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The Relationship between Water Quality, Watermilfoil Frequency, and Weevil Distribution in the State of Washington

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ABSTRACT

During the summer of 1997, we surveyed 50 waterbodies in Washington State to determine the distribution of the aquatic weevil *Euhrychiopsis lecontei* Dietz. We collected data on water quality and the frequency of occurrence of watermilfoil species within selected watermilfoil beds to compare the waterbodies and determine if they were related to the distribution of *E. lecontei*. We found *E. lecontei* in 14 waterbodies, most of which were in eastern Washington. Only one lake with weevils was located in western Washington. Weevils were associated with both Eurasian (*Myriophyllum spicatum* L.) and northern watermilfoil (*M. sibiricum* K.). Waterbodies with *E. lecontei* had significantly higher ($P < 0.05$) pH (8.7 ± 0.2) (mean ± 2SE), specific conductance (0.3 ± 0.08 mS cm^{-1}) and total alkalinity (132.4 ± 30.8 mg $CaCO_3$ L^{-1}). We also found that weevil presence was related to surface water temperature and waterbody location ($\chi^2_2 = 24.3$, $P \leq 0.001$) and of all the models tested, this model provided the best fit (Hosmer-Lemeshow goodness-of-fit $\chi^2_8 = 4.0$, $P = 0.9$). Our results suggest that in Washington State *E. lecontei* occurs primarily in eastern Washington in waterbodies with pH ≥8.2 and specific conductance ≥0.2 mS cm^{-1}. Furthermore, weevil distribution appears to be correlated with waterbody location (eastern versus western Washington) and surface water temperature.

Key words: Euhrychiopsis lecontei, *Myriophyllum spicatum*, *Myriophyllum sibiricum*, weevil presence, temperature, pH.

INTRODUCTION

In Washington State, Eurasian watermilfoil (*Myriophyllum spicatum* L) is found in at least 86 lakes and rivers throughout the state (Parsons 1997). In several of these waterbodies, Eurasian watermilfoil has become a nuisance by displacing native aquatic plants and interfering with boating and swimming activities. Methods such as mechanical harvesting, chemical treatment, bottom barriers, and biological control using triploid grass carps (*Ctenopharyngodon idella* V) are being used to control Eurasian watermilfoil.

The aquatic weevil *Euhrychiopsis lecontei* Dietz has been associated with declines of Eurasian watermilfoil in North America (Creed and Sheldon 1995, Sheldon 1997, Jester et al. 1997, Creed 1998). In addition, laboratory and field studies in Vermont and Minnesota have found that this native weevil is a watermilfoil species specialist and that it can have a negative impact on Eurasian watermilfoil (Sheldon and Creed 1995, Solarz and Newman 1996). Given that *E. lecontei* occurs in Washington (Tamayo et al. 1999) and that other states have reported declines of Eurasian watermilfoil associated with the weevil, we began to evaluate *E. lecontei* as a potential biological control for Eurasian watermilfoil. Our evaluation, conducted in 1996 and 1997, focused on two main research questions: 1) Is *E. lecontei* present throughout Washington State? and 2) Is there a relationship between weevil distribution and water quality, as well as with the frequency of occurrence of the watermilfoil (herein all mention of watermilfoil alone indicates all species of the genus *Myriophyllum*)?

The Cascade Mountains divide the State into two main regions, eastern and western Washington, that have very different climatic and often water quality conditions. Researchers have reported that water quality (e.g. pH, water temperature, dissolved oxygen) can influence the distribution of aquatic insects (Resh and Rosenberg 1984). In order to address our research questions and generate hypotheses about the distribution of *E. lecontei*, we compared the water quality of different lakes and rivers in Washington, and determined if there was a correlation between weevil presence and water quality. Similarly, we wanted to know if the frequency of occurrence of the watermilfoil and the location of the waterbody (i.e., eastern versus western Washington) were related to weevil presence. For example, were we more likely to find *E. lecontei* in Eastern Washington hard water lakes that had higher watermilfoil frequency of occurrence? The present paper reports the results from our 1997 surveys.

