Management of Biological Invasions (2015) Volume 6, Issue 4: 319–328
doi: http://dx.doi.org/10.3391/mbi.2015.6.4.01

Open Access

Viewpoint

Implementing invasive species control: a case study of multi-jurisdictional coordination at Lake Tahoe, USA

Marion E. Wittmann[1]*, Sudeep Chandra[1], Kim Boyd[2] and Christopher L. Jerde[1]

[1]*University of Nevada Reno, Department of Biology, 1664 N. Virginia Street Reno, NV 89557 USA*

[2]*Tahoe Resource Conservation District, 870 Emerald Bay Road, Suite 108 South Lake Tahoe, CA 96150 USA*

**Corresponding author*

E-mail: mwittmann@gmail.com

Received: 22 August 2015 / Accepted: 8 September 2015 / Published online: 5 October 2015

Handling editor: Marnie Campbell

Abstract

Biological invasions are increasing in frequency and the need to mitigate or control their effects is a major challenge to natural resource managers. Failure to control invasive species has been attributed to inadequate policies, resources or scientific knowledge. Often, natural resource managers with limited funds are tasked with the development of an invasive species control program without access to key decision-support information such as whether or not an invasive species will cause damage, and what the extent of that damage may be. Once damages are realized, knowing where to allocate resources and target control efforts is not straightforward. Here we present the history of invasive species policy development and management in a large, multi-jurisdictional and multi-use aquatic ecosystem. We present a science-based decision-support tool for on-the-ground aquatic invasive species (AIS) control to support the development of a sustainable control program. Lastly, we provide a set of recommendations for managers desiring to make an AIS control implementation plan based upon our development of novel invasive species research, policy and management in Lake Tahoe (USA). We find that a sustainable invasive species control program is possible when science, coordination and outreach are integrated.

Key words: water resources, aquatic ecosystems, aquatic invasive species, exotic plant control, management plan

Introduction

Biological invasions are increasing in frequency and continue to cause unwanted effects to ecological and economic systems (Simberloff et al. 2013). The realized damages of species invasions have incentivized species control as a necessary or relevant management option. However, despite significant investments in the science and practice of invasive species control, these programs often fail due to inadequate policies, absence of collective effort, funding, and scientific knowledge (Simberloff et al. 2005; Epanchin-Niell et al. 2010).

Invasive species control actions are challenging and are implemented through various mechanical, chemical or biological removal techniques. Eradication has the highest probability of success during the establishment stage, or during the earliest part of the spread stage (Myers et al. 2000). When eradication becomes impractical, containment or adaptation may be the most appropriate strategy (Drury and Rothlisberger 2008). Containment and control strategies seldom have an end point, and often the size of the infestation is positively correlated with the time required to control the infestation (Rejmánek and Pitcairn 2002). In many cases, the resources or technologies necessary to successfully control species are not available (Simberloff et al. 2005). Further, resource managers with limited funds and labor often react to immediate threats, with few resources remaining for developing and implementing comprehensive long-term invasive species management plans (Larson et al. 2011).

As the decision to invest in invasive species management is contingent upon the damages it may cause, a major uncertainty facing natural resource managers is how to allocate the appropriate resources for an invader, particularly when future damages the species may cause are largely unknown. Additionally, in a system where there are multiple regulatory or other governing bodies and stakeholders, this decision is further complicated (Epanchin-Niell et al. 2010). Lack of coordination between agencies, or inaction by a single agency may create a “weakest-link” issue that can hinder control efforts and in some cases increase the unwanted effects of invasions (Perrings et al. 2002; Peters and Lodge 2009). However, the development of policy level decisions when there is a common goal, in this case the control of invasive species, will increase the chances of accomplishing a desired outcome (Ostrom 1990). We suggest that regional control of biological invasions can be successful, and requires collective effort by all affected resource managers and stakeholders.

Here we provide a case study for Lake Tahoe, a large ecologically and economically valuable lake in the United States, as an example of how stakeholders within a multi-jurisdictional system have addressed the issue of aquatic invasive species (AIS). We present the history of AIS management and policy development and describe the use of an “implementation plan” as a science-based, decision-support tool for on-the-ground aquatic invasive species control actions. Lastly, we provide a set of recommendations based upon our experience developing the AIS control program at Lake Tahoe. We feel this information will be of value to researchers, managers or policy makers who desire to develop a sustainable invasive species control program in multi-use and multi-jurisdictional settings.

Background and Aquatic Invasive Species Problem Statement

Lake Tahoe is a large (surface area: 497 km^2, max depth 501 m) oligotrophic lake located in the Sierra Nevada mountain range between California and Nevada (USA) at a subalpine elevation of 1898 m. Approximately 3 million people visit Lake Tahoe each year and there is a resident population of about 50,000 people. The lake is designated an Outstanding Natural Resource Water under the Clean Water Act (CWA Section 106) due to its water quality and extraordinary clarity (approximate Secchi depth = 20 m). Due to this designation and additional state regulations, the use of pesticides (including herbicides) to control AIS and introductions of any other chemicals is highly restricted. Since the 1960s, water clarity has declined in Lake Tahoe due to progressive cultural eutrophication and the loading of fine sediments from an increasingly urbanized and developed watershed (Goldman 2000; Chandra et al. 2005).

