CALFED BAY-DELTA PROGRAM

CALFED SCIENCE FELLOWS PROGRAM

In cooperation with the

California Sea Grant College Program

Sea Grant California

FELLOWSHIP APPLICATION COVER PAGE

APPLICANT TYPE [X] Postdoctoral Researcher [ ] Ph.D. Graduate Student

PROJECT NUMBER

PROJECT TITLE The impacts of global climate change on Delta fishes: Predicting fish abudance, distribution and commmunity changes

FINANCIAL SUMMARY

First Year CALFED Funds Requested:	$65,500
Total CALFED Funds Requested:	$191,875
Duration:	3 yrs
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APPROVAL SIGNATURES

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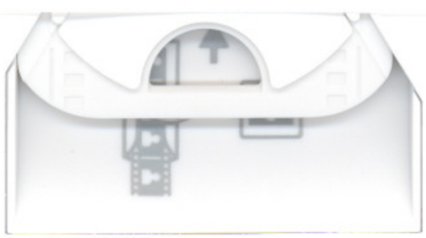
Will animal subjects be used? [X] Yes [ ] No

APPROVAL DATE: November 2005 PROTOCOL #: 10920 PENDING:

Does this application involve any recombinant DNA technology or researcl [ ] Yes [X] No



Introduction/Question/Objectives:

Issue and Impact

Of particular and increasing concern is the evidence that global climate change is occurring and will have far-reaching effects on ecological systems. It is necessary to downscale climate change predictions to a regional level for management of complex watersheds such as California's largest hydrologic system, the San Francisco Bay, Delta and Sacramento and San Joaquin Rivers (BDRW). Approximately 50 percent of California's average annual runoff, derived from 40 percent of its surface area, flows through the BDRW system. Currently, tidal and river processes influence the hydrodynamics and associated water quality of the Delta. The regional climate change projections by year 2100 include sea level rise of 0.3-0.9 m along coastal California (Field et al. 1999, Church and Gregory 2001, Mount et al. 2006), moderately less precipitation (Dettinger 2005), and air temperatures warmer by 2 - 7 ºC (Cubasch and Meehl 2001, Hayhoe et al. 2004, Dettinger 2005). While the precise magnitude of these changes varies with the global climate models (GCMs), there is strong evidence that these major changes are likely (Church and Gregory 2001, Hayhoe et al. 2004, Dettinger 2005, Maurer and Duffy 2005, Mount et al. 2006).

What do the predicted climate changes mean for the BDRW system? Sea level rise will result in greater erosion along coasts, and saltwater will intrude farther into the Delta, changing channel volume and salinity regime (Church and Gregory 2001, Mount et al. 2006). Precipitation will increase earlier in the year with less snow accumulation and earlier snowmelt, thus the overall magnitude and seasonality of water flow will be adversely affected (Synder et al. 2002, Knowles and Cayan 2004, Hayhoe et al. 2004, Maurer and Duffy 2005). Seasonal runoff will have higher flood peaks during the rainy season and reduced warm-season flows starting in late spring and summer (Gleick and Chalecki 1999, Snyder et al. 2002, Knowles and Cayan 2004, Dettinger 2005). These hydrologic changes will propagate downstream to the Delta and Estuary, resulting in an altered salinity regime (Knowles and Cayan 2002, 2004). During the seasonal low inflows, the changes due to sea level rise will become more pronounced, resulting in large changes in hydrodynamics and water quality. The BDRW levee systems will experience more strain due to the increased water volume and differential elevations between the interior of islands and Delta channels, amplifying the probability for levee failure (DWR 2006, Mount et al. 2006). Annual atmospheric temperature projections show a consistent warming pattern across California, with summer temperature increases greater than the increases expected for winter (Hayhoe et al. 2004). Changes in atmospheric temperature directly affect the warming of aquatic ecosystems, and thus impact many species that depend on the BDRW system.

Management will play a key role in the mitigation of climate change effects, particularly with regard to water quality, water supply and the region's biota. Working groups within the CALFED Bay-Delta Authority (CBDA) and research projects funded by CBDA, such as CASCaDE (USGS 2005), are working on a model-based approach to ecological forecasting (Clark et al. 2001) to project future states of the Rivers and Delta ecosystems under prescribed scenarios of change. CASCaDE focuses primarily on linking climatic, hydrological, hydrodynamic, biogeochemical, sediment/geomorphic and biological models in a hierarchical manner. Different combinations of climate change affects will be followed as they propagate from the climate systems to watersheds to river networks of the BDRW system. However, the emphasis of climate change research, even within CASCaDE, is on environmental change. Knowledge of how climate change will affect key aquatic species and ecosystems is less well developed and necessary for the development of long-term goals and management of native and non-native species in the BDRW system.