MATERIALS AND METHODS

We surveyed once 50 waterbodies from mid June to early September. Of the 50 sites, 26 were in eastern Washington and 24 were in western Washington. The majority of waterbodies had either Eurasian (24 sites) or northern watermilfoil (18 sites) (*M. sibiricum* K). Whorled watermilfoil (*M. verticillatum* L) was present in three lakes, western watermilfoil (*M. hippuroides* N) in one site, and Eurasian and northern watermilfoil occurred sympatrically in two waterbodies. Watermilfoil was not detected in four lakes.

The shoreline of each waterbody was surveyed by boat in order to locate and map watermilfoil beds. If possible, five watermilfoil beds within each waterbody were randomly se-

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lected. We then conducted three snorkeling surveys at each bed (15 snorkeling surveys per waterbody) to assess weevil presence. Each survey consisted of snorkeling for 5 minutes and examining the top 0.50 m of the watermilfoil plants (all *Myriophyllum* spp.) for adult weevils and larval damage unique to *E. lecontei* (Creed and Sheldon 1994, 1995; Sheldon and O'Bryan 1996). The snorkeling surveys focused on the top section of the watermilfoil because field observations in Minnesota, Washington, Wisconsin and Vermont have noted that both weevil adults and larvae are commonly found on this part of the plant (Sheldon and Creed 1995, Sheldon and O'Bryan 1996, Jester et al. 1997, Tamayo et al. 1999). In addition, at each watermilfoil bed we used a 20 m transect line to determine the frequency of occurrence of the watermilfoil. The transect line was placed within the watermilfoil bed, approximately 1 m from the outer the edge of bed (deep end), parallel to the shoreline. For each 1 m interval on the line, the presence or absence of watermilfoil directly below the interval was recorded (frequency of occurrence). If watermilfoil was present at an interval, we noted the species (i.e., Eurasian, northern, whorled and/or western watermilfoil).

Water depth measurements were taken every 5 m along the transect line. A water sample was collected for each bed at 0.25 m below the water surface and within the watermilfoil for total alkalinity analysis. Surface water temperature, pH, dissolved oxygen, and specific conductance were also measured at 0.25 m below the water surface and within the watermilfoil bed using a Hydrolab® Recorder (Hydrolab® Inc., Austin, TX). We took the measurements at this depth (0.25 m) in order to characterize the area where we were conducting the snorkeling surveys. A Secchi reading was taken in deep water adjacent to each bed. All water quality measurements were collected between 0900 and 1600.

Two sample t-tests (Zar 1996) were used to compare the water quality and watermilfoil frequency of occurrence between waterbodies with *E. lecontei* and those where weevils were not detected. Logistic regression (Hosmer and Lemeshow 1989, Agresti 1990, Trexler and Travis 1993, Daniel 1995, Noruŝis 1997) was used to determine if there were was a relationship between weevil presence and pH, specific conductance, Secchi depth, total alkalinity, water temperature, dissolved oxygen, water depth, watermilfoil species, watermilfoil frequency of occurrence, and/or waterbody location (i.e., eastern versus western Washington). We selected logistic regression because it is appropriate for analyzing dichotomous dependent variables (e.g., weevil presence) (Hosmer and Lemeshow 1989, Trexler and Travis 1993, Daniel 1995). In addition, this type of analysis can be used with continuous (e.g., pH) and/or discrete (e.g., watermilfoil species) independent variables (Hosmer and Lemeshow 1989, Trexler and Travis 1993, Daniel 1995, Neter et al. 1996). Since logistic regression is "sensitive to colinearities among the independent variables" (Hosmer and Lemeshow 1989), we conducted Pearson and Spearman's correlation analyses to test if any of the independent variables were correlated to each other. Variables that showed significant correlation levels of 0.70 or greater were considered highly correlated and were not used simultaneously in any model. We assessed how significant the independent variable(s) of a model was in explaining the variation in weevil presence by using the likelihood ratio test (Hosmer and Lemeshow 1989). The likelihood ratio test compares two models, one with and another without the independent variable(s) of interest, and "tests the hypothesis that the excluded independent variable is equal to zero and has one degree of freedom" (Trexler and Travis 1993). We then used the Hosmer-Lemeshow goodness-of-fit test (Hosmer and Lemeshow 1989, Noruŝis 1997) to assess how effective a model was in describing weevil presence. The latter test compares the observed and predicted values of a model. A model was considered a good fit when the Hosmer-Lemeshow χ^2 was insignificant (i.e., the difference between the predicted and the observed values was small). All statistical analyses were conducted both at the state and regional levels (eastern versus western Washington). Data were analyzed using SPSS® 7.5 statistical software and an alpha level of 0.05.