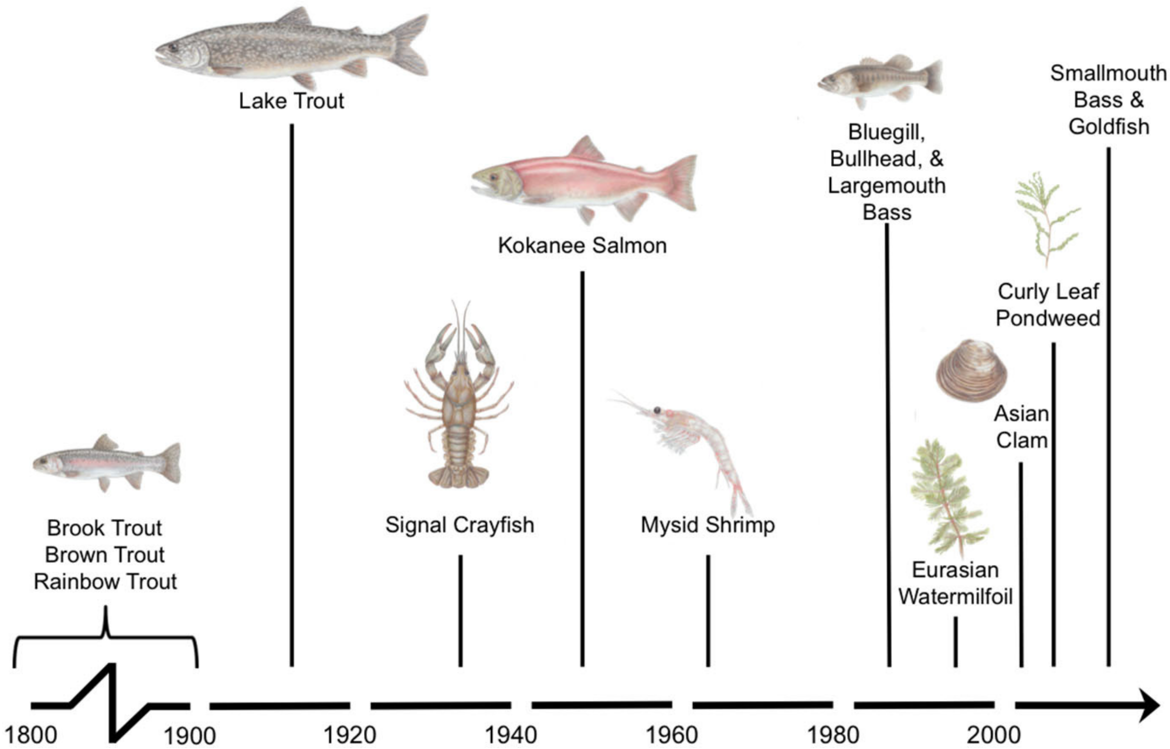
Along with changes to Tahoe's clarity, there have been alterations to the lake’s biological community over time. In the mid to late 1800s, Lake Tahoe had a relatively simple biological community containing 8 native fish taxa, 6 zooplankton species, 12 benthic invertebrate taxa, and 5–8 plant taxa including higher plants, algae, and mosses (Chandra et al. 2005; Caires et al. 2013). From the late 1800's to the present there have been a number of intentional and unintentional species introductions to Lake Tahoe which have altered the food web structure and littoral zone dynamics (Box 1). These introductions have negatively impacted nearshore aesthetics, recreation and navigation in the lake. The AIS that now inhabit Lake Tahoe have measurably changed ecosystem dynamics as well as recreational use of the nearshore region, resulting in public awareness and support for active management of AIS in the Basin (Eiswerth et al. 2000; Kamerath et al. 2008; TRPA 2014).

Efforts in the Tahoe Basin related to AIS control

With the realized damages of AIS in Lake Tahoe and the 2007 discovery of the first major western United States infestation of invasive Dreissenid mussels (Quagga; *Dreissena bugensis*) in Lake Mead [USA], regulators, managers, and scientists have acknowledged the ecological and economic threats posed by AIS to the Tahoe region (TRPA 2014). As a result, multiple policy actions occurred which led to the development of an AIS prevention program and the maturation of an AIS removal control program in the Lake Tahoe Basin (Box 2).

The first control actions to remove AIS in Tahoe occurred in the 1980’s within a converted wetland ecosystem to resort community in the southern region of the Lake called the Tahoe Keys. Nuisance plant growth (native Coontail, *Ceratophyllum demersum;* non-native Eurasian watermilfoil, *Myriophyllum spicatum*) was removed via harvesters as a means to keep navigation pathways clear for boating traffic and swimming (Greenfield et al. 2004). Managers learned this treatment unexpectedly increased nuisance plant biomass and similar to observations from other systems, this likely promoted the spread of Eurasian watermilfoil through fragmentation (Crowell et al. 1994). Despite the unwanted impacts,

Box 1. Lake Tahoe Aquatic Species Introduction Timeline: 1800's – present. Species illustrations by S. Adler.



