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Climate Change Vulnerability of Freshwater Fishes of the San Francisco Bay Area

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Climate change is expected to progressively shift the freshwater environments of the San Francisco Bay Area (SFBA) to states that favor alien fishes over native species. Native species likely will have more limited distributions and some may be extirpated. Stream-dependent species may decline as portions of streams dry or become warmer due to lower flows and increased air temperatures. However, factors other than climate change may pose a more immediate threat to native fishes. Comparison of regional vs. statewide vulnerability (baseline and climate change) scores suggests that a higher proportion (56% vs. 50%) of SFBA native species, as compared to the state's entire fish fauna, are vulnerable to existing anthropogenic threats that result in habitat degradation. In comparison, a smaller proportion of SFBA native species are vulnerable to predicted climate change effects (67% vs. 82%). In the SFBA, adverse effects from climate change likely come second to estuarine alteration, agriculture, and dams. However, the relative effect of climate change on species likely will grow in an increasingly warmer and drier California. Maintaining representative assemblages of native fishes may require providing flow regimes downstream from dams that reflect more natural hydrographs, extensive riparian, stream, and estuarine habitat restoration, and other management actions, such as modification of hatchery operations.

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ABSTRACT

Climate change is expected to progressively shift the freshwater environments of the San Francisco Bay Area (SFBA) to states that favor alien fishes over native species. Native species likely will have more limited distributions and some may be extirpated. Stream-dependent species may decline as portions of streams dry or become warmer due to lower flows and increased air temperatures. However, factors other than climate change may pose a more immediate threat to native fishes. Comparison of regional vs. statewide vulnerability (baseline and climate change) scores suggests that a higher proportion (56% vs. 50%) of SFBA native species, as compared to the state's entire fish fauna, are vulnerable to existing anthropogenic threats that result in habitat degradation. In comparison, a smaller proportion of SFBA native species are vulnerable to predicted climate change effects (67% vs. 82%). In the SFBA, adverse effects from climate change likely come second to estuarine alteration, agriculture, and dams. However, the relative effect of climate change on species likely will grow in an increasingly warmer and drier California. Maintaining representative assemblages of native fishes may require providing flow regimes downstream from dams that reflect more natural hydrographs, extensive riparian, stream, and estuarine habitat restoration, and other management actions, such as modification of hatchery operations.

KEY WORDS

vulnerability assessment, native fishes, alien species

INTRODUCTION

In a recent paper, we suggested that a majority of California's native inland (largely freshwater) fishes will be hastened to extinction by climate change effects on already deteriorating populations (Moyle et al. 2013). We also presented a methodology to systematically evaluate vulnerability to extinction or extirpation as a result of baseline conditions (i.e., existing anthropogenic threats) and to new conditions created by climate change (e.g., warmer temperatures, altered stream flows). But climate change is not affecting California uniformly. Regions within the state will experience alterations to temperature and hydrologic patterns in different ways (e.g., Cayan et al. 2008), depending, for example, on their proximity to the ocean or median elevation. Existing threats to freshwater fishes (as defined in Moyle 2002) also differ among regions of the state. Consequently, vulnerability of species to extinction or extirpation must be assessed at regional scales in order to increase the efficacy of conservation actions. Here, we rate baseline, climate change, and overall vulnerabilities (as in Moyle et al. 2013) of freshwater fishes in the San Francisco Bay area (SFBA), as the first in a series of analyses to address vulnerability to extinction of freshwater fishes in different regions of the state. We define SFBA to include all tidally influenced freshwater habitats (e.g., Cache Slough) and streams flowing into the San Francisco Estuary (estuary) and Sacramento–San Joaquin Delta (Delta).