Climate change affects ecosystems and their function, communities, populations and their structure, species ranges and distributions, and even individual fitness (Parmesan 1996, Booth and Visser 2001, McCarthy 2001, Walther et al. 2002, King and McFarlane 2006). Habitat changes caused by climate change threaten both species diversity and the delivery of critical ecosystem services. Predictions of climate-induced population extinctions are supported by recent correlative evidence that numerous species have shifted their ranges in response to climatic change (Clark et al. 2001, Parmesan and Yohe 2003, Tolimieri and Levin 2004, Anderson et al. 2006). Terrestrial and aquatic organisms, in particular fish, have specific tolerance ranges of environmental conditions (Attrill 2002, Barton et al. 2002). Unlike most mammals and birds, fish are limited in their ability to re-distribute over large geographic scales in response to climate warming because aquatic ecosystems have distinct physical and chemical boundaries. Additionally, most fish have a much narrower temperature tolerance range compared to mammals and birds. Fish differ in their physiology and behavior, which will result in unique responses to climatic trends and environmental variation. For example, temperature is an exacting mechanism on discrete developmental events, larvae survivorship, sex differentiation, smolting, maturation, activity duration, reproductive potential and spawning cues (Elliot 1981, Cech et al. 1990, Claireaux and Audet 2000, McCarty 2001, Myrick and Cech 2004, Thrope 2004, Roessig et al. 2004, Portz et al. 2006). Consequently, climate change effects on water quality and habitat availability are of considerable importance in determining future fish distributions, abundances, survivorship, and viability.

Because a fish's physiology and performance is strongly influenced by ambient temperature, fish will likely track their preferred water temperature causing changes in distribution, migration routes and timing, which could result in altered community structures and ecosystem services. For example, a temperature increase of 0.5 ºC will cause an increase in the rate of biochemical reactions and thus an increase in fish metabolism. Fish will behaviorally regulate their metabolism by seeking thermal refuges at small spatial scales, such as water column depth or cool tributary inflows. If these refuges are not available, thermal exposure (and thus thermal stress) will be unavoidable and possibly fatal (Gamperl et al. 2002, Roessig et al. 2004). Thermal stress (Figure 1) disturbs normal physiological functions resulting in energy expended towards stress responses (i.e., sub-optimal range and/or beyond; Figure 2). If the conditions persist at chronic levels (i.e., long-term), critical physiological processes (e.g., osmo-regulation, immune system function) are hampered, and individual growth, reproductive potential and survivorship will decrease over time (Figure 1; Brett 1958, Fry 1971, Barton et al. 2002, Woodley and Cech *in prep*). The severity of thermal stress responses may also depend on ecological factors (e.g., predation threat, food availability) and water quality constituents (e.g., dissolved oxygen, salinity; Hettler 1976, Claireaux and Audet 2000, Rose 2000). Laboratory studies can determine the environmental optimal, sub-optimal, and tolerance ranges of a species, and by combining this information with ecological observations, researchers can predict fishes responses to thermal changes (Cech et al. 1990, Thorpe 2004, Woodley and Cech *in prep*).

Many estuarine and delta fishes live near their tolerance limits. As a result, these ecosystems will likely exhibit early responses to regional environmental changes, including changes in abundance of native and exotic species (Kennedy 1990, Carlton 1996, Moyle 2002, Roessig et al. 2004). For practical reasons, many early studies of climate change effects on fishes used single species and single site analyses. Unfortunately, using single sites or habitats to consider the effects of water quality on a species is not always appropriate, because many species may use multiple habitats or regions within a watershed at different life stages (Clark et al. 2001, Johnson and Leggett 2002). This approach sacrifices biological realism when exploring the effects climate change because of the lack of information for many fish species and model over-simplicity (Rose 2000, Clark et al. 2001). Studying the effects of climate change requires watershed-level analysis inclusive of various habitats and regions important to a species' life history. In order to predict effects on multiple populations spread over large geographic areas more realistic projections are needed. Such predictions can be made by combining geographic information systems (GIS), life history and abundance data, and dynamic bio-energetically based population models. The novel approach of coupling dynamic bio-energetically based, life stage specific population models (DEBs) to GIS databases, in order to scale up environmental effects on individuals to regional population responses, offers a promising approach for watershed assessments.

Dynamic bio-energetically based population models are useful tools for managers, because they can be applied to a variety of ecological processes ranging from basic consumption and metabolism to the accumulation of contaminants, life history strategies, predator-prey interactions, and population-level consequences (Brett and Groves 1979, Hewett and Johson 1992, Kareiva and Wennergren 1995, Nisbet et al. 2000). The DEBs concept is based on an energetic balance between the demand of physiological maintenance, consumption, metabolic and waste loss, growth (somatic and/or gonadal), reproductive potential, and survival. DEB models, if expanded to include more physiological details, are capable of predicating organism-level responses (e.g., growth) based on the primary (e.g., endocrine changes) and secondary physiological responses (e.g., respiration changes) to a particular stressor. When a species' physiologically optimal conditions and behavioral preferences are known, the DEB model can be used to confirm (or predict) optimal metabolic homeostasis, growth and reproduction under specified environmental conditions (Brown et al. 1990; Nisbet et al 2000). The Ecological Society of America recently acknowledged DEB models as useful tools for understanding ecological dynamics, especially in cases of complex communities (Thorpe 2004, Anderson et al. 2006). If the model is constructed in a manner to include stressors, such as climate warming, that are known to disrupt homeostasis, then the model can predict growth, fecundity and survivorship under sub-optimal conditions associated with climate change or altered watersheds.

Understanding and applying the downscaled climate change projections to the BDRW system is essential for predicting the potential effects on fishes. The possible changes resulting from climate change could greatly affect water quality and habitat availability for fishes. Many of the fishes in critical need of conservation or restoration in the BDRW system have complicated life history patterns, use a variety of habitats, and can migrate long distances. Effective management requires understanding how abiotic conditions, in particular temperature, affect fish populations in the current BDRW system and how these conditions may change under the influence of climate change. By synthesizing known information on species life histories, geo-referencing fish populations and studying their energetic expenditures to specific abiotic factors, we can begin to investigate how regional climate changes would affect BDRW fish populations.

