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The native and introduced fishes of Clear Lake: a review of the past to assist with decisions of the future

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We reviewed the history of Clear Lake, California, and its fish community, including geology, limnology, aquatic biology, and human influences that have shaped the condition of the lake and the composition and abundance of native and introduced fish species. We summarized impacts experienced by the lake and its fish community, identified correlations between native fish abundance and non-native fish introductions and abundance, and described other human impacts. Causal relationships were difficult to ascertain from existing data, but we identified numerous research opportunities that would address these uncertainties, including: (1) field studies of Clear Lake hitch (*Lavinia exilicauda chi*) and largemouth bass (*Micropterus salmoides*) interactions; (2) field surveys to determine the current population dynamics of native fish species, including hitch, Sacramento blackfish (*Orthodon microlepidotus*), and Sacramento pikeminnow (*Ptychocheilus grandis*); (3) development of a hitch population dynamics model to explore the relative importance of potential bottlenecks in the species' life cycle; (4) development of a multi-species computer simulation model to bring together the existing knowledge about the Clear Lake ecosystem, and use of the model to simulate the results of management choices; (5) development of a watershed hydrology model, incorporating predictions of future climate through the 21st century, to predict how spring stream flows may change under climate change, and how this may affect hitch spawning access and timing; and, (6) conduct of a nation-wide survey of lake managers to identify management strategies that have been effective in delaying or halting the invasion of dreissenid mussels, and to discover how invasions have been addressed.

Key words: California, Clear Lake, environmental impacts, history, *Lavinia exilicauda chi*, management, *Micropterus salmoides*, native fishes, non-native fishes, *Orthodon microlepidotus*, *Ptychocheilus grandis*

Clear Lake, California, has complex and intertwined natural and human histories that span millennia. The lake, for which the Pomo Indian name is Lupiyoma (large water; Horne 1975[app]), is the largest natural lake located within the boundaries of California. The fish fauna of Clear Lake has changed drastically over the past 150 years, with declines in the abundance of all native fish species and the extirpation of some (Stone 1876, Jordan and Gilbert 1895, Bairrington 2000[app]), yet the causes of the decline of particular species remain uncertain. This uncertainty complicates discussion of which impacts should be addressed and which restoration actions should be given priority, and hampers the ability to restore native species effectively and efficiently.

Understanding past impacts to the fish species of Clear Lake is important not only to manage the present fish community but also to predict the impacts of future events, impacts, and management strategies. While there is a large body of literature regarding Clear Lake and its fishes, this information has not recently been compiled and synthesized to allow a comparison of the trends in abundance of native and non-native fish species with the pattern and timing of events that may have impacted the fish community from the time of European settlement to the present.

In this paper we provide a synthesis of events at Clear Lake and offer suggestions for future research that may inform lake and fishery management. Our hypothesis was that the patterns of decline in native fish species are correlated with patterns of human impacts, including non-native fish introductions and impacts to habitat. To address this question we identified five goals: (1) summarize the natural habitat features (e.g., climate, geochemistry, soils) of Clear Lake which may influence fish species; (2) summarize trends in native fish abundance; (3) summarize the human activities that may have impacted native fish species, including introductions of non-native fish species; (4) graphically determine correlations between native fish abundance, non-native fish abundance, and other human impacts; and, (5) suggest further research that may help to determine causal relationships and, in turn, assist in the development of management strategies to conserve native fishes.

Materials and Methods

We conducted an extensive literature search to gather information on the natural habitat features of Clear Lake and its watershed, native and non-native fish species, and human activities that may have impacted fishes. We determined the native and non-native fish species present in Clear Lake over time, and estimated the relative abundance of fishes. Data sources included peer-reviewed literature, agency reports and surveys, commercial catch records, California Department of Fish and Game field notes and memoranda, and verbal communications with stakeholders. We compiled a detailed chronology of events at Clear Lake, and graphically compared the trends in relative abundance of native and non-native fish species with the timing of occurrence of human impacts. We described the correlations we observed between native fish species abundance and human impacts, including non-native fish species introductions, in terms of potential causal relationships. We then identified research activities that would clarify causal relationships and guide future management actions.

Results

Natural habitat features.—Clear Lake is located 113 km north of the San Francisco Bay (39° 01' N, 122° 45' W), at an elevation of 396 m (Carpenter et al. 1931). The lake is approximately 27 km long and 2–10 km wide, with 114 km of shoreline (Carpenter et al. 1931, Bairrington 1999[app]). Total water storage capacity of the lake is 1.4 billion m^3 (Bairrington 1999[app]). Depending on lake elevation, the surface area of Clear Lake is 16,000–17,700 ha (Lindquist et al. 1943, Macedo 1991). Average depth of the lake has been reported to be between 6.5 and 8 m, with a maximum depth of 15–18 m (Lindquist et al. 1943, Macedo 1991).

Formation of the lake occurred about 2.5 million years ago (Macedo 1991) when a landslide blocked the Cold Creek outlet (Mauldin 1968). Rising water linked the upper and lower lake portions of Clear Lake (Mauldin 1968). Prior to this event, the upper portion of Clear Lake drained into the East Branch of the Russian River via Cold Creek (Mauldin 1968), while the lower portion of the lake flowed to Cache Creek and into the Sacramento River (Mauldin 1968). Clear Lake is located over numerous faults to the northeast and southwest, and tectonic activity has contributed to the shape of the lake and its drainages. Approximately 0.5 million years ago, Mt. Konocti and Bald Mountain erupted, separating the lake into three basins (Horne 1975[app]): the Upper Arm, Lower Arm, and the Oaks Arm. The largest basin of the lake has a continuous sediment record of at least 75,000 years (Horne 1975[app]). During this time the lake has maintained a steady depth, in spite of an annual sedimentation rate of 0.7 mm due to subsidence from geological activity.

Geological deposits in the Clear Lake basin are rich with copper, zinc, silver, gold, mercury, lead, uranium, and arsenic (Slowey et al. 2007). The Clear Lake basin contains four general soil types: residual soils from sedimentary rocks, residual soils from volcanic flows, soils from old valley-filling material (stream deposits) or recent alluvium, and serpentine soils (Simoons 1952). Soil fertility played an important role in the settlement patterns of the basin as farmers began vast conversions of native habitat to agricultural production.

The lake is fed by several large intermittent creeks (Scotts, Kelsey, Middle, Adobe, Seigler Canyon, and Schindler). Beginning in late spring and extending into late fall, the lower-most reaches of all inlet creeks are void of surface water. Historically, the level of the lake and rate of outflow to the Sacramento River has been regulated by the Grisby Riffle, a natural constriction in the Cache Creek outlet. Following construction and operation of the Cache Creek Dam by the Yolo County Flood Control District, Clear Lake's outflow is still controlled by this riffle (Bairrington 1999[app]).

The Clear Lake basin has a Mediterranean climate with hot, dry summers and cool, wet winters (Simoons 1952, Adam and West 1983, Parker 1994, Bairrington 1999[app]). Winter air temperatures infrequently persist below freezing, while summer temperatures often exceed 37° C (Simoons 1952, Parker 1994). Precipitation generally occurs between October and April, ranging altitudinally from 61 cm at Clear Lake State Park (lake level) to 165 cm on Cobb Mountain (Bairrington 1999[app]). Average surface water temperature of the lake varies from 6° C in winter to 26° C in summer, and some areas may reach 32° C in late summer (Horne 1975[app]). Portions of the lake can freeze, albeit rarely, and the water temperature can drop below 4° C, which is lethal to threadfin shad (*Dorosoma petenense*), and sub-lethal to juvenile bass(*Micropterus salmoides*), giving rise to some predation from catfish holding around benthic warm water vents (P. K. Bairrington, California Department of Fish and Game, personal communication, September 2012). Clear Lake is polymictic (i.e., it mixes frequently during a given year). Since the lake does not usually freeze in winter, wind-mixing recirculates nutrients from deeper waters and bottom sediments. Such frequent mixing, in combination with the Coriolis force, plays a role in the distribution of chemicals and elements throughout the lake (Rueda and Schladow 2003).

Clear Lake is eutrophic and its sediments are naturally high in phosphorus, as opposed to being contributed by municipal or agricultural waste waters (Horne and Goldman 1972, Horne 1975[app]). Blue-green algae are the most prevalent phytoplankton and, while native to the lake, they have historically formed nuisance blooms in spring and fall. In spring the water column quickly reaches 15^{o} C and temporarily stratifies, producing conditions under which blue-green algae may be able to out-compete other spring algae (Horne 1975[app]). During stratified periods, bottom waters may become anoxic and intolerable to most fishes, but release nutrients such as phosphate and ammonia. Storms bring winds that mix the lake, re-oxygenate deeper waters, and bring nutrients to the surface. Calm periods following storms often exhibit blooms of blue-green algae. Excess solar radiation may cause the bloom to die catastrophically, resulting in masses of dead algae and foul odors (Horne and Goldman 1972, Horne 1975[app]). The lake experiences a clear period in mid-summer (Horne 1975[app]), then the blue-green algae *Anabaena* and *Microcystis* appear in late summer. They form a fall bloom as winds increase and bring nutrients to the surface and persist into winter, then decline as light levels decrease due to diminished sunlight and increased turbidity.