Freshwater fishes in SFBA represent a regional fish fauna that has been well-studied (Moyle 2002; Leidy 2007; Cloern and Jassby 2012). The extant SFBA inland fish fauna is comprised of about equal parts native (25) and alien (23) species (Tables 1 and 2). The status of pink (*Oncorhynchus gorbuscha*) and chum (*O. keta*) salmon in the area is uncertain and so they were not included in our analysis. The aquatic ecosystems of which these species are part are already highly altered (e.g., through draining and diking, changes in nutrient cycling, introductions of alien species etc.) and so can be regarded as novel ecosystems (Hobbs et al. 2006), with poorly understood structure and function. Leidy et al. (2011) have shown that so far most native fishes have done remarkably well in streams of the SFBA, although populations are often fragmented and require releases of water from dams. Estuary-dependent freshwater fishes are doing much worse (e.g., Feyrer et al. 2007; Sommer et al. 2007). Both environments have experienced extirpations of species such as coho salmon (*O. kisutch*), coastrange sculpin (*Cottus aleuticus*), thicktail chub (*Gila crassicauda*), and Sacramento perch (*Archoplites interruptus*). Coho salmon and coastrange sculpin were historically uncommon in the SFBA, but thicktail chub and Sacramento perch were once among the most abundant species (Moyle 2002; Leidy 2007). Another goal of this paper is to evaluate the threats that native fishes face in the SFBA.

MATERIALS AND METHODS

We evaluated major threats (a.k.a. anthropogenic causes of decline) to native fishes in SFBA as in Moyle et al. (2011). Threats to each species were rated as critical, high, medium, low, or none, based on available gray and primary literature, and authors' expert opinion. The threats considered were major dams, agriculture, grazing, rural residential development, urbanization, instream mining, hard-rock mining, transportation, logging, wildfire, estuarine alteration, recreation, harvest, hatcheries, and alien species (Table 3). Full descriptions of threats considered, and the rubric used to develop overall threat ratings, are available in Moyle et al. (2011).

We also reviewed all available gray and primary literature and used expert opinion to rate species' baseline, climate change, and overall vulnerabilities to extinction or extirpation in the next 100 years. Ratings were calculated as in Moyle et al. (2013). Ten metrics were scored within each of two categories: baseline vulnerability (vulnerability to existing threats) and climate change vulnerability. Baseline vulnerability provided a measure of species declines from potential threats other than climate change. Baseline vulnerability metrics were current population size, long-term population trend, current population trend, long-term range trend, current range trend, current vulnerability to threats, future vulnerability to threats, life span and reproductive plasticity, vulnerability to stochastic events, and dependence on human intervention. In contrast, climate change vulnerability provided a measure of the ability of species to respond to predicted climate change effects. Climate change vulnerability metrics were as follows:

- physiological and behavioral tolerances to temperature increase,
- physiological and behavioral tolerances to precipitation change,
- vulnerability to extreme weather events,
- dispersive capability,
- degree of habitat specialization,
- likely future habitat change,
- ability of species to shift at the same rate as habitat,
- availability of habitat within new range,
- dependence on exogenous factors, and
- vulnerability to alien species.

Table 1 Baseline (Vb), climate change (Vc), and overall (Vo) vulnerabilities of extant native species (n = 25) in the SFBA (modified where applicable from statewide scores in Moyle et al. [2013]). C = critically vulnerable, H = highly vulnerable, V = less vulnerable, L = least vulnerable, B = likely to benefit. Superscript symbols denote increases (+) or decreases (–) in vulnerability as compared to statewide scores.