Question
What effects will climate change have on native and alien fish species in the BDRW system, emphasizing selected species of concern?

Objective
Our objective is to determine how the distributions, foraging, growth and reproductive potential of selected native (many of which are endangered or threatened) and invasive (resident and possible new introductions) species would change under various climate change regimes.

Approach/Plan of Work

Species selection
To examine the impact of climate change on species, we have chosen several species that represent thermal guilds (species with similar temperature requirements) and/or species that require special attention due to their importance or impact on the BDRW system.

For potential invasive species, we have chosen northern pike *Esox lucius* and white bass *Morone chrysops* as potential Delta invaders. We have selected largemouth bass *Micropterus salmoides* as an important successful invader. The northern pike represents an important potential predatory threat to fishes in the BDRW systems. Northern pike is a cool-water ambush predator with great potential to affect populations of soft-rayed fishes (e.g., salmonids and splittail). Northern pike is strongly associated with the decline of many cyprinid species, and accelerated growth rates and increased predation rates can occur in warm habitats (Craig and Kipling 1983, Cook and Bergersen 1988, Robertson and Tonn 1989, Cassellman and Lewis 1996, Jackson and Mandrak 2006). In Alaska, northern pike was introduced in the 1950's in Bulchitna Lake. Since the introduction, the northern pike has dispersed throughout the Susitna drainage, south-central Alaska and Kenai peninsula, adversely impacting various salmon stocks (AK DFG 2002). Portions of the Sacramento-San Joaquin watershed match the preferred habitat (e.g., water quality and flow) of the northern pike (Craig and Kipling 1983, Jackson and Mandrak 2006). With climate change, northern pike may have even more favorable habitat conditions. If northern pike does become established it will likely become the major BDRW system predator, and exacerbate the decline of many native fish species. This species has received considerable management attention as scientists are working hard to extirpate it (currently CBDA supports 3 ERP grants).

White bass pose a serious threat to the Delta similar to northern pike (Moyle 2002). This species was introduced in 1965 into Lake Nacimiento, San Luis Obispo Co. Later, they were illegally introduced into

Kaweah Lake, Tulare Co., from which they were eradicated. However, before the eradication was complete, irresponsible persons introduced white bass into Pine Flat Reservoir, Fresno Co., where a self-sustaining population had been established. A moratorium has been placed on further introductions of this species by the CA DFG because of possible damage to the sport fishery in Delta waters should the white bass become established there. This species and northern pike are the only species of fish, which by law must be killed immediately when taken. White bass have developed large populations in reservoirs, but were thought to not thrive in rivers. Yet, in Missouri, white bass increased in abundance after river modifications took place (Pflieger and Grace 1987). Additionally, within their native range this species prefers large rivers, cool to warm waters and are tolerant of low salinities. Under the projected climate changes and altered flow regimes, this species would likely be a successful invader putting additional pressure on the native BDRW fishes (Matern et al. 2002, Schoenebeck and Hansen 2005).

Largemouth bass is a warm-water centrarchid that became established in California shortly after its introduction in 1891 (Moyle 2002). In its native range largemouth bass inhabits marshes, swamps, ponds, lakes, reservoirs, and creeks to large rivers. In river systems, largemouth bass can be found in pools and backwaters. It prefers warm, generally clear water, and is less tolerant of turbidity than other basses. It is a voracious predator that begins to eat fish when at ca. 5 cm in total length. It swallows live fish and other aquatic life whole, so prey size is limited by their gape. It is an opportunistic feeder that will typically ambush anything that moves nearby. Largemouth bass can tolerate a range of salinities and is found in estuaries, but in California, it is unusual to find them in waters greater than 3 psu. In the Delta, largemouth bass is found in tidally influenced freshwater sloughs (Moyle 2002). We have included largemouth bass as an established invasive species that is an important predator on native species, such as Sacramento perch.

For native fishes in the BDRW systems, we selected delta smelt, Sacramento perch, green sturgeon, the winter-run steelhead and fall-run Chinook salmon. Delta smelt (*Hypomesus transpacificus*) is a cool water, semi-anadromous species that has become a major focus of environmental concern in California. Though recent research efforts have yielded vitally important information on delta smelt, there still is a need to define the factors that limit its carrying capacity and its response to altered environmental quality via climate warming (Swanson et al. 2000, Bennett 2005). This is particularly important given recent declines in a number of pelagic organisms in the Delta, which includes delta smelt.

Researchers at University of California-Davis (UCD) are confident that Sacramento perch (*Archoplites interruptus*) is extirpated from most of its native range. The new information gained from the CBDA supported restoration project (ERP 02-P34) indicates that this species is truly a cool-water centrarchid that has a similar life history pattern to many Delta fishes (e.g., floodplain spawning; Woodley and Cech *in prep*). Restoration attempts are in progress with the CA DWR, UCD and the Contra Costa Mosquito and Vector Control District (e.g., Black Loch tidal marsh, ERP-01-C04, and the Mein's Landing project). Including Sacramento perch in this study will benefit the current efforts to restore populations of this once prized game fish.

In April 2006, NOAA Fisheries Service listed the southern distinct population segment of North American green sturgeon (*Acipenser medirostris*) as threatened under the Endangered Species Act. Green sturgeon is a coldwater anadromous species that uses the BDRW system. Scientists at UCD are tracking green sturgeon within the BDRW, and suspect that the southern population will be affected if cold-water habitat declines with climate change (CBDA project #98-C15; PA Klimley and JJ Cech Jr. personal communications).