RESULTS AND DISCUSSION

Distribution. We found *E. lecontei* in 14 (28%) of the 50 waterbodies surveyed. Weevils were present in seven counties across Washington State: Ferry, Grant, King, Lincoln, Okanogan, Pend Oreille and Spokane. Of the 14 waterbodies with *E. lecontei*, only one (Lake Sawyer) (7%) was located in western Washington; all other sites were in eastern Washington (93%) (Table 1). Although we only detected weevils in one western Washington lake, we did find weevils in a second lake (Lake Meridian, King County) in 1996 (Tamayo et al. 1999). Weevil abundance may have been too low in Lake Meridian in 1997 for the snorkeling surveys to detect weevil presence. We only found weevils in one riverine site (Okanogan River at Oroville) in 1997, however in 1993 *E. lecontei* was also detected in 3 additional sites in the Columbia and Okanogan Rivers (Tamayo et al. 1999). *E. lecontei* adults and larval damage were observed in 12 lakes, whereas in the other two weevil sites (Evergreen Lake and the Okanogan River at Oroville), we only detected larval damage. To date, our data and that collected by Creed (Tamayo et al. 1999) suggest that *E. lecontei* is more widespread in eastern than western Washington.

E. lecontei was associated with both Eurasian and northern watermilfoil. Weevils were observed primarily on Eurasian watermilfoil in western Washington. In contrast, in eastern Washington, *E. lecontei* was present in more waterbodies with northern watermilfoil (9 lakes) than Eurasian watermilfoil (2 waterbodies) (Table 1). These results provide further evidence that northern watermilfoil is a native host to *E. lecontei* (Creed and Sheldon 1994). In Aeneas and Stan Coffin Lakes, *E. lecontei* was observed simultaneously on Eurasian and northern watermilfoil.

The distribution of *E. lecontei* in Washington may be related to the distribution of northern watermilfoil. Although northern watermilfoil is present throughout Washington, it is more commonly found in eastern Washington (Parsons 1997). Aiken and Walz (1979) suggested that a period of winter vernalization for the overwintering buds (turions) of northern watermilfoil appeared to be important for plant development during the spring and summer. Climatic conditions in eastern Washington may be more favorable for winter vernalization than those in western Washington. The winters in eastern Washington are colder, where most of the

TABLE 1. WATERBODIES IN WASHINGTON WHERE *EUHRYCHIOPSIS LECONTEI* WAS DETECTED IN 1997. THE NUMBER OF WEEVIL ADULTS FOUND DURING SNORKELING SURVEYS AND WHILE MAPPING WATERMILFOIL BEDS (ALL *MYRIOPHYLLUM* SPP.) ARE PRESENTED, AS WELL AS WHETHER LARVAL DAMAGE WAS PRESENT. THE WATERMILFOIL SPECIES PRESENT ([1]*MYRIOPHYLLUM SIBIRICUM*, [2]*MYRIOPHYLLUM SPICATUM*) IN THE WATERBODIES AND WHERE WEEVIL ADULTS AND LARVAL DAMAGE WERE FOUND ARE ALSO SHOWN.