Native species		Vulnerabilities		
Common name	**Scientific name**	**Baseline (Vb)**	**Climate change (Vc)**	**Overall (Vo)**
Delta smelt	*Hypomesus transpacificus*	C	C	C
Central Valley fall Chinook salmon	*Oncorhynchus tshawytscha*	C	C	C
Central Valley late fall Chinook salmon	*Oncorhynchus tshawytscha*	C	C	C
Central Valley winter Chinook salmon	*Oncorhynchus tshawytscha*	C	C	C
Central Valley spring Chinook salmon	*Oncorhynchus tshawytscha*	C	C	C
Longfin smelt	*Spirinchus thaleichthys*	H	C	H
Sacramento perch [a]	*Archoplites interruptus*	H	H	C
River lamprey	*Lampetra ayersi*	H	C+	C
Western brook lamprey	*Lampetra richardsoni*	H+	H	C+
Pacific lamprey	*Entosphenus tridentatus*	H	H	H
Central California Coast steelhead	*Oncorhynchus mykiss*	H	H	H
White sturgeon	*Acipenser transmontanus*	H	H	H
Sacramento tule perch	*Hysterocarpus traskii traskii*	H	H	H
Southern green sturgeon	*Acipenser medirostris*	H	V	H
Hardhead	*Mylopharodon conocephalus*	V–	C	H–
Sacramento splittail	*Pogonichthys macrolepidotus*	V	H	H
Riffle sculpin	*Cottus gulosus*	V	H	H
Sacramento speckled dace	*Rhinichthys osculus*	V	H	V
Sacramento hitch	*Lavinia exilicauda*	H	V	V
Sacramento blackfish	*Orthodon microlepidotus*	V	L	V
Central California roach	*Lavinia symmetricus*	V	V	V
Coastal threespine stickleback	*Gasterosteus aculeatus*	V	V	V
Sacramento sucker	*Catostomus occidentalis*	V	V	V
Sacramento pikeminnow	*Ptychocheilus grandis*	V	V	V
Prickly sculpin	*Cottus asper*	L	L	L

a Extinct in its native range but translocated within SFBA.

Full descriptions of metrics are available in Moyle et al. (2013). Maximum metric scores ranged from 3 to 6, depending on their relative effect on vulnerability. Scores were then binned into categories from critically vulnerable to least vulnerable to rate baseline vulnerability (Vb), and from critically vulnerable to likely benefit for climate change vulnerability (Vc). The two ratings were then combined to calculate an overall vulnerability (Vo) to extinction (Tables 1 and 2). SFBA vulnerability scores were subsequently compared to scores calculated in Moyle et al. (2013) of the entire statewide fish fauna.

RESULTS

Fifteen SFBA native species were found to be critically (n = 5) or highly vulnerable (n = 10) to extinction from threats other than climate change (Vb; baseline vulnerability) (Table 1). The one major threat shared by all but two (Sacramento perch, Western brook lamprey *Lampetra richardsoni*) critically or highly vulnerable species was estuarine alteration; these were mostly (86%) estuarine or anadromous species. No alien fish species, in contrast, was rated as critically or highly vulnerable to extinction (Table 2). Only two species (American shad *Alosa sapidissima*,

Table 2 Baseline (Vb), climate change (Vc), and overall (Vo) vulnerabilities of alien species in the SFBA. (Modified from statewide scores in Moyle et al. [2013], where applicable). C = critically vulnerable, H = highly vulnerable, V = less vulnerable, L = least vulnerable, B = likely to benefit. Superscript symbols denote increases (+) or decreases (–) in vulnerability as compared to statewide scores. Vulnerability scores for alien species are the same on both SFBA and statewide scales.

Alien Species		Vulnerabilities		
Common name	**Scientific name**	**Baseline (V_b)**	**Climate Change (V_c)**	**Overall (V_o)**
American shad	*Alosa sapidissima*	V	H	V
Striped bass	*Morone saxatilis*	V	H	V
Brown trout	*Salmo trutta*	L	H	V
Rainwater killifish	*Lucania parva*	L	V	L
Shimofuri goby	*Tridentiger bifasciatus*	L	V	L
Fathead minnow	*Pimephales promelas*	L	L	L
Smallmouth bass	*Micropterus dolomieu*	L	L	L
Bigscale logperch	*Percina macrolepida*	L	V	L
Threadfin shad	*Dorosoma petenense*	L	V	L
Brown bullhead	*Ameiurus nebulosus*	L	L	L
White catfish	*Ameiurus catus*	L	L	L
Western mosquitofish	*Gambusia affinis*	L	B	L
Mississippi silverside	*Menidia audens*	L	L	L
Black crappie	*Pomoxis nigromaculatus*	L	V	L
Common carp	*Cyprinus carpio*	L	L	L
Golden shiner	*Notemigonus crysoleucas*	L	L	L
Black bullhead	*Ameiurus melas*	L	B	L
Bluegill	*Lepomis microchirus*	L	L	L
Redear sunfish	*Lepomis microlophus*	L	L	L
Green sunfish	*Lepomis cyanellus*	L	B	L
Largemouth bass	*Micropterus salmoides*	L	L	L
Goldfish	*Carassius auratus*	L	B	L
Channel catfish	*Ictalurus punctatus*	L	V	L