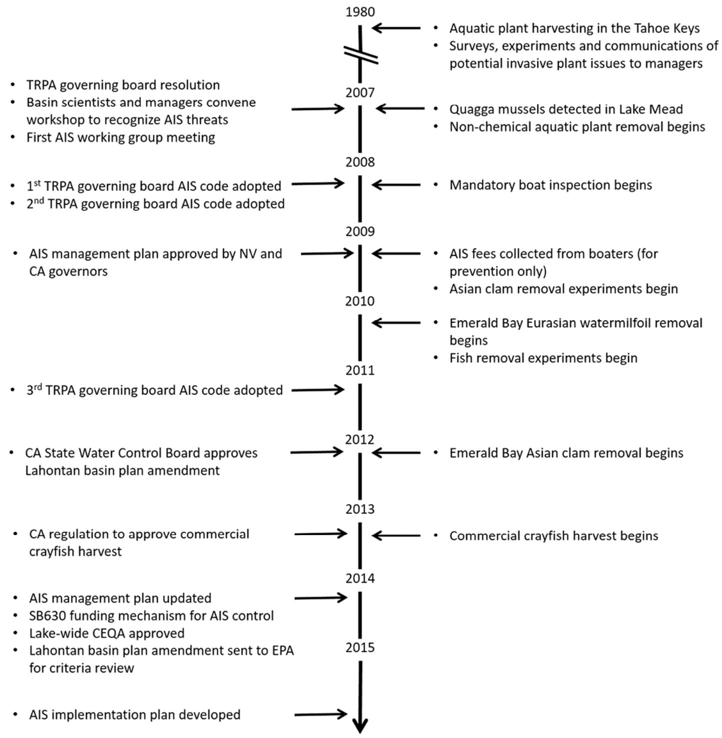
Intentional species introductions. Between the 1880's to 1940's there was a series of federally and state sanctioned species introductions into Lake Tahoe. Trout species were repeatedly introduced during this time, which included brown trout (*Salmo trutta*), rainbow trout (*Oncorhynchus mykiss*), and most notably, lake trout (*Salvelinus namaycush*), which is the lake's dominant fish predator today. Lake trout was considered established by 1912 and likely played a major role in eliminating the lake's native Lahontan cutthroat trout (Dill and Cordone 1997). By the mid-1930's the final introduction (of many introduction events) of the signal crayfish (*Pacifasticus leniusculus*) occurred. Signal crayfish was introduced to support the trout fishery in Tahoe and provide a source of protein to regional residents (Abrahamsson and Goldman 1970). Finally, in the mid-1940's kokanee salmon (*Oncorhynchus nerka*) was introduced to Lake Tahoe and populations were maintained by stocking and rearing small fishes (Dill and Cordone 1997).

By 1960, the food web of Lake Tahoe had changed substantially (Vander Zanden et al. 2003; Chandra et al. 2005). In contrast to the native food web, it was comprised of two major fishes, kokanee salmon and lake trout. Resource managers from California and Nevada believed these game fishes in Lake Tahoe were largely limited by food. As a result, the agencies introduced mysid shrimp (*Mysis diluviana*). This was the last sanctioned introduction of a species into Lake Tahoe. The introduction of mysid shrimp had profound changes to the food web and biological composition of Lake Tahoe, and the food web of Lake Tahoe became increasingly reliant upon pelagic resources. This shift to pelagic resources resulted in two distinct, seasonal food webs; a nearshore food web with fewer top predators and offshore profundal food web (Vander Zanden et al. 2003).

Unintentional species introductions. Between the mid-1960s and the present, a series of unintentional (i.e., not government sanctioned) fish, invertebrate and plant establishments occurred (Figure 2). These included Eurasian watermilfoil (*Myriophyllum spicatum*), curlyleaf pondweed (*Potamogeton crispus*), Asian clams (*Corbicula fluminea*), nonnative warm water fishes such as largemouth bass (*Micropterus salmoides*), and bluegill (*Lepomis macrochirus*). These species have impacted Lake Tahoe by hindering recreation, water quality, and aesthetic values, altering phosphorus cycling, outcompeting native taxa, and providing habitat for other nonnative species in the lake (Walter 2000; Kamerath et al. 2008; Wittmann et al. 2012a; Caires et al. 2013; TRPA 2014; Wittmann et al. 2015).

Today, nearly 25 non-native aquatic species are established in Lake Tahoe watershed which includes 2 aquatic macrophytes, 16 non-native fishes, 1 pelagic invertebrate, 2 benthic invertebrates, 1 parasitic copepod and 1 bullfrog. An analysis of potential AIS economic impacts to recreation value, tourism spending, property values, and increased boat/pier maintenance was estimated to be between \$22.4 and \$78 million per year (TRPA 2014).

Box 2. Policy and management efforts in Lake Tahoe to control invasive species began in the 1980's and continues today. The left side of the diagram represents policy-level developments and the right side shows associated management actions.



The Lake Tahoe watershed and natural and socio-cultural resources are managed by state (Nevada, California) and federal agencies which include land, water, and air resource managers. Non-governmental organizations and citizen stakeholder groups have historically played an important role in shaping public policy developed by resource managers. Until the 1960s, development of the land within the watershed was regulated by the US Forest Service and state land management agencies with some areas set aside for recreation by state park agencies. Policies for land development and alterations to aquatic resources through species introductions were not uniform between agencies and there was a growing concern about the decline of water quality in the lake due to increased tourism, land development, and influx of sewage into the ecosystems. Recognizing the large changes occurring to the basin and water quality, a bi-state, bipartisan compact between California and Nevada was ratified by the United Stated Congress to address development issues at the lake forming the Tahoe Regional Planning Agency (TRPA).

Today the TRPA along with the state, county and city agencies and a tribal group (Washoe Native people) work under a framework for conserving the lake called the Environmental Improvement Program (TRPA 2010). Launched in 1997, this program was developed to protect and improve the natural and recreational resources of the watershed. Program participants address issues of water quality, forest management, air quality, transportation, recreational and scenic resources, and facilitate scientific research related projects to the conservation or restoration of Lake Tahoe.