Trends in native fish abundance.—In the 1870s the native fish community of Clear Lake probably included fourteen species (Figure 1, Appendix 1). Twelve native species were listed by Stone (1876) in what was the first of numerous surveys to determine the fish fauna of Clear Lake (Cook et al. 1966). These species were: Clear Lake splittail (*Pogonichthys ciscoides*), Clear Lake hitch (*Lavinia exilicauda chi*), Pacific lamprey (*Lampetra tridentata*), prickly sculpin (*Cottus asper*), rainbow trout or steelhead, or both (*Oncorhynchus mykiss*), Sacramento blackfish (*Orthodon microlepidotus*), Sacramento perch (*Archoplites interruptus*), Sacramento pikeminnow (*Ptychocheilus grandis*), Sacramento sucker (*Catostomus occidentalis*), thicktail chub (*Gila crassicauda*), threespine stickleback (*Gasterosteus aculeatus*), and tule perch (*Hysterocarpus traski*). A subsequent survey by Jordan and Gilbert (1895) noted the presence of an additional native fish, *Ptychocheilus harfordi*, although they did not actually observe it. Jordan and Gilbert (1895) quoted a local angler's description of the *P. harfordi*: "Much smaller and darker than *P. oregonensis* [Sacramento pikeminnow], with smaller scales and does not take the trolling spoon." We

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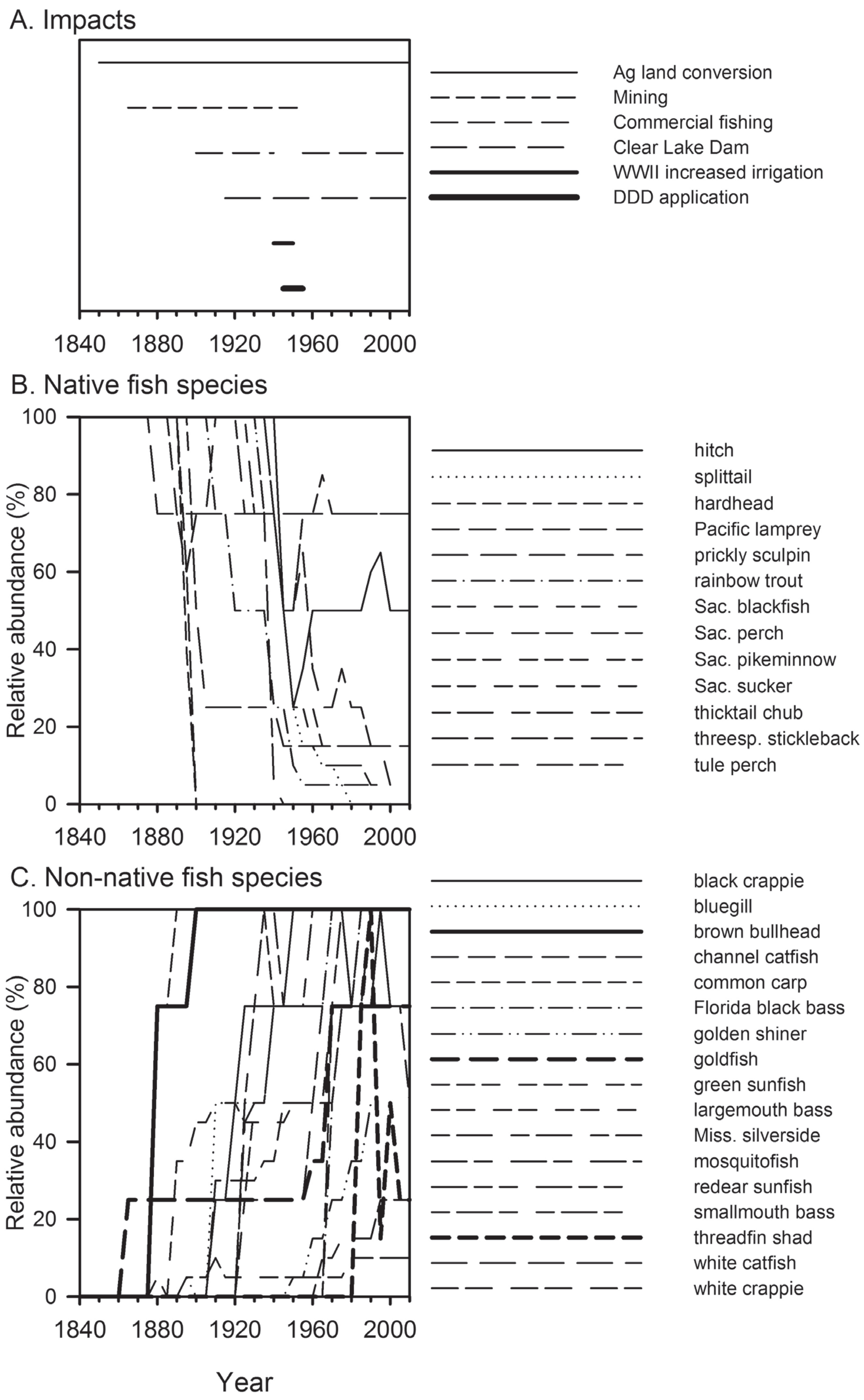
Figure 1.—Environmental impacts and relative abundance of native and non-native fishes at Clear Lake, California. Pacific lamprey and threespine stickleback have not been observed in the lake since 1894, but may still be present in tributaries (Week 1983[app]). We omitted native species California roach, and non-native species brown trout, fathead minnow, and pumpkinseed, due to insufficient information. We also omitted four non-native species whose initial introduction was unsuccessful (lake trout, lake whitefish, mud pickerel/grass pickerel, and yellow perch). Sources of fish abundance data: Stone (1876), Jordan and Gilbert (1895), Coleman (1930), Lindquist et al. (1943), Murphy (1951), Pintler (1957), Cook et al. (1966), Puckett (1972a[app], 1972b), Vestal (1974[app]), Cech (1978[app]), Moyle and Holzhauser (1978), Macedo (1991), Bairrington (1995[app], 1999[app], 2000[app]), Colwell et al. (1997), CDFG (1998[app], 2000a[app], 2000b[app]), Moyle (2002), Rowan (2008[app]), LCVCD (2013[app]), and Hinton (n.d.[app]).


A. Impacts
Ag land conversion
Mining
Commercial fishing
Clear Lake Dam
WWII increased irrigation
DDD application
1840
1880
1920
1960
2000
B. Native fish species
Relative abundance (%)
100
80
60
40
20
0
hitch
splittail
hardhead
Pacific lamprey
prickly sculpin
rainbow trout
Sac. blackfish
Sac. perch
Sac. pikeminnow
Sac. sucker
thicktail chub
threesp. stickleback
tule perch
C. Non-native fish species
black crappie
bluegill
brown bullhead
channel catfish
common carp
Florida black bass
golden shiner
goldfish
green sunfish
largemouth bass
Miss. silverside
mosquitofish
redear sunfish
smallmouth bass
threadfin shad
white catfish
white crappie
Year

suspect that *P. harfordi* may, in fact, have been hardhead (*Mylopharodon conocephalus*), since the angler's description concurs with our observations of hardhead appearance and behavior during angling from several Sierra Nevada streams in 2010 (L. C. Thompson, personal observation, May 2010). However, *P. harfordi* is a synonym for Sacramento pikeminnow, and hardhead were not observed in subsequent surveys of Clear Lake. The hardhead is very similar in appearance to the Sacramento pikeminnow, albeit with a smaller mouth, so it is likely that it was present during Stone's (1876) and Jordan and Gilbert's (1895) visits, but was not identified as a separate species. A fourteenth native species, California roach (*Lavinia symmetricus*), was observed in subsequent surveys (Bairrington 2000[app]).

The highly productive nature of the lake led to historically large populations of native species (Moyle 2002). Early records suggested that the anadromous species, steelhead trout and Pacific lamprey, entered the lake through its outlet, Cache Creek, and then spawned in its tributaries (Stone 1876). These migrations would have been halted by the construction of the Cache Creek Dam in 1915 (Murphy 1951). However, rainbow trout are reportedly still caught occasionally, and may occur near mouths of streams or near cold springs (Bairrington 1999[app]). Historically, hitch were very important to the diets of native peoples (Pomo tribes) and wildlife (Benson and Mauldin 1974, Moyle et al. 1995, Windrem 2008[app]). Hitch were once so abundant that during their upstream spawning migration they would displace one another out of the creeks and onto the bank (Rideout 1899, Benson and Mauldin 1974). Reports stated that "The little streams and tule swamps were filled side to side with fish in such numbers that they could be walked upon" (Murphy 1948a, Benson and Mauldin 1974). Historically, hitch also have been reported spawning in ditches and flooded meadows near tributaries (Moyle et al. 1995, Moyle 2002). However, hitch abundance has declined relative to its pre-1940s levels (Windrem 2008[app]).