striped bass *Morone saxatilis*) were rated as less vulnerable while the rest of the alien fishes rated as having least vulnerability (Table 2).

Upon rating how climate change will likely increase vulnerability to extinction, eight native species were found to be critically vulnerable, while nine, six, and two species were rated as highly vulnerable, less vulnerable and least vulnerable, respectively (Table 1). No native species were rated as likely to benefit from climate change. In comparison, alien species rated mostly as less vulnerable (n = 6) and least vulnerable (n = 10). No alien species were rated as critically vulnerable, but three rated as highly vulnerable and four rated as likely to benefit from climate change (Table 2).

The combined baseline and climate change vulnerability ratings (Vo; Figure 1) indicated that native fishes already in decline are likely to continue to do so into the future, while most alien species will likely persist (as in Leidy 2007; Leidy et al. 2011). Loss of aquatic habitat (e.g., dry streams) resulting from climate change should adversely affect both groups (Moyle et al. 2013).

Comparison of species vulnerabilities at the state and regional scales suggests that SFBA fishes are more immediately threatened by existing threats than climate change. About 56% of SFBA fishes scored as critically or highly vulnerable to existing threats (Vb) as compared to 50% statewide (n = 129 native species; see Moyle et al. 2013). The reverse was true for

Table 3 Potential anthropogenic threats, not including climate change, to native fishes in the SFBA. (Source: Moyle et al. 2013.)

POTENTIAL ANTHROPOGENIC THREAT	CONSIDERATIONS
Large dams	Effects to species if migration is blocked; effects to habitat quality from alterations of physical, chemical, and biological properties
Agriculture	Effects to habitat quantity from diversions; effects to habitat quality from increased erosion and pollution (from pesticides etc.)
Grazing	Effects to habitat quality from livestock trampling of banks, removal of vegetation, lowering of water tables, and pollution
Rural residential development	Effects to habitat quality from water removal, streambed alteration, and pollution
Urbanization	Effects to habitat quantity from water removal, diking, and armoring; effects to habitat quality from sewage and impervious surface runoff
Instream mining	Effects to habitat quantity from excavation and dredging; effects to habitat quality from erosion of stream banks
Hard-rock mining	Effects to habitat quality from pollution (e.g., acidic drainage)
Transportation	Effects to habitat quality from pollution (e.g., siltation, vehicle emissions)
Logging	Effects to habitat quality from siltation and reduction of habitat heterogeneity
Wildfire	Effects to habitat quality from erosion, vegetation removal, and pollution (e.g., from fire-fighting chemicals)
Estuarine alteration	Effects to habitat quantity from diking, draining, and filling; effects to habitat quality from siltation, pollution, and sand bar removal
Recreation	Effects to habitat quality from erosion, vegetation removal, and disruption of fish migration refuges (i.e. holding habitat)
Harvest	Effects to species numbers from legal and illegal harvest
Hatcheries	Effects to species genetic, morphological, and behavioral characteristics; potential for interbreeding between wild and hatchery-produced fishes
Alien species	Effects to species from hybridization, competition, predation, and disease transmission

climate change vulnerability scores; a smaller proportion (67%) of SFBA fishes scored (Vc) as critically or highly vulnerable to predicted climate change effects as compared to 82% statewide (Moyle et al. 2013). However, these comparisons should be seen as general patterns rather than predictions because of the high correlation between data sets (r = 0.69).