The first policy actions concerning AIS in Lake Tahoe came after almost two decades of federal agency (USDA ARS) and university (UC Davis and UN Reno) assessment of Tahoe invasive plants in the field and laboratory and dissemination of this information at state, federal and professional society meetings. In 2007, over 100 scientists and managers convened a two-day workshop to identify the risk of AIS at Lake Tahoe. This coincided with one of the first detections of invasive Quagga mussel in the western United States at Lake Mead, AZ-NV, in 2007. At this time, the TRPA governing board passed a resolution to acknowledge the invasion of Quagga mussels in the region as a major ecological and economic threat. A first aquatic invasive species (AIS) working group was convened while voluntary boat inspections continued during the beginning of the year. This group addressed not only the threat of species coming from outside the Basin, like Quagga mussels, but species established in the Basin, such as the invasive aquatic plants. In the following year, the TRPA passed its 1st and 2nd AIS codes which required watercraft inspections.

There was also a realized need for a sustainable management plan and paired funding source for AIS. A Lake Tahoe AIS Coordination Committee (AISCC) was formed in 2009 comprised of representatives from local, state and federal agencies. The AISCC developed a regional AIS management plan to address early detection, control and eradication, rapid response, and prevention of AIS within the Basin. In addition to the AISCC, which meets monthly, there are other smaller committees that deal with more focused efforts such as the Nearshore Aquatic Weed Working Group and the Asian Clam Working Group.

In 2009, the first Lake Tahoe Interstate AIS Management Plan (LTAIS Management Plan) was approved by the state governors and a national AIS Task Group. In 2014, the first update of the original 2009 plan was also approved and incorporated developments in the implementation of AIS prevention and other management efforts in the Tahoe Region, and primarily focused on changes needed to make the LTAIS Management Plan as useful as possible for management, policy and funding decisions in the region.

Between 2006 and 2014, a series of opportunistic AIS experimental control actions took place for nuisance aquatic plants, Asian clams, warm water fish and crayfish with varying levels of successful removal. In 2009, a focused effort to remove Eurasian watermilfoil from Emerald Bay, a California State Park and the most visited location by boaters on Lake Tahoe commenced. After four years of removal, maintenance and monitoring in this location, Emerald Bay has been declared "weed free". This effort is the impetus for continued investment in non-chemical control of other aquatic plant species in Lake Tahoe. Some AIS removal efforts in the basin involved regulatory actions at the state level. For example, in 2012, an amended regional water quality control board basin plan to consider applications for pesticide use in Lake Tahoe to control nuisance plant growth and later in 2015 this amendment was sent to the Environmental Protection Agency (EPA) for criteria review; in 2013, the state of California approved commercial harvest of crayfish in Tahoe; in 2014, and a lake wide permit under California Environmental Quality Act (CEQA) was also approved for nuisance plant control on a whole-lake scale (on the California side of the lake). In 2015, the Lake Tahoe implementation plan was developed and control actions under this framework are currently underway.

the need to keep watercraft navigation pathways clear remains, and harvesting in this area continues annually at a significant cost to the homeowners (TKPOA 2015).

Between 1980 – mid 2000's there was extensive assessment of invasive plant establishment in Tahoe by federal agencies (United States Department of Agriculture Agricultural Research Service) and universities (University of California, University of Nevada). This information was disseminated at the state and federal levels as well as to professional society meetings, however there was no real acknowledgement of an ecological or economic problem throughout this time. By 2005, Eurasian watermilfoil had spread to over 15 other locations in the Lake (Wittmann et al. 2015) and in 2007 a workshop was convened by over 100 scientists and managers in the basin to identify the AIS threat to Tahoe. The regional planning agency also recognized the need for comprehensive nuisance aquatic plant control, particularly in high use areas. Non-chemical control methods such as bottom barriers and diver assisted suction removal were opportunistically applied between 2005–2009 in various locations with little success (e.g., rapid recolonization or increased growth post-treatment), largely due to inconsistent treatments and unavailable resources for monitoring or follow-up removal (Wittmann and Chandra 2015).

In 2009, a focused effort to remove Eurasian watermilfoil from Emerald Bay, a California State Park and the most visited location by boaters on Lake Tahoe (Wittmann et al. 2015), commenced. This effort was led by two agencies, the California Department of Parks and Recreation (the landowner) and the Tahoe Resource Conservation District (the implementer) (Brockett et al. 2013). Starting with approximately six acres of Eurasian watermilfoil in 2010, and after four years of annual bottom barrier and hand removal, no plants have been observed since 2015 (Shaw, pers. comm. 2015). The Emerald Bay Eurasian watermilfoil removal project is seen as a successful control effort with the potential for classification as a localized "eradication." This effort is the impetus for continued investment in non-chemical control of other aquatic plant species in Lake Tahoe.

Various experimental or pilot project removals have occurred for other AIS in the lake including electroshocking removal for various warm water fish species (S. Chandra, unpubl. data), harvesting and gas impermeable bottom barriers for Asian clam (*Corbicula fluminea*) (Wittmann et al. 2012a; Wittmann et al. 2012b) and the establishment of a commercial crayfishery to decrease Signal crayfish (*Pacifastacus leniusculus*) abundances. Through these programs, it has been determined that Asian clam recolonization rates are too high for effective control (Wittmann et al. 2013), and the amount of effort and resources allocated for warm water fish and crayfish removal seems to be a limiting factor in the reduction of these populations (S. Chandra, unpubl. data).