Finally, the winter-run steelhead (*Oncorhynchus mykiss*) and fall-run Chinook salmon (*O. tshawytscha*) were chosen because these are coldwater anadromous species at the southern-most extent of their distribution (Fisher 1994, Moyle et al. 1995). These runs move into the BDRW when the system can be quite warm, thus like green sturgeon, salmon may suffer increased thermal stress with climate change. Additionally, steelhead occupy freshwater systems for longer time periods (up to 3 years; McCullough 1999) compared to Chinook salmon and thus would likely be more vulnerable to climate warming or more extreme interannual variations in water temperature regimes.

Specific approaches
Research Question 1- What are the life history requirements of each species? At what life-history stage are they most likely to be affected by climate change?

Objective 1- The objective is to construct life history models by compiling published information and expert advice on the selected species (Figure 3). For some of the species, a life history model exists (i.e., Delta smelt, Chinook salmon; Moyle 2002, Bennett 2005), but for the majority of the species we do not have accessible qualitative life history models within the BDRW system.

Hypothesis 1- We expect that the limiting stage for most species will be the egg/larval and/or juvenile stages because these stages vulnerable experience different selective pressures than do the adults. Egg and larval stages typically have fewer physiological mechanisms in place to deal with environmental quality changes and lack the mobility to escape suboptimal environments compared with adult fish.

Approach 1- A common complaint of stakeholders in the BDRW system is that despite the large volume of research that has been conducted, species information is difficult to find or access due to the diverse nature of publication outlets or because the data are unpublished. Federal and state agencies, private consulting firms, non-profit organizations and academic institutions have conducted biological and ecological studies on the selected species. We will compile information on the ecology and distribution of each species as a "baseline" to help guide our evaluations of the effects of climate change and construct life history models. These qualitative models will help identify habitat requirements, physiological tolerances, and behavioral preferences as they relate to environmental quality (Figure 1and 2). For species with hatchery populations, we will only address natural populations.

Research Question 2- How will climate change affect the temperature and salinity in the BDRW system? In particular, what are the expected environmental conditions, including water temperatures, salinity, and flow regime, in regions known to be important to the species in question? How will climate change affect critical habitats necessary for the native species?

Objective 2- For this objective, we will first establish current thermal regime of the BDRW system and then overlay the predicted climate change for 4 seasons at 4 intervals of 25 years to create baseline models. Salinity and flow patterns, where available, would be layered onto the baseline models. This approach will generate 16 thermal models of the current and predicted changes for each species.

Hypothesis 2- We expect to find an overall increase in water temperatures accompanied by changes in salinity and flow regimes.

Approach 2- To test for climate period and location effects, we first need to establish current temperature, salinity and flow patterns in the BDRW system. We will obtain temperature, salinity and flow data from collaborators with CASCaDE (specifically, the "Sacramento-San Joaquin Watershed and San Francisco Bay" and the "Delta" modeling groups) and other agencies and academic institutions with long –term research collections (e.g., Suisun Marsh project, P.I. P.B. Moyle). We will divide the environmental parameters into four "seasons": 1) March 1 – May 31, 2) June 1 – August 15, 3) August 16 – November 31, and 4) December 1 – February 31. The March 1 – May 31 season corresponds to increasing flow and slowly increasing water temperature. During this time period, a suite of our selected species spawn: delta smelt, green sturgeon, and Sacramento perch. Additionally, juvenile fall-run Chinook salmon outmigration peaks during this period. The June 1 – August 15 period corresponds to decreasing flow, rapidly increasing water temperature, and outmigration of late-fall run Chinook salmon. The August 16 – October 31 period corresponds to declining temperature, low flows, and the peak inward migration of adult fall-run Chinook salmon. Finally during the December 1 – February 31 period the temperatures are cold-cool, with flows increasing due to the winter rains. It is during this time period we see a peak for late fall-run Chinook salmon and steelhead upstream migrations. Analysis of variance (ANOVA) tests of temperature change can be conducted to determine daily anomalies, the differences between a daily temperature and the long-term average temperature on that day and location. By using the temperature anomalies we can test for trends present within a season, and test deviations from the long-term average.

Once the temperature baseline has been established, we can then overlay the predicted regional climate changes from the CASCaDE project. Again, we will be working very closely with the CASCaDE group to access the current and derived predicted climate change effects on environmental quality in BDRW system. The climate change predictions will be partitioned into 25 years (year 2025), 50 years (year 2050), 75 years (year 2075) and 100 years (year 2100) segments based on Dettinger (2005). The end product would be maps with the thermal, salinity and flow regimes for the BDRW system as best defined as possible. The climate change effects on the rivers, in particular thermal patterns, are a realistic expectation. However, we believe at this time, the DeltaTrim outputs will be limited and only reflect a few climate change scenarios and/or focus on particular locations within the Delta. For the Delta, we may have to extrapolate thermal regimes from larger scale studies, like Dettinger (2005), to specific locations. We may also lose the ability to look at detailed salinity intrusions, but could grossly estimate salinity for this question. The GIS models will provide an accurate quantitative means of determining the abiotic components for the next simulations, so that the various environmental quality parameters can be modeled simultaneously. The combination of the individual-based modeling and GIS approach results in a biologically realistic regional-scale analysis of fish population responses to global climate change.

Research Question 3- How would altered environmental quality due to climate change affect the selected species? In particular, if the current habitats are no longer accessible due to the predicted changes, where would the populations most likely redistribute? If redistribution is not possible or optimal habitat no longer exists, how would the growth and reproductive potential change in the sub-optimal environmental conditions?

