PROJECTED EFFECTS OF FUTURE CLIMATES ON FRESHWATER FISHES OF CALIFORNIA

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DISCLAIMER

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ABSTRACT

A methodology is presented that allows systematic evaluation of climate change impacts on freshwater fishes in California (121 native fish taxa and 43 aliens). The methodology uses expert opinions of the authors and literature reviews of status and biology of the fishes to score both status of each species ("baseline vulnerability") and likely impact of climate change ("climate change vulnerability"). Baseline and climate change vulnerability scores were highly correlated with one another and were consistent among different scorers. Native species were found to have both greater baseline and greater climate change vulnerability than alien species. Fifty percent of natives had critical or high baseline vulnerability versus none for aliens; 83 percent had critical or high climate change vulnerability versus 19 percent for aliens. Fishes with high baseline vulnerability were also likely to have highest vulnerability to climate change. These results show that predicted climate change effects on fresh water environments will dramatically change the fish fauna at all scales and at all elevations. The research team concluded that most native fishes will suffer population declines and become more restricted in their distributions; some will likely be driven to extinction, if present trends continue. Fishes requiring cold water (<22°C [72°F]) are particularly likely to go extinct. In contrast, most alien fishes will thrive, with many species likely to increase in abundance and range. However, even many aliens will ultimately be negatively affected through loss of aquatic habitats during severe droughts and stressful conditions in most waterways during summer months. On a regional scale (e.g., San Francisco Bay tributaries), vulnerability patterns follow statewide patterns and indicate the need for conservation strategies adapted to local conditions. Studies of three streams with long-term data on fish abundance indicate that native and alien species respond in different ways to variability in stream flow, which is likely to become more variable with climate change.

Keywords: endangered species, alien, invasive species, native fishes, global warming

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Section 1: Introduction

California has a highly distinctive freshwater fish fauna. Most (63 percent) of the 129 native taxa are endemic to the state, while an additional 19 percent are shared with just one neighboring state (Moyle 2002; Moyle et al. 2011). The state has also been invaded by ca. 50 alien species of fish (Moyle 2002). Unfortunately, the native freshwater fishes are in decline because of intense human use of the state's water and land, a pattern typical for regions with arid or Mediterranean climates (Carlisle et al. 2011). Moyle et al. (2011) found that about 80 percent of the native fishes are extinct, threatened with extinction in the near future, or vulnerable to extinction if present trends continue. Although about one fish per year has been listed under state and federal Endangered Species Acts for the past 20 years, there are a number of other fishes that merit listing (Moyle et al. 2011). Future climate change will clearly accelerate the decline of native fish species, leading to more extinctions.

Moyle et al. (2012a) review the general effects of climate change on the fishes of California, focusing on the San Francisco Bay region, while Quiñones and Moyle (2012) describe impacts to Klamath River fishes. While these reviews (and others) provide the basic background on how various climate change scenarios will likely affect fish and aquatic ecosystems, they do not include predictions for individual species that can be used for conservation planning at various scales, from local to statewide. The purpose of this study, therefore, is to present a methodology for evaluating effects of climate change on freshwater fish species, together with vulnerability assessments for 164 species in California. Our study has the following components:

1. A description of the methodology we developed to assess vulnerability to climate change of the inland fishes of California.
2. A test of the methodology using Klamath Basin fishes, because we had just completed a review of climate changes effects on the basin (Quiñones and Moyle 2012).
3. An analysis of vulnerability of 121 taxa of native fishes and 43 species of alien (non-native) fishes to climate change (Appendix A). This is virtually the entire extant inland fish fauna of California.
4. A comparison of vulnerability to climate change of native and non-native species in diverse fish families, to look for taxonomic patterns of vulnerability.
5. An analysis of the vulnerability of fishes of the San Francisco Bay Area to climate change, as an example of a regional analysis, chosen because of the background study of Leidy et al. (2011).
6. An examination of long-term changes to the fish fauna of three streams for which long-term data sets exist: Martis Creek (Kiernan and Moyle 2012), Putah Creek (Kiernan et al. 2012), and Sagehen Creek.

Section 2: Methods

2.1 Metrics

The methods used here were derived from the methodological framework that Galbraith and Price (2009) developed to assess vulnerability of threatened and endangered vertebrate species to climate change. We adopted their basic methodology because it was repeatable and transparent to users of the information generated. However, we modified their metrics to make them better suited for a broad suite freshwater fishes, not just listed species.

To assess vulnerability, we developed 20 metrics (based on those of Galbraith and Price 2009), divided into two 10-metric modules that could be scored for each species.[1] Module 1 (Appendix Figure B-1) scored the baseline vulnerability of each species to any major change in their environment; species already in decline or with small populations would receive low scores on the assumption that such species would be more vulnerable to additional stress posed by climate change. Module 2 (Appendix Figure B-2) then scored characteristics of the species that would make it more (or less) vulnerable to climate change. The metrics varied in their maximum scores from 3 to 6 points, depending on their perceived importance (by both us and Galbraith and Price 2009) in contributing to climate change vulnerability. Scores in Module 1 (baseline vulnerability: V_b) potentially ranged from 10 to 42, while scores in Module 2 (climate change vulnerability: V_c) potentially ranged from 10 to 35. Justification for each score was provided on a separate form (Appendix Figure B-3). Each individual metric in each module was scored based on information in species accounts in Moyle (2002), Moyle et al. (2008), and Moyle et al. (2012b), with additional references consulted as needed. The three aforementioned reports provide access to the literature on each species, as well as assessments of status and population trends. As a check on consistency of the methodology, a group of species from the Klamath basin was rated independently by the four coauthors. The Klamath Basin was chosen because it is largely dominated by native fishes and had recently been intensely studied by Quiñones and Moyle (2012).

In total, baseline and climate change vulnerability scores were developed for 121 native taxa and 43 alien (non-native) species (Appendix A). Seven species now extinct in California were excluded from the analyses, as were flannelmouth suckers (*Catostomus latipinnis*) and Central Valley steelhead trout (*Oncorhynchus mykiss*). The latter two taxa could not be scored because of conflicting information about current status. In addition,

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[1] Includes species, subspecies, evolutionarily significant units (ESU), and distinct population segments (DPS). These categories are all considered "species" under the federal Endangered Species Act of 1973. See Moyle et al. (2008) for definitions.

seven species of alien fishes were excluded due to taxonomic uncertainties (*Oreochromis spp.*), recent eradication (*Esox lucius*), or uncertain status.[2]

Two methods for evaluating certainty/uncertainty were incorporated into the scoring system. First, each of the metrics was assigned a *best estimate* score and an *alternate* score. The best estimate is derived from empirical evidence or professional judgment of the most likely case. Alternate scores represent less likely, but not unreasonable, estimates for a given parameter. Where there was reasonable certainty surrounding the best estimate score, an alternate score was not assigned. Contrasting the best estimate total score in each module (i.e., sum of the 10 metrics) with the highest and lowest score totals (derived from either the best or alternate estimates) provided an indication of the range of status scores likely for the taxon. Second, each best estimate score in this module was assigned a numeric certainty evaluation of high (score = 3), medium (score = 2), or low (score = 1). These ordinal rankings were based on expert judgment concerning the quantity and quality of the information that was the basis of the best estimate scores. Generally, a certainty score of 3 meant the judgment was strongly supported by published reports, especially in the peer-reviewed literature. A score of 2 indicated less support in the literature but strong support from professional judgment from authors most familiar with the species. A score of 1 indicated limited support in the literature so professional judgment of one or more of the authors was relied upon more heavily than for other species.

2.1.1. Module 1: Baseline Vulnerability Metrics

1. **Current population size (in the last 10 years)**. Taxa with small populations are likely to be less resilient, and therefore more vulnerable to extinction, than those with larger populations. Because exact numbers for population size were generally lacking, likely population size at the time of scoring was estimated as belonging to one of six categories:[3] (1) < 100 , (2) 100–500, (3) 500–1,000, (4) 1,000–10,000, (5) 10,000–50,000, or (6) >50,000. The number refers only to adult and sub-adult fish that are likely to contribute to the breeding population or potential breeding population. In cases where artificial propagation programs exist, as is the case for many salmonid species, population sizes are based on best estimates of the mean annual number of *naturally* spawning fish in California waters over the previous 10-year period. If many of these fish are of hatchery origin, it is noted in the justification section.

2. **Long-term population trend.** Taxa with declining populations are likely to be more vulnerable to extinction than those with stable or increasing populations.

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[2] Scientific names of other species mentioned in this paper are given in Appendix A.

[3] The overlap in numbers in this metric and others reflects that the estimates are not precise, as might be assumed if numbers such as 100–499 are used, rather than 100–500.

Assessment of long-term population trends were not restricted to any discrete time period (e.g., last 50 years) in order to capture important causes of decline that occurred more than 50 years ago (e.g., construction of major dams) and to permit inferences to be made from disparate data sources (e.g., commercial fisheries, quantitative escapement estimates, and other historical accounts). The categories are: (1) >80 percent reduction, (2) > 50 percent reduction, (3) >20 percent reduction, (4) apparently stable, or (5) increasing.

3. **Current population trend (in the last 10 years).** This metric is based on the 10-year period ending at the time of evaluation. The metric has four categories: (1) rapid decline, (2) slow decline, (3) apparently stable, or (4) increasing. The assumption behind this metric is that the more rapid the current rate of population decline, the more likely a taxon is to go extinct, with or without climate change. Short-term trends are typically harder to detect than long-term trends because of population variability (e.g., see Kiernan and Moyle 2012), so our rating depended more on professional judgment than for #2.

4. **Long-term range trend**. Taxa that have suffered range (i.e., extent of distribution) contractions in the past are more likely to be vulnerable to extinction than those with stable or expanding ranges. Past contractions in their range is evidence that they are already under stress. The assessment of range trend is not restricted to any discrete time period (e.g., last 50 years) to permit the inclusion of all relevant data sources. Additionally, we consider range fragmentation as part of this metric and assume that fragmentation generally increases extinction risk for freshwater fishes. Thus, a taxon that occupies much of its historic range but persists only in isolated population fragments would receive a lower score than a taxon whose range is not fragmented. The categories are: (1) >80 percent reduction, (2) >50 percent reduction, (3) >20 percent reduction, (4) apparently stable, or (5) increasing.

5. **Current range trend**. The current rate of range change, as discussed in #4 (above), is based where possible on empirical data or on best estimates for the previous 10 years. The categories are: (1) rapid decline, (2) slow decline, (3) apparently stable, or (4) increasing. There is typically some uncertainty among these scores because most species are not monitored on an annual basis, but documentation in Moyle et al. (2008, 2012b) indicates significant range declines over the past 10–20 years for many species. This determination, however, often relied on professional judgment of the author(s) or colleagues who know the species well.

6. **Current vulnerability to stressors other than climate change.** Many fish taxa are either vulnerable to, or affected by, multiple stressors such as water diversion, pollution, or harvest. In order to rate the simultaneous effects of multiple stressors on each species, 13 stressor categories were evaluated in a stressor narrative form for each species (Figure 3). The nature of each of the 13 categories of stressors is explained in Moyle et al. (2011). For each species, stressors were rated according to

their likely negative impact on the species, as critical, high, moderate, low, or no effect (Appendix Figure B-4). The combined ratings of current vulnerability of fish taxa to multiple stressors other than climate change were scored as: (1) highly vulnerable, (2) vulnerable, or (3) having low or no vulnerability.

7. **Future vulnerability to stressors other than climate change.** Some fish taxa may be more vulnerable to natural stressors, such as disease or invasive species, than are others. A taxon's vulnerability to such events could affect its ability to persist. The future vulnerability of a taxon to stressors other than climate change has three categories: (1) highly vulnerable, (2) vulnerable, or (3) having low or no vulnerability.

8. **Life span and reproductive plasticity.** Short-lived fish taxa that must spawn annually may be more vulnerable to stochastic events and demographic failures than long-lived taxa with multiple life history strategies. This metric assumes that longer life span and reproductive plasticity improve the probability of a taxon's persistence through stressful periods (e.g., extended drought). Therefore, taxa are scored as: (1) must spawn annually, typical life span < 2 years, (2) lifespan 2–5 years; single life-history, (3) lifespan 4–10 years, usually with multiple life-histories, or (4) long-lived, usually mobile taxa.

9. **Vulnerability to stochastic events**. Some taxa, because of habitat preferences, small population sizes, or limited ranges, may be more at risk from stochastic events, whether natural or anthropogenic, than others. *Stochastic events* refers to large-scale physical or chemical events that disrupt an organism's life cycle or alter habitats, such as a massive flood event, a toxic contaminant spill into a river, or a large landslide. Taxa are scored as: (1) highly vulnerable, (2) vulnerable, or (3) having low or no vulnerability to major stochastic events.

10. **Current dependence on human intervention.** Increasingly, the fate each fish species depends on societal values or policy objectives (either of which may change through time). Thus taxa that are heavily dependent on human intervention or management, or on specific policies (e.g., hatcheries, water management, artificial barriers) for their continuing survival are likely to be more vulnerable to extinction than those that depend less, or not at all, on such interventions. A high level of human intervention indicates that a species is already in serious decline. In addition, human intervention, such as captive breeding, may actually select for traits that reduce survival in the wild. Current dependence on human intervention is scored as:

    (1) Highly dependent: a captive broodstock program or similar continuous active effort is required to prevent extinction, or persistence requires continuous active management.

(2) Dependent: population persistence requires annual monitoring and intervention when needed (e.g., management of barriers, special flows, removal of alien species, establishment of refuge populations).

(3) Somewhat dependent: population persistence requires periodic intervention or habitat improvements (e.g., gravel augmentation or habitat restoration). This category may also include taxa which indirectly benefit from interventions aimed at other species (e.g., lamprey that benefit from various salmonid management actions).

(4) Not dependent: populations require no intervention to persist.

The individual scores for each metric are then combined in Module 1 for a score for each species. While the individual scores fall into a continuum of baseline vulnerability, we have divided the scores into categories following Galbraith and Price (2009):

- **Critically vulnerable (score <18)** – Species that are at imminent risk of extinction).
- **Highly vulnerable (score = 18–25)** – Species that are approaching extinction and are likely to be re-categorized as critically vulnerable if their populations or ranges are diminished further.
- **Less vulnerable (score = 26–33)** – Widespread species that are declining or stable but have large ranges, so have low risk of extinction.
- **Least vulnerable (score 34–42)** – Species that have comparatively large and stable (or increasing) populations or ranges.

2.1.2. Module 2: Climate Change Vulnerability Metrics

1. **Physiological/behavioral tolerance to temperature increase**. Stream water temperature is often closely linked to air temperature, and significant warming trends have already been documented in aquatic ecosystems for which long-term temperature data are available (Barnett et al. 2008; Kaushal et al. 2010). Fish taxa that require cold water, such as sculpins (Cottidae) and trout (Salmonidae), will be most likely be adversely affected by increased water temperatures leading to reduced ranges. At the other end of the tolerance spectrum, fish taxa that are physiologically or behaviorally tolerant to increased temperatures and/or lowered dissolved oxygen concentrations (e.g., alien cyprinids or ictalurids) may increase in abundance or range. Evaluations of thermal tolerances for each taxon are mostly based on experimental evidence or robust observational data. When such data are unavailable, rankings are based on inferences from closely related taxa. A taxon's tolerance to increasing water temperatures in the ranges predicted by climate change models is categorized as: (1) very low, (2) low, (3) moderate, or (4) high. A taxon rated "4" is likely to benefit from future change.