All native fish species in Clear Lake have shown general downward trends in abundance (Figure 1), and four native species have been extirpated from the lake (Figure 1). The last recorded observations of hardhead and Pacific lamprey occurred in 1894 (Jordan and Gilbert 1895), although lamprey may persist in tributaries to the lake (Week 1983[app]). Thicktail chub were last seen in 1938 (Cook et al. 1964, 1966), and Clear Lake splittail in 1969 (Puckett 1972a[app], 1972b). Small native populations of rainbow trout have been recorded as resident fish in tributaries to Clear Lake, such as Kelsey Creek, Scotts Creek and Middle Creek, with a few large runs during the 1960s (Cook et al. 1966). Of the 14 species native to Clear Lake only six may still be common: California roach, Clear Lake hitch, prickly sculpin, Sacramento blackfish, Sacramento sucker, and tule perch (Bairrington 2000[app], CDFG 2000a[app], LCVCD 2013[app]).

Anthropogenic impacts.—Historical or contemporary anthropogenic impacts to Clear Lake have included introductions of non-native fish and plant species, artisanal and commercial fishing, farming, water diversions, mining, timber harvesting, recreational activities and, over time, an increase in human population. Below we summarize the major impacts likely to have influenced native fish species.

Introductions of non-native species.—There have been numerous sanctioned and non-sanctioned introductions of non-native fish species into the lake (Table 1). Introduced fishes have played an important, and often conflicting, role in Clear Lake for more than 100 years (Dill and Cordone 1997). Often viewed as a "testing ground" by late nineteenth century fish enthusiasts, Clear Lake was frequently subjected to introductions without consideration of the impacts to native fishes. In fact, early fish biologists introduced fish with disregard to the native species that they viewed as "unworthy" of consideration. Twenty-

Table 1.—Species of fish recorded from Clear Lake, Lake County, California. Presented are scientific name, year(s) of introduction(s) for non-native species, result(s) of introduction(s), the most recent recorded observation, and the citation for information included in the table.

Common name	Scientific name	Year(s) introduced	References	Introduction successful; still present?	Year last reported	References
California roach	*Lavinia symmetricus*	native	N/A	Y	c. 1995	Bairrington 2000[app]
Clear Lake hitch	*Lavinia exilicauda chi*	native	N/A	Y	2012	G.A. Giusti, personal observation, 2013
Clear Lake splittail	*Pogonichthys ciscoides*	native	N/A	N	1969	Puckett 1972b
Clear Lake tule perch	*Hysterocarpus traskii pomo*	native	N/A	Y	2012	LCVCD 2013[app]
hardhead	*Mylopharodon conocephalus*	native	N/A	N	1894	Jordan and Gilbert 1895
Pacific lamprey	*Lampetra tridentata*	native	N/A	N	1894	Jordan and Gilbert 1895
prickly sculpin	*Cottus asper*	native	N/A	Y	2012	G.A. Giusti, personal observation, 2013
rainbow trout/steelhead	*Oncorhynchus mykiss*	native	N/A	Y	c. 1995	Bairrington 2000[app]
Sacramento blackfish	*Orthodon microlepidotus*	native	N/A	Y	2000	CDFG 2000a[app]
Sacramento perch	*Archoplites interruptus*	native	N/A	Y	2000	CDFG 2000a[app]
Sacramento	*Ptychocheilus*	native	N/A	Y	2012	G.A. Giusti, personal

TABLE 1 (CONTINUED)

Common name	Scientific name	Year(s) introduced	References	Introduction successful; still present?	Year last reported	References
pikeminnow	*grandis*					observation, 2013
Sacramento sucker	*Catostomus occidentalis*	native	N/A	Y	2012	G.A. Giusti, personal observation, 2013
thicktail chub	*Gila crassicauda*	native	N/A	N	1938	Cook et al. 1964 and 1966
threespine stickleback	*Gasterosteus aculeatus*	native	N/A	Y	c. 1995	Bairrington 2000[app]
black crappie	*Pomoxis nigromaculatus*	1909	Murphy 1951	Y	2012	G.A. Giusti, personal observation, 2013
bluegill	*Lepomis macrochirus*	1909	Coleman (1930), Murphy 1951	Y	2012	G.A. Giusti, personal observation, 2013
brown bullhead	*Ameiurus nebulosus*	1880	Coleman (1930), Murphy 1951	Y	2012	G.A. Giusti, personal observation, 2013
		1961	McCammon and Seeley 1961			
brown trout	*Salmo trutta*	1924	Murphy 1951, Coleman (1930) saw "European brown, *Salmo fario*" in 1925	Y	c. 1995	Bairrington 2000[app]. Also Coleman 1930, Murphy 1951, Bairrington 1999[app]
common carp	*Cyprinus carpio*	1880	Coleman (1930) saw these in 1925 survey, Moyle and Holzhauser 1978	Y	2012	G.A. Giusti, personal observation, 2013
channel catfish	*Ictalurus punctatus*	c. 1900	Coleman (1930) saw blue catfish, which also has deeply forked tail). Puckett 1972b, Macedo 1991, Dill and Cordone 1997	Y	2012	G.A. Giusti, personal observation, 2013
		1969	Bairrington 1999[app]			
fathead	*Pimephales*	1950s	Dill and Cordone	Y	c. 1995	Bairrington 2000[app]

Common name	Scientific name	Year(s) introduced	References	Introduction successful; still present?	Year last reported	References
minnow	*promelas*		1997, Bairrington 1995[app]			
Florida black crappie	*Pomoxis nigromaculatus*	1985	Macedo 1991, Bairrington 1995[app], 1999[app]; Moyle 2002	Y	2008	K.L. Weber, personal observation via beach seines with Lake County Vector Control, 2008
Florida largemouth bass	*Micropterus salmoides floridanus*	1969-1971	Puckett 1972a[app], Pelzman 1980	Y	2012	G.A. Giusti, personal observation, 2013
golden shiner	*Notemigonus crysoleucas*	1896	Murphy 1951, Dill and Cordone 1997	N	1896	Murphy 1951
		1950	McCammon et al. 1964, Moyle and Holzhauser 1978, Moyle 2002	Y	c. 1995	Bairrington 2000[app]
goldfish	*Carassius auratus*	c. 1860s	Dill and Cordone 1997	Y	2012	G.A. Giusti, personal observation, 2013
green sunfish	*Lepomis cyanellus*	1909	Murphy 1951	Y	2000	CDFG 1998[app], 2000b[app]
lake trout	*Salvelinus namaycush*	1924	Murphy 1951	N	1924	Murphy 1951
lake whitefish	*Coregonus clupeaformis*	1873	Stone 1876	N	1873	Murphy 1951, Dill and Cordone 1997
Mississippi silverside	*Menidia audens*	1967	Cook and Moore 1970. Li et al. 1976, Moyle and Holzhauser 1978, Week 1983[app], Dill and Cordone 1997, Moyle 2002	Y	2012	G.A. Giusti, personal observation, 2013
mud	*Esox americanus*	1896	Murphy 1951	N	1896	Murphy 1951

TABLE 1 (CONTINUED)

Common name	Scientific name	Year(s) introduced	References	Introduction successful; still present?	Year last reported	References
pickerel/grass pickerel	*vermiculatus*					
northern largemouth bass	*Micropterus salmoides salmoides*	1888	Coleman 1930, Murphy 1951, Dill and Cordone 1997	Y	2012	G.A. Giusti, personal observation, 2013
		1969	Pelzman 1980			
		1975	Moyle and Holzhauser 1978			
pumpkinseed	*Lepomis gibbosus*	Uncertain	Bairrington 1999[app]	Y	c. 1995	Bairrington 2000[app]
redear sunfish	*Lepomis microlophus*	1963	Cook et al. 1964	Y	2008	K.L. Weber, personal observation via beach seines with Lake County Vector Control, 2008
smallmouth bass	*Micropterus dolomieu*	1895	Murphy 1951	Y	2012	G.A. Giusti, personal observation, 2013
threadfin shad	*Dorosoma petenense*	c. 1985	Bairrington 1999[app]	Y	2008	K.L. Weber, personal observation via beach seines with Lake County Vector Control, 2008
		c. 1997	Bairrington 1999[app]			
western mosquitofish	*Gambusia affinis*	1925	Murphy 1951	Y	c. 1995	Bairrington 2000[app]
white catfish	*Ameiurus catus*	c. 1874-1880	Murphy 1951	N	--	Murphy 1951 (Table 6, referred to Cal Fish and Game Report, 1895-96)
		1923	Murphy 1951, Dill and Cordone 1997	Y	--	Murphy 1951 (Table 6, referred to Cal Fish and Game Report, 1895-96)
		1961	McCammon and Seeley 1961	Y	2012	G.A. Giusti, personal observation, 2013
white crappie	*Pomoxis annularis*	c. 1925	Coleman 1930, Li et al. 1976, Moyle 2002	Y	1998	CDFG 1998[app], 2000b[app]
yellow perch	*Perca flavescens*	1909	Murphy 1951	N	1909	Murphy 1951

five non-native fish species or sub-species have been introduced to Clear Lake since 1873 (Table 1), of which 21 are still present (Table 1, Figure 1). In addition, blue catfish ("Great Blue, or Fork-Tail Cat", *Ictalurus furcatus*) were reportedly observed in 1925 (Coleman 1930), but subsequent surveys did not mention this species and it may have been the more commonly observed channel catfish (*I. punctatus*) which also has a deeply forked tail. The "brown-spotted cat" (*Ameirus* [sic] *platycephalus* Girard) was reported by Coleman (1930), but subsequent reviewers suggested that this was probably the brown bullhead (*Ameiurus nebulosus*) (Dill and Cordone 1997).

