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Rapid response for invasive waterweeds at the arctic invasion front: Assessment of collateral impacts from herbicide treatments

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ABSTRACT

The remoteness of subarctic and arctic ecosystems no longer protects against invasive species introductions. Rather, the mix of urban hubs surrounded by undeveloped expanses creates a ratchet process whereby anthropogenic activity is sufficient to introduce and spread invaders, but for which the costs of monitoring and managing remote ecosystems is prohibitive. *Elodea* spp. is the first aquatic invasive plant to become established in Alaska and has potential for widespread deleterious ecological and economic impacts. A rapid eradication response with herbicides has been identified as a priority invasion control strategy. We conducted a multi-lake monitoring effort to assess collateral impacts from herbicide treatment for *Elodea* in high latitude systems. Variability in data was driven by seasonal dynamics and natural lake-to-lake differences typical of high latitude waterbodies, indicating lack of evidence for systematic impacts to water quality or plankton communities associated with herbicide treatment of *Elodea*. Impacts on native macrophytes were benign with the exception of some evidence for earlier onset of leaf senescence for lily pads (*Nuphar* spp.) in treated lakes. We observed a substantial increase in detected native flora richness after *Elodea* was eradicated from the most heavily infested lake, indicating potential for retention of native macrophyte communities if infestations are addressed quickly. While avoiding introductions through prevention may be the most desirable outcome, these applications indicated low risks of non-target impacts associated with herbicide treatment as a rapid response option for *Elodea* in high latitude systems.

1. Introduction

Subarctic and arctic regions comprise a mix of a limited number of urban centers within a remote and relatively undeveloped surrounding expanse. At first glance, remoteness and a lack of easily accessible transportation routes such as roads would seem to protect subarctic and arctic systems from invasive species; however, sufficient anthropogenic activity exists in most high latitude regions that this is no longer the case (e.g. Carey et al., 2016). For example, many communities throughout the subarctic and arctic state of Alaska—a large number of which are remote and off the road system—experienced population growth since the turn of the millennium, with overall statewide population increasing linearly (Sethi et al., 2014). While remote, transportation networks with potential to introduce aquatic invasive species stretch throughout these subarctic and arctic regions via small planes and boats (Carey et al., 2016). In line with this dynamic socioecological landscape, the freshwater waterweed *Elodea* spp. (henceforth, "*Elodea*") has been recognized as a circumpolar invasive plant and the first aquatic invasive species to become established in Alaska. Here, we present results from a multiple lake monitoring study from *Elodea* eradication efforts in Alaska to provide information useful for managers to assess the relative ecological risks and benefits of herbicide treatments as a rapid response tool for invasive waterweeds in high latitude systems.

Elodea was first recorded in 1982 in the southeast region of Alaska and remained localized for nearly two decades before a burst of infestations were recently detected, beginning with lakes in the populated southcentral region of the state (Professional Fisheries Consultants,

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1985; Carey et al., 2016). *Elodea* can establish vegetatively (Spicer and Catling, 1988; Xie et al., 2010; Sarneel, 2013), and spread by floatplane traffic is suspected as a major transport vector in subarctic regions. The threat for spread of existing *Elodea* infestations across Alaska continues, where in the summer of 2015, the waterweed was found in Lake Hood at the Anchorage international airport which can experience as many as 190 floatplane flights per day during the busy summer season (FS-R10-FHP, 2016).

As a stand-forming aquatic waterweed, *Elodea* has potential to alter physical and ecological processes in both lentic and lotic environments, altering nutrient cycling (Thiébaut, 2005; Heikkinen et al., 2009), excluding native macrophytes (Mjelde et al., 2012; Schultz and Dibble, 2012), and potentially facilitating other invasive species such as the ambush predator invasive northern pike (*Esox lucius*). The economic impacts associated with invasive waterweeds such as *Elodea* or other similar taxa like Eurasian Milfoil (*Myriophyllum spicatum*) have demonstrated reductions in recreational and commercial fishing opportunities, loss of property values, and high costs of mechanical or chemical control measures (Oreska and Aldridge, 2011; Luizza et al., 2016; Schwoerer and Little, 2017). As a result of the potential ecological and economic threats associated with *Elodea*, prevention and eradication of this invasive waterweed has become a top aquatic management priority in Alaska. *Elodea* along with three other potentially invasive aquatic plants were banned for import into the state in 2014 (Havemeister, 2014), however, at that point multiple invasions had already occurred.

The costs of monitoring against invasive species introductions and managing existing infestations is prohibitively high in the remote expanses of subarctic and arctic regions, such that prevention of introductions is a critical strategy in avoiding the establishment of invasive species. Once introduced to subarctic and arctic landscapes, a rapid eradication response may be the only management option available to prevent the spread of aquatic invasive species from urban centers to outlying remote and rural areas. That said, *Elodea* infestations have proved difficult to eradicate. Because *Elodea* can reproduce vegetatively from tissue fragments, mechanical removal of the plant is ineffective at eradicating infestations and may actually exacerbate its dispersal to connected waterbodies. Shading out *Elodea* via benthic matting can eliminate localized infestations, however, the approach is highly labor intensive, and thus costly, over a protracted period of treatment (Caffrey et al., 2010). Biological control of *Elodea* with herbivorous fish such as grass carp (*Ctenopharyngodon idella*) has been investigated (e.g. Zehnsdorf et al., 2015); however, this approach carries high risks of unintended spread of exotic herbivore species and non-specific macrophyte cropping, and thus is unlikely to be politically viable in Alaska.