Of the threats considered, three (agriculture, dams, estuarine alteration) were major threats to 45% of the native fish fauna in SFBA; while another three (alien species, harvest, urbanization) were major threats to another 24% of native fishes (Figure 2). In this context, estuarine alteration was a measure of changes to the configuration and function of the estuary through diking, draining and filling. Urbanization, in contrast, considered changes on the landscape related to increases in impervious surfaces and potential sources of pollution (e.g., runoff from gardens and roads) associated with developed areas.

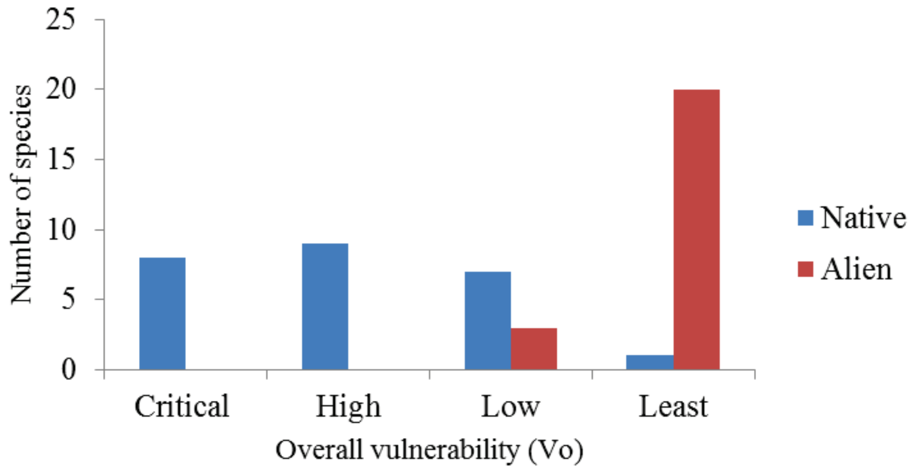

Figure 1 Estimated overall vulnerability (Vo) to extinction (baseline and climate change vulnerabilities combined) of extant native and alien freshwater fish species in the SFBA

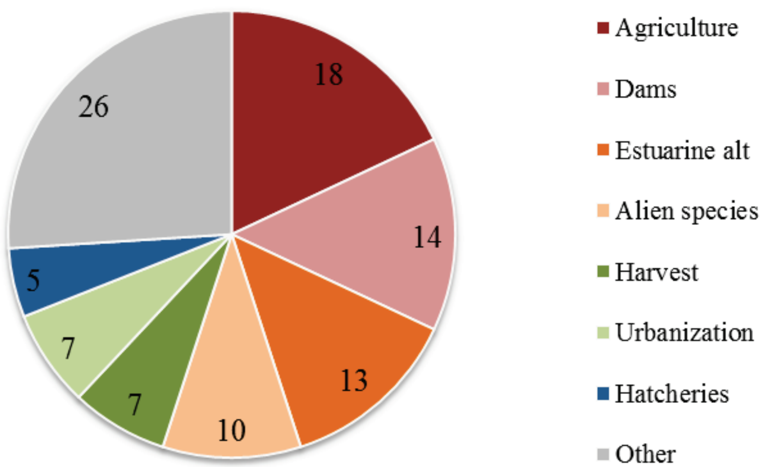

Figure 2 Percent of native freshwater species affected by major threats that exist in the SFBA. Estuarine alt = estuarine alteration. See Table 3 for definitions.

DISCUSSION

Though the reasons for native fish species declines are multiple, most native species have reduced, more isolated populations with a long history of decline (Moyle 2002; Moyle et al. 2011). This is especially true of species adapted to estuarine conditions, much altered since the 19th century (reviewed in Booker 2013). Many native species prefer cool (<22° C), perennial streams (e.g., Alameda Creek), which are increasingly being diminished in SFBA watersheds.

Some native fishes persist in protected headwaters, in streams with drought refuges (including some reservoirs), and in areas where alien species are scarce (Leidy 2007). Some species that persist are euryhaline or among the most physiologically tolerant of the species (Leidy et al. 2011). However, many native species also are unable to colonize new habitats because of their inability to migrate among watersheds through saltwater habitats or around natural or man-made barriers.