The first recorded introduction of non-native fishes at Clear Lake began with the unsuccessful stocking of lake whitefish (*Coregonus clupeaformis*) in 1873 (Stone 1876), although goldfish (*Carassius auratus*) were likely added in the 1860s (Dill and Cordone 1997). Common carp (*Cyprinus carpio*), brown bullhead, and white catfish (*Ameiurus catus*) were introduced by 1880 (Murphy 1951, Davis 1963, Moyle and Holzhauser 1978).

The introduction of northern largemouth bass (*Micropterus salmoides salmoides*) (Coleman 1930, Murphy 1951, Dill and Cordone 1997) and catfish in the 1880s contributed to a booming recreational fishery. By 1910, bass fishing was already considered excellent (Murphy 1951). Bluegill (*Lepomis macrochirus*) and black crappie (*Pomoxis nigromaculatus*) were introduced in 1909 and have maintained abundant numbers since then (Murphy 1951, Bairrington 2000[app]). Young-of-year crappie, bluegill, and bass compete with native species, particularly hitch, for food sources in tule nursery habitat surrounding the lake (Week 1982). Brown trout (*Salmo trutta*) were introduced in 1924 (Coleman 1930, Murphy 1951) and, while rare in the lake, they are reportedly caught and may occur near mouths of streams or near cold springs (Bairrington 1999[app]). Western mosquitofish (*Gambusia affinis*) were introduced in 1925 as an effective means to combat the gnats and mosquitos that plagued the area (Murphy 1951). This introduction also provided a valuable forage food for bass, catfish, bluegill, and crappie (Moyle 2002).

Mississippi silverside (*Menidia audens*) were introduced in 1967 (Cook and Moore 1970), and within one year became the most abundant fish in the lake (Moyle and Holzhauser 1978), providing a new source of prey for piscivores. In 1969 the California Department of Fish and Game introduced 456 Florida strain largemouth bass (*Micropterus salmoides floridanus*) (Puckett 1972a[app], Vestal 1974[app]). The Florida strain may have a faster growth rate than the northern largemouth bass, leading to a greater population growth rate (Moyle and Holzhauser 1978). The illegal introduction of threadfin shad occurred in the mid-1980s and provided yet another forage species for predatory fish (Bairrington 1999[app]); their abundance was short-lived, however, as cold winters in the early 1990s drove them to near extinction. Shad numbers increased in the 2000s, but by 2011 their abundance again was low (T. Knight, Lake County Record-Bee, personal communication, August 2011).

In addition to non-native fish species, other animal and plant species have been introduced, and may impact native fishes. Asian clams are thought to be present in the lake, but to our knowledge no work has been published on their role in the ecosystem. *Hydrilla*, an invasive aquatic plant first observed in Clear Lake in 1994 (Bairrington 1995[app]), provides some habitat value but results in increased applications of herbicide to the lake. The potential impact of dreissenid mussels (e.g., quagga and zebra mussels) is large, but is speculative at this time (Giusti 2010[app]).

Artisanal and commercial fishing.—The Pomo and pre-Pomo peoples of the Clear Lake region have inhabited the basin consistently since 6,000–8,000 years BP (Kaufman

1980, Parker 1994). By 5,000–6,000 years BP, evidence suggests that the entire lakeshore was utilized at some point in the year by the Pomo (Parker 1994). The majority of the population appears to have lived within 8 km of the lakeshore, and between April and May of each year fishing camps were established along the shoreline (Kniffen 1939, Parker 1994). The abundance and variety of fish in Clear Lake (Knapp 1855[app], Joaquin 1989) made fishing a specialized profession where men could trade their catch for other goods (Brown and Andrews 1969). Fishing techniques included fish hooks, spearing, nets, weirs, seine nets, gill nets, scoop nets, fish traps, dams, plant-derived poisons, and simply catching fish by hand (Knapp 1855[app], Brown and Andrews 1969, Joaquin 1989, Moss 1989). During the spring spawning period, Clear Lake hitch, Clear Lake splittail and Sacramento pikeminnow were readily available for capture from the lake's tributaries: "The Indian people around the lake used to collect enough fish in ten days, the usual hitch season, to last a whole year" (Moss 1989). Shortly after capture the fish were grilled, baked, dried, or smoked for preservation (Brown and Andrews 1969).

Commercial fishing has been conducted at Clear Lake since the 1900s for native blackfish, as well as carp and catfishes. The commercial catfish fishery was active from 1900 until 1941, when it was banned by legislative action (Murphy 1951). The commercial fishery for blackfish was banned in 1948 in order to increase the number of juvenile blackfish and, thus, increase Clear Lake's supply of forage for largemouth bass. Blackfish numbers recovered, and by 1954 the commercial fishery was re-instated (Moyle and Holzhauser 1978). Commercial fishing still occurs on the lake, with carp, blackfish, and goldfish comprising most of the catch (CDFG 2000a[app]).

Water management and dams.—Land conversion and water diversions for agricultural uses likely began concurrently with the arrival of European settlers in the Clear Lake basin. The first recorded contact between the Pomo and Europeans was during 1832–1833, when Hudson's Bay Company trappers made their way through the basin (Simoons 1952, Parker 1994). Agricultural production in the Clear Lake basin was, and is, important to the local economy. Agriculture products produced in the basin have included livestock, citrus, figs, walnuts, alfalfa, grain, apples, peaches, pears, and grapes (Carpenter et al. 1931). Between 1966 and 1986, the population of Lake County tripled, increasing municipal land use for housing, as well as municipal water requirements (Follansbee 1996).

Dams have been built on tributaries and the outflow of Clear Lake that impact natural hydrologic functions and flows and could, thereby, affect migratory fish populations. The completion of the Cache Creek Dam (Clear Lake Dam) in 1915 blocked access to spawning areas of anadromous migratory species (Pacific lamprey and steelhead; Murphy 1951). Adobe Creek, Highland Creek, Clover Creek, and Kelsey Creek (Macedo 1994, Lindblom 2004[app], Smythe 2008[app]) have experienced a reduction in fish spawning since the installation of dams and increased irrigation (Murphy 1951, Macedo 1994, Lindblom 2004[app], Smythe 2008[app]). Three of the most critical streams used for by Clear Lake hitch (Kelsey Creek, Seigler Creek, and Adobe Creek) have a total of nine barriers that potentially affect migration (Moyle et al. 1995, Bairrington 2000[app], Chi Council 2007[app], Windrem 2008[app]). Many creeks were channelized in response to frequent flooding and are now bounded by levees (Macclanahan et al. 1972[app], Army Corps of Engineers 1974[app]), although Lake County has begun to restore channelized streams to their more natural instream and riparian conditions. Also, minimum stream flows to allow fish passage and spawning have been established for the Kelsey Creek Detention Structure (Smythe 2008[app]).

Mining.—Mining of the abundant mineral deposits in the Clear Lake Basin commenced in the latter part of the nineteenth century (Anonymous 1859[app], Asher 2003). Though mining techniques have improved substantially, mid-nineteenth and early twentieth century techniques created long-term impacts that are still evident today (Slowey et al. 2007). Historical mining and dredging for gravel has occurred since early settlement (Kim 1999), and must be considered alongside current activities when assessing contemporary stream, marsh and water quality habitat conditions.

The presence of a borax lake and a sulphur bank resulted in the opening of the Sulphur Bank Mercury Mine (SBMM) on the eastern shore of the Oaks Arm of Clear Lake (Anonymous 1859[app]). The mine operated from 1865 to 1957 as a sulfur mine. In 1872, operations expanded to include mercury (Heeraman 1999, Asher 2003, Engle et al. 2008). The mine was ultimately abandoned in 1957 (Chamberlin et al. 1990[app], Suchanek et al. 2000, Asher 2003, Engle et al. 2008). During the 1920s, SBMM operations changed from open cut and shaft mining to removing overburden and waste rock (Suchanek et al. 2000), ultimately creating the Herman Pit. Much of the overburden and waste rock was bulldozed into the lake (Chamberlin et al. 1990[app], Suchanek et al. 2000), causing a dramatic increase in mercury entering the lake (Richerson et al. 2000, Suchanek et al. 2000, Asher 2003). In the 1950s a waste rock dam was built in an attempt to decrease mineral and acidic water flow from Herman Pit to Clear Lake (Asher 2003, Engle et al. 2008). However, the dam actually resulted in more mercury and other minerals entering the lake, due to water seeping through the waste rock and into the lake (Asher 2003, Engle et al. 2008).