As an alternative to mechanical removal or biological control, chemical treatment of *Elodea* and related waterweeds has been utilized with some success (Harman et al., 2005; Wagner et al., 2007). An advantage of herbicide-based control is that it can treat large areas, or whole lakes, and requires labor over a few discrete application events. *Elodea* have been shown to be sensitive to fluridone, a systemic herbicide that disrupts photosynthesis (e.g. Bowmer et al., 1995), providing opportunity to target the invasive waterweed at low chemical concentrations. Systemic herbicides such as fluridone can be applied in pelleted form for localized treatments, or be applied at broader scales for whole lake treatments. Contact herbicides, such as diquat, are commonly used in conjunction with fluridone to spot treat localized infestations of invasive waterweeds (Glomski et al., 2005).

While herbicides provide a tool to quickly eradicate aquatic invasive plant infestations (e.g. over one or two growing seasons), there are few studies available that investigate the risks for collateral ecological impacts to native waterweeds or other macrophytes, water quality, or other non-target ecosystem components. In one example, fluridone treatment of Eurasian Milfoil in Washington state, U.S.A., was found to reduce the abundance of floating leaf aquatic plants such as pond lily (*Nymphaea* spp.; Farone and McNabb, 1993). Information on the potential collateral ecological impacts associated with herbicide treatments of *Elodea* in high latitude systems with cold-adapted aquatic communities and extreme photo periods is particularly rare.

Our goal in this study was to address current priority management knowledge needs regarding the risks and benefits of herbicide treatment of invasive waterweeds in subarctic and arctic systems (cf. Carey et al., 2016). To accomplish this, we implemented a large monitoring study across a suite of lakes to assess the potential for collateral ecological impacts associated with fluridone and diquat herbicide treatment of *Elodea* in subarctic southcentral Alaska. Taking a holistic approach to aquatic assessments, two untreated and uninfested lakes and two herbicide treated lakes infested with *Elodea* were monitored for changes in water quality, phytoplankton production, zooplankton community dynamics, and macrophyte community dynamics through a multiple season herbicide treatment course. By investigating replicate lakes over multiple years, we were able to explore dynamics related to herbicide treatment versus those related to natural lake-to-lake and seasonal variability.

2. Methods

2.1. Study area

Four natural lakes on the Kenai Peninsula within the vicinity of Nikiski, AK (60.708°N, 151.268°W) near the western border of the Kenai National Wildlife Refuge were monitored during the study (Fig. 1). The Köppen climate classification for the region is subarctic (Peel et al., 2007). Study lakes are predominately groundwater fed, small in size, and mesotrophic (Table 1). All four lakes are on the road system and experience boat and float plane traffic. Daniels and Beck Lakes are infested with *Elodea* identified to be a hybrid *E. canadensis* × *nuttallii* cross (Morton et al., 2014), with the first recorded sightings of the invasive waterweed in the study lakes occurring in 2012 and 2013, respectively. At the commencement of herbicide treatment in 2014, Daniels Lake contained a set of five localized *Elodea* patches whereas Beck Lake was heavily infested throughout the littoral zone of the waterbody (Morton et al., 2014). Douglas and Island Lakes were monitored as uninfested replicate untreated lakes.

2.2. Herbicide treatment

Elodea infestations were primarily treated with the systemic herbicide fluridone (Sonar® SePRO, Carmel, IN, U.S.A.), a photosynthesis disrupter taken up through shoots and roots of submerged plants (Morton et al., 2014). *Elodea* has been shown to be particularly sensitive to fluridone at low concentrations (≤ 8 ppb), with lethality occurring after two to three months of treatment. High (acute) and low (chronic) testing of fluridone has indicated low toxicity to aquatic invertebrates and fish (e.g. Archambault et al., 2015 and references therein), and the chemical was approved for use around potable water sources by the U.S. Environmental Protection Agency (www.epa.gov/pesticides). Waterbodies purge fluridone as the chemical is degraded by sunlight (Saunders and Mosier, 1983) or is adsorbed in soils and degraded therein (Marquis et al., 1982). Fluridone was applied to treated lakes in a combination of pellets (SonarONE®; SePro, 2015a) and aqueous form (Sonar Genesis®; SePRO, 2015b) to maintain a target concentration of 6–8 ppb over a 2014–2015 treatment period (Table S1). A whole lake treatment was conducted on Beck Lake with applications occurring in June and September 2014. A partial lake treatment was conducted on the larger Daniels Lake (≈ 1/5 of lake area treated) with applications occurring in June and September 2014, and July and October 2015. In addition to fluridone, a single targeted application of contact herbicide diquat (Reward™, Syngenta, Basel, Switzerland) was applied in the initial June 2014 treatment of Daniels Lake at half the manufacturer's recommended rate of 19.0 L/ha in liquid form. Diquat disrupts plant cell membranes and results in rapid aquatic plant kill. Diquat has a