2. **Physiological and behavioral tolerance to precipitation change.** Climate change models generally predict changes in the amount and timing of precipitation throughout California. Perhaps most important, the state is expected to experience advancement in the timing of precipitation events and increase in the ratio of rain to snow (Knowles and Cayan 2002; Miller et al. 2003). This will result in more high flow events during winter, increased variability in flows, diminished spring snowmelt pulses, and protracted periods of low (base) flows. Such changes in precipitation and flow regimes will likely alter seasonal availability of spawning and rearing habitat for some native fish taxa (e.g., Chinook salmon) and favor fishes (mostly aliens) that can persist during long periods when stream flows are low and intermittent. The more the "natural" flow regime is altered, the less native fishes will be favored (Kiernan and Moyle 2012). Physiological and behavioral tolerance to precipitation change is categorized as: (1) very low, (2) low, (3) moderate, or (4) highly tolerant (suggesting that it is likely to benefit from future change).

3. **Vulnerability to change in frequency or degree of extreme weather events.** Some fish face greater risk of extinction or population or range reduction if climate change results in increased frequency or magnitude of stochastic events such as extreme floods and prolonged droughts. Fish taxa are categorized as likely to be: (1) strongly negatively affected, (2) moderately negatively affected, (3) unaffected, or (4) favorably affected by an increase in extreme events.

4. **Dispersive capability**. Fish taxa with high dispersal capabilities are likely less vulnerable to climate change compared to more sedentary organisms. In this metric, taxa are rated according to their ability to disperse from localized effects of climate change. Dispersive capability is ranked as low, moderate, or high, where:

    (1) A low rating is assigned to taxa that are unable to disperse at all, unlikely to move, or move no more than a few kilometers from their natal area without human assistance (e.g., pupfish, redband trout).

    (2) A moderate rating indicates that a taxon may be able to disperse and colonize new habitats in the same general region in which it is native (e.g., mountain sucker), assuming natural dispersal corridors remain open.

    (3) A high rating refers to highly mobile animals that can disperse long distances to other regions, typically by moving through salt water (e.g., Pacific salmon).

5. **Degree of physical habitat specialization.** Fish taxa that have a high degree of habitat specialization (i.e., that are not flexible in their choice of habitats) for one or more portions of their life-cycle, may be highly vulnerable to climate change even if they have high behavioral and physiological tolerances to change, if their habitats are also strongly altered by climate change. Thus a pupfish that has extreme physiological tolerances may still go extinct if springs it inhabits go dry or become

smaller. In scoring this variable, taxa are assigned to one of three habitat specialization categories:

(1) Highly specialized: taxa that are restricted to a well-defined habitat (e.g., pupfish in desert spring pools).

(2) Moderately specialized: taxa that are able to tolerate variability within their typical habitats (most fishes).

(3) Generalist: taxa that are able to exploit a wide variety of habitats (e.g., Sacramento sucker).

6. **Likely future habitat change due to climate change.** In this variable, expert opinion of the authors is used to judge likely impact of climate change on spatial extent of a taxon's main habitats by 2100, as in Galbraith and Price (2009). These classifications should not be assumed to have a high degree of accuracy or precision. Rather, they are intended to be reasonable approximations. Many fish may depend on two or more habitats during their annual or lifetime cycles. For this variable, fish were scored according to the largest negative effect. For example, if a taxon has two critical habitats and the putative effects are estimated to be 20 percent for one and 80 percent for the other, the latter percentage should determine the score. Likely future habitat change by 2100 due to climate change is categorized as: (1) loss of all or most habitat (>50 percent reduction), (2) some loss (20–50 percent reduction), (3) no change, (4) some gain (20–50 percent), or (5) large gain (>50 percent).

7. **Ability of species to shift at same rate as habitat.** The spatial distribution of suitable aquatic habitat for a given taxon may shift in response to climate change. However, because the distribution of habitats for most native fishes is generally bounded and limited by topography, they will not be able to shift appreciably in response to climate change, unless it is in an upstream direction. However, alien game fishes are typically immune to this limitation because they will be rapidly moved to additional habitats by humans. The likelihood of species being able to shift at the same rate as habitats are scored as: (1) highly unlikely, (2) unlikely, or (3) likely. This metric helps to distinguish fishes from more mobile taxa, such as birds.

8. **Availability of habitat within new range.** Given the discrete nature of watersheds, it is likely that the only way that native fishes can colonize new habitats (without human intervention) is by moving within a drainage network, including moving upstream to cooler water. However, most suitable habitats are expected to already be colonized or be above barriers, so the potential for large-scale shifts among non-anadromous fishes is typically extremely limited. Availability of habitat within new range is categorized as: (1) none, (2) limited in extent, or (3) large in extent.

9. **Dependence on exogenous factors**. This variable describes a fish species narrow/strong dependence on one or more exogenous factors either annually or at

some specific life stage. These special exogenous factors can be related to water quality (e.g., narrow temperature range needed for egg incubation), hydrology (e.g., elevated stream flows to trigger spawning or movement), or biology (e.g., availability of specialized prey at key periods or need for cover and shade created by a few tree species). Fish taxa are characterized as being: (1) highly dependent, (2) moderately dependent, or (3) somewhat dependent.

10. **Vulnerability to alien (non-native) species.** Alien species (all kinds; microbes, plants, vertebrates, and invertebrates) may exacerbate effects of climate change by stressing native fishes through predation, competition, disease, and habitat modification, especially if the alien species is favored by the changing conditions. Carlisle et al. (2011) found that throughout the United States, fishes adapted to lake or pond environments tend to dominate streams as the streams suffer from reduced flows, a likely major impact of climate change on California fishes. In California, most alien fishes can be characterized as being adapted to lentic or slow-moving riverine environments (Moyle 2002). This is particularly a problem with fishes in California because virtually all aquatic ecosystems host alien aquatic species, and these species now dominate many habitats and watersheds. Here we rate inland fish species as being (1) highly vulnerable, (2) moderately vulnerable, or (3) somewhat vulnerable to known alien species that have invaded or can invade their habitats. In some cases (e.g., Colorado cutthroat trout) an established but rare alien species may be vulnerable to the invasion another species.

Each of the above 10 variables are assigned numerical scores, which are then combined to produce an overall evaluation of the species' potential vulnerability to climate change. The individual scores for each metric in Module 2 are then combined for a total score for each species. While the individual scores fall into a continuum of climate change vulnerability, we have divided the scores into categories following Galbraith and Price (2009):

- **Critically vulnerable (score <17)** – The species is extremely likely to be driven to extinction before year 2100 without conservation measures.
- **Highly vulnerable (score = 17–22)** – The species is on the path toward extinction as the result of climate change.
- **Less vulnerable (score = 23–27) –** The species is likely to decline or become more limited in distribution, but extinction is unlikely by 2100.
- **Least vulnerable (score = 28–32)** – The species is likely to be relatively unaffected by climate change, with range and populations remaining stable.
- **Likely to benefit from climate change (>32)** – The species is likely to increase in range and abundance as the result of climate change.

2.1.3. Combined (Overall) Vulnerability Ratings

When the total scores for the two modules are combined, they produce a score that indicates the overall likelihood of each species persistence into the next century, on the assumption that climate change alters vulnerability to other factors. While the individual scores fall into a continuum of vulnerability, we have divided the scores into categories following Galbraith and Price (2009):

- **Critically vulnerable (score <35)** – The species is extremely likely to become extinct in the wild before 2100 without conservation measures.
- **Highly vulnerable (score = 35–47)** – The species is on the path toward extinction in the wild.
- **Less vulnerable (score = 48–60) –** The species is likely to decline or become more limited in distribution, but extinction is unlikely by 2100.
- **Least vulnerable (score = 61–74)** – The species population and range is likely to remain stable.
- **Likely to benefit from change (>74)** –The species is likely to increase in range and abundance.

Section 3: Results

3.1 Methodology Evaluation

3.1.1 Klamath Basin Fishes

As a test of the consistency of our scoring system, the four investigators of this study independently completed the two vulnerability modules for 18 species found in the Klamath Basin in northern California, using the same sources of information (e.g., Moyle 2002; Moyle et al. 2008, 2012b; Quiñones and Moyle 2012). Two of the scorers (R. M. Quiñones and P. B. Moyle) had considerable familiarity with the fishes of the basin, while the two others (J. D. Kiernan and P. K. Crain) had more expertise on fishes of other regions. The spread in range in total scores for metrics in the baseline and climate change modules was, with one exception, 0–7 points (out of a possible 10–45 points), suggesting that the scoring system was reasonably consistent among scorers (Tables 1 and 2). The scores were generally close enough so that the overall vulnerability ratings for all species were the same or nearly the same for all scorers.

Table 1. Ranges of Baseline Vulnerability Scores of Expert Reviewers (N) for Native Fishes of the Lower Klamath River. Vb = range of total scores for all 10 metrics (Range = 0–13, mean = 3.7). The scores translate into the ratings: Vb1 = critically vulnerable, Vb2 = highly vulnerable, Vb3 = less vulnerable, Vb4 = least vulnerable. Scientific names of all taxa can be found in Appendix A.

Taxon	*N*	Vb (total)	Vb (high)	Vb (low)	Vb(mean)	Certainty scores	Rating
Pacific lamprey	3	21-24	28-30	19-21	22	19-21	Vb2
Klamath River lamprey	3	19-32	24-34	15-30	27	12-13	Vb3
Western brook lamprey	4	26-33	29-33	20-27	28	10-16	Vb3
Northern green sturgeon	3	26-29	29-33	20-27	27	20-21	Vb3
Klamath largescale sucker	3	19-24	23-26	16-17	21	13-15	Vb2
Eulachon	3	16-18	23-25	15-18	17	21-24	Vb1
Upper Klamath-Trinity fall Chinook salmon	4	20-24	23-28	17-21	22	22-28	Vb2
Upper Klamath-Trinity spring Chinook salmon	4	15-18	17-22	13-17	17	26-28	Vb1
Southern Oregon Northern California coast fall Chinook salmon	3	21-26	27-32	18-24	25	21-22	Vb2
Southern Oregon Northern California coast coho salmon	3	13-14	17-20	12	13	24-27	Vb1
Pink salmon	4	15-19	23-26	14-17	17	16-19	Vb1
Chum salmon	4	18-22	23-28	16-18	20	13-17	Vb2
Klamath Mountains Province winter steelhead	2	21-27	25-27	18-20	24	23	Vb2
Klamath Mountains Province summer steelhead	3	15-17	21-23	13-16	16	21-26	Vb1
Coastal cutthroat trout	3	26-29	31-32	22-26	28	17-21	Vb3
Lower Klamath marbled sculpin	4	32	32-34	26-31	32	15-19	Vb3
Coastal Prickly sculpin	3	36-37	36-37	31-32	36	23-30	Vb4
Coastrange sculpin	3	32	34-35	26-28	32	17-21	Vb3

Table 2. Ranges of Climate Change Vulnerability Scores of Expert Reviewers (N) for Native Fishes of the Lower Klamath River. Vc = ranges of total score for the 10 climate change metrics (range of ranges 0–7, mean = 2.8). The scores translate into the ratings: Vc1 = critically vulnerable, Vc2 = highly vulnerable, Vc3 = less vulnerable, Vc4 = least vulnerable. Overall vulnerability ratings (Vo) follow the same scale as the Vc ratings.

Taxon	*N*	Vc (total)	Vc (high)	Vc (low)	Vc (mean)	Certainty	Rating	Combined Vb +Vc	Overall
Pacific lamprey	3	17-22	24-26	14-16	22	21-22	Vc2	38-46	Vo1
Klamath River lamprey	3	15-20	21-22	12-17	18	12-14	Vc2	34-51	Vo2
Western brook lamprey	4	15-18	21-23	13-15	17	12-19	Vc2	42-51	Vo2
Northern green sturgeon	3	18-20	21-24	20-27	19	14-15	Vc2	46-47	Vo2
Klamath largescale sucker	3	15-22	21-25	16-17	17	13-16	Vc2	34-46	Vo1
Eulachon	3	15-20	21-25	11-18	18	19-24	Vc2	31-38	Vo1
Upper Klamath-Trinity fall Chinook salmon	4	16-18	21-23	13-15	15	21-27	Vc1	36-42	Vo1
Upper Klamath-Trinity spring Chinook salmon	4	14-15	17-21	13-14	15	23-27	Vc1	31-33	Vo1
Southern Oregon Northern California coast fall Chinook salmon	3	17-18	19-21	13-16	18	25-26	Vc2	39-44	Vo1
Southern Oregon Northern California coast coho salmon	3	14-15	16-21	13-14	15	24-29	Vc1	27-29	Vo1
Pink salmon	4	16-19	19-24	14-15	17	18-24	Vc2	33-37	Vo1
Chum salmon	4	17-18	19-23	13-15	18	17-24	Vc2	36-39	Vo1
Klamath Mountains Province winter steelhead	2	18-21	18-21	16-19	15	26-27	Vc1	39-48	Vo1
Klamath Mountains Province summer steelhead	3	11-16	14-21	11-12	14	23-26	Vc1	28-31	Vo1
Coastal cutthroat trout	3	16-18	20-24	14-15	17	23-24	Vc2	42-47	Vo2
Lower Klamath marbled sculpin	4	19-21	23-26	16-18	20	16-22	Vc2	51-53	Vo2
Coastal Prickly sculpin	3	26-28	27-30	23-25	27	22-28	Vc3	62-65	Vo4
Coastrange sculpin	3	23-20	24-26	18-20	22	21-24	Vc2	52-55	Vo2

3.1.2 Evaluating Certainty

Because we were concerned that more available information on a given taxon might bias vulnerability scores either upward or downward, we examined the relationships between certainty scores, baseline vulnerability scores, and climate change vulnerability scores. Linear regression analysis showed no significant relationship between a taxon's baseline vulnerability scores and the level of certainty associated with that score ($R^2 = 0.03$, $F_{[1,121]} = 3.33$, $P = 0.07$) but a weak negative relationship between climate change vulnerability scores and certainty ($R^2 = 0.06$, $F_{[1,121]} = 7.88$, $P < 0.01$; Figure 1). The latter suggests that better information increases likelihood that a species will be scored as being vulnerable to climate change effects.

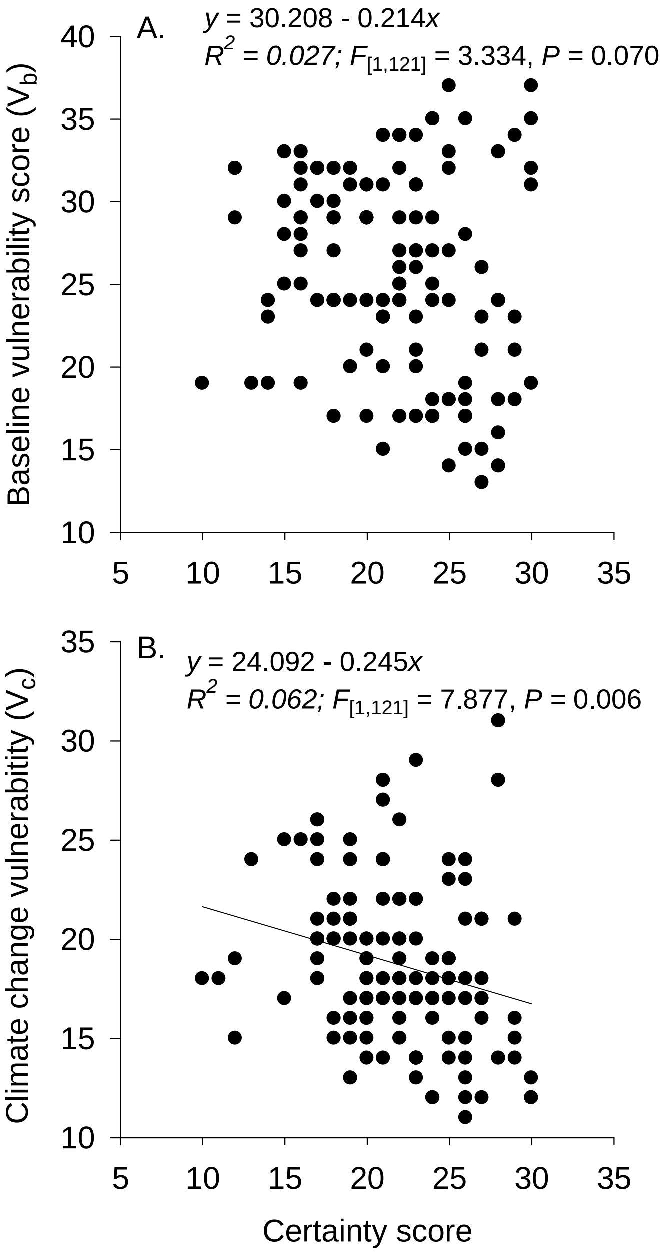


Figure 1. Relationships between Baseline (A) and Climate Change (B) Vulnerability Scores and Certainty Scores

3.1.3 Comparisons

The scores from our baseline vulnerability analysis were highly correlated with the scores from our climate change vulnerability analysis (Figure 2). The scores from both analyses had strong positive correlations with species status scores from an evaluation done prior to the present evaluation, using different metrics (Moyle et al. 2011). Essentially, Moyle et al. (2011), using seven metrics, rated the status of each species of native fish in California on a scale of 1.0–5.0, where 1.0 would be a species on verge of extinction and 5.0 would be a species that was widespread and abundant. The scores from Moyle et al. (2011) showed a strong correlation with the scores from this study (Figure 3).