Mercury can bioaccumulate in fish and other wildlife (specifically fish-eating birds) and, ultimately, result in health issues for humans (Ross 2001, Asher 2003, Thompson 2004[app]). In the 1970s, scientists discovered that fish in Clear Lake had significantly elevated levels of mercury in their tissues (Suchanek et al. 2000, Asher 2003). As a result, health advisories occurred in the 1980s regarding fish consumption (Asher 2003, Thompson 2004[app]). Due to the large amounts of pollution entering the lake from the SBMM each year, the mine was designated an Environmental Protection Agency Superfund Site in 1990, and steps have been taken to stop pollutants from entering the lake (Heeraman 1999, Asher 2003, Engle et al. 2008).

In addition to the SBMM, smaller scale mining and dredging for gravel in tributary streams have occurred since early settlement (Kim 1999), altering stream gravels and impacting fish spawning habitat. Mining on Kelsey, Scotts, and Middle creeks has further impacted spawning habitat by lowering the water table, thereby causing creeks to go dry earlier in the summer than under natural, unimpaired flows (Moyle 2002).

To summarize, the declines in abundance of Clear Lake native fish species are correlated with many of the human impacts described in this section. The first declines began in the 1880s (Figure 1B), by which time the human impacts included the start of land conversion to agriculture, water diversions, the introduction of several non-native fish species, and mining (Figure 1A, C). Declines in the abundance of more native fish species began between the 1890s and 1930s, and were correlated with the previously mentioned impacts, plus commercial fishing, the construction of the Clear Lake Dam, and the addition of approximately ten more species of non-native fish. A large wave of declines in native fish species abundance began in the 1940s. While commercial fishing was halted during this period, the other impacts continued, irrigation withdrawals from streams increased during World War II, and dichloro-diphenyl-dichloroethane (DDD) applications began (Hunt and Bischoff 1960, Cook and Connors 1963). Few new non-native fish species were introduced, but those already present in the lake increased in abundance. From the 1960s to present, some native fish populations continued to decline in abundance, while others stabilized or showed short term increases. During this period mining activities and DDD applications were halted, while commercial fishing resumed. New non-native fish species were introduced, and most non-native fish species increased or maintained abundance.

Discussion

As described above, Clear Lake and its fishes have experienced substantial changes in the past 150 years. A suite of major impacts is correlated with the decline of many native fish species, while many introduced fish species (except threadfin shad) have increased in abundance. While it is impossible to infer causality from these multiple impacts, since the 1840s all native fish species declined in abundance, and several have been extirpated from the lake (Figure 1).

The downward trends of native fish species abundance in Clear Lake can be attributed to numerous human impacts including the introduction of non-native fish species, land use change, dams, water diversions, and mining. However, because so many impacts occurred simultaneously or in quick succession, fish abundance may be correlated with multiple impacts. Thus, it is difficult to identify what proportion of a given native species' decline is attributable to a given human impact or increase in abundance of a non-native species and, in turn, to determine what restoration actions will be most effective.

To illustrate this point, numerous explanations have been suggested for the decrease in hitch abundance, the most prevalent being that irrigation demand causes streams to dry up earlier than normal, so adult and juvenile hitch lack sufficient time to migrate to and from the lake (Murphy 1948a, 1951; Benson and Mauldin 1974; Moyle et al. 1995; Moyle 2002; Windrem 2008[app]). Changes in stream flows have been caused by diversions for irrigation, domestic needs, and declining annual precipitation (Macedo 1994, Moyle et al. 1995). Additionally, dams along Adobe, Highland, Clover, and Kelsey creeks block or impair upstream migration for hitch (Macedo 1994, Lindblom 2004[app]). Past gravel mining contributed to the down-cutting of some stream channels and created fish migration barriers, often at older road crossings (Lindblom 2004[app]). Stream gravel provides crucial incubation habitat for the non-adhesive hitch eggs (Murphy 1948a).

In dry years, spawning by hitch may be limited because they cannot migrate up tributaries to Clear Lake. Hitch may be forced to spawn in the lake; however, in the lake there is often heavy egg predation (Kimsey 1960, Moyle et al. 1995). Additionally, those juvenile hitch that do survive predation and drying stream conditions are further stressed by the lack of suitable nursery habitat (Moyle et al. 1995, Windrem 2008[app]). Since 1840, approximately 85% of juvenile hitch rearing habitat and emergent vegetation has been destroyed or altered (Bairrington 1999[app]). It is generally perceived that introduced fish species have negatively affected hitch populations, competing both for food and space, while some introduced fishes are also aggressive predators that feed on all life stages of hitch (Geary 1978, Moyle et al. 1995, Moyle 2002). Acid mine drainage may also have affected hitch abundance, as it has been linked to decreased ecological diversity, habitat loss, and bioaccumulation (Asher 2003).

Research needs.—It may be possible to clarify the role of these impacts and inter-species relationships through research targeted to reduce the uncertainty in our understanding of Clear Lake and its fishes. Here we describe six research needs and outline approaches to address them, including field studies, modeling, and surveys.

It is unclear to what extent bass predation affects the hitch population. Field studies of hitch and largemouth bass could provide knowledge about their interactions. For example, the frequent bass fishing tournaments held at Clear Lake offer an opportunity to tag bass in order to determine post-release movements of bass, the frequency of recapture, bass population trends, and the potential for interaction between bass and hitch at particular locations around the lake. Bass captured during fishing tournaments could be tagged (Guy et al. 1996) prior to release, which typically occurs at a centralized location. Members of the public, including Clear Lake residents, local anglers, local tackle shops, and bass tournament anglers, would be notified of the presence of tagged bass, and would be asked to report the time and place that tagged bass are recaptured. This "citizen scientist" approach would be a cost-effective way to collect recapture data. If tournament bass stomach contents were examined following weigh-in, it may also be possible to determine the proportion of bass diet contributed by hitch and other prey species, and to extrapolate the biomass of prey species consumed. The citizens of Lake County have shown a longstanding commitment to Clear Lake (e.g., Chi (hitch) Council, Lake County Invasive Species Council), so it is likely that such a project would attract strong participation.

The current population dynamics of native fish species, including hitch, Sacramento blackfish, and Sacramento pikeminnow, are uncertain. While these species have declined in abundance relative to historical conditions, a lack of detailed knowledge of their life histories contributes to management and challenges. Field surveys could be conducted to determine within-lake distribution, movement, growth rates, diet, age structure, and size-related mortality.

Among the native fish species of Clear Lake, the hitch attracts considerable public attention and scrutiny of trends in abundance and potential limiting factors. A hitch population dynamics model could be developed to help determine the relative importance of potential bottlenecks in the species' life cycle (e.g., spawning habitat availability, young-of-year outmigrant survival, and juvenile in-lake survival). The model would incorporate current knowledge of hitch biology and new information gained from the previously mentioned field studies, and suggest which intervention(s) could be most beneficial.

The complexity of the Clear Lake food web and the multitude of environmental impacts and non-native fish introductions make it challenging to track the interconnections and to predict the outcome of management actions. The considerable economic value of the bass sport fishery and associated tournaments to Lake County complicates management of the lake. While bass prey on native species, it may be possible to determine whether a management regime exists that will allow the bass fishery to continue while also ensuring the long term survival of native species. Computer modeling approaches such as ECOPATH (Pauly et al. 2000) can be used to bring to together the existing knowledge about an ecosystem, including feeding networks, production of species (biomass), predation mortality, and fisheries catch. The model can then be used to simulate management choices, and to predict resultant changes in the abundance of species of concern. For example, an ECOPATH model was constructed for Lake Victoria in Africa's rift valley (Moreau et al. 1993), where changes in the fish community mirror changes in Clear Lake. A diverse assemblage of catfish, cichlids, and haplochromine species was present in Lake Victoria until the late 1970s when the Nile perch (*Lates niloticus*), a highly predatory species, was introduced (Moreau et al. 1993). The sudden increase in predation by Nile perch reduced the native diversity to three dominant species, a situation that may be comparable to the effect of bass on native species in Clear Lake.

In this paper we have focused on past and current conditions affecting Clear Lake fishes, but changes in climate predicted for California as a whole (Hayhoe et al. 2004) raise the question of how future climate conditions may affect the Clear Lake watershed. A watershed hydrology model, incorporating predictions of future climate through the 21st century, could be constructed to predict how spring stream flows are affected by climate change, and how this may affect hitch spawning access and timing (e.g., see Thompson et al. 2012). Such a model would allow better targeting of stream restoration activities and fish passage projects.