Objective 3- Using the information gathered for the life history models and the environmental quality models, we would describe physiologically optimal, sub-optimal, and detrimental ranges for each species for the climate change scenarios. Within the optimal and sub-optimal ranges, we will predict the expected foraging, growth, and reproductive potential changes of each species.

Hypothesis 3- We expect that with climate warming, the optimal range for the non-native species will increase, as well as their growth and reproductive potential in the BDRW system. Conversely, we expect that the native species will have less optimal habitat, while the sub-optimal range increases; thus affecting their growth and reproductive potential.

Approach 3- The first step would be to use the life history models and GIS coverage generated in the prior research questions. By overlaying the qualitative life history, physiological and behavioral data on thermal, flow and salinity maps, we can generate geo-referenced maps and probability scenarios that would depict the redistribution of each species under the climate change scenarios without the DEB models. This step provides us with a more detailed understanding of habitat availability to each species. These results will also provide for a more thorough understanding of what information is available for use in the DEB model at each life stage. In a few cases, especially the responses of the selected species to salinity, we would need to collect new data on physiological tolerances, metabolic rates, and behavioral preferences.

The second approach for a few species would include collecting data on physiological tolerances, metabolism and behavioral preference. Physiological tolerance test yield the incipient lethal levels (Figure 2) which is vital to understand in the current habitat if the species lives near its limits or well within its limits. The determinate endpoints of these tests are the loss of equilibrium. Loss of equilibrium in fish indicates physical disorganization due to the experimental variable which can be monitored by oxygen consumption measurements and the loss of the fish's ability to escape from conditions leading to its death (critical thermal maxima and minima; Becker and Genoway 1979). This endpoint also allows experimental recovery of these fish. A horizontal, annular environmental gradient tank (1.0 m or 3 m diameter) with a telethermometer/probes/water sampling tubes array in the swimming path and a video camera/monitor system will be used for behavioral preferences (temperature and salinity) experiments. Environmental gradients will be produced by the simultaneous introductions of water (of either different temperatures, salinities) from plastic reservoirs into mixing chambers outside the annulus. These waters (and their mixtures) will flow towards a center drain in the apparatus, via holes and v-notches, through the annulus where the individual fish will be exposed to the resulting gradient as it swims through the annular path. This apparatus has, so far, been successfully used with steelhead (*Oncorhynchus mykiss*), Sacramento perch (*Archoplites interruptus*) and green sturgeon (*Acipenser medirostris*) exposed to temperature and salinity gradients. Data will be analyzed using appropriate statistical models (e.g., ANOVA) to determine significance among treatment group means.

The third step is to develop an environmentally sensitive DEB model using STELLA (Ver. 9, isee Systems, Lebanon, NH) and MATLAB (Ver. 7.2, The Mathworks, Natick, MA) for simulating fish growth, reproductive potential, and population responses in environmental regimes that have simultaneous temporal variation in temperature, dissolve oxygen, salinity (or conductivity) and food availability. The model would run for the season and time periods covered in Objective 2.

The DEB model (Figure 4) is derived from the basic bioenergetic model presented by Brett and Groves (1979). There is one base equation for the energy budget that balances fish consumption against the metabolic expenditures due maintenance metabolism, activity, specific dynamic action (the metabolic costs associated with food digestion), and waste, with the resultant energy incorporated into body tissues (somatic and gonadal):

$$C = R + A + S + F + U + \Delta B$$

Where *C* is food consumption; *R* is metabolism; *A* is activity; *S* is specific dynamic action; *F* is egestion (or feces production); and *U* is excretion (or urine production); and Δ*B* is somatic and gonadal growth.

For this study, we will use the derived base equation (Hewett and Johnson 1992):

$$(dB / (B * dt)) = C - (R + S + F + U)$$

where the terms definitions' are similar to Brett and Groves (1979). We have slightly modified the adjoining calculations for these terms to incorporate water quality as a stressor. The various equations used in the DEB model are listed in Table 1 and parameter definitions in Table 2. Most of the equations are temperature- and mass- dependent.

Table 1. Equations used to estimate the basic energetics balance for a fish. This does not include the water quantity sensitive subunit or the equations needed to predicted reproductive fecundity.

Equations use	**Equation**
Basic bioenergetics model (Brett and Groves 1979)	$C = R + A + S + F + U + \Delta B$
Derived bioenergetics equation (Hewett and Johnson 1992)	$(dB / (B * dt)) = C - (R + S + F + U)$
Food consumption (Hewett and Johnson 1992)	$C = \text{Max } C * P * f(\text{T con})$
Mass and feeding rate of the organism	$\text{Max } C = CA * (\text{Weight}^{CB})$
Temperature dependence of each process (Kitchell et al. 1977)	$f(\text{T con})$ or $(\text{T res}) = V^{X} * e^{(X-(1-V))}$
f(T con) (Hewett and Johnson 1992)	$V = (TMC - T) / (TMC - TOC)$ $X = (Z^{2} * ((1+ 40) / Y)^{0.5})^{2}) / 400$ $Z = \ln(CQ) * (TMC - TOC)$ $Y = \ln(CQ) * (TMC - TOC + 2)$
Growth as related to SDA (Jobling 1983)	$S = SDA * (C - F)$
Egestion (Elliot 1976)	$F = FA * T^{FB} * e^{(FG*P)} * C$
Excretion (Elliot 1976)	$U = UA * T^{UB} * e^{(UG*P)} * (C-F)$
Mass-Total length relationship	$B = a * L^{b}$

Table 2. A description of the parameters used in the basic energetic models.