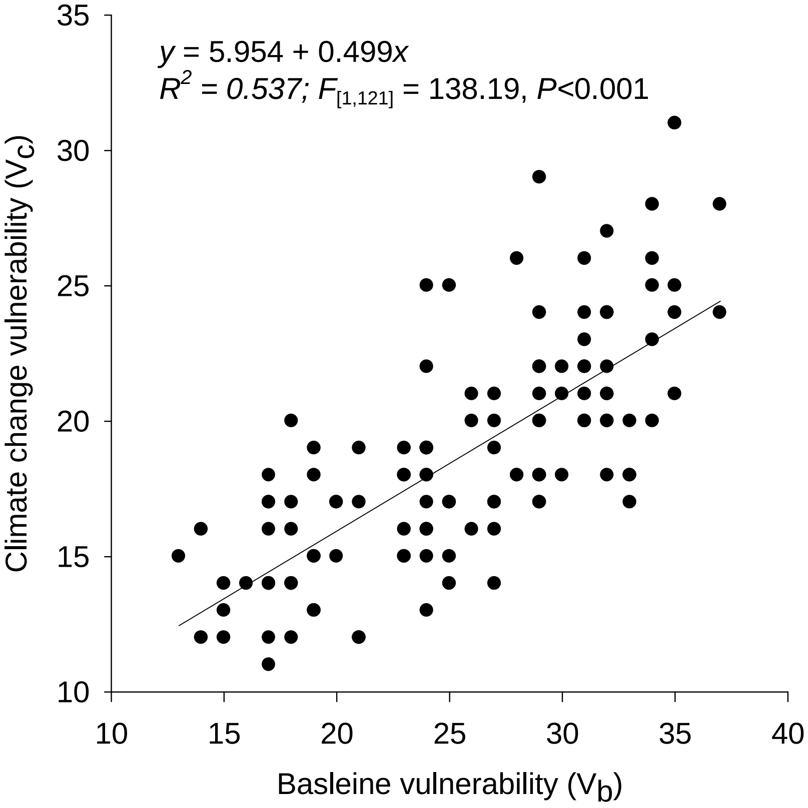


Figure 2. Regression of Scores for Climate Change Vulnerability against Scores from Baseline Vulnerability Analysis

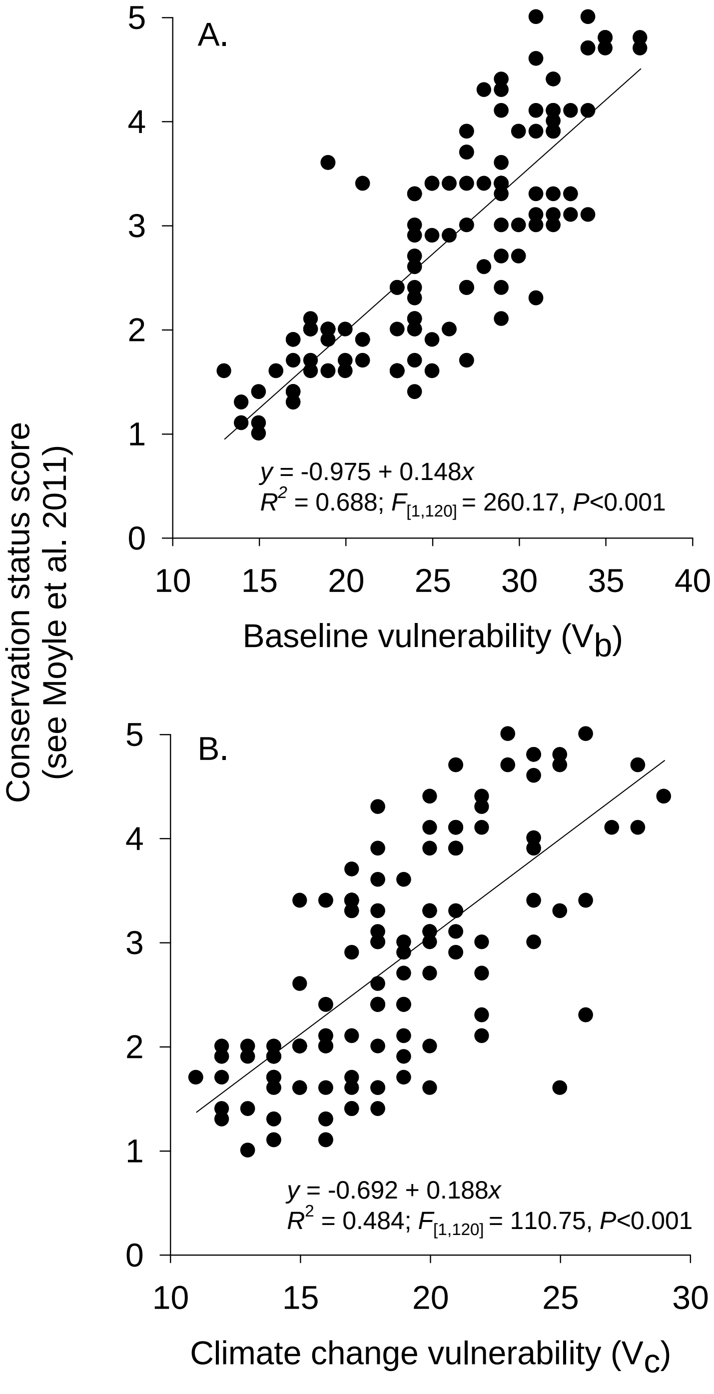


Figure 3. Relationship between the Baseline (A) and Climate Change (B) Vulnerability Scores Derived for California Fishes as Part of this Study and Conservation Status Scores Reported by Moyle et al. (2011)

3.2 Vulnerability Analyses

For baseline vulnerability, native fishes had a mean score of 25.6 (± 1 standard error, SE = 0.55; $N = 121$) and scores for individual taxa ranged from a low of 13 (Southern Oregon

Northern California Coast coho salmon) to a high of 37 (Lahontan redside). Sixteen taxa scored as critically vulnerable, 44 as highly vulnerable, 50 as less vulnerable, and 11 as least vulnerable (Figure 4). In all, 50 percent of native taxa had critical or high vulnerability to extinction, even without future climate change. Conversely, alien fishes (N = 43) had a mean baseline score of 36.7 ± 0.5, with individual species ranging from 28 (striped bass, American shad, and Colorado cutthroat trout) to 40 (goldfish and channel catfish). All but five of the alien species scored as least vulnerable, and none showed critical or high vulnerability.

For climate change vulnerability, native fishes had a mean score of 18.7 ± 0.4. Klamath Mountains Province summer steelhead trout was the most vulnerable taxon (11), whereas staghorn sculpin was the least vulnerable native taxon (31). Thirty-six native taxa scored as critically vulnerable, 64 as highly vulnerable, 17 as less vulnerable, and 4 as least vulnerable (Figure 5). No native taxon was scored as likely to benefit from climate change (Figure 6). In short, 83 percent of native fishes are critically or highly vulnerable to climate change. Alien fishes had a mean score of 27.5 ± 0.8 with a range of 17 to 35, for kokanee and black bullhead, respectively (Figure 7). None scored as critically vulnerable, 8 as highly vulnerable, 13 as less vulnerable, 16 as least vulnerable, and 6 as likely to benefit (Figure 7). In short, only 19 percent of alien fishes showed a high vulnerability to climate change, although 86 percent (37 species) showed at least some vulnerability to climate change, reflecting that aquatic habitat quality and quantity are likely to decline under most scenarios.

From a broad taxonomic perspective, fishes in families native to California tended to fare more poorly than fishes in families not native to California (Tables 3 and 4). In contrast, families dominated by alien species tended to be less affected by climate change. Species in the Centrarchidae, for example, were mostly (92 percent) likely to be unaffected by or benefit from climate change. It is significant that the 11 "least vulnerable" centrarchid species are all alien species, and the one species rated as highly vulnerable, the Sacramento perch, is native. Native anadromous species in the families Salmonidae, Acipenseridae, and Petromyzontidae generally showed high vulnerability to climate change, as well as high baseline vulnerabilities. Thus of 31 anadromous taxa, 13 were rated critically vulnerable, 14 as vulnerable, 2 as having low vulnerability, and none as being least vulnerable or likely to benefit.

Overall, the results of our assessment show that native species are characterized by greater baseline vulnerability (as also shown in Moyle et al. 2011) than alien species; 50 percent natives scored as critically or highly vulnerable versus none for aliens. Native species also show greater vulnerability to climate change than aliens; 83 percent scored as being critically or highly vulnerable, while only 19 percent of alien species showed similar vulnerabilities. While alien species are much more likely to benefit from climate change, even many of these species ultimately will be negatively affected by climate change through loss of aquatic habitats during severe droughts and increasingly stressful conditions in most waterways during summer months.

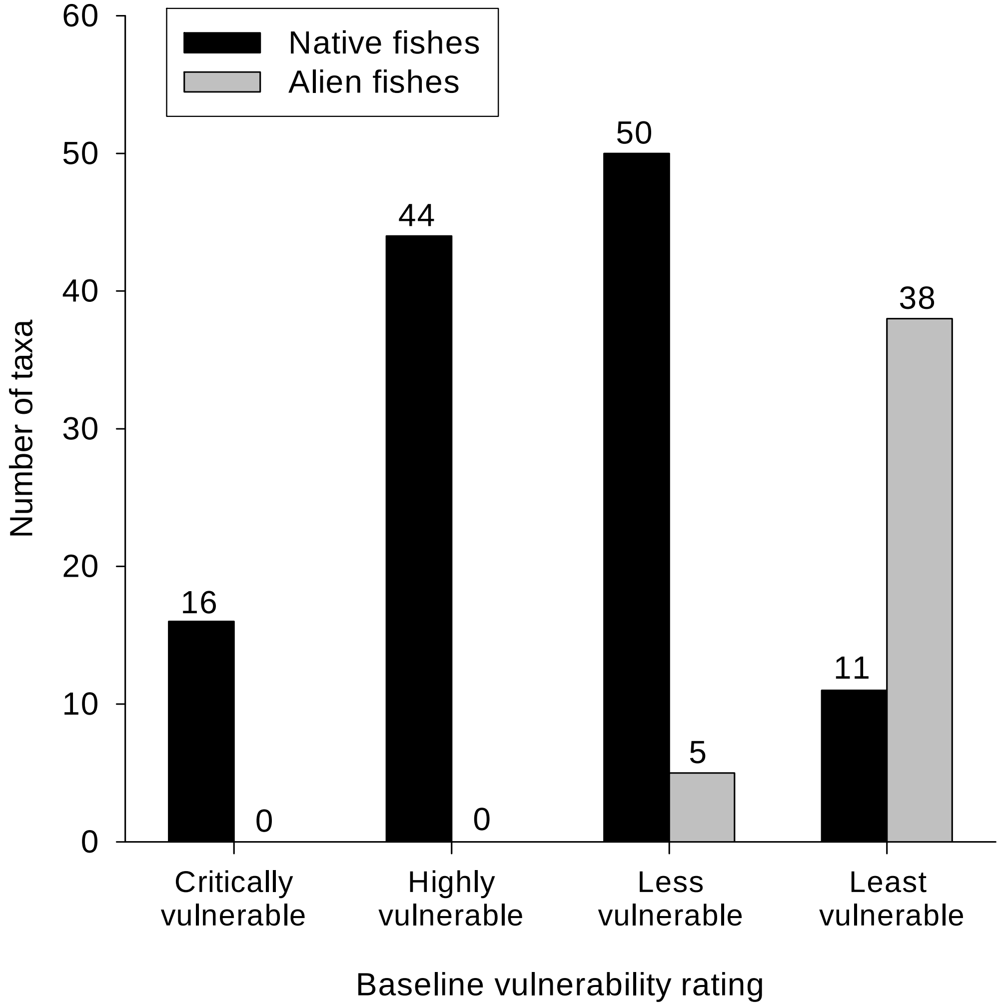


Figure 4. Number of Native and Alien Fish Species in California Classified into Four Categories of Baseline Vulnerability to Extinction by 2100. See the text for explanation of the scoring system and categories.

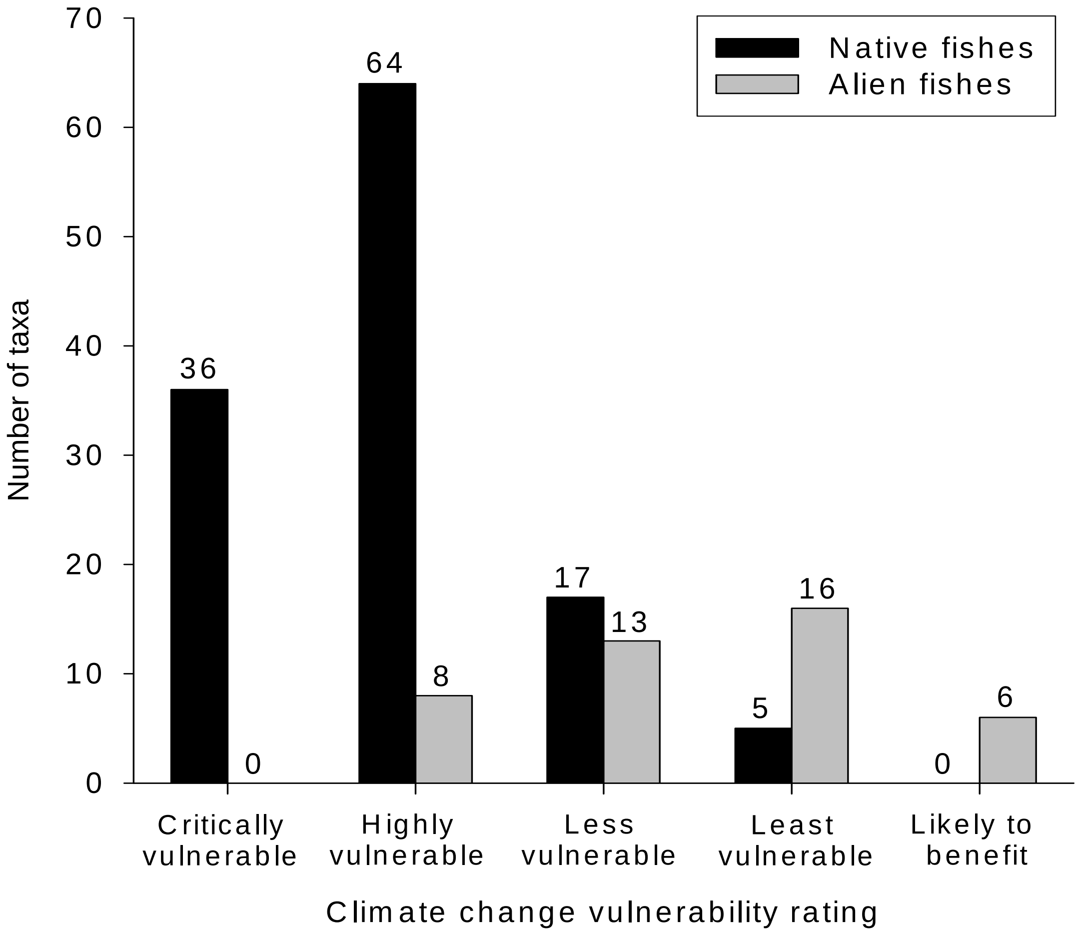


Figure 5. Number of Native and Alien Fish Species in California Classified into Four Categories of Vulnerability to Extinction as the Result of Climate Change by 2100. See the text for explanation of the scoring system and categories.