Dreissenid mussels have recently been introduced into water bodies in southern California, and the Lake County Invasive Species Council was formed to coordinate local efforts to prevent the spread of mussels into Clear Lake (Giusti 2010[app]). These efforts are ongoing, but the large number of public access points surrounding Clear Lake makes it difficult to screen incoming vessels effectively, leaving the lake vulnerable to introductions. A nation-wide survey could be developed and administered to managers of lakes with access conditions similar to Clear Lake; the survey could identify management strategies that have been effective in delaying or halting invasions of dreissenid mussels, and how invasions have been addressed.

In conclusion, the native fish species of Clear Lake have declined in abundance since the 1840s, likely due to the effects of a suite of human impacts. While some species have been extirpated, many also survive, offering the opportunities to develop management strategies for recovery and persistence. Implementation of research and management experiments, such as those described herein, can increase our understanding of which impacts have been most devastating, inform development of management plans, and help to determine what restoration actions will be most effective.

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Appendix I: Historical time line of Clear Lake and its fishes

The following timeline summarizes key events in the Clear Lake basin, including the introduction of non-native fish species, loss of native fish species, harvest of native and non-native fishes, weather patterns, and environmental impacts. Full citations are listed in Literature Cited or in Appendix II.

- Pre-1840
    - Historically Clear Lake hitch have been very important to the people (Pomo Tribes) of Clear Lake as a staple food in their diets (Benson and Mauldin 1974, Windrem 2008[app])
- 1840
    - European settlers first appear in the Clear Lake area (Bairrington 1995[app], 1999[app])
- c. 1860s
    - Goldfish introduced (Dill and Cordone 1997)
- 1866
    - Borax and soda found in large quantities near Clear Lake (Anonymous 1866[app])
    - Miners are extracting 2.7 metric tons/day of sulphur. They believe the mines can produce up to 9 metric tons/day (Anonymous 1866[app])
    - Perch and trout are taken from Clear Lake in large numbers weighing between 1.4 and 6.8 kg (Anonymous 1866[app])
- 1870
    - Cinnabar, mercury and sulphur are mined at Sulphur Bank Mercury Mine until 1957 when the mine is closed (Harnly et al. 1997)
- 1873
    - 25,000 lake whitefish are introduced into Clear Lake by the California Fish Commission (CFC) (Stone 1876, Murphy 1951, Dill and Cordone 1997), but the introduction proved unsuccessful
    - Fish species observed in Clear Lake: Clear Lake splittail, Clear Lake hitch, Pacific lamprey, prickly sculpin, rainbow trout and/or steelhead, Sacramento blackfish, Sacramento perch, Sacramento pikeminnow, Sacramento sucker, thicktail chub, threespine stickleback, tule perch (Stone 1876)
- 1878
    - 1,000 catfish were placed in Clear Lake by the CFC (Murphy 1951)
    - Large carp ponds established around Clear Lake (Cobb Mountain, Anderson Springs, and Boggs Mill between Glenbrook and Kelseyville) (Benson and Mauldin 1974)
- 1880
    - Start of successful fish introductions into Clear Lake (Moyle and Holzhauser 1978)
    - First white catfish[a] introduction of 74 individuals by CFC is unsuccessful (Murphy 1951)
    - Brown bullhead and common carp are introduced into Clear Lake (Moyle and Holzhauser 1978)

- 1888
  - Largemouth bass are introduced into Clear Lake by the CFC (Murphy 1951, Dill and Cordone 1997)
- 1894
  - Fish species observed in Clear Lake: Clear Lake splittail, Clear Lake hitch, Pacific lamprey, prickly sculpin, rainbow trout and/or steelhead, Sacramento blackfish, Sacramento perch, Sacramento pikeminnow, Sacramento sucker, thicktail chub, threespine stickleback, tule perch, *Ptychocheilus harfordi* (hardhead or Sacramento pikeminnow) (Jordan and Gilbert 1895)
- 1895
  - Smallmouth bass unsuccessfully introduced into Clear Lake by the CFC (Murphy 1951)
  - Sacramento pikeminnow are abundant (Cook et al. 1966)
  - Sacramento perch are becoming scarce possibly due to the introduction of carp (Cook et al. 1966)
  - Thicktail chub are common (Cook et al. 1966)
  - There are 13 native fish species and four introduced species in the lake (Bairrington 1995[app], 1999[app])
- 1896
  - Three grass pickerel[a] are unsuccessfully introduced. Also, 296 golden shiner are introduced into three California lakes including Clear Lake. The Clear Lake introduction was unsuccessful. Both introductions were sanctioned by the CFC (Murphy 1951, Dill and Cordone 1997, Moyle 2002)
- 1899
  - The fish are so abundant that they are crowding each other out of the tributaries (Kelsey Creek) where they spawn. Clear Lake hitch spawning runs last several days (Rideout 1899, Benson and Mauldin 1974, Dill and Cordone 1997)
- 1900
  - Carp are abundant in the lake (Mauldin 1968)
- 1903
  - Reports of rainbow trout in the lake (Dill and Cordone 1997)
- 1908
  - Clear Lake supports a huge catfish fishery (Altouney et al. 1966[app], Dill and Cordone 1997)
- 1909
  - Black crappie (successful), yellow perch (unsuccessful), bluegill (successful) and green sunfish (successful) are all introduced by the CFC (Murphy 1951, Moyle 2002)
- 1910
  - Largemouth bass fishing in Clear Lake is already good (Murphy 1951)
  - There is a large Clear Lake hitch run on Kelsey Creek but many fish die due to quick drying of the creek (Mauldin 1968)

- 1912
  - Sacramento pikeminnow are most dense in Kelsey Creek (Mauldin 1968)
- 1914
  - Rainbow trout are common in Clear Lake before the building of Cache Creek Dam in 1915 (Cook et al. 1966
- 1915
  - The Cache Creek Dam (on the only outlet from Clear Lake) is built (Murphy 1951; Kimsey 1957; Bairrington 1995[app], 1999[app])
- 1923
  - Second white catfish[a] introduction; successful (Murphy 1951, Dill and Cordone 1997)
- 1924
  - Heavy rains (Coleman 1930)
  - 135,000 brown trout and lake trout are introduced (Murphy 1951, Dill and Cordone 1997). Lake trout introduction is unsuccessful
- 1925
  - A drought occurs dropping the lake level 0.5 m (Coleman 1930)
  - Mosquitofish are successfully introduced (Murphy 1951)
  - Clear Lake splittail are very abundant (Coleman 1930, Hopkirk 1974)
  - Streams and tule swamps are filled side to side with fish (Benson and Mauldin 1974)
  - It has been noted that at Clearlake Oaks the fish were so abundant that you could walk upon them (Benson and Mauldin 1974)
  - White crappie are observed (Coleman 1930)
- 1926
  - An eruption at the bottom of Soda Bay releases large amounts of sulfuric acid resulting in a fish kill (Coleman 1930)
  - Thicktail chub are becoming less common in the lake (Cook et al. 1966)
- 1929
  - Clear Lake still supports a huge catfish fishery (Altouney et al. 1966[app], Dill and Cordone 1997)
- 1930s
  - Sacramento sucker are common (Cook et al. 1966)
  - There is a good Clear Lake hitch run on Kelsey Creek but in the last mile of the creek many fish died for an unknown reason (Mauldin 1968)
- 1930s-1951
  - Catfish were 80.0% of the catch (Puckett 1972b)
- 1930
  - Many young fish in Clear Lake (Coleman 1930)
  - Sacramento perch are abundant within the lake (Murphy 1948a)
  - Clear Lake splittail are abundant (Cook et al. 1966)

- 1932-1936
  - There is increase in rough fish catch in California due to their abundance in Clear Lake (Davis 1963)
  - Catch from Clear Lake is 133,810 kg/yr (Bairrington 1999[app])
- 1938
  - Thicktail chub are last seen (Cook et al. 1964, 1966)
  - Sacramento pikeminnow are abundant (Cook et al. 1966)
  - Some fish species within Clear Lake, from most to least abundant: Clear Lake splittail, Clear Lake hitch, carp, white catfish[a], Sacramento perch (Lindquist et al. 1943, Hopkirk 1974)
  - Clear Lake hitch are abundant (Cook et al. 1966)
- 1940s
  - Sacramento pikeminnow, Clear Lake splittail, thicktail chub populations crash (Cook et al. 1966)
  - Sacramento perch populations are reduced (Cook et al. 1966)
- 1940
  - Reports of fish kills (Lindquist et al. 1943)
  - Clear Lake splittail abundant but shortly after 1940 their numbers begin to decline quickly (Cook et al. 1966)
- 1941
  - Catfish fishing is banned (Bairrington 1999[app])
- 1943
  - Sacramento perch is moderately abundant (Cook et al. 1966)
  - Large Clear Lake splittail and Clear Lake hitch runs (Lindquist et al. 1943)
  - Fish species known to be in Clear Lake (Lindquist et al. 1943): White catfish[a], bluegill, black crappie, Sacramento perch, Clear Lake hitch, Clear Lake splittail, carp, largemouth bass, green sunfish, Sacramento blackfish, thicktail chub, Sacramento pikeminnow, Sacramento sucker, prickly sculpin[b]
- 1943-1944
  - Kelsey Creek held a big Clear Lake hitch run but it is the last successful spawning season for some time (Murphy 1948a)
- 1944
  - A drop in fishing quality (Murphy 1951)
- 1946
  - Almost no Clear Lake hitch have been spawning (Murphy 1948a)
  - Clear Lake splittail are almost absent (Murphy 1951, Hopkirk 1974)
- 1946-1947
  - Sacramento perch have maintained small, healthy populations (Cook et al. 1966)
- 1946-1950
  - Sacramento blackfish, carp, and Sacramento suckers have fair population numbers; Clear Lake hitch, Sacramento pikeminnow, and Clear Lake splittail are rare (Murphy 1951)