Parameter	**Parameter Defined**
a	Intercept coefficients for the total length-weight regression
A	Activity
Act	An activity multiplier for respiration costs
ΔB	Growth - somatic and gondal
B	Total mass
b	Slope coefficients for the total length-weight regression

C	Food consumption
CA	Intercept of the allometric mass function
CB	Slope of the allometric mass function
CQ	Q10 - a rate function for any biological rate increase over a 10ºC range
Day	Day
F	Egestion
FA	Intercept of the proportion of consumed energy egested at a water temperature
FB	Coefficient of water temperature dependence of egestion
FG	Coefficient for feeding level dependence of egestion (based on P-value)
f(T con)	Temperature dependence function for respiration
f(T res)	Temperature dependence function for respiration
Max C	Mass and feeding rate of the organism
P	Realized proportion of maximum consumption
R	Metabolism
RA	Mass intercept of the allometric mass function
RB	Slope of the allometric mass function
RMR	Routine metabolic rate which includes activity
S	Growth
SDA	Specific dynamic action
SMR	Standard metabolic rate
TMC	Maximum water temperature above which consumption decreases
TMR	Maximum lethal water temperature
TOC	Preferred optimal temperature
TOR	Water temperature for optimum respiration
U	Excretion
UA	Intercept of the proportion of consumed energy excreted at a water temperature
UB	Coefficient of water temperature dependence of excretion
UG	Coefficient for feeding level dependence (based on P-value) of excretion

Environmental stressors effects

This section focuses on the added components of environment stress into the basic bio-energetics model. Hewett and Johnson (1992) present a basic respiration equation as:

$$R = RA * W^{RB} * f(\text{T res}) * \text{Activity}$$

We altered the routine metabolic respiration, R, to include standard metabolic rate, SMR, and activity. This is estimated as:

$$RMR = R = SRM * Act$$

SMR is the standard metabolic rate (g O_2 * g $fish^{-1}$* day^{-1}).

By splitting RMR from SMR, the increased standard metabolic rate from the environmental stressor can be included.

SMR is estimated as:

$$SMR = [RA * Weight^{RB} * f(\text{T res})] + [RA * Weight^{RB} * f(\text{T res}) * \text{Environmental stress coeff})]$$

----SMR normal---- ----additional SMR from stress----

The model contains an additional provision for changes in SMR with environmental changes in concentrations. The *SMR* and *Environmental stress coeff* equations allow for the *SMR Δ* relationship to take a non-linear form. To incorporate this stressor into the model, we have represented that relationship in the model as a linear function:

$$SMR\ \Delta = (\text{Ambient Environmental factor} - SMR)$$

Where *Ambient Environmental* factor is estimated from values in nature. The model uses several environmental effects that are incorporated into STELLA.

In a constant environment a population will ultimately grow exponentially and it is possible to calculate the rate of exponential growth in any given environment from generalizations of the Lotka equation (Kooijman

& Metz 1984). A population at equilibrium neither grows nor declines, implying that the average lifetime reproductive output, Ro, per individual in the population is one.

$$Ro = B(t) * S(t)dt$$

Where *S(t)* denotes the proportional of a cohort that survive to age *t*, and *B(t)* is the reproductive rate which can be obtained from the DEB model solutions and field acquired data. Survival in most populations is determined in part by the hazard rate, which is obtained from the DEB model, but also by other factors (e.g. predation, parasitism) that are unrelated to energetics. The DEB model can be used to determine the food density at which the population will be in equilibrium. We can calculate demographic properties of a population at equilibrium (Gurney et al. 1996; de Roos et al. 1997, Anderson et al. 2006), including time to reproductive maturity, mean fecundity, and the ratio of adults to juveniles based on information in the literature for each species.

Needed parameters for DEB

Biological information is often scarce for rare, endangered, or little-studied species, and our chosen species are no exception. For example, the SDA parameters for our selected species may not be available from the literature; however, data may exist for related species. SDA and similar physiological variables are highly conserved among species that 1) reside in similar habitats and belong to similar foraging guilds, and 2) between species within the same family (Kitchell et al.1974, Santucci and Wahl 2003). For example, the SDA from the published literature on bluegill *Lepomis macrochirus* in similar water temperature regimes to the Delta can be used in the bioenergetics model of Sacramento perch (Woodley and Cech, *in prep*). Estimated parameters can be replaced by measured values as new physiological data are collected on any of the selected species. In most cases, the data needed for each species model are available in the literature. However in a few cases, especially the responses of the selected species to salinity, we would need to collect new data on physiological tolerances, metabolic rates, and behavioral preferences.

Model Output

This modeling approach can predict individual growth and reproductive potential in optimal or sub-optimal conditions. Many of the selected native species are in decline or are already at low abundance in the BDRW system; and the added stress of climate change might further reduce populations of these species. For the non-native species in consideration, a model of this nature would allow for a better understanding of the responses of established species to environmental changes and the potential success of new invaders. The most important output of this proposed study is the models themselves, which can be used to: 1) assist managers and biologists with the restoration and conservation of the BDRW system by giving them a tool to predict the benefits of specific combinations of water quality and habitat for selected fishes; and 2) to make assist with the determination if more extensive studies of climate change effects on the BDRW fishes are warranted.