AIS control at Lake Tahoe has been largely opportunistic and dependent on the availability of resources and agency participation. Further, follow-up treatments or efficacy monitoring were rarely built into any control projects. Consequently, there was no measureable reduction of AIS (aside from Emerald Bay) and the need for a more structured program was recognized. Through an inter-agency collaboration, a regional AIS management plan for the Tahoe basin was approved in 2009 (and later updated in 2014) by state governors and a national invasive species task force (TRPA 2014). This document identified problem species and outlined the range of general strategies concerning prevention and control options for AIS.

Despite the utility this regional AIS management plan provided, Tahoe Basin managers tasked with control or removal of AIS remained burdened with uncertainty about which taxa and locations to prioritize their control efforts. Specifically, there was no direction to determining which species to remove and where to focus removal efforts, particularly under limited and ephemeral funding scenarios. Thus, the need to provide information concerning the *implementation* of the control efforts to reduce impacts of AIS in the Tahoe Basin was identified as a priority knowledge gap.

Lake Tahoe Implementation plan

In 2015, an implementation plan for Lake Tahoe (Wittmann and Chandra 2015) was created to provide specific guidance for on-the-ground decision-making with respect to AIS control actions within Lake Tahoe. The goals of the implementation plan were to identify AIS candidates for control efforts in Lake Tahoe, assess feasible control strategies for each species, and provide an ecologically-based framework to prioritize specific sites for control efforts in Lake Tahoe over a short (3–5 year) period.

To select taxa as control targets, three management groupings were identified for Lake Tahoe AIS based on the feasibility of control actions and regulations currently in place in Lake

Tahoe. Levels of ecological or economic impact were not utilized to make this selection as the 2014 regional AIS management plan already specified which species were considered "invasive". The management groupings were as follows:

A. Species having feasible control options available at this time. Potential control actions are for species or species groups for which information exists from studies at Tahoe or the scientific literature, and where removal of one species may lead to the reduction of additional AIS (e.g., fish-plant interaction);

B. Species with potential control actions, but there is concern about efficacy. This includes species groups for which there is some evidence of control or biomass reduction, but whether these strategies have long-term feasibility, or ability to be successfully applied in the Tahoe environment is unknown; and

C. No feasible control options are available. This designation is based upon experimentation or practice observed either in Lake Tahoe or outside of Lake Tahoe. Reasons for the infeasibility of control options are attributed to biological or ecological characteristics of species which may prohibit effective control, a lack of technologies or tools, public disdain and lawful limitations for application, or cost-prohibitiveness.

To prioritize sites for species removal, a quantitative model was developed to include the following invasion-ecology based principles: (1) species interactions; (2) size of infestation; (3) human interaction with infestations; and (4) connectivity between established populations within the lake (e.g., nearest neighbor). Overall site prioritization was determined through a combination of the categorical (species presence/ absence) and continuous (e.g., size of infestation, human pressure, satellite populations) variables described above. The sites were then ranked according to the overall score received through the aggregation of these variables. See Wittmann and Chandra (2015) for details concerning the prioritization model methodology.

Thus, control strategy recommendations were provided, which included a list of taxa to focus control efforts on (management grouping A), a list of taxa to focus resources on research rather than control (management grouping B), and an identification of taxa that do not have any feasible control options at this time (management grouping C). Lastly, significant knowledge gaps were identified. To evaluate the implementation plan, an international panel of invasive species scientists and managers was brought to the Lake Tahoe site to provide a rigorous scientific critique. Further, members of a local AIS coordination committee and other stakeholders provided written and verbal feedback.

Outcomes of the Implementation Plan Process

Throughout the development of the AIS Implementation plan there was extensive communication between the scientifically trained author team and the AIS Coordination Committee (which consisted of at least 8 different management agencies). Bi-weekly communications with the entire committee or subsets of the committee provided constructive criticism and important feedback to ensure usefulness of the document and buy in from all participants. The implementation plan development, evaluation and revision occurred rapidly; starting in January 2015 and a finalized version was accepted 7 months later. As a result of the implementation plan process, there were six major outcomes:

1. Identification of prioritized species for immediate control actions and determination of species for which further research or pilot removal actions were necessary;

2. Identification of prioritized sites within Lake Tahoe for immediate control actions;

3. Identification of major scientific and management knowledge gaps associated with all three AIS categories;

4. Recommended development of an "action list" to pair control actions with available and future funding resources. This action list will serve to outline actions for a 3–5 year period;

5. Recommended development of an explicit research plan. Through the implementation plan process, the Aquatic Invasive Species Coordination Committee (AISCC) acknowledged the value of integrating site and ecosystem level research in order to facilitate a sustainable AIS control program; and

6. Buy-in from agency representatives to the implementation plans, outcomes and recognition amongst all participants that the AIS control program at Lake Tahoe is a "living process". That is, categorizations, recommendations or other suggested actions may be subject to change once new knowledge or information is collected through AIS control activities or other research endeavors.

Recommendations for a sustainable AIS control strategy

Through the recent development of a comprehensive AIS control strategy in Tahoe, including regional level programming and localized implementation plan, we provide the following recommendations for natural resource managers and invasion scientists who are faced with the creation of a sustainable AIS control program. We believe these recommendations are applicable to multiple aquatic ecosystem types with various management and stakeholder infrastructures. In particular, these recommendations should be relevant to those systems in which the lake, reservoir, or other waterbody is multi-use (e.g., drinking water supply, recreational, commercial), and where there are a diverse group of stakeholders ranging from water purveyors, local users, visitors, conservationists, and those with commercial or residential interests.