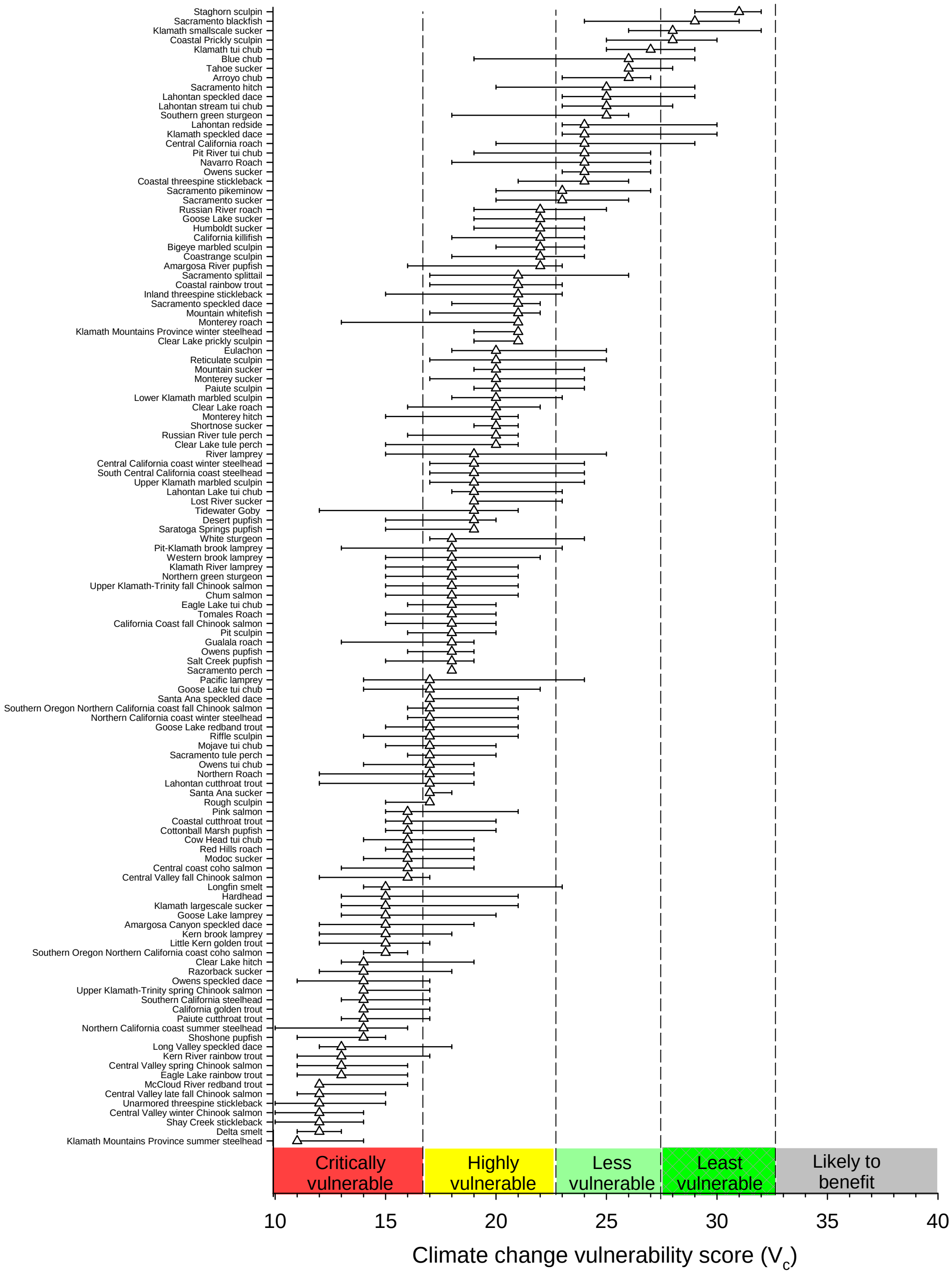


Figure 6. Climate Change Vulnerability Scores for California's Extant Native Fish Fauna. Taxa are arranged from highest (top) to lowest (bottom). The triangle indicates the best vulnerability score for the taxon, while the lines indicate the range from maximum to minimum scores. See Appendix A for values.

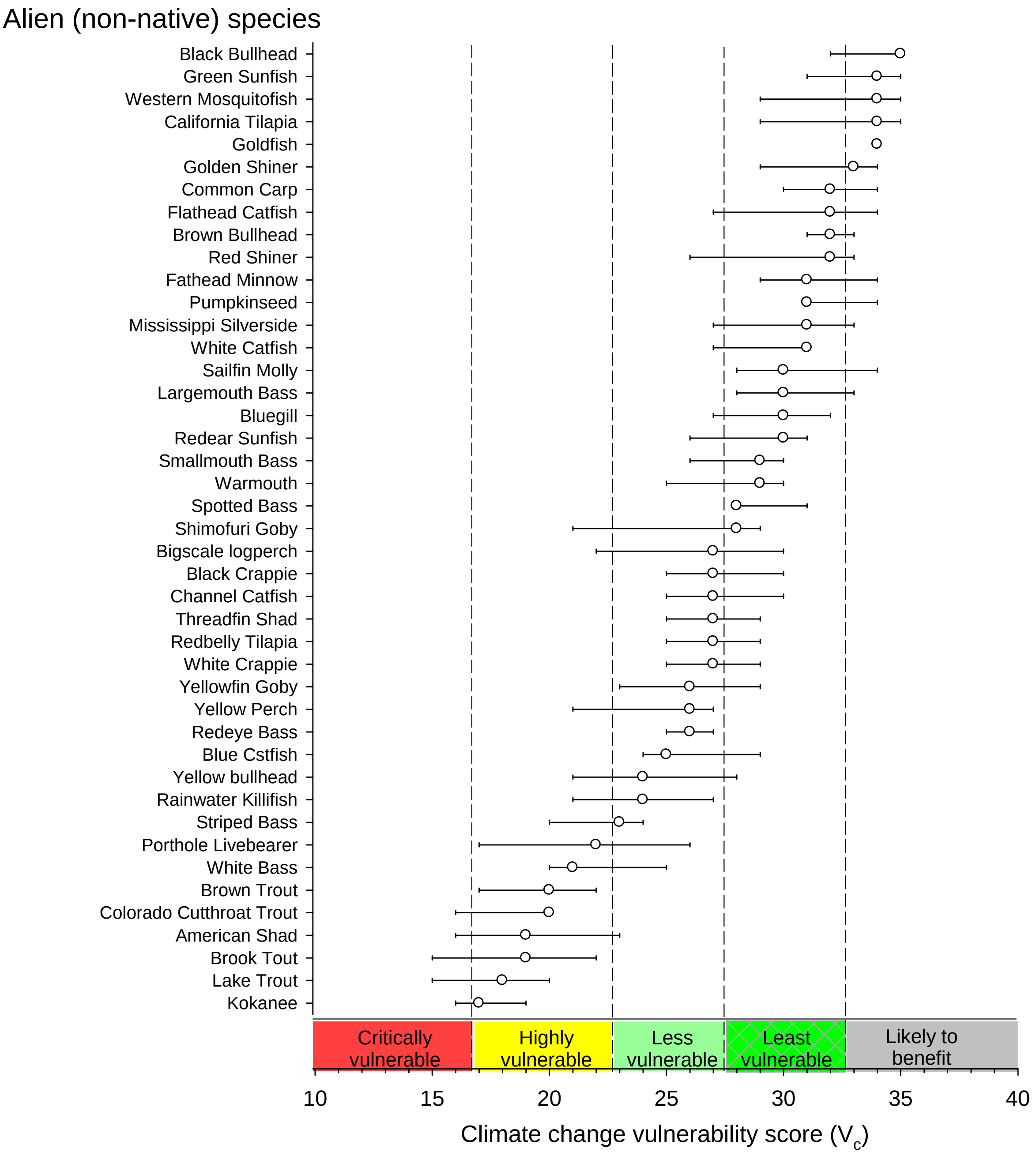


Figure 7. Climate Change Vulnerability Scores for California's Alien (Non-Native) Freshwater Fish Species. Taxa are arranged from highest (top) to lowest (bottom). The circle indicates the best vulnerability score for the taxon, while the lines indicate the range from maximum to minimum scores. See Appendix A for actual values.

Table 3. Baseline Vulnerabilities (Vb) of Freshwater Fishes Found in California, by Family

			Baseline Vulnerability Rating (Vb)							
			Critically vulnerable		Highly vulnerable		Less vulnerable		Least vulnerable	
Family	No. taxa	% Native	*N*	%	*N*	%	*N*	%	*N*	%
Acipenseridae	3	100			2	67	1	33		
Atherinopsidae	1	0							1	100
Catostomidae	14	100	1	7	4	29	7	50	2	14
Centrarchidae	12	8			1	8	1	8	10	83
Cichlidae	2	0							2	100
Clupeidae	2	0					1	50	1	50
Cottidae	12	100			1	8	9	75	2	17
Cyprinidae	45	89	4	9	8	18	18	40	10	22
Cyprinodontidae	8	100	2	25	3	38	2	25		
Embiotocidae	3	100			1	33	1	33	1	33
Fundulidae	2	50					1	50	1	50
Gasterosteidae	4	100	2	50			2	50		
Gobiidae	3	33			1	33			2	67
Ictaluridae	7	0							7	100
Moronidae	2	0					1	50	1	50
Osmeridae	3	100	1	33	2	67				
Percidae	2	0							2	100
Petromyzontidae	7	100			4	57	3	43		
Poeciliidae	3	0					1	33	2	67
Salmonidae	36	86	6	17	17	47	7	19	5	14

Table 4. Climate Change Vulnerabilities (V_c) of Freshwater Fishes Found in California, by Family

			Climate Change Vulnerability Rating (V_c)									
			Critically vulnerable		Highly vulnerable		Less vulnerable		Least vulnerable		Likely to benefit	
Family	No. taxa	% Native	*N*	%	*N*	%	*N*	%	*N*	%	*N*	%
Acipenseridae	3	100			2	67	1	33				
Atherinopsidae	1	0							1	100		
Catostomidae	14	100	3	21	7	50	3	21	1	7		
Centrarchidae	12	8			1	8	3	25	7	58	1	8
Cichlidae	2	0					1	50			1	50
Clupeidae	2	0			1	50	1	50				
Cottidae	12	100			10	83			2	17		
Cyprinidae	45	89	7	16	15	33	12	27	4	9	2	4
Cyprinodontidae	8	100	2	25	5	63						
Embiotocidae	3	100			3	100						
Fundulidae	2	50			1	50	1	50				
Gasterosteidae	4	100	2	50	1	25	1	25				
Gobiidae	3	33			1	33	1	33	1	33		
Ictaluridae	7	0					3	43	3	43	1	14
Moronidae	2	0			1	50	1	50				
Osmeridae	3	100	2	67	1	33						
Percidae	2	0					2	100				
Petromyzontidae	7	100	2	29	5	71						
Poeciliidae	3	0			1	33			1	33	1	33
Salmonidae	36	86	18	50	17	47						

3.2 Vulnerability of San Francisco Bay Area Fishes

The streams tributary to the San Francisco Estuary and the freshwater portions of the estuary contain many of the fish species, both native and alien, that live in Central California. They therefore make a good demonstration for the potential impacts of climate change on a well-documented (Leidy 2007; Leidy et al. 2011) regional fish fauna. We used our statewide scores for 22 native fishes and 23 alien fishes, according to their baseline vulnerability and their climate change vulnerability. Scores for the two sets of fishes were arrayed graphically from the lowest to highest scores and place in four categories: critically vulnerable, highly vulnerable, less vulnerable, and least vulnerable (Figures 8 and 9). For baseline vulnerability, native fishes had a mean score of 25.1 (± 1.3, range = 14–36; *N* = 22). Two taxa scored as critically vulnerable, 9 as highly vulnerable, 9 as less vulnerable, and 2 as least vulnerable (Figure 8). Alien fishes had a mean score of 36.8 (± 0.7, range = 28–40; *N* = 23). All but two of the alien species scored as least vulnerable.

For climate change vulnerability, native fishes had a mean score of 19.9 (± 0.9, range = 12–29). Four taxa scored as critically vulnerable, 10 as highly vulnerable, 7 as less vulnerable, 1 as least vulnerable, and none as likely to benefit (Figure 13). Alien fishes had a mean score of 29.0 (± 0.9, range = 19–35). None scored as critically vulnerable, 3 as highly vulnerable, 6 as less vulnerable, 10 as least vulnerable, and 4 as likely to benefit.

This analysis reflects the general phenomenon that native fishes are in decline while non-native fishes are becoming more abundant or at least holding their own in the region (Leidy 2007; Leidy et al.2011). While climate change is predicted to have a negative impact on both groups, through loss of aquatic habitat, by 2100 native fish populations in general will be in worse condition and some alien fishes will be thriving under the new conditions. Not surprisingly, native fishes with lowest scores for both baseline and climate change vulnerability (e.g., Delta smelt, coho salmon) are already listed as threatened or endangered species, or are regarded as Fish Species of Special Concern by the California Department of Fish and Game. While the reasons for this result are many and often species–specific, native species in general have smaller, more isolated populations with a long history of decline. In addition, many prefer cool (<22°C [72°F]), flowing water, which is in increasingly short supply in Bay Area watersheds. Alien fishes in general thrive in altered habitats, especially those that are more lake-like, with high summer temperatures. Native fishes persist in protected headwaters, in streams with drought refuges (including some reservoirs), and where alien fishes are not abundant; many of the species are euryhaline or are otherwise among the most physiologically tolerant of the native fishes (Leidy et al. 2011). However, many native species also have few opportunities for colonizing new habitats because of their inability to move among watersheds or above natural or human-made barriers within watersheds, without human assistance. In any case, suitable habitat for most native species is likely to shrink; especially cool-water streams during extended periods of drought, a situation exacerbated by interactions with alien fishes (Leidy et al. 2011; Moyle et al. 2012a).

Overall, in the San Francisco Bay Area, climate change will result in an accelerated shift in the nature of aquatic habitats toward those that favor alien fishes over native species. A number of native species will have more limited distributions in Bay Area streams and the estuary (e.g., California roach, tule perch), and some may become extirpated (e.g. hardhead, delta smelt), repeating the recent extirpation of coho salmon. Stream-dependent species will decline as stream reaches dry up or become much warmer as the result of lower flows and increasing air temperatures. Proportionally, there will be more aquatic habitat in impoundments, which mostly favor alien fishes, although water stored in reservoirs may also be used to enhance late summer flows to favor native fishes in some streams (Leidy et al. 2011). Maintaining representative assemblages of native fishes in these streams will require considerable conservation effort, including providing increased summer flows downstream from dams.