- 1947
    - Few Clear Lake hitch have been spawning but a dam release caused a freshet and some fish spawned (Murphy 1948a)
- 15 June 1947
    - Sacramento perch are seen spawning in Clear Lake (Curtis 1949)
- 1948
    - Clear Lake hitch spawning runs are in serious decline (Murphy 1948a)
    - Clear Lake hitch are rare (Cook et al. 1966, Mauldin 1968)
    - Sacramento perch are scarce, possibly due to the bluegill introduction (Murphy 1948b)
    - The Sacramento blackfish fishery is banned to create more largemouth bass food (Murphy 1950, McCammon et al. 1964, Moyle and Holzhauser 1978)
    - Beach seines show the most prominent fish in Clear Lake appear to be largemouth bass, bluegill, sculpin and Sacramento blackfish (Murphy 1949)
- September 1949
    - TDE (DDD) (dichloro-diphenyl-dichloroethane) treatment of Clear Lake for pest control (specifically the Clear Lake gnat, *Chaoborus astictopus*) begins (Hunt and Bischoff 1960, Cook and Connors 1963, Cairns and Parfitt 1980)
- 1949
    - 1,000 Nesting pairs of western grebes (*Aechmophorus occientalis*) are found around the lake (Hunt and Bischoff 1960)
    - Significant numbers of Sacramento perch in Clear Lake (Curtis 1949)
    - The once prosperous catfish fishery closes (Dill and Cordone 1997)
- 1949-1964
    - 226,796 kg dichloro-diphenyl-trichloroethane (DDT) used for pest control on the lands around Clear Lake for agriculture (Cairns and Parfitt 1980)
- 1950s
    - Sacramento perch is common in the lake (Cook et al. 1966)
    - Fathead minnow introduced (Moyle 2002)
    - Percentage of fish catch for 1950s (Puckett 1972b): Centrarchids (80.0%), bass (5.0-10.0%), crappie (2.0-56.0%)
- 1950
    - Second golden shiner introduction (McCammon et al. 1964, Moyle and Holzhauser 1978, Dill and Cordone 1997)
    - There are 12 native fish species and 8 introduced species in the lake (Bairrington 1995[app], 1999[app])
- 1951
    - Sacramento pikeminnow are now almost extinct from the lake; Sacramento perch and trout are very scarce (Murphy 1951)
    - Fish species known to be in Clear Lake (Murphy 1951):
        - Native species - rainbow trout, Sacramento sucker, Sacramento blackfish, Clear Lake hitch, Sacramento pikeminnow, thicktail chub, Clear Lake splittail, California

roach[a], Sacramento perch (<1%) and Clear Lake tule perch, prickly sculpin[b], threespine stickleback
      - Introduced species: carp, white catfish[a] (70%), brown bullhead (2%), mosquitofish, largemouth bass (10%), green sunfish, bluegill, black crappie (not over-exploited)

- July 1951
  - Gnat larvae are found in the lake (Hunt and Bischoff 1960)
- September 1954
  - Second TDE treatment of Clear Lake (Hunt and Bischoff 1960, Cook and Connors 1963, Cairns and Parfitt 1980)
- December 1954
  - 100 western grebes found dead in and around the lake (Hunt and Bischoff 1960)
- 1954
  - White crappie are stocked (Li et al. 1976, Moyle 2002)
  - The Sacramento blackfish fishery is reinstated (it had been banned in 1948) (Moyle and Holzhauser 1978)
- March 1955
  - More dead western grebes are found (Hunt and Bischoff 1960)
- 1955-1956
  - The gnat problem begins to increase again (Hunt and Bischoff 1960)
- 1956
  - Observations of Clear Lake hitch spawning in Clear Lake, and of carp eating Clear Lake hitch eggs (Kimsey 1960)
- 25 April 1957
  - Clear Lake hitch are observed spawning around the Clearlake Oaks portion of the lake (Kimsey 1960)
- 3 May 1957
  - Clear Lake hitch are observed spawning in the lake at 1900 hours. There are no observations of Clear Lake hitch spawning in Middle Creek and Lyons Creek (Kimsey 1960)
- 9 May 1957
  - No Clear Lake hitch were observed spawning in Schindler Creek (Kimsey 1960)
- September 1957
  - Third TDE treatment of Clear Lake. 54,431 kg of TDE have been used (Hunt and Bischoff 1960, Cook and Connors 1963, Cairns and Parfitt 1980)
- December 1957
  - 75 western grebes found dead; eventually linked to TDE usage. A few of the western grebes were analyzed and it was discovered they had over 1,600 mg/L DDD in their bodies (Hunt and Bischoff 1960, Linn and Stanley 1969)
- 1957
  - Sulphur Bank Mercury Mine closes down (Harnly et al. 1997)
  - Over-fishing does not appear to be an issue for fish populations (Kimsey 1957)

- 1958
  - Decreasing TDE levels in animals (Linn and Stanley 1969)
- March 1958
  - Several types of fish are analyzed to see how much DDD remained in their system. Results ranged from 40.0 mg/L in carp to 2,500 mg/L in brown bullhead (Hunt and Bischoff 1960)
- July 1958
  - More analyses show white catfish[a] and largemouth bass contain the largest amounts of DDD (Hunt and Bischoff 1960)
- 1958-1959
  - Less than 25 nesting pairs of western grebes located around the lake. This is down from 1,000 in 1949 before TDE treatments began (Hunt and Bischoff 1960)
- 1960s
  - 5,443 kg of Sacramento blackfish taken from Clear Lake via seining (Davis 1963)
  - Nine adult and zero juvenile Sacramento perch found in the lake (Cook et al. 1966)
- 1960
  - Heavy commercial fishing in Clear Lake (Davis 1963)
  - Largemouth bass comprise 42.0% of the catch (Puckett 1972b)
- 1961
  - Huge stocks of white catfish[a] and brown bullhead are placed in Clear Lake (McCammon and Seeley 1961)
  - Clear Lake splittail are almost absent (Cook et al. 1964, Benson and Mauldin 1974)
- 1961-1962
  - Beach seine hauls contain 20.0% Clear Lake hitch and Sacramento blackfish (Geary 1978)
- 1962
  - The lake experiences *Anabaena* blooms, low zooplankton levels and a decrease in chironomids (Cook and Connors 1963)
  - Methyl parathion is applied annually (3-4 times/summer) (Cook and Connors 1963, Apperson et al. 1976)
  - Adobe Creek and Highland Springs Dams are built (ICE 1997[app])
  - Clear Lake hitch and Sacramento blackfish are abundant (Cook and Connors 1963)
- 7 April 1962
  - Clear Lake hitch are present in Seigler Canyon Creek (Swift 1965)
- 12 April 1963
  - Clear Lake hitch are present in a ditch near Lakeport (Swift 1965)
- 1963
  - Redear sunfish introduced (Cook et al. 1964)
  - Rainbow trout are not found in the lake but there are some populations that subsist in the lake's tributaries (Cook et al. 1966)
  - Brown trout are known in the Clear Lake watershed and have possible limited occurrence in the lake (Cook et al. 1964)