1. Do not act alone: Increases and improvements in the available scientific knowledge and policies related to AIS has led to increased integration of control and eradication goals for freshwater ecosystem management objectives. However, the removal of AIS continues to be a novel management problem that requires either the reinterpretation of old regulations or the creation of new regulations to execute control programs. Often, regulations were developed to protect ecosystem services (e.g. water quality or quantity) prior to the concept of "invasive species" becoming widely accepted amongst managers or scientists. As a result, these regulations may not support the actions necessary to tackle AIS removal. For example, actions such as dredging invasive species near drinking water intakes, covering a lake bottom with synthetic fabrics or experimenting with other novel technologies often require additional regulatory permitting.

Further, in complex regulatory landscapes with many managers, each agency assumes responsibility for a smaller portion of the total damages imposed by invasive species, diminishing the incentive to control AIS (Epanchin-Niell et al. 2010). Therefore, managing AIS requires an environment with a framework where decisions can be made by managers on a near "real time" basis to acquire permits, modify regulations, and facilitate novel solutions to removing AIS. It is important to have a framework or committee that is empowered to facilitate interagency communications, intra-agency requirements, and satisfy any state or federal requirements necessary to employ AIS control actions. A single agency operating solely in a complex regulatory environment will be less likely to succeed in acquiring the necessary permissions or access to carry out a long term control program.

2. Determine the magnitude of unwanted impacts: As the decision to invest in AIS control is dependent upon how much damage a species, or set of species, will cause (Keller et al. 2009), investing in ecological or economic impact studies is a key element to support a sustainable control program. There is a tendency to assign the label of "invasive" to any non-native species discovered within a system (Davis et al. 2011). However, not all non-native species cause damage, and this may preclude them from the assignment of "invasive" and the subsequent need to invest in their immediate removal or research. Observations of the potential or realized ecological or environmental impacts to ecosystem services, recreation or commerce are a major component of the designation of species by which to include or exclude from control activities. The ability to quantify uncertainties associated with known or unknown elements of the impacts of biological invasion can further guide future research objectives for species where the need for immediate control actions is not obvious. To achieve this, reiterative risk assessments (see 5 below), regular monitoring to quantify the expansion or contraction of native species relative to AIS population growth, or cataloguing of costs incurred to practitioners or recreationists can support information gathering related to AIS damages assessment over time and space. Further, when considering recommendation (1), a problem may be that estimated damages associated with AIS are partitioned to small amounts through different agencies. As a result, full damages across water quality, habitat restoration, recreational opportunities, etc. are not realized if not aggregated across management groups.

3. Avoid "invasion fatigue" by establishing metrics to evaluate success of AIS control. Similar to the psychological barriers that limit climate change mitigation and adaptation in humans (Gifford 2011), repeated communications of new invasive species detections, spread or unwanted impacts without evidence of control progress may serve to fatigue stakeholders and create an environment of inaction. Formally setting goals (e.g., "eradication" or "containment") and establishing metrics by which to evaluate the outcomes of control action goals (e.g., biomass decrease, improved recreation) provides invaluable tools to evaluate the efficacy of actions, amend those actions (if needed), and identify successes. Most importantly, the identification of these goals and metrics will avoid loss of motivation due to communications of haphazard efforts and associated failures, or help diagnose why a failure may have occurred.

4. Sustained public outreach is imperative before and after project implementation. The benefits of integrating emotional well-being with medical care in hospitals have long been acknowledged (Clark et al. 2003). Similarly, the need to provide open lines of communication between the public, regulators, managers and scientists is a key component of maintaining a healthy relationship between ecosystem stakeholders and those that may be managing control programs. Through increased understanding of the uncertainties and difficulties associated with AIS control, outreach can decrease the "invasion fatigue" described in (3). The development of this trust can be achieved through communication vehicles such as public information meetings (e.g., AIS forums, home-owners association meetings, club gatherings), regular distribution of control action information materials (Nathan et al. 2014), or outreach professionals present at sites of AIS control and removal to demystify the process through printed materials and discussion with individuals. These risk communication strategies should occur on regular, formal bases before and after the implementation of a control project, and managers should be careful not to exclude uncertainties in their communications. To be effective with stake-holders, it is of upmost importance to understand how the public perceives AIS as a risk. Thus, opportunities for two-way communications and receipt of feedback are necessary components of these risk communication strategies. Further, the private-public partnership gained through outreach actions can help to avoid litigation or inaction (Orr et al. 2008; USEPA 2013).

5. Re-evaluation is key. Over time, knowledge is gained through the implementation of AIS control programs: new technologies may increase the ability to cost-effectively control some species, new regulatory tools may improve ease of field action, citizen science groups may provide information or the labor resources needed to carry out a seasonal removal. Re-evaluation and integration of new knowledge to AIS control programs on a regular basis improves decision-support tools and will likely increase cost savings over the longer term (Wittmann et al. 2014). Further, without the re-evaluation of risk or efficacies, there may be missed opportunities to prevent invasions, or inefficient uses of resources to control one established species while another goes unchecked.

6. Integration of programming. One advantage of having a broad group of resource managers contributing to an AIS control program is the possibility of coupling non-AIS resource management with AIS management. For instance, creel surveys to monitor fish harvest provides an opportune time to ask anglers about the catch of unidentified or recently established and detected fish species. Similarly, macrophyte removal efforts can be used to quantify the abundance and distribution of native macrophytes or the co-occurrence of invasive macrophytes with invasive freshwater fish and invertebrates. The benefit provided by this type of integration is that AIS control as a program will not exist in isolation where it may be threatened for funding when resources become scarce or another more pressing problem presents itself. Integration of AIS control with water quality management objectives or other broader programs such that may encompass recreational use or watershed level objectives can improve program longevity.