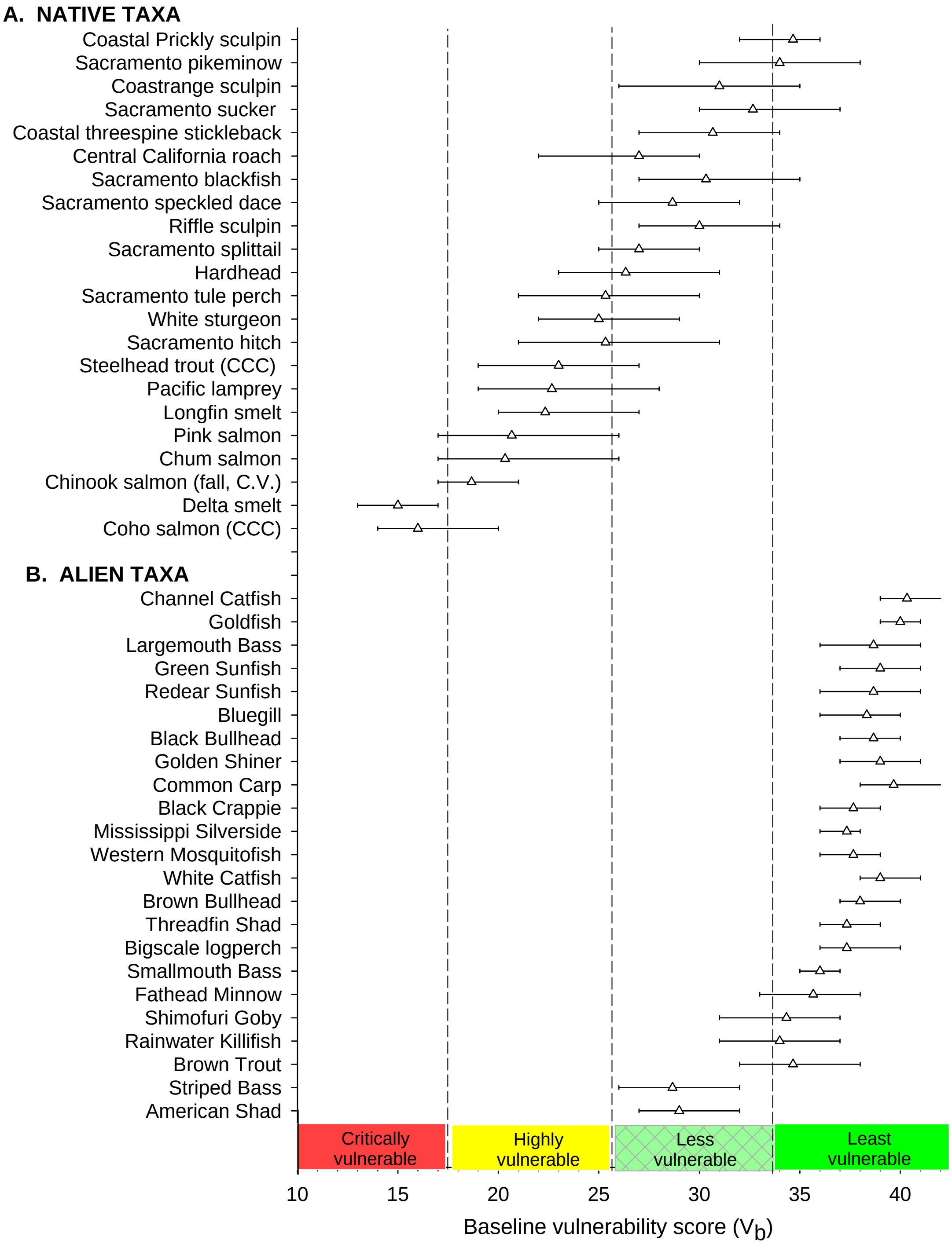


Figure 8. Baseline Vulnerability Scores for Native (A) and Alien (B) Fishes in the San Francisco Bay Area, Arrayed from Highest to Lowest Scores. The triangle indicates the best vulnerability score for the species, while the lines indicate the range from maximum to minimum scores.

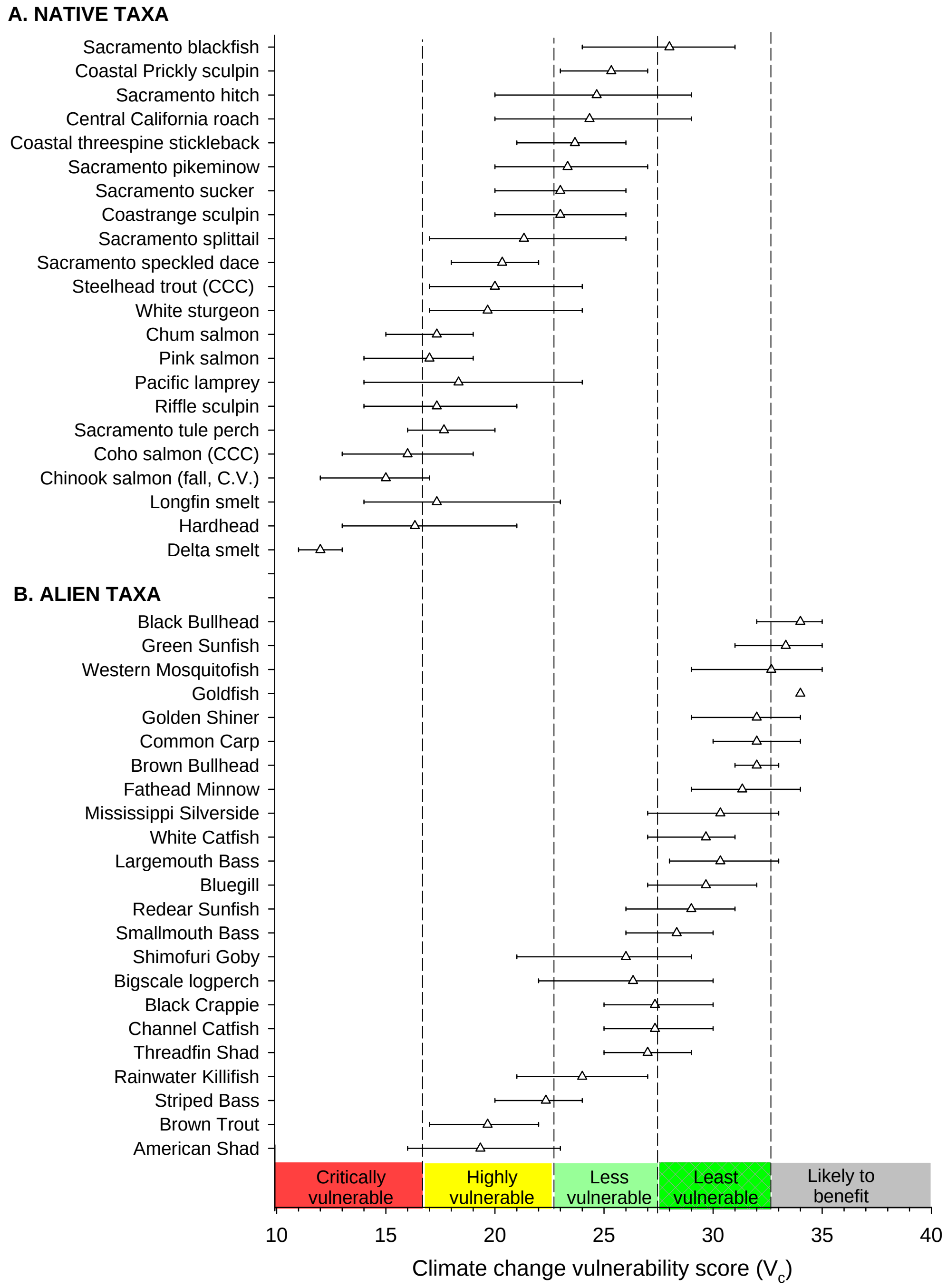


Figure 9. Climate Change Vulnerability Scores for Native (A) and Alien (B) Fishes in the San Francisco Bay Area, Arrayed from Highest to Lowest Scores. The triangle indicates the best vulnerability score for the species, while the lines indicate the range from maximum to minimum scores.

3.3 Climate Change Effects on Fishes in Three California Streams

Detection of recent climate change effects on fishes in streams is difficult because fish populations are naturally so variable. Continuous monitoring over extended periods of time can help reveal these effects. Here we summarize studies on three streams with long-term fish sampling programs by the senior author: Martis Creek, Putah Creek, and Sagehen Creek. These three streams have the longest fish sampling programs of any streams in California (30+, 20+, and 60+ years, respectively) so provide insights into how recent environmental changes have affected the fish fauna.

3.3.1 Martis Creek

Martis Creek is a small stream in the eastern Sierra Nevada (Placer County) that has been sampled annually since 1979 at four stations (Kiernan and Moyle 2012). The stations are all below a flood-control dam which mainly reduces peak flows. The 14 species are a mixture of native and alien species, although in most years either alien brown trout or alien (to eastern Sierra Nevada) rainbow trout dominate.

We used three decades of fish abundance data to examine (1) the persistence and resilience of the Martis Creek fish assemblage to environmental stochasticity; (2) whether native and alien fishes respond differently to a natural hydrologic regime (e.g., timing and magnitude of high and low flows); and (3) the importance of various hydrologic and physical habitat variables in explaining abundances of native and alien fish species through time (Kiernan and Moyle 2012). Our results showed that fish assemblages were persistent at all sample sites but exhibited marked inter-annual variability in density and biomass. The density and biomass of native fishes generally declined over the study period, while most alien species showed no trends. Only alien rainbow trout increased in both density and biomass at all sites over time. The relative importance of physical habitat versus hydrologic factors in explaining the density of individual species was inconsistent across taxa, but alien brown trout density was generally an important factor affecting the abundances of most taxa. For the fish community as a whole, the proportion of the total assemblage composed of alien species was inversely related to mean annual stream flow, one-day maximum discharge in both winter and spring, and the frequency of springtime floods. We conclude that the Martis Creek fish assemblage is principally regulated by the flow regime and that biotic interactions become increasingly important under benign environmental conditions (e.g., in years without extreme high or low flows). Our results highlight the need for continuous monitoring of streams with highly-variable flow regimes because apparent successes or failures in stream management may appear differently under long-term study. Long-term studies in particular are needed to distinguish the effects of climate change from deliberate management actions (Kiernan and Moyle 2012).

3.3.2 Putah Creek

Putah Creek flows east from the Coast Range, historically reaching the Sacramento River. The flows of the lower 30 km of stream are regulated by Putah Creek Diversion Dam (Yolo and Solano Counties), currently to favor a native fish assemblage (Kiernan et al. 2012). The fish in this reach have been monitored at multiple stations for 17 years (Kiernan et al. 2012). The 35 species are a mixture of native and alien species, with natives dominating the fauna of the upper end and aliens dominating the fauna of the lower end.

Using this long-term data set, we examined the response of fishes of lower Putah Creek to establishment of a new flow regime. The new flow regime was designed to mimic the natural hydrograph in terms of the seasonal timing of increases and decreases in streamflow but not water volume. We monitored fish assemblages annually at six sample sites distributed over ~30 km of stream for eight years before and nine years after the new flow regime was established. At the onset of our study, fish taxa were strongly partitioned along an upstream-downstream gradient, with native cold-water fishes restricted to habitat immediately (<1 km) below the diversion dam and alien (non-native) species numerically dominant at all other sample sites. Following implementation of the new flow regime, native fishes regained dominance of more than 20 km of lower Putah Creek. This redistribution resulted from the creation of favorable spawning and rearing conditions for native fishes (e.g., elevated spring flows) and the displacement of alien fishes by naturally occurring high discharge events, cooler water temperatures, and the maintenance of lotic (flowing) conditions over the length of the creek. The results demonstrate that natural flow regimes can be used to effectively manipulate and manage fish assemblages in regulated rivers at relatively low water cost. Moreover, the results suggest that deliberate flow management has the potential to ameliorate some effects of climate change, which is likely to increase habitat for alien fishes at the expense of native fishes (Kiernan et al. 2012)

3.3.3 Sagehen Creek

Sagehen Creek (Nevada County) is another eastern Sierra Nevada stream which has been extensively studied. Fish were quantitatively sampled at 7–9 stations in the creek in three time periods: 1953–1971, 1982, and 2003–2010. The fish fauna is largely dominated by three species of alien salmonids. Our analysis of the Sagehen Creek fish data is not yet complete, due to difficulties in making different data sets compatible. However, preliminary analyses indicate the following (V. Boucher, J. Kiernan, P. Moyle, and P. Crain, in preparation):

1. Over 60+ years, the flows of the creek have been remarkably constant for a Sierra Nevada stream, although extreme high flow events do affect abundances of fish species in different ways.

2. Three species of alien trout (brook, rainbow, and brown) have remained the most abundant species, along with native Paiute sculpin, over the 60-year period, although their relative distributions and abundances have shifted back and forth over the years.

3. The construction of Stampede Reservoir, which covered up the lowermost reaches of the creek, eliminated two species of native fish from the creek and resulted in the invasion of two alien species.

4. Overall, Sagehen Creek and its fishes may be less vulnerable climate change than most Sierra Nevada streams, unless the predicted reduced snowpack results in less water in summer flowing from the aquifers which feed the creek.

Section 4: Conclusions

It is clear that predicted climate change effects on freshwater environments in California will dramatically change the fish fauna at all levels, from local to regional to statewide. Basically, most native fishes will become more restricted in their distributions, and some will likely be driven to extinction, if present trends continue. In contrast, most alien fishes will suffer much less from climate change but still show some decline, through the loss of total aquatic habitat as streams and reservoirs dry up under extreme conditions. Some species, however, are likely to increase in abundance and range. Obviously, variability in response exists among the two groups; a few natives will also thrive in many streams, and some aliens will decline considerably. Beyond these broad conclusions, our study has the following findings:

1. Our methodology was successful at indicating relative vulnerability of California fish species to climate change. The strength of the methodology is that it is repeatable by other fish biologists, with scores changing as new information is acquired. If there is bias in the methodology, it is that improved information tends to show somewhat greater vulnerability of fish species to climate change, suggesting that our vulnerability scores are often conservative. However, both baseline and climate change vulnerability scores correlate well with status ratings developed using a different method (Moyle et al. 2011). The metrics can also be used to develop new ratings for species at a regional scale; species with high vulnerability statewide might have lower vulnerability in some regions and higher vulnerability in others. This should allow managers in specific regions to develop strategies to protect the most vulnerable species or groups of species, or even to use triage to determine most effective use of conservation dollars (Hanak et al. 2011).

2. Fishes with low baseline vulnerability scores, usually because of limited distribution or specialized habitat requirements, are also most likely to have low climate change vulnerability scores. Most fishes with low baseline vulnerability scores are usually listed as endangered, threatened, or special concern species (Appendix A). Some of this baseline vulnerability can be attributed to recent climate change effects, such as warmer stream temperatures.

3. No native fishes are likely to benefit from climate change. Some species, such as Sacramento sucker or Lahontan redside, obtained fairly low vulnerability ratings, but they are likely to at best hold their own as conditions change because of (1) overall decreases in stream habitat (2) somewhat lower temperature preferences than many alien fishes, and (3) competition and predation from alien fishes. Putah Creek may be a model for how streams can be affected by climate change; Kiernan et al. (2012) show that if flows released from a dam decrease and change in pattern, alien fishes will be favored over native fishes. Presumably increases in late summer temperatures will increase the shift; even today, the

warm lower-most reaches of the creek are largely devoid of native fishes in summer (Kiernan et al. 2012).

