes between current conditions and predicted future conditions. X axis (“new habitat”) illustrates a gain of new suitable habitat, y axis (“old habitat”) represents percentage of area remaining suitable for the species whereas z-axis (“lost habitat”) highlights a reduction in suitable habitat. The population “remains” in its original space, when more than 60 % of habitat stays suitable. If the portion of lost habitat is greater than the portion gained the overall population will “decrease” (loss>gain, right sector), if vice versa the population will “increase” (gain>loss, left sector). If the proportions of loss and gain are almost equal, a species migration will occur (“migrate”, lower middle sector).



***S1 Text Fig B****: Elevation range of Maxent models for fish species (A: trout, B: grayling, C: stone loach, D: perch, E: roach, F: catfish) under current (solid black line) and future conditions in Baden-Württemberg (light blue 2050, RCP 4.5; blue: 2050, RCP 8.5; orange: 2070 4.5, red: 2070 RCP8.5). Gray bars represent the elevation range of the study area in southern Germany.*



**S1 Text Fig C:** Species occurrence and distribution map of brown trout (Salmo trutta) under current and future climatic conditions in the study area of Baden-Württemberg. Species occurrence (blue points) results in a Maxent binary map under current conditions (10P cut off, blue area), future graphs display gradient maps for 13 different climatic models for near (2050) and far future (2070) under two different RCP scenarios. White area contains no surface water bodies; grey indicates unsuitable habitat conditions. The more models predict suitability, the darker the colors. (Base layer of the map is from https://udo.lubw.baden-wuerttemberg.de/public/).



**S1 Text Fig D:** Species occurrence and distribution map of grayling (Thymallus thymallus) under current and future climatic conditions in the study area of Baden-Württemberg. Species occurrence (blue points) results in a Maxent binary map under current conditions (10P cut off, blue area), future graphs display gradient maps for 13 different climatic models for near (2050) and far future (2070) under two different RCP scenarios. White area contains no surface water bodies; grey indicates unsuitable habitat conditions. The more models predict suitability, the darker the colors. (Base layer of the map is from https://udo.lubw.baden-wuerttemberg.de/public/).



**S1 Text Fig E**: Species occurrence and distribution map of stone loach (Barbatula barbatula) under current and future climatic conditions in the study area of Baden-Württemberg. Species occurrence (blue points) results in a Maxent binary map under current conditions (10P cut off, blue area), future graphs display gradient maps for 13 different climatic models for near (2050) and far future (2070) under two different RCP scenarios. White area contains no surface water bodies; grey indicates unsuitable habitat conditions. The more models predict suitability, the darker the colors. (Base layer of the map is from https://udo.lubw.baden-wuerttemberg.de/public/).



**S1 Text Fig F:** Species occurrence and distribution map of perch (Perca fluviatilis) under current and future climatic conditions in the study area of Baden-Württemberg. Species occurrence (blue points) results in a Maxent binary map under current conditions (10P cut off, blue area), future graphs display gradient maps for 13 different climatic models for near (2050) and far future (2070) under two different RCP scenarios. White area contains no surface water bodies; grey indicates unsuitable habitat conditions. The more models predict suitability, the darker the colors. (Base layer of the map is from https://udo.lubw.baden-wuerttemberg.de/public/).



**S1 Text Fig G:** Species occurrence and distribution map of roach (Rutilus rutilus) under current and future climatic conditions in the study area of Baden-Württemberg. Species occurrence (blue points) results in a Maxent binary map under current conditions (10P cut off, blue area), future graphs display gradient maps for 13 different climatic models for near (2050) and far future (2070) under two different RCP scenarios. White area contains no surface water bodies; grey indicates unsuitable habitat conditions. The more models predict suitability, the darker the colors. (Base layer of the map is from https://udo.lubw.baden-wuerttemberg.de/public/).



**S1 Text Fig H**: Species occurrence and distribution map of catfish (Silurus glanis) under current and future climatic conditions in the study area of Baden-Württemberg. Species occurrence (blue points) results in a Maxent binary map under current conditions (10P cut off, blue area), future graphs display gradient maps for 13 different climatic models (10P cut off) for near (2050) and far future (2070) under two different RCP scenarios. White area contains no surface water bodies; grey indicates unsuitable habitat conditions. The more models predict suitability, the darker the colors. (Base layer of the map is from https://udo.lubw.baden-wuerttemberg.de/public/).

Environmental data used in this manuscript (in Figs 1,2, and C-H in S1 Text) are from the “Umweltinformationssystem” (UIS) of the “LUBW Landesanstalt für Umwelt Baden-Württemberg”; which can be found here:

<https://udo.lubw.baden-wuerttemberg.de/public/>.

***background elevation layer***:

<https://rips-dienste.lubw.baden-wuerttemberg.de/rips/ripsservices/apps/geodatenexport/udo/download.ashx?id=12>

Geobasisdaten/Schummerungskarte/Schummerungskarte (ausDHM30)

***mountainous regions***:

<https://rips-dienste.lubw.baden-wuerttemberg.de/rips/ripsservices/apps/geodatenexport/udo/download.ashx?id=7>

Natur und Landschaft/Naturräume/Naturräumliche Gliederung

***river network system*** (drainage areas and surface water bodies):

<https://rips-dienste.lubw.baden-wuerttemberg.de/rips/ripsservices/apps/geodatenexport/udo/download.ashx?id=417>

Wasser/Amtliches Gewässernetz/Gewässereinzugsgebiete/Basiseinzugsgebiet

<https://rips-dienste.lubw.baden-wuerttemberg.de/rips/ripsservices/apps/geodatenexport/udo/download.ashx?id=590>

Wasser/Oberflächengewässer/Fließgewässer/Fischgemeinschaften