- 1964
  - Sacramento perch found in low numbers (Cook et al. 1964)
  - There are 12 native fish species and 12 introduced species in the lake (Bairrington 1995[app], 1999[app])
  - Clear Lake hitch occur in low numbers (Cook et al. 1966)
  - No observations of the threespine stickleback or California roach[a] (Cook et al. 1964)
- 1965
  - Threespine stickleback is rare in the lake (Cook et al. 1966)
- 1966
  - Clear Lake splittail populations are stressed (Cook et al. 1966)
  - Pacific lamprey are not observed in the lake (Cook et al. 1966)
  - Sacramento blackfish appear in large numbers (Cook et al. 1966)
  - Prickly sculpin appear in good numbers (Cook et al. 1966)
  - Clear Lake tule perch is reasonably abundant (Cook et al. 1966)
  - Sacramento perch are considered rare (Cook et al. 1966)
  - Thicktail chub may be extirpated by this point (Cook et al. 1966)
- October 1967
  - 3,000 Mississippi silverside[c] are introduced into Clear Lake as a forage fish, reduction of plankton and to assist in gnat and midge control. This was not authorized by the CFC (Cook and Moore 1970, Li et al. 1976, Geary 1978, Moyle and Holzhauser 1978, Week 1983[app], Dill and Cordone 1997, Moyle 2002)
- 1968
  - Beach seining shows Mississippi silversides[c] are the most abundant fish in the lake (Cook and Moore 1970, Moyle and Holzhauser 1978)
- 1969
  - 1,000 mg/L TDE detected in some animals (Linn and Stanley 1969)
  - Percentage of catch for 1969 (Puckett 1972b, Macedo 1991): Black crappie (36.9%), bluegill (22.8%), white crappie (19.1%), brown bullhead (6.9%), largemouth bass (5.0%), green sunfish (2.0%), channel catfish (1.0%), Clear Lake hitch/Clear Lake splittail/Sacramento blackfish/Sacramento perch/redear sunfish (<1.0%)
  - Fish species thought to be in Clear Lake (Puckett 1972b): Rainbow trout, Sacramento sucker, carp, goldfish, golden shiner, Sacramento blackfish, Clear Lake hitch, Sacramento pikeminnow, thicktail chub, Clear Lake splittail, California roach[a], fathead minnow, channel catfish, brown bullhead, mosquitofish, largemouth bass, green sunfish, redear sunfish, bluegill, Sacramento perch, white crappie, black crappie, Mississippi silverside[c], Clear Lake tule perch, prickly sculpin[b], threespine stickleback
  - Commercial fishing (Puckett 1972b):
    - Sacramento blackfish catch is 88,450 kg
    - Carp catch is 109,769 kg
- April 1969
  - Planting of northern largemouth bass due to decrease in largemouth bass numbers (Puckett 1972b, Pelzman 1980)

- 1969-1971
  - Florida largemouth bass are introduced (Moyle and Holzhauser 1978, Pelzman 1980, Dill and Cordone 1997)
- 1969-1983
  - Intermittently through these years channel catfish were restocked in Clear Lake (Bairrington 1999[app])
- 1969-1993
  - Intermittently through these years largemouth bass were restocked in Clear Lake (Bairrington 1999[app])
- 1970s
  - Clear Lake hitch numbers continue to decline (T. Knight, Lake County Record-Bee, personal communication, August 2008)
- 1970
  - Mississippi silverside[c] population is growing quickly (Puckett 1972b, Moyle 2002)
- 1971
  - Although Clear Lake hitch numbers are in decline there is still a substantial run on Kelsey Creek (Benson and Mauldin 1974)
- 1972
  - Crappie equal 56.0% of catch (Macedo 1991)
- 1973
  - The Sacramento perch population appears stable (Aceituno and Nicola 1976)
  - Beach seine hauls contain <1.0% Clear Lake hitch and Sacramento blackfish (down from 1961-1962 numbers of 20%) (Geary 1978)
  - Clear Lake splittail and thicktail chub thought to be extirpated from the lake (Hopkirk 1974)
- 1974
  - Observations of large fish kills due to drying of creeks during spawning (Benson and Mauldin 1974)
- 1975
  - 40,000 northern strain largemouth bass are introduced into the lake (Moyle and Holzhauser 1978)
- 1976
  - Anderson Marsh temporarily converted to agriculture (Bairrington 1995[app], 1999[app])
  - Mississippi silverside[c] population is somewhat low resulting in less competition with native species (Geary 1978)
  - April-October electrofishing results, from most to least abundant (Week 1983[app]): Mississippi silverside, bluegill, carp, Clear Lake tule perch, green sunfish, prickly sculpin, black crappie, goldfish, largemouth bass, white catfish, Sacramento blackfish, Clear Lake hitch, brown bullhead, white crappie, channel catfish, Sacramento perch
- Late 1970s
  - White crappie population declines and never fully recovers (Moyle 2002)

- 1980s
  - Kelsey Dam is built (T. Knight, Lake County Record-Bee, personal communication, August 2008)
- 1982
  - August electrofishing results, from most to least abundant (Week 1983[app]): Mississippi silverside, bluegill, carp, Clear Lake tule perch, largemouth bass, green sunfish, prickly sculpin, black crappie, goldfish, white catfish, Sacramento blackfish, Clear Lake hitch, brown bullhead, white crappie, channel catfish, Sacramento perch
  - Pacific lamprey and threespine stickleback have not been observed in the lake since 1894, but may still be present in tributaries (Week 1983[app])
- 1984
  - Clear Lake hitch are seen spawning in storm drains (T. Knight, Lake County Record-Bee, personal communication, August 2008)
- 1985
  - Florida black crappie are introduced (Macedo 1991; Bairrington 1995[app], 1999[app]; Moyle 2002)
  - Threadfin shad introduced (illegally). They undergo a population boom which threatens Clear Lake hitch populations because they occupy the same niche in the food web (Geary 1978; Bairrington 1995[app], 1999[app]; Moyle 2002)
- 1988
  - Clear Lake has green, yellow-green, and blue-green algae (Macedo 1991)
  - Percentage of catch by species (Macedo 1991): bass 67.0%, bluegill 15.0%, crappie 6.0%, catfish/Clear Lake hitch/carp/perch 12.0%
  - Sacramento perch population up to 1.0% from <1.0% in 1969 and 1976 (Macedo 1991)
  - Crappie population in decline (Macedo 1991)
- Late 1980s
  - Few juvenile largemouth bass are found in seines (Bairrington 1999[app])
- 1990
  - Sulphur Bank Mercury Mine becomes a superfund site (Harnly et al. 1997)
- 1990-1991
  - Threadfin shad die off but Mississippi silverside[c] numbers increase (Bairrington 1999[app], Moyle 2002)
- 1991
  - From this time on, no live bait harvesters have been on Clear Lake (Bairrington 1999[app])
  - Catfish are documented using the spawning structures (Bairrington 1999[app])
  - Juvenile fish experience a population boom (Bairrington 1999[app])
  - Catfish catch abundances in the sport fishery (Macedo 1991, Dill and

Cordone 1997), from most to least abundant: brown bullhead, white catfish[a], channel catfish

- 1993-1995
  - Shad population crashes (Bairrington 1995[app], 1999[app])
- 1993
  - Placement of spawning gravel at Anderson Marsh and Clear Lake State Park (Bairrington 1999[app])
  - Kelseyville Main Street Bridge fish ladder put in to aid Clear Lake hitch in getting upstream to spawn. Does not appear to be as effective as planned. There are still obstructions further upstream (T. Knight, Lake County Record-Bee, personal communication, August 2008; P.F. Windrem, Chi Council, personal communication, August 2008)
- October – December 1993
  - Tule transplants between Nice and Lucerne to create fish nursery areas (Bairrington 1999[app])
- 1994
  - Hydrilla found in the lake (Bairrington 1995[app], 1999[app])
- 1995
  - Past and present fish in Clear Lake (Bairrington 1999[app]):
    - Native species: rainbow trout, Pacific lamprey, Sacramento sucker, Sacramento blackfish, Clear Lake hitch, Sacramento pikeminnow, Clear Lake splittail, thicktail chub, Sacramento perch, Clear Lake tule perch, California roach[a], prickly sculpin, threespine stickleback, hardhead
    - Introduced species: goldfish, carp, brown bullhead, channel catfish, white catfish[a], largemouth bass, smallmouth bass, bluegill, redear sunfish, green sunfish, mosquitofish, Mississippi silverside[c], threadfin shad, fathead minnow, pumpkinseed
  - Sacramento perch numbers are stable while crappie numbers are in decline (Moyle 2002)
- 1997
  - Threadfin shad illegally reintroduced into the lake (Bairrington 1999[app], Moyle 2002)
- 2002
  - Clear Lake tule perch, Clear Lake hitch, Sacramento blackfish and prickly sculpin are the four native species of Clear Lake fishes that have managed to persist in large numbers since the introductions of non-natives in the 1880s (Geary and Moyle 1980, Moyle 2002)
- 2008
  - Sacramento perch believed to be gone from Clear Lake (D.L. Woodward, Lake County Vector Control District, personal communication, August 2008)

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[a] White catfish (*Ameiurus catus*) was also referred to as fork-tailed catfish (Jordan and Gilbert 1895) and by the scientific name *Ictalurus catus* (Murphy 1951). Grass pickerel

(*Esox americanus vermiculatus*) was also referred to as mud pickerel (Murphy 1951). California roach (*Lavinia symmetricus*) was formerly referred to as western roach (*Hesperoleucus symmetricus*) (Murphy 1951).

[b] Prickly sculpin (*Cottus asper*) is native to Clear Lake. Riffle sculpin (*Cottus gulosus*) was never present in Clear Lake (Jordan and Gilbert 1895; Murphy 1951; P.B. Moyle, University of California Davis, personal communication, August 2008).

[c] The species of silversides introduced into Clear Lake was Mississippi silversides (*Menidia audens*) not inland silversides (*Menidia beryllina*) as some literature suggests. Previously the two species were considered one species but they are currently considered two distinctly separate species (Nelson et al. 2004; P.B. Moyle, University of California Davis, personal communication, August 2008).

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