Timeline

June 2007 (Month 0)	The work would begin for this project.
January 2008 (Month 8)	The life history models for each of the selected species would be completed. A white paper would be written focusing on the life history models of the selected species.
June 2008 (Month 12)	First progress report, including abstracts for presentations given at professional meetings and progress of any early publications would be submitted. Data species responses to temperature and salinity for which suitable data could not be found in the literature would be collected.
August 2008 (Month 16)	The members of CASCaDE are currently working to address many the predictions and parameters we would need for to describe an environmental baseline as well as the predicted effects due to climate change. We expect to have a functional baseline with the predicted climate changes overlaid of the essential habitats of the selected species. Findings will be distributed for comments and suggestions to

	the biologists, agencies, and CBDA.
June 2009 (Month 24)	Second progress report including abstracts for presentations given at professional meetings and status of publications
August 2009 (Month 26)	The DEB outputs and verification data will be available.
June 2010 (Month 36)	Models described thoroughly and released to CBDA. Findings will be distributed for comments and suggestions to biologist, agencies and within CALFED. The final completion report including abstracts for presentations given at professional meetings and publications

<u>Output/Anticipated Products and Benefits:</u>

Anticipated outcomes by year

Year 1- Before the close of Year 1, we would have life history models based on the literature and unpublished local data. Any information collected would be compiled into a white paper and made available to biologists, managers, and agencies for comment.

Year 2- By Year 2 we would have current habitat availability for each species, and habitat available to each species after alterations due to climate change

Year 3- By Year 3 we would have the likely species redistributions, and growth and reproductive potential as affected by climate change. We expect to publish the findings in peer-reviewed scientific journals in addition to a final report/white paper that would include all results and suggest conservation strategies. When completed, copies would be sent to appropriate biologists, managers, and agencies for comment and possible action.

Anticipated Benefits to CALFED

The combination of geo-referencing species' life-history patterns, physiological tolerances and metabolic requirements, and behavioral preferences allow for the construction of DEB models and optimal habitat models (derived from life history data and geo-referencing populations), which are useful as a framework for future restoration of fish or aquatic invertebrates. By knowing "how" a species responds to water quality changes, managers can narrow conservation and restoration efforts to sites that will neither activate the species stress-response nor alter their normal energy budget. A stressor sensitive energetics model has the ability to estimate changes in individual growth, food consumption, and fecundity as energy allocation fluctuates due to chronic environmental perturbations. The geo-referencing of populations enhances the ability of managers to project population responses to chronic environmental perturbations as specific as altered critical habitats. These models would be beneficial to time- and cost-effective management by helping identify appropriate locations for restoration of particular species based on species' responses to environmental changes.

Anticipated benefits to fellow, mentor and community mentors

The anticipated benefits for the fellow would be close interaction with the academic and community mentors. The mentors are heavily involved with state and federal-level government agencies and can provide valuable advice for learning how to function in this environment. The mentors are all interested in and involved in interdisciplinary sciences to resolve watershed level issues. The fellow has a background in ecological physiology and would benefit from more technical experience using the knowledge gained from research (e.g., her dissertation work with Sacramento perch) for implementation and application in management issues. This project would familiarize the fellow with new techniques, such as climate and GIS modeling, as well as using and developing the DEB models.

This project will dovetail nicely with ongoing investigations of Suisun Marsh and Delta fishes by Drs. Peter B. Moyle and William A. Bennett. The results will likely to be applied to their ongoing investigations, suggest new avenues of applied research, and lead to better interpretation of their results in light of climate change. This project also compliments proposed research at University of California, Davis for green sturgeon (P.A. Klimley, S.I. Doroshov, D. Kültz, and JJ Cech) and for riparian habitat assessments proposed by P.B. Moyle, A. Engilis, et al.)

It also has multiple benefits for Dr. Larry R. Brown, who is the lead on translating the modeling outputs of the CASCaDE project into fish effects. The promised products for CASCaDE fish effects are modest and limited to simple life history models and qualitative evaluations of responses to climate change for a selection of species. This proposal will allow for much more detailed utilization of the CASCaDE outputs and a variety of products, including DEB models. This collaboration has the potential to greatly increase the value of the CASCaDE project to CALFED and will contribute to the professional development of all the participants.

Figures

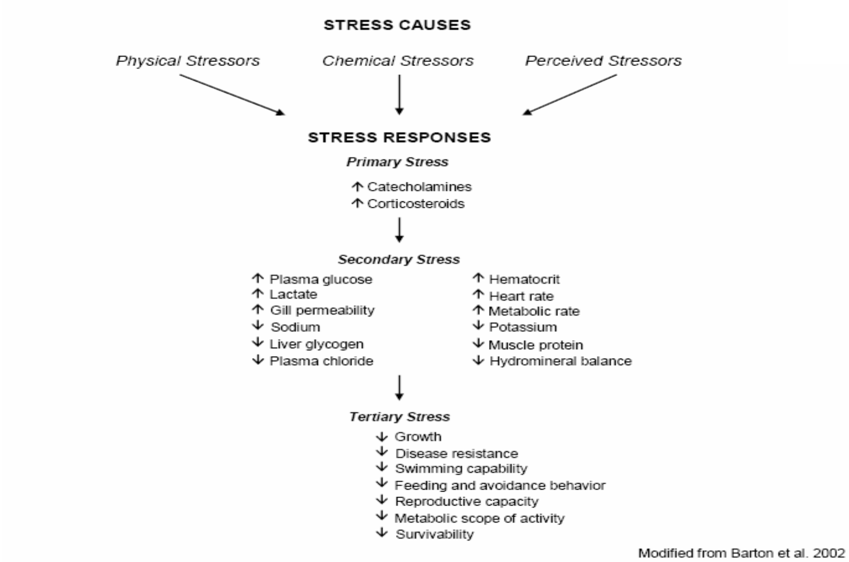


Figure 1: Adaptive mostly consisting of the primary and secondary responses and detrimental (mostly consisting of the tertiary responses) aspects of the major response pathways in fish. Dashes arrows indicate possible extensions of the stress response (to the tertiary) level with exposure to long-term or especially severe stress (Portz et al. 2006).