7. In times of resource scarcity, stay connected and get creative. As the resources necessary to control species invasions are typically scarce, managers and researchers are often tasked with maintaining AIS control programs with limited financial resources. In the case of Lake Tahoe, when most of the federal or regional funding became scarce during economic downturns, those managers and researchers tasked with AIS control took two major actions. First, they continued regular (though less frequent) meetings. At these meetings there were "project prioritization" exercises to identify sites or species most in need of control efforts, even though the resources were not available to manage them. This allowed for the coordination committee to remain active, as well as to be "ready" for those times when resource scarcity may not be as severe. Second, managers and researchers continued active outreach to local, regional, and national policy makers. This provided two benefits: local needs for AIS control were still being communicated to representatives at state capitols, and creative means for funding and other resource allocations to the Lake Tahoe system were discovered and implemented. In agreement with the recommendations provided in (1), the continued communication amongst Tahoe managers and scientists and between Tahoe AIS workers and state legislators kept the Tahoe AIS control program from existing in isolation. Development of outreach efforts (recommendation 4) and continued, organized efforts to present the rationale for funding needs allows an organized team to be in the front of the line when funding becomes available.

Conclusion

Prevention of AIS may be the most cost-effective way to minimize the associated ecological or economic damages (Leung et al. 2002; Vander Zanden et al. 2010) and has been expressed through federal, state and regional programming that focuses on recreational boats or fishing equipment as vectors (Horvath 2008; Rothlisberger et al. 2010). However, when species evade prevention programs and become established and spread within a system, the need to minimize damages associated with the invasion becomes a reality. Controlling invasive species requires science-based strategies and collaboration of all stakeholder groups. Because of coordinated efforts that rely on scientific information, AIS control programming at Lake Tahoe may well avoid the "weakest link" problem often associated with invasive species management. While the Lake Tahoe AIS control program is in the early stages of its development, coordinated control efforts amongst land managers, integration of scientific research and an active outreach environment are likely to increase effectiveness of and reduce costs of AIS control work.

Acknowledgements

Most of the information presented in this paper was funded by Senate Bill 630 State of California funding from the California Tahoe Conservancy via the Tahoe Resource Conservation District to S. Chandra and M. Wittmann. Additional funding for the AIS program was provided in the last decade to S. Chandra, M. Wittmann and others from the Southern Nevada Public Lands Management Act, Nevada Division of State Lands, Tahoe Regional Planning Agency, and the Lahontan Regional Water Quality Control Board. We thank L.W.J. Anderson and two anonymous reviewers for their critical and thorough consideration of this manuscript.

References

Abrahamsson SAA, Goldman CR (1970) Distribution, Density and Production of the Crayfish *Pacifastacus leniusculus* Dana in Lake Tahoe, California - Nevada. *Oikos* 21: 83–91, http://dx.doi.org/10.2307/3543843

Brockett J, Boyd K, Shaw D, Stone P (2013) Invasive Aquatic Weed Control Program Lake Tahoe, CA: Bureau of Reclamation Final Report No. R10AP20613, South Lake Tahoe, CA, 28 pp

Caires AM, Chandra S, Hayford BL, Wittmann ME (2013) Four decades of change: dramatic loss of zoobenthos in an oligotrophic lake exhibiting gradual eutrophication. *Freshwater Science* 32: 692–705, http://dx.doi.org/10.1899/12-064.1

Chandra S, Vander Zanden MJ, Heyvaert AC, Richards DC, Allen BC, Goldman CR (2005) The effects of cultural eutrophication on the coupling between pelagic primary producers and benthic consumers. *Limnology and Oceanography*. 50: 1368–1376, http://dx.doi.org/10.4319/lo.2005.50.5.1368

Clark PA, Drain M, Malone MP (2003) Addressing patients' emotional and spiritual needs. *Joint Commission Journal on Quality and Safety* 29: 659–670

Crowell W, Troelstrup N, Queen L, Perry J (1994) Effect of harvesting on plant communities dominated by Eurasian watermilfoil in Lake Minnetonka, MN. *Journal of Aquatic Plant Management* 32: 56–60

Davis MA, Chew MK, Hobbs RJ, Lugo AE, Ewel JJ, Vermeij GJ, Brown JH, Rosenzweig ML, Gardener MR, Carroll SP, Thompson K, Pickett STA, Stromberg JC, Del Tredici P, SUding KN, Ehrenfeld JG, Grime JP, Mascaro J, Briggs JC (2011) Don't judge species on their origins. *Nature* 474: 153–154, http://dx.doi.org/10.1038/474153a

Dill WA, Cordone AJ (1997) History and status of introduced fishes in California, 1871-1996. California Department of Fish and Game Fish Bulletin No. 178, Sacramento, CA, 414 pp

Drury KLS, Rothlisberger JD (2008) Offense and defense in landscape-level invasion control. *Oikos* 117: 182–190, http://dx.doi.org/10.1111/j.2007.0030-1299.16081.x

Eiswerth ME, Donaldson SG, Johnson WS (2000) Potential Environmental Impacts and Economic Damages of Eurasian Watermilfoil (*Myriophyllum spicatum*) in Western Nevada and Northeastern California. *Weed Technology* 14(3): 511–518

Epanchin-Niell RS, Hufford MB, Aslan CE, Sexton JP, Port JD, Waring TM (2010) Controlling invasive species in complex social landscapes. *Frontiers in Ecology and the Environment* 8: 210–216, http://dx.doi.org/10.1890/090029