Overall, climate change is expected to progressively shift the nature of SFBA aquatic habitats (Cloern et al. 2011) so that alien fishes are favored over native species. A number of native species are expected to have more limited distributions (e.g., California roach, *Lavinia symmetricus*; tule perch, *Hysterocarpus traskii traskii*), while some may become extirpated (e.g., hardhead, *Mylopharodon conocephalus*; delta smelt, *Hypomesus transpacificus*), similar to the recent extirpation of coho salmon. Stream-dependent species likely will decline as portions of streams dry or become warmer because of lower flows and increasing air temperatures. There will be relatively more aquatic habitat in impoundments, which mostly favor alien fishes, than in surface streams, although dam releases may be used to enhance late summer flows to favor native fishes in some streams (Leidy et al. 2011). Extended periods of drought will likely shrink suitable habitat for most native species, especially in cool streams. Shrinking habitats will likely result in declining abundances, a situation exacerbated by interactions with alien species (Leidy et al. 2001; Moyle et al. 2013). Alien fishes, on the other hand, generally thrive in altered aquatic habitats because they usually have less restricted environmental tolerances (Novak et al. 2011).

CONCLUSIONS

Maintaining representative assemblages of native fishes in SFBA will require considerable conservation effort. If action is not taken soon, listing of more fish species under state and federal endangered species acts will likely occur. Such listings may lead to mandated large-scale, species-oriented actions, rather than more desirable actions aimed at enhancing entire ecosystems, and the native biota they support. Conservation should also address potential extinction debts already accrued by many SFBA native fishes due to the magnitude (most SFBA freshwater ecosystems) and duration (since the 1800s) of habitat degradation. If this is the case, many species may already be irrevocably moving towards extinction, which has not yet occurred because of delayed effects from population declines and metapopulation fragmentation (Hylander and Ehrlén 2013). Conservation plans should furthermore consider species interactions which can create and intensify extinction debt (Norberg et al. 2012).

Because climate change is expected to exacerbate the negative effects of existing conditions, we recommend ameliorating existing threats as a way to improve the probability of native fish survival into the future. Based on our threats assessment, reform of agricultural practices and dam operations, and restoration of estuarine habitats may have the greatest effect on SFBA native fish conservation. However, each species has its own distinctive array of factors that affect its ability to persist through this century.

RECOMMENDATIONS

We offer the following recommendations for improving the status of native fishes:

- Re-operate dams wherever possible to provide flow regimes in regulated streams that favor native fishes.
- Increase the rate of restoration of riparian, stream, and estuarine habitats.
- Actively manage floodplain areas known to be important spawning and rearing areas for some fish species (e.g., Sacramento splittail, *Pogonichthys macrolepidotus*, and Chinook salmon, *O. tshawytscha*).
- Reduce inputs of pollutants, especially from agriculture and urban runoff. Mercury, selenium, ammonia, and PCBs are just some of the pollutants identified as threatening fishes in SFBA.
- Use conservation hatcheries judiciously to increase the abundance of some species (e.g., Sacacramento perch and white sturgeon, *Acipenser transmontanus*) through reintroductions to suitable habitats. However, the use of hatcheries needs to be carefully monitored so unintended adverse effects (domesticated behaviors, genetic introgression etc.) are avoided. The success of native fish introductions may also be largely dependent on alien species suppression and eradication.

- Establish refuge areas, including the Cache Slough region, Napa River, and low elevation streams, to protect species (e.g., Sacramento blackfish, *Orthodon microlepidotus*, and tule perch) native to lowland areas.
- Systematically survey native species populations. This is the greatest single need for most native species to monitor their status and identify their evolving conservation needs as conditions and conservation opportunities change.

All aquatic ecosystems in the SFBA will continue to change, requiring creative management if native species are to be maintained as significant components. This need for creative management has increased as climate change puts additional stresses on already altered ecosystems.

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