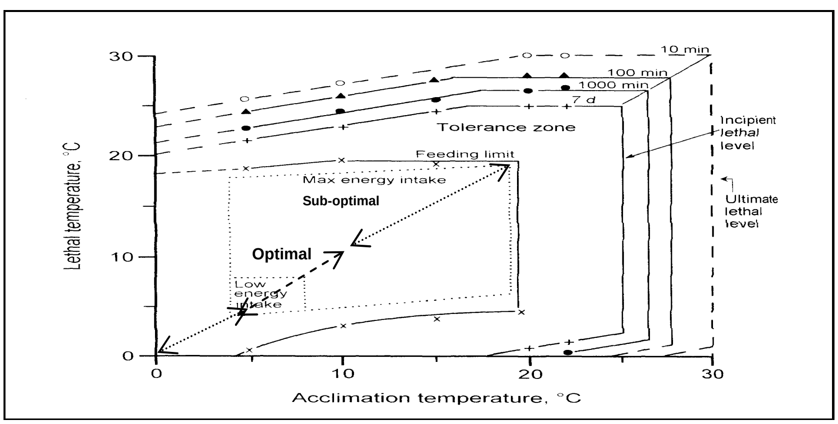


Figure 2: The thermal limit to feeding and lethal temperature in Brown trout (*Salmo trutta*) as a function of acclimation temperature and tolerance limits (modified from Elliot 1981).

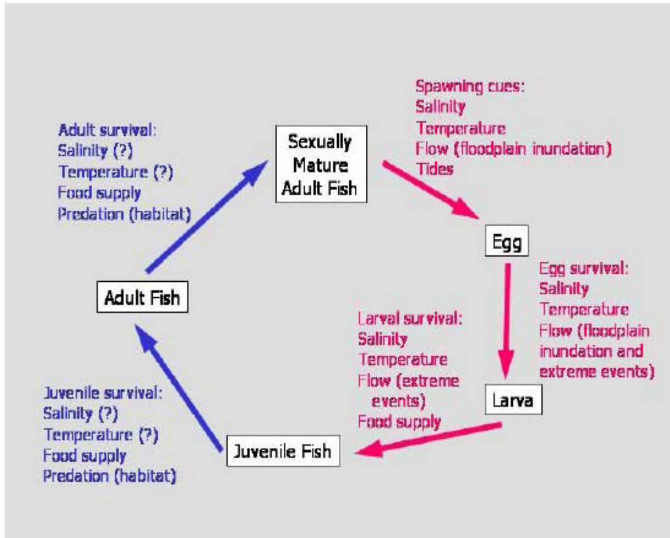


Figure 3: A hypothetical example of a life-cycle model for a species of interest. This figure exemplifies the abiotic parameters that are important for either the fish species or typical of the habitat that the species uses for each life stage (Larry Brown, USGS, CASCaDE, personal communication).

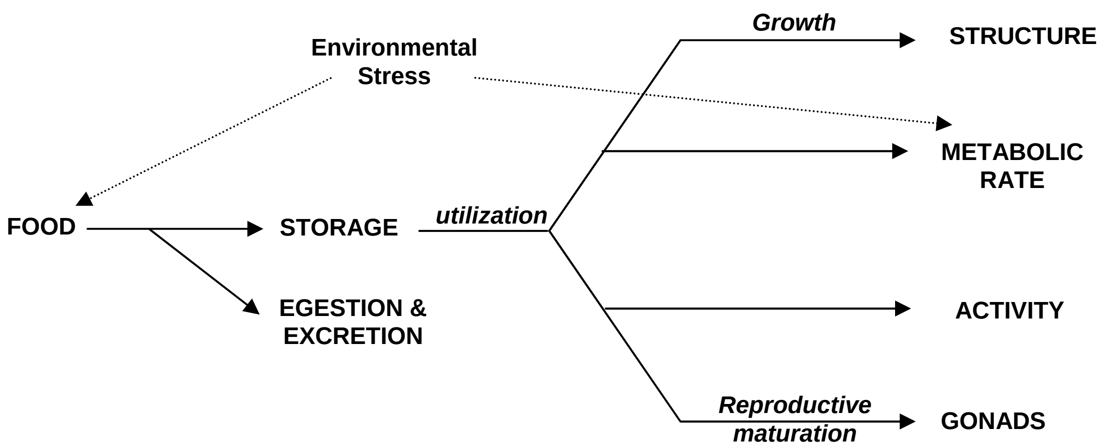


Figure 4. An example of a DEB model. An organism ingests food at a rate dependent on its size and the food density. Energy is extracted from food and added to the reserves. The rate at which energy becomes available to the organism depends on its size and stored energy density. Somatic maintenance has absolute priority for energy. The available energy is allocated to somatic maintenance and growth combined, and the remaining to either maturation or to reproduction and maturity maintenance. The organism may reproduce, provided that energy made available exceeds the requirements for somatic and maturity maintenance (modified from Nisbet et al. 2000).

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