4. The San Francisco Bay fishes analysis indicates that regional vulnerabilities reflect statewide vulnerabilities, but that conservation strategies have to be modified to fit local conditions. The analysis, following Leidy et al. (2011), indicates that refuges against climate change can exist even in urban areas.
5. All native anadromous fishes were rated as highly or critically vulnerable to climate change. Most species requiring cold water (<22°C [72°F]) habitats were similarly rated, such as all members of the Salmonidae, including alien species. Such fishes are already stressed by other anthropogenic changes to their streams (Katz et al. 2012).
6. Higher order taxonomy (family level) was a reasonably good predictor of climate change vulnerability. Fishes in the families, Cyprinodontidae, Embiotocidae, Osmeridae, Petromyzontidae, Salmonidae, for example, were almost all highly or critically vulnerable. It is worth noting, however, that the family with the most species (Cyprinidae) had 18 species scoring in the three categories indicating least vulnerability to climate change.
7. The studies of Martis, Sagehen, and Putah creeks indicate that different species respond in different ways to variability in flow, which is likely to increase with climate change (Kiernan and Moyle 2012; Kiernan et al. 2012). Declining trends may be hard to detect without long-term monitoring as a consequence. The success of reestablishing native fishes in Putah Creek indicates that managing flow regimes in regulated streams may be a powerful tool to counter the negative effects of climate change, as may the establishment of cool-water refuges for fish, even in urban areas such as streams in the San Francisco Bay region.
8. Overall, our study strongly suggests that existing knowledge of California fishes is sufficient to reliably determine which species will need special conservation attention and which will not, as climate change proceeds. In particular, it shows that native fishes will decline, while alien fishes are likely to increasingly dominate the diminished aquatic systems, as the effects of climate change on aquatic ecosystems play out on the California landscape. Understanding these patterns on both a statewide and regional basis should permit development of conservation strategies to reduce vulnerability to climate change, at least for the next 100 years.

References

Barnett, T. P., D. W. Pierce, H. G. Hidalgo, C. Bolfils, B. D. Santer, D. Tapash, G. Bala, A. W. Wood, T. Nozawa, A. A. Mirin, D. R. Cayan, and M. D. Dettinger. 2008. "Human-induced changes in the hydrology of the western United States." *Science* **319**:1080–1083.

Carlisle, D. M., D. M. Wolcock, and M. R. Meador. 2011. "Alteration of streamflow magnitudes and potential ecological consequences: A multiregional assessment." *Frontiers in Ecology and the Environment* **9**: 264–270.

Galbraith, H., and J. Price. 2009. A framework for categorizing the relative vulnerability of threatened and endangered species to climate change. USEPA, National Center for Environmental Assessment, Washington, D.C.; EPA/600/R-09/011.

Hanak, E., J. Lund, A. Dinar, B. Gray, R. Howitt, J. Mount, P. Moyle, and B. Thompson. 2011. *Managing California's Water: From Conflict to Reconciliation.* PPIC, San Francisco. 482 pp.

Katz, J., P. B. Moyle, R. M. Quiñones, J. Israel, and S. Purdy. 2012. "Impending extinction of salmon, steelhead, and trout (Salmonidae) in California." *Environmental Biology of Fishes* DOI 10.1007/s10641-012-9974-8.

Kaushal, S. S., G. E. Likens, N. A. Jaworski, M. L. Pace, A. M. Sides, D. Seekell, K. T. Belt, D. H. Secor, and R. L. Wingate. 2010. "Rising stream and river temperatures in the United States." *Frontiers in Ecology and the Environment* doi:10.1890/090037.

Kiernan, J. D., and P. B. Moyle. 2012. "Flows, droughts, and aliens: Factors affecting the fish assemblage in a Sierra Nevada, California, stream." *Ecological Applications.* doi:http://dx.doi.org/10.1890/11-1047.1.

Kiernan, J. D., P. B. Moyle, and P. K. Crain. 2012. "Restoring native fish assemblages to a regulated California stream using the natural flow regime concept." *Ecological Applications*. doi:http://dx.doi.org/10.1890/11-0480.1.

Knowles, N., and D. R. Cayan. 2002. "Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary." *Geophysical Research Letters* **29**:1891–1895.

Leidy, R. A. 2007. *Ecology, assemblage structure, distribution, and status of fishes in streams tributary to the San Francisco estuary, California.* San Francisco Estuary Institute, Contribution 530: 194 pp.

Leidy, R. A., K. Cervantes-Yoshida and S. M. Carlson. 2011. "Persistence of native fishes in small streams of the urbanized San Francisco Estuary, California: Acknowledging the role of urban streams in native fish conservation." *Aquatic Conservation: Marine and Freshwater Ecosystems* **21**: 472–483.

Miller, N. L., K. E. Bashford, and E. Strem. 2003. “Potential impacts of climate change on California hydrology.” *Journal of the American Water Resources Association* **39**:771–784.

Moyle, P. B. 2002. *Inland fishes of California, revised and expanded.* University of California Press, Berkeley, California.

Moyle, P. B., J. A. Israel, and S. E. Purdy. 2008. S*almon, steelhead, and trout in California: Status of an emblematic fauna.* UC Davis Center for Watershed Sciences. 316 pp. http://watershed.ucdavis.edu/pdf/SOS-Californias-Native-Fish-Crisis-Final-Report.pdf.

Moyle, P. B., J. V. E. Katz, and R. M. Quiñones. 2011. “Rapid decline of California’s native inland fishes: A status assessment.” *Biological Conservation* **144**: 2414–2423.

Moyle, P. B., R. M. Quiñones, and J. D. Kiernan. 2012a. Effects of climate change on the inland fishes of California, with emphasis on the San Francisco Estuary region. California Energy Commission. CEC-500-2012-029.

Moyle, P. B., J. V. E. Katz and R. M. Quiñones. 2012b. Fish Species of Special Concern in California. Sacramento: California Department of Fish and Game. In preparation.

Quiñones, R. M., and P. B. Moyle. 2012. Integrating global climate change into salmon and trout conservation: A case study of the Klamath River *in* T. L. Root, K. R. Hall, M. Herzog, and C. A. Howell, editors. *Linking Science and Management to Conserve Biodiversity in a Changing Climate.* Berkeley: University of California Press.

Appendix A: Status of California Fishes in Relation to Climate Change

Baseline and climate change vulnerability scores for native and alien fishes were determined by methods discussed in this paper. The status score and conservation status designations for native species are from Moyle et al. (2011), based on the standards of the International Union for the Conservation of Nature (IUCN). Status scores of 1.0–1.9 indicate the species is endangered (EN), 2.0–2.9 indicate it is vulnerable to becoming endangered (VU), 3.0–3.9 indicate the species is in decline but not in immediate danger of extinction (near-threatened, NT), and 4.0–5.0 indicate the species of least concern (LC). LC is equivalent to WA for alien species. An asterisk (*) indicates the species is formally listed under state and/or federal endangered species acts. For alien species, WA indicates a species is widespread and abundant in California, RD indicates it has a restricted distribution in fresh water, either by habitat or by watershed (Moyle 2002).

	Vulnerability scores						Conservation
	baseline			climate change		Status	status
Taxon	best	range		best	range	score	(IUCN)
Native taxa							
Petromyzontidae							
Pacific lamprey, *Entosphenus tridentata*	21	19-28		17	14-24	3.4	NT
Goose Lake lamprey, *Entosphenus sp.*	24	20-28		15	13-20	2.6	VU
Klamath River lamprey, *E. similis*	32	30-34		18	15-21	3.9	NT
River lamprey, *Lampetra ayersi*	19	15-25		19	15-25	3.6	NT

		Kern brook lamprey, *L. hubbsi*	19	16-22		15	12-18	2.0	VU
		Western brook lamprey, *L. richardsoni*	33	27-33		18	15-22	3.1	NT
		Pit-Klamath brook lamprey, *L. lethophaga*	29	24-33		18	13-23	3.6	NT
	Acipenseridae								
		Northern green sturgeon, *Acipenser medirostris*	29	27-33		18	15-21	2.4	VU
		Southern green sturgeon, *A. medirostris*	25	19-28		25	18-26	1.6	EN*
		White sturgeon, *A. transmontanus*	24	22-29		18	17-24	2.0	VU
	Cyprinidae								
		Thicktail chub, *Siphatales crassicauda*	0			0		0.0	Extinct
		Goose Lake tui chub, *S. t. thalassinus*	29	25-32		17	14-22	3.4	NT
		Pit River tui chub, *S. thalassinus subsp.*	32	29-33		24	19-27	4.0	LC
		Cow Head tui chub, *S. t. vaccaceps*	24	23-29		16	14-19	2.1	VU

		Klamath tui chub, *S. b. bicolor*	32	29-33		27	25-29	4.1	LC
		High Rock Springs tui chub, *S. b. subsp.*	0			0		0.0	Extinct
		Lahontan Lake tui chub, *S. b. pectinifer*	27	25-31		19	18-23	2.4	VU
		Lahontan stream tui chub, *S. b. obesus*	34	33-38		25	23-28	4.7	LC
		Eagle Lake tui chub, *S. b. subsp.*	33	30-35		18	16-20	3.3	NT
		Owens tui chub, *S. b. snyderi*	17	16-22		17	14-19	1.4	EN*
		Mojave tui chub, *S. mohavensis*	17	16-19		17	15-20	1.4	EN*
		Bonytail, *Gila elegans*	0			0		0.0	Extinct
		Blue chub, *Gila coerulea*	28	22-31		26	19-29	3.4	NT
		Arroyo chub, *Gila orcutti*	31	31-34		26	23-27	2.3	VU
		Lahontan redside, *Richardsonius egregius*	37	33-37		24	23-30	4.8	LC
		Sacramento hitch, *Lavinia e. exilicauda*	24	21-31		25	20-29	3.3	NT
		Clear Lake hitch, *L. e. chi*	25	22-30		14	13-19	1.9	EN
		Monterey hitch, *L. e. harengeus*	29	25-31		20	15-21	2.7	VU

		Central California roach, *L. s. symmetricus*	29	22-30		24	20-29	3.4	NT
		Red Hills roach, *L. s. subsp.*	24	21-25		16	15-19	2.0	VU
		Russian River roach, *L. s. subsp*	31	28-33		22	19-25	3.0	NT
		Clear Lake roach, *L s. subsp.*	31	27-35		20	16-22	3.1	NT
		Monterey roach, *L. s. subditus*	31	26-34		21	13-21	3.3	NT
		Navarro Roach, *L. s. navarroensis*	32	31-37		24	18-27	3.0	NT
		Tomales Roach, *L. s. subspecies*	30	27-32		18	15-20	3.0	NT
		Gualala roach, *L. parvipinnus*	29	26-31		18	13-19	3.0	NT
		Northern Roach, *L. mitrulus*	25	22-29		17	12-19	2.9	VU
		Sacramento blackfish, *Orthodon microlepidotus*	29	27-35		29	24-31	4.4	LC
		Sacramento splittail, *Pogonichthys macrolepidotus*	26	25-30		21	17-26	2.9	VU
		Clear Lake splittail, *P. ciscoides*	0			0		0.0	Extinct
		Hardhead, *Mylopharodon conocephalus*	25	23-31		15	13-21	3.4	NT

		Sacramento pikeminow, *Ptychocheilus grandis*	34	30-38		23	20-27	4.7	LC
		Colorado pikeminnow, *P. lucius*	0			0		0.0	Extinct
		Sacramento speckled dace, *Rhinichthys osculus subp.*	29	25-32		21	18-22	4.1	LC
		Lahontan speckled dace, *R. o. robustus*	35	34-36		25	23-29	4.8	LC
		Klamath speckled dace, *R. o. klamathensis*	35	34-35		24	23-30	4.8	LC
		Owens speckled dace, *R. o. subsp.*	17	14-20		14	11-17	1.9	EN
		Long Valley speckled dace, *R. o. subsp.*	15	14-20		13	12-18	1.0	EN
		Amargosa Canyon speckled dace, *R. o. nevadensis*	23	20-28		15	12-19	1.6	EN
		Santa Ana speckled dace, *R. o. subsp.*	20	17-25		17	17-21	1.6	EN
	Catostomidae								
		Tahoe sucker, *Catostomus tahoensis*	34	34-37		26	26-28	5.0	LC
		Owens sucker, *C. fumeiventris*	32	32-39		24	23-27	3.9	NT

		Mountain sucker, *C. platyrhynchus*	29	26-29		20	19-24	3.3	NT
		Sacramento sucker, *C. o. occidentalis*	31	30-37		23	20-26	5.0	LC
		Goose Lake sucker, *C. o. lacusanserinus*	29	29-29		22	19-24	2.1	VU
		Monterey sucker, *C. o. mnioltiltus*	33	26-34		20	17-24	4.1	LC
		Humboldt sucker, *C. o. humboldtianus*	29	26-33		22	19-24	4.3	LC
		Modoc sucker, *Catostomus microps*	23	21-23		16	14-19	1.6	EN*
		Klamath smallscale sucker, *C. rimiculus*	34	34-39		28	26-32	4.1	LC
		Klamath largescale sucker, *C. snyderi*	19	16-23		15	13-21	2.0	VU
		Lost River sucker, *C. luxatus*	24	19-27		19	19-23	1.7	EN*
		Santa Ana sucker, *C. santaanae*	20	18-22		17	17-18	1.7	EN*
		Shortnose sucker, *Chasmistes brevirostris*	26	21-26		20	19-21	1.6	EN
		Razorback sucker, *Xyrauchen texanus*	17	17-20		14	12-18	2.0	VU*

	Osmeridae								
		Eulachon, *Thaleichthys pacificus*	18	18-25		20	18-25	1.6	EN*
		Longfin smelt, *Spirinchus thaleichthys*	20	20-27		15	14-23	2.0	VU *
		Delta smelt, *Hypomesus pacificus*	15	13-17		12	11-13	1.4	EN*
	Salmonidae								
		Mountain whitefish, *Prosopium williamsoni*	30	26-33		21	17-22	3.9	NT
		Bull trout, *Salvelinus confluentus*	0			0		0.0	Extinct
		Upper Klamath-Trinity fall Chinook salmon, *Oncorhynchus tshawytscha*	24	21-28		18	15-21	2.4	VU
		Upper Klamath-Trinity spring Chinook salmon, *O. tshawytscha*	16	13-17		14	14-17	1.6	EN
		Southern Oregon Northern California coast fall Chinook salmon, *O. tshawytscha*	27	24-31		17	16-21	3.7	NT
		California Coast fall Chinook	23	19-26		18	15-20	2.4	VU *

		salmon, *O. tshawytscha*							
		Central Valley winter Chinook salmon, *O. tshawytscha*	18	16-18		12	10-14	2.0	VU *
		Central Valley spring Chinook salmon, *O. tshawytscha*	19	17-22		13	11-16	2.0	VU *
		Central Valley late fall Chinook salmon, *O. tshawytscha*	21	18-24		12	11-15	1.7	EN
		Central Valley fall Chinook salmon, *O. tshawytscha*	18	17-21		16	12-17	2.0	VU
		Central coast coho salmon, *O. kisutch*	14	14-20		16	13-19	1.1	EN*
		Southern Oregon Northern California coast coho salmon, *O. kisutch*	13	12-17		15	14-16	1.6	EN*
		Pink salmon, *O. gorbuscha*	17	16-24		16	15-21	1.3	EN
		Chum salmon, *O. keta*	19	18-28		18	15-21	1.6	EN
		Northern California coast winter steelhead, *O. mykiss*	24	20-27		17	16-21	3.3	NT*

		Northern California coast summer steelhead, *O. mykiss*	17	16-21		14	10-16	1.9	EN*
		Klamath Mountains Province winter steelhead, *O. mykiss*	27	20-27		21	19-21	3.9	NT
		Klamath Mountains Province summer steelhead, *O. mykiss*	17	16-21		11	11-14	1.7	EN
		Central California coast winter steelhead, *O. mykiss*	24	23-28		19	17-24	2.7	VU *
		Central Valley steelhead, *O. mykiss*						2.4	VU *
		South Central California coast steelhead, *O. mykiss*	23	19-27		19	17-24	2.4	VU *
		Southern California steelhead, *O. mykiss*	18	16-22		14	13-17	1.7	EN*
		Coastal rainbow trout, *O. m. irideus*	35	32-36		21	17-23	4.7	LC
		McCloud River redband trout, *O. m. stonei*	21	18-21		12	12-16	1.9	EN
		Goose Lake redband trout, *O. m. subsp.*	33	31-36		17	15-21	3.3	NT
		Eagle Lake rainbow trout, *O. m. aquilarum*	24	23-25		13	11-16	1.4	EN