Gifford R (2011) The dragons of inaction: Psychological barriers that limit climate change mitigation and adaptation. *American Psychologist* 66: 290–302, http://dx.doi.org/10.1037/a0023566

Goldman CR (2000) Four decades of change in two subalpine lakes. *Proceedings of the International Association of Theoretical and Applied Limnology* 27: 7–26

Greenfield BK, David N, Hunt J, Wittmann ME, Siemering G (2004) Aquatic Pesticide Monitoring Program: Review of Alternative Aquatic Pest Control Methods for California Waters. Oakland, CA, 106 pp

Horvath T (2008) Economically viable strategy for prevention of invasive species introductions: Case study of Otsego Lake, New York. *Aquatic Invasions* 3: 3–9, http://dx.doi.org/10.3391/ai.2008.3.1.2

Kamerath M, Chandra S, Allen B (2008) Distribution and impacts of warm water invasive fish in Lake Tahoe, USA. *Aquatic Invasions* 3: 35–41, http://dx.doi.org/10.3391/ai.2008.3.1.7

Larson DL, Phillips-Mao L, Quiram G, Sharpe L, Stark R, Sugita S, Wiler A (2011) A framework for sustainable invasive species management: Environmental, social, and economic objectives. *Journal of Environmental Management* 92: 14–22, http://dx.doi.org/10.1016/j.jenvman.2010.08.025

Leung B, Lodge DM, Finnoff D, Shogren JF, Lewis MA, Lamberti G (2002) An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. *Proceedings of the Royal Society B Biological Sciences* 269: 2407–2413, http://dx.doi.org/10.1098/rspb.2002.2179

Myers JH, Simberloff D, Kuris AM, Carey JR (2000) Eradication revisited: Dealing with exotic species. *Trends in Ecology and Evolution* 15: 316–320, http://dx.doi.org/10.1016/S0169-5347(00)01914-5

Nathan LR, Jerde CL, Mcveigh M, Mahon AR (2014) An assessment of angler education and bait trade regulations to prevent invasive species introductions in the Laurentian Great Lakes. *Management of Biological Invasions* 5: 319–326, http://dx.doi.org/10.3391/mbi.2014.5.4.02

Orr PJ, Emerson K, Keyes DL (2008) Environmental conflict resolution practice and performance: An evaluation framework. *Conflict Resolution Quarterly* 25: 283–301, http://dx.doi.org/10.1002/crq.209

Ostrom E (1990) Governing the Commons. Cambridge University Press, New York, 298 pp, http://dx.doi.org/10.1017/CBO9780511807763

Perrings C, Williamson M, Barbier EB, Delfino D, Dalmazzone S, Simmons P, Watkinson A (2002) Biological Invasion Risks and the Public Good: An Economic Perspective. *Conservation Ecology* 6:1

Vander Zanden MJ, Hansen GJA, Higgins SN, Kornis MS (2010) A pound of prevention, plus a pound of cure: Early detection and eradication of invasive species in the Laurentian Great Lakes. *Journal of Great Lakes Research* 36: 199–205, http://dx.doi.org/10.1016/j.jglr.2009.11.002

Walter KM (2000) Ecosystem effects of the invasion of Eurasian watermilfoil (*Myriophyllum spicatum*) at Lake Tahoe, CA-NV. Master Thesis, University of California Davis, 263 pp

Wittmann ME, Chandra S (2015) Implementation Plan for the Control of Aquatic Invasive Species within Lake Tahoe. Reno, NV, 52 pp, http://dx.doi.org/10.3391/mbi.2015.6.4.01suppl

Wittmann ME, Chandra S, Reuter JE, Schladow GS, Allen BC, Webb KJ (2012a) The control of an invasive bivalve, *Corbicula fluminea*, using gas impermeable benthic barriers in a large natural lake. *Environmental Management* 49: 1163–1173, http://dx.doi.org/10.1007/s00267-012-9850-5

Wittmann ME, Chandra S, Reuter JE, Caires AM, Schladow GS, Denton ME (2012b) Harvesting an invasive bivalve in a large natural lake: species recovery and impacts on native benthic macroinvertebrate community structure in Lake Tahoe, USA. *Aquatic Conservation: Marine and Freshwater Ecosystems* 597: 588–597, http://dx.doi.org/10.1002/aqc.2251

Wittmann ME, Chandra S, Schladow SG, Reuter JE (2013) Natural and Human Limitations to Asian clam distribution and recolonization--Factors that Impact the Management and Control in Lake Tahoe (P057): A report submitted to the Pacific Southwest Research Station, US Forest Service, 91 pp

Wittmann ME, Jerde CL, Howeth JG, Maher SP, Deines AM, Jenkins JA, Whitledge GW, Burbank SR, Chadderton WL, Mahon AR, Tyson JT, Gantz CA, Keller RP, Drake JM, Lodge DM (2014) Grass carp in the Great Lakes region: Establishment potential, expert perceptions, and re-evaluation of experimental evidence of ecological impact. *Canadian Journal of Fisheries and Aquatic Sciences* 71: 992–999, http://dx.doi.org/10.1139/cjfas-2013-0537

Wittmann ME, Kendall BE, Jerde CL, Anderson LWJ (2015) Estimating relative risk of within-lake aquatic plant invasion using combined measures of recreational boater movement and habitat suitability. *PeerJ* 3: e845, http://dx.doi.org/10.7717/peerj.845