		Kern River rainbow trout, *O. m. gilberti*	19	17-21		13	11-17	1.9	EN
		California golden trout, *O. m. aguabonita*	18	15-20		14	14-17	2.0	VU
		Little Kern golden trout, *O. m. whitei*	23	22-26		15	12-17	2.0	VU *
		Coastal cutthroat trout, *O. clarki clarki*	26	26-32		16	15-20	3.4	NT
		Paiute cutthroat trout, *O. c. seleneris*	27	27-28		14	13-17	1.7	EN*
		Lahontan cutthroat trout, *O. c. henshawi*	18	16-21		17	12-19	2.1	VU *
	Fundulidae								
		California killifish, *Fundulus parvipinnis*	31	26-32		22	18-24	4.1	LC
	Cyprinodontidae								
		Desert pupfish, *Cyprinodon macularius*	21	17-22		19	15-20	1.9	EN*
		Owens pupfish, *C. radiosus*	17	16-17		18	16-19	1.4	EN*
		Saratoga Springs pupfish, *C. n. nevadensis*	24	21-26		19	15-19	2.1	VU

		Amargosa River pupfish, *C. n. amargosae*	24	21-28		22	16-23	2.3	VU
		Tecopa pupfish, *C. n. calidae*	0			0		0.0	Extinct
		Shoshone pupfish, *C. n. shoshone*	15	14-17		14	11-15	1.1	EN
		Salt Creek pupfish, *C. s. salinus*	28	26-30		18	15-19	2.6	VU
		Cottonball Marsh pupfish, *C. s. milleri*	27	24-28		16	15-20	2.4	VU *
	Cottidae								
		Rough sculpin, *Cottus asperrimus*	27	23-27		17	15-17	3.4	NT*
		Bigeye marbled sculpin, *C. klamathensis macrops*	30	26-33		22	20-24	2.7	VU
		Lower Klamath marbled sculpin, *C.k. polyporus*	32	31-32		20	18-23	3.3	NT
		Upper Klamath marbled sculpin, *C. k. klamathensis*	24	20-28		19	17-24	3.0	NT
		Coastal Prickly sculpin, *C. asper subsp.*	37	32-37		28	25-30	4.7	LC
		Clear Lake prickly sculpin, *C. a. subsp.*	32	29-33		21	19-21	3.1	NT

		Coastrange sculpin, *C. aleuticus*	32	27-35		22	18-24	4.4	LC
		Riffle sculpin, *C. gulosus*	29	27-34		17	14-21	3.4	NT
		Pit sculpin, *C. pitensis*	28	24-32		18	16-20	4.3	LC
		Paiute sculpin, *C. beldingi*	32	28-33		20	19-24	4.4	LC
		Reticulate sculpin, *C. perplexus*	31	29-32		20	17-25	3.9	NT
		Staghorn sculpin, *Leptocottus armatus*	35	33-35		31	29-32		
	Gasterosteidae								
		Coastal threespine stickleback, *Gasterosteus a. aculeatus*	31	27-34		24	21-26	4.6	LC
		Inland threespine stickleback, *G. a. microcephalus*	32	28-34		21	15-23	4.1	LC
		Unarmored threespine stickleback, *G. a. williamsoni*	17	14-20		12	10-15	1.9	EN*
		Shay Creek stickleback, *G. a. subsp.*	14	13-17		12	10-14	1.3	EN
	Centrarchidae								
		Sacramento perch, *Archoplites*	23	23-25		18	18-18	1.6	EN

		interruptus							
	Embiotocidae								
		Sacramento tule perch, *Hysterocarpus t. traski*	25	21-30		17	16-20	3.4	NT
		Russian River tule perch, *H. t. pomo*	34	30-35		20	16-21	3.1	NT
		Clear Lake tule perch, *H. t. lagunae*	27	25-31		20	15-21	3.0	NT
	Gobiidae								
		Tidewater goby, *Eucyclogobius newberryi*	24	21-27		19	12-21	2.9	VU *
Alien (non-native) taxa									
		Clupeidae							
		American shad, *Alosa sapidissima*	28	27-32		19	16-23		RD
		Threadfin shad, *Dorosoma cepedianum*	37	36-39		27	25-29		WA
		Cyprinidae							
		Fathead minnow,*Pimephales promalas*	36	33-38		31	29-34		WA

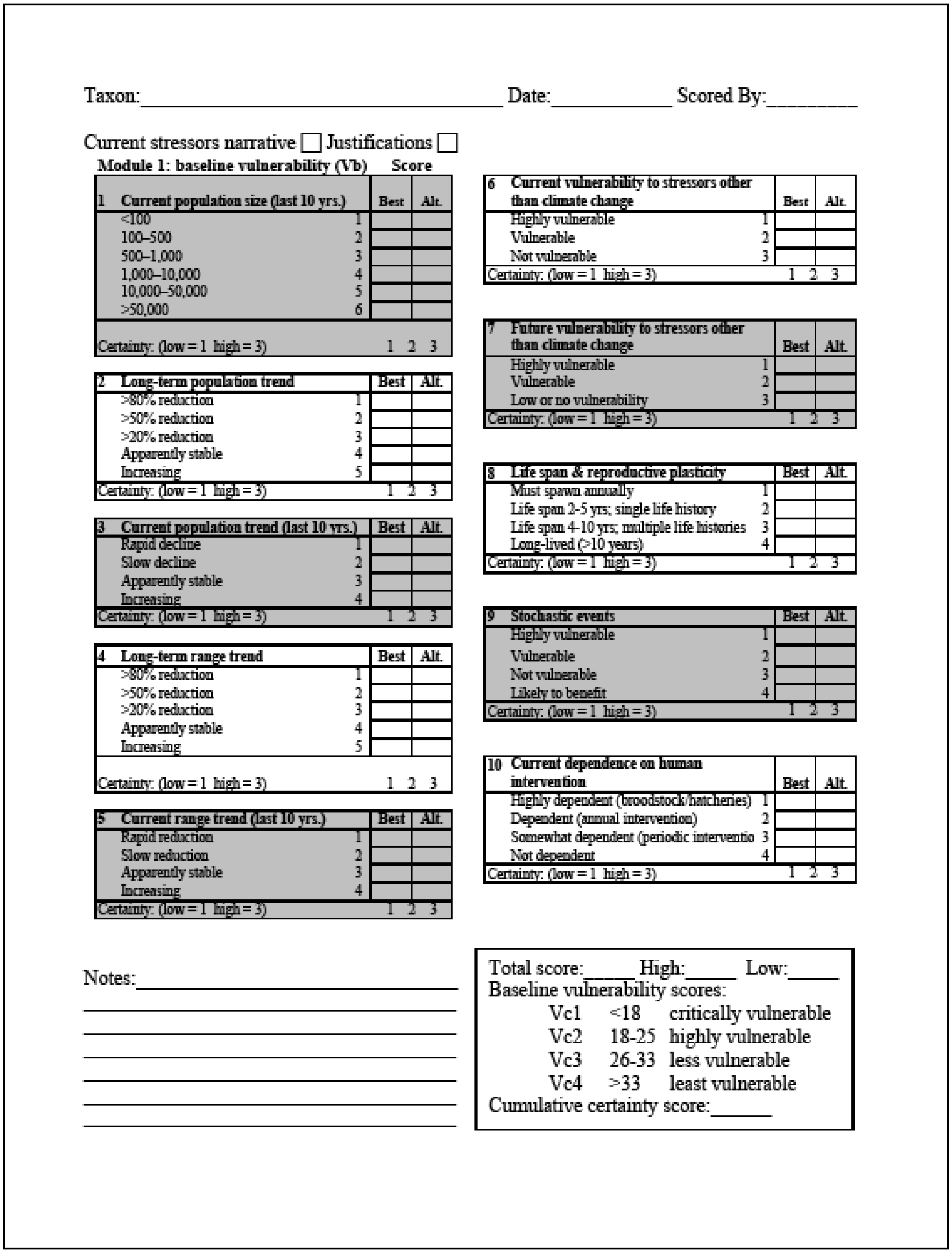
		Golden shiner, *Notemigonus chrysoleucas*	39	37-41		33	29-34		WA
		Red shiner. *Cyprinella lutrensis*	39	36-39		32	26-33		WA
		Goldfish, *Carassius auratus*	40	39-41		34	34-34		WA
		Common carp, *Cyprinus carpio*	39	38-42		32	30-34		WA
		Ictaluridae							
		Channel catfish, *Ictalurus punctatus*	40	39-42		27	25-30		WA
		Blue catfish. *I. furcatus*	39	35-41		25	24-29		RD
		White catfish, *Ameiurus catus*	38	38-41		31	27-31		WA
		Brown bullhead, *A. nebulosus*	37	37-40		32	31-33		WA
		Black bullhead, *A. melas*	39	37-40		35	32-35		WA
		Yellow bullhead. *A. natalis*	36	34-38		24	21-28		RD
		Flathead catfish, *Pylodictus olivaris*	39	38-41		32	27-34		WA
		Salmonidae							
		Brook trout, *Salvelinus fontinalis*	34	34-38		19	15-22		WA
		Lake trout, *S. namaycush*	37	34-40		18	15-20		RD

		Brown trout, *Salmo trutta*	34	32-38		20	17-22		WA
		Kokanee, *Oncorhynchus nerka*	39	34-39		17	16-19		WA
		Colorado cutthroat trout, *O. clarki pleuriticus*	28	27-29		20	16-20		RD
	Atherinopsidae								
		Mississippi silverside. *Menidia audens*	38	36-38		31	27-33		WA
	Poeciliidae								
		Western mosquitofish, *Gambusia affinis*	38	36-39		34	29-35		WA
		Sailfin molly, *Molliensia latipinnis*	37	36-40		30	28-34		WA
		Porthole livebearer, *Poecilopsis gracilis*	32	30-34		22	17-26		RD
	Fundulidae								
		Rainwater killifish, *Lucania parva*	34	31-37		24	21-27		RD
		Moronidae							
		Striped bass, *Morone saxatilis*	28	26-32		23	20-24		WA
		White bass, *M. chrysops*	37	35-38		21	20-25		RD

	Percidae								
		Yellow perch, *Perca flavescens*	39	36-39		26	21-27		WA
		Bigscale logperch, *Percina macrolepida*	36	36-40		27	22-30		WA
	Centrarchidae								
		Green sunfish, *Lepomis cyanellus*	39	37-41		34	31-35		WA
		Redear sunfish, *L. microlophus*	39	36-41		30	26-31		WA
		Bluegill, *L. macrochirus*	39	36-40		30	27-32		WA
		Pumpkinseed, *L. gibbosus*	39	37-40		31	31-34		WA
		Warmouth, *L. gulosus*	35	31-40		29	25-30		WA
		Black crappie, *Pomoxis nigromaculatus*	38	36-39		27	25-30		WA
		White crappie, *P. annularis*	36	34-39		27	25-29		WA
		Smallmouth bass, *Micropterus dolomieui*	36	35-37		29	26-30		WA
		Largemouth bass, *M. salmoides*	39	36-41		30	28-33		WA
		Spotted bass, *M. punctulatus*	38	36-38		28	28-31		WA
		Redeye bass, *M. coosae*	33	32-36		30	26-33		WA

	Cichlidae								
		California tilapia, *Oreochromis sp.*	38	37-40		34	29-35		WA
		Redbelly tilapia, *Tilapia zilli*	36	32-36		27	25-29		RD
	Gobiidae								
		Yellowfin goby, *Acanthogobius flavimanus*	40	35-40		26	23-29		WA
		Shimofuri goby, *Tridentiger bifasciatus*	35	31-37		28	21-29		WA

Appendix B: Forms Used to Evaluate Vulnerability



Taxon:________________________________ Date:___________ Scored By:________

Current stressors narrative ☐ Justifications ☐

Module 1: baseline vulnerability (Vb) **Score**

1	**Current population size (last 10 yrs.)**		**Best**	**Alt.**
	<100	1		
	100–500	2		
	500–1,000	3		
	1,000–10,000	4		
	10,000–50,000	5		
	>50,000	6		
Certainty: (low = 1 high = 3)			1 2 3	

2	**Long-term population trend**		**Best**	**Alt.**
	>80% reduction	1		
	>50% reduction	2		
	>20% reduction	3		
	Apparently stable	4		
	Increasing	5		
Certainty: (low = 1 high = 3)			1 2 3	

3	**Current population trend (last 10 yrs.)**		**Best**	**Alt.**
	Rapid decline	1		
	Slow decline	2		
	Apparently stable	3		
	Increasing	4		
Certainty: (low = 1 high = 3)			1 2 3	

4	**Long-term range trend**		**Best**	**Alt.**
	>80% reduction	1		
	>50% reduction	2		
	>20% reduction	3		
	Apparently stable	4		
	Increasing	5		
Certainty: (low = 1 high = 3)			1 2 3	

5	**Current range trend (last 10 yrs.)**		**Best**	**Alt.**
	Rapid reduction	1		
	Slow reduction	2		
	Apparently stable	3		
	Increasing	4		
Certainty: (low = 1 high = 3)			1 2 3	

6	**Current vulnerability to stressors other than climate change**		**Best**	**Alt.**
	Highly vulnerable	1		
	Vulnerable	2		
	Not vulnerable	3		
Certainty: (low = 1 high = 3)			1 2 3	

7	**Future vulnerability to stressors other than climate change**		**Best**	**Alt.**
	Highly vulnerable	1		
	Vulnerable	2		
	Low or no vulnerability	3		
Certainty: (low = 1 high = 3)			1 2 3	

8	**Life span & reproductive plasticity**		**Best**	**Alt.**
	Must spawn annually	1		
	Life span 2-5 yrs; single life history	2		
	Life span 4-10 yrs; multiple life histories	3		
	Long-lived (>10 years)	4		
Certainty: (low = 1 high = 3)			1 2 3	

9	**Stochastic events**		**Best**	**Alt.**
	Highly vulnerable	1		
	Vulnerable	2		
	Not vulnerable	3		
	Likely to benefit	4		
Certainty: (low = 1 high = 3)			1 2 3	

10	**Current dependence on human intervention**		**Best**	**Alt.**
	Highly dependent (broodstock/hatcheries)	1		
	Dependent (annual intervention)	2		
	Somewhat dependent (periodic interventio	3		
	Not dependent	4		
Certainty: (low = 1 high = 3)			1 2 3	

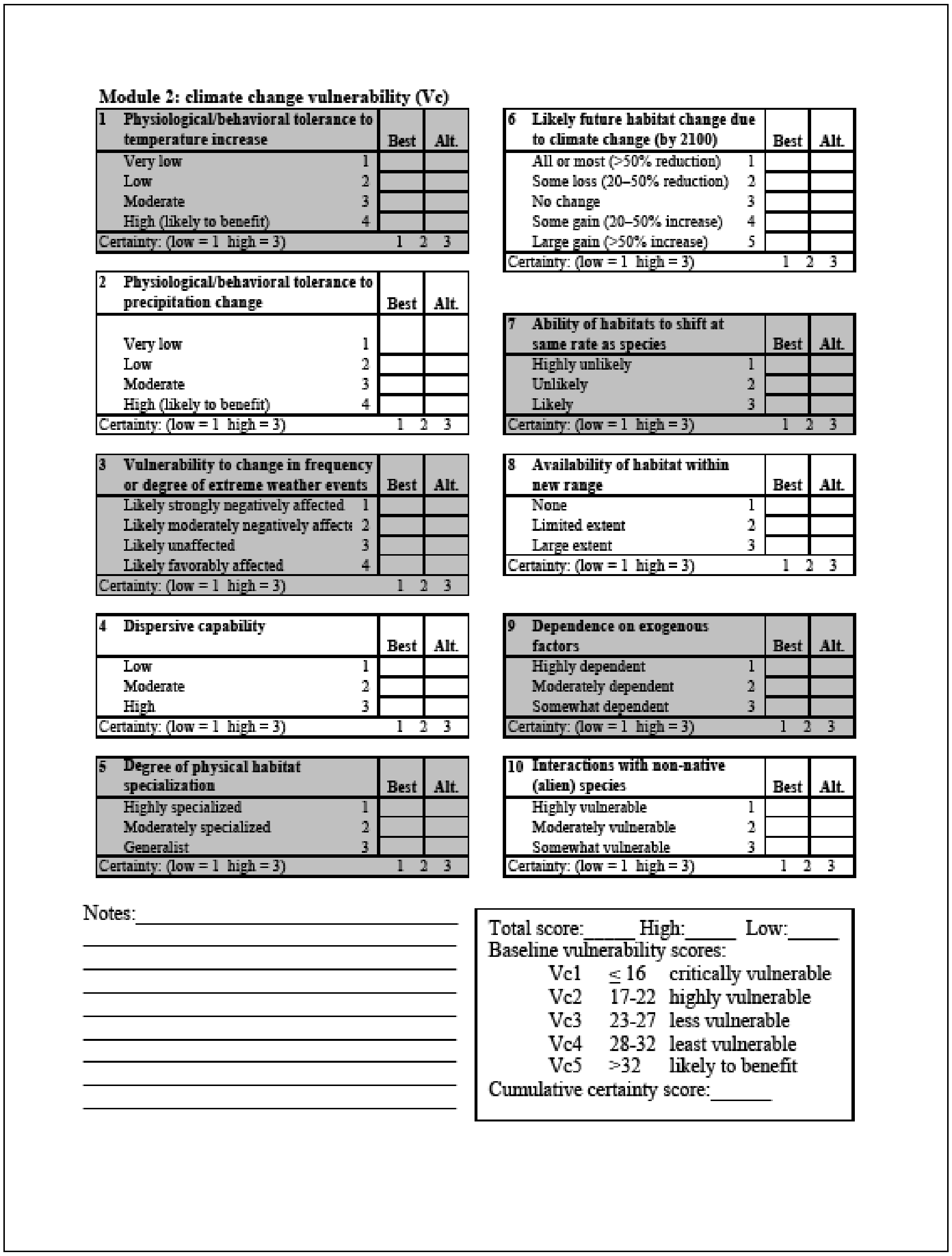
Notes:______________________________
____
____
____
____
____
____

Total score:_____ High:_____ Low:_____
Baseline vulnerability scores:

Vc1	<18	critically vulnerable
Vc2	18-25	highly vulnerable
Vc3	26-33	less vulnerable
Vc4	>33	least vulnerable

Cumulative certainty score:______

Figure B-1. Score Sheet for the 10 Metrics Used to Assess a Fish Species Baseline Vulnerability (Module 1)



Module 2: climate change vulnerability (Vc)

1	**Physiological/behavioral tolerance to temperature increase**		**Best**	**Alt.**
	Very low	1		
	Low	2		
	Moderate	3		
	High (likely to benefit)	4		
Certainty: (low = 1 high = 3)			1 2 3	

2	**Physiological/behavioral tolerance to precipitation change**		**Best**	**Alt.**
	Very low	1		
	Low	2		
	Moderate	3		
	High (likely to benefit)	4		
Certainty: (low = 1 high = 3)			1 2 3	

3	**Vulnerability to change in frequency or degree of extreme weather events**		**Best**	**Alt.**
	Likely strongly negatively affected	1		
	Likely moderately negatively affect	2		
	Likely unaffected	3		
	Likely favorably affected	4		
Certainty: (low = 1 high = 3)			1 2 3	

4	**Dispersive capability**		**Best**	**Alt.**
	Low	1		
	Moderate	2		
	High	3		
Certainty: (low = 1 high = 3)			1 2 3	

5	**Degree of physical habitat specialization**		**Best**	**Alt.**
	Highly specialized	1		
	Moderately specialized	2		
	Generalist	3		
Certainty: (low = 1 high = 3)			1 2 3	

6	**Likely future habitat change due to climate change (by 2100)**		**Best**	**Alt.**
	All or most (>50% reduction)	1		
	Some loss (20–50% reduction)	2		
	No change	3		
	Some gain (20–50% increase)	4		
	Large gain (>50% increase)	5		
Certainty: (low = 1 high = 3)			1 2 3	

7	**Ability of habitats to shift at same rate as species**		**Best**	**Alt.**
	Highly unlikely	1		
	Unlikely	2		
	Likely	3		
Certainty: (low = 1 high = 3)			1 2 3	

8	**Availability of habitat within new range**		**Best**	**Alt.**
	None	1		
	Limited extent	2		
	Large extent	3		
Certainty: (low = 1 high = 3)			1 2 3	

9	**Dependence on exogenous factors**		**Best**	**Alt.**
	Highly dependent	1		
	Moderately dependent	2		
	Somewhat dependent	3		
Certainty: (low = 1 high = 3)			1 2 3	

10	**Interactions with non-native (alien) species**		**Best**	**Alt.**
	Highly vulnerable	1		
	Moderately vulnerable	2		
	Somewhat vulnerable	3		
Certainty: (low = 1 high = 3)			1 2 3	

Notes:______________________________

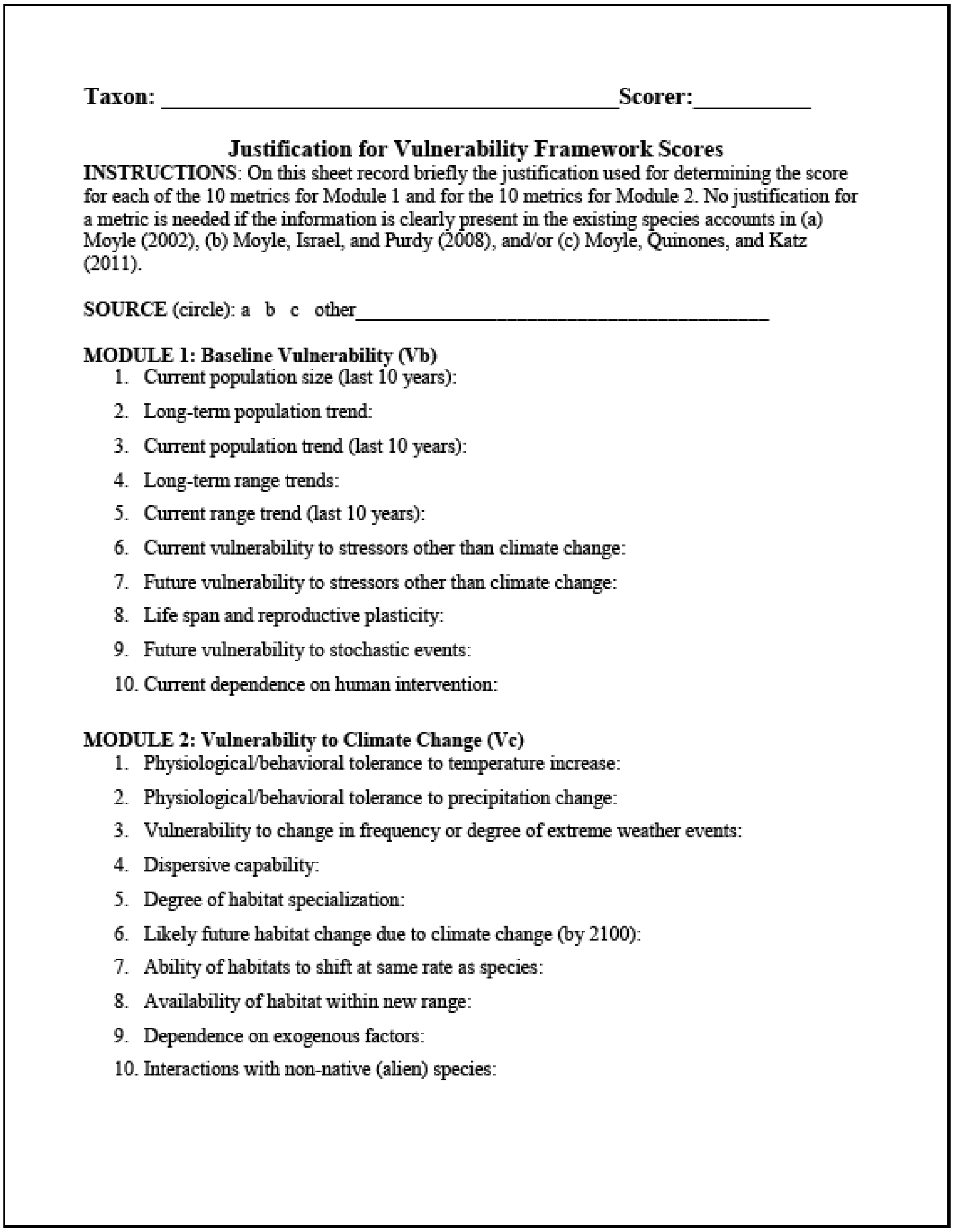
Total score:_____ High:_____ Low:_____

Baseline vulnerability scores:

Vc1	≤ 16	critically vulnerable
Vc2	17-22	highly vulnerable
Vc3	23-27	less vulnerable
Vc4	28-32	least vulnerable
Vc5	>32	likely to benefit

Cumulative certainty score:______

Figure B-2. Score Sheet Illustrating the 10 Metrics Used to Assess a Fish Species Vulnerability to Climate Change (Module 2)



Taxon: ____ **Scorer:**__________

Justification for Vulnerability Framework Scores

INSTRUCTIONS: On this sheet record briefly the justification used for determining the score for each of the 10 metrics for Module 1 and for the 10 metrics for Module 2. No justification for a metric is needed if the information is clearly present in the existing species accounts in (a) Moyle (2002), (b) Moyle, Israel, and Purdy (2008), and/or (c) Moyle, Quinones, and Katz (2011).

SOURCE (circle): a b c other____

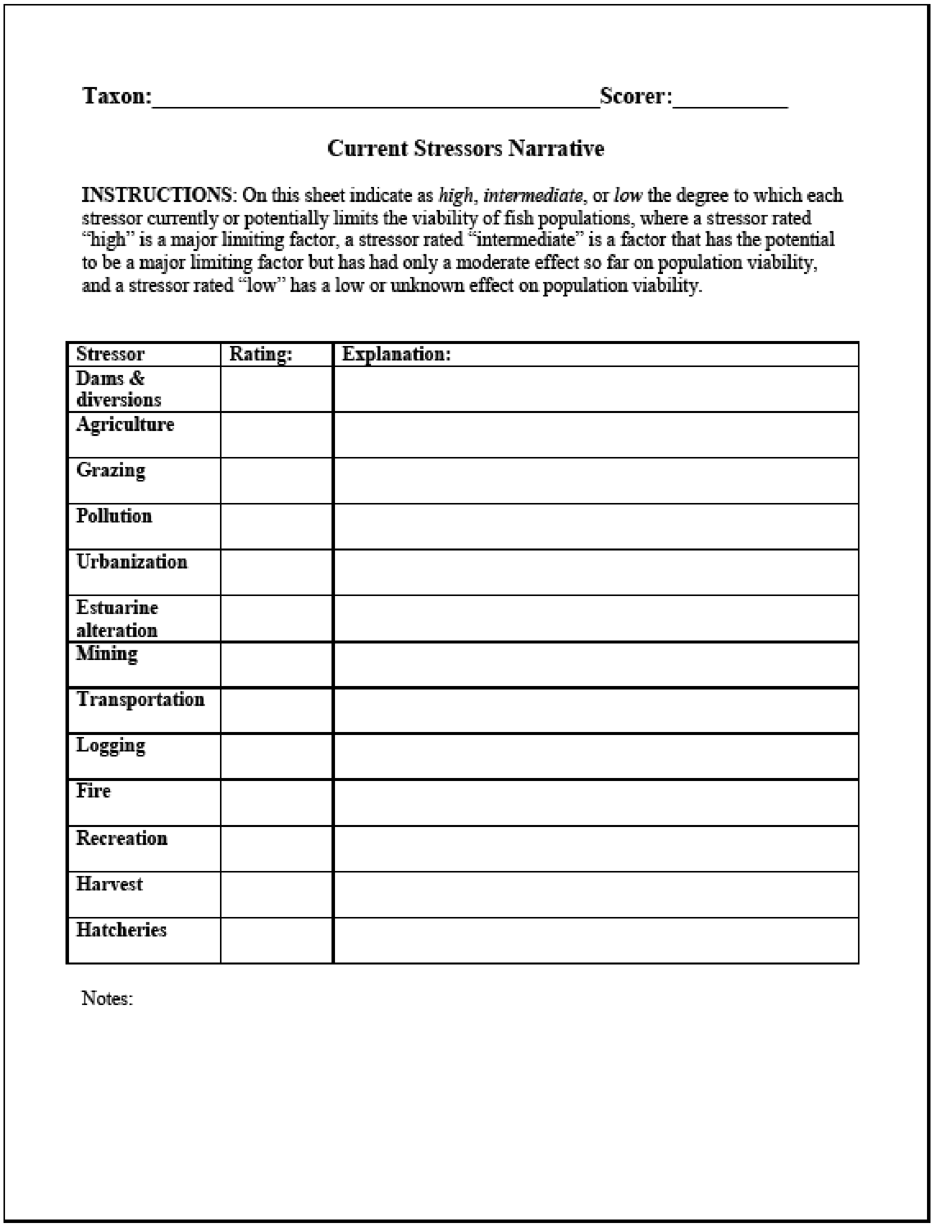
MODULE 1: Baseline Vulnerability (Vb)

1. Current population size (last 10 years):
2. Long-term population trend:
3. Current population trend (last 10 years):
4. Long-term range trends:
5. Current range trend (last 10 years):
6. Current vulnerability to stressors other than climate change:
7. Future vulnerability to stressors other than climate change:
8. Life span and reproductive plasticity:
9. Future vulnerability to stochastic events:
10. Current dependence on human intervention:

MODULE 2: Vulnerability to Climate Change (Vc)

1. Physiological/behavioral tolerance to temperature increase:
2. Physiological/behavioral tolerance to precipitation change:
3. Vulnerability to change in frequency or degree of extreme weather events:
4. Dispersive capability:
5. Degree of habitat specialization:
6. Likely future habitat change due to climate change (by 2100):
7. Ability of habitats to shift at same rate as species:
8. Availability of habitat within new range:
9. Dependence on exogenous factors:
10. Interactions with non-native (alien) species:

Figure B-3. Template for Recording Justifications for Scores of Each Metric



Taxon:___________________________________**Scorer:**__________

Current Stressors Narrative

INSTRUCTIONS: On this sheet indicate as *high*, *intermediate*, or *low* the degree to which each stressor currently or potentially limits the viability of fish populations, where a stressor rated "high" is a major limiting factor, a stressor rated "intermediate" is a factor that has the potential to be a major limiting factor but has had only a moderate effect so far on population viability, and a stressor rated "low" has a low or unknown effect on population viability.

Stressor	Rating:	Explanation:
Dams & diversions		
Agriculture		
Grazing		
Pollution		
Urbanization		
Estuarine alteration		
Mining		
Transportation		
Logging		
Fire		
Recreation		
Harvest		
Hatcheries		

Notes:

Figure B-4. Sheet Used to Record General Stressors Likely to Be Limiting Range and Abundance of Fish Species at the Present Time