Waterbody	County	No. of adults	Larval damage	Watermilfoil species
		Eastern Washington		
Curlew Lake	Ferry	0	Yes	Northern[1]
Canal Lake	Grant	1	Yes	Northern
Corral Lake	Grant	4	Yes	Northern
Evergreen Lake	Grant	0	Yes	Eurasian[2]
Stan Coffin Lake	Grant	4	Yes	Eurasian & Northern
Warden Lake	Grant	0	Yes	Northern
Fishtrap Lake	Okanogan	3	Yes	Northern
Aeneas Lake	Okanogan	1	Yes	Eurasian & Northern
Fish Lake	Okanogan	0	Yes	Northern
Okanogan River at Oroville	Okanogan	0	Yes	Eurasian
Fan Lake	Pend Oreille	5	Yes	Northern
Badger Lake	Spokane	1	Yes	Northern
Williams Lake	Spokane	0	Yes	Northern
		Western Washington		
Lake Sawyer	King	9	Yes	Eurasian

precipitation falls as snow (Franklin and Dyrness 1988) and lakes often freeze. In contrast, western Washington has a longer frost-free season and the winters are milder and wet. Most of the precipitation in western Washington falls as rain (Franklin and Dyrness 1988). Furthermore, Warrington (1986) reported that in British Columbia, Canada, northern watermilfoil was more commonly found in lakes with pH ≥8.2 and tolerated harder, more alkaline waters than Eurasian watermilfoil. Lakes in eastern Washington generally tend to have harder waters than lakes in western Washington, which can be attributed to the presence of large expanses of basalt in the region as well as to the soils, which often show accumulations of calcium carbonate (Franklin and Dyrness 1988). The water quality and the climatic conditions seen in eastern Washington may be more optimal for northern watermilfoil and in part may explain why this plant is more prevalent in the eastern side of the state. Given the latter and that northern watermilfoil is a native host plant to *E. lecontei* (Creed and Sheldon 1994), it would be expected that weevils would also be more prevalent in eastern Washington. A comparison of the historical distribution of northern watermilfoil and *E. lecontei* in Washington State as well as in North America would help test this hypothesis.

Another hypothesis that may explain the weevil's prevalence in eastern Washington is the weevil's ability to disperse to other waterbodies. *E. lecontei* adults are able to fly, although evidence suggests that most flying takes place during the spring and fall when weevils are moving to and from the overwintering grounds (Newman and Ragsdale 1995). Even though *E. lecontei*'s dispersal rate and range are currently unknown, it is feasible that the weevil has not fully dispersed into western Washington. Potentially, the Cascade Mountains may be acting as a geographical barrier, although *E. lecontei* is found east and west of the Rocky Mountains. An additional, and also complimentary hypothesis that warrants testing is that *E. lecontei* may have a slow dispersal rate, particularly over large distances (>50 km), and is slowly increasing its range into western Washington.

Water quality and other variables. At the state level, water quality and watermilfoil frequency of occurrence varied widely among the survey lakes and rivers. During our sampling, water temperatures ranged from 15.6 to 25.6C, Secchi depth from 1.0 to 7.1 m and dissolved oxygen from 7.7 to 15.4 mg L^{-1}. Total alkalinity and watermilfoil frequency of occurrence showed the greatest variation, 8.0 to 262.6 mg $CaCO_3$ L^{-1} and 0 to 100%, respectively. We found that waterbodies with *E. lecontei* had significantly higher pH, total alkalinity and specific conductance ($P < 0.05$) (Figure 1). Water depth was significantly less in lakes and rivers with weevils ($P < 0.05$). On average waterbodies with weevils had a pH of 8.7 (±0.2) (±2SE), a total alkalinity of 132.4 (±30.8) mg of $CaCO_3$ L^{-1} and a water depth of 1.5 (±0.4) m (Table 2). Our results suggest that, in Washington State, *E. lecontei* occurs primarily in lakes and rivers with pH ≥8.2, specific conductance ≥0.2 mS cm^{-1} and total alkalinity ≥61.9 mg of $CaCO_3$ L^{-1}. Weevils in Washington may have adapted to harder water conditions because its native host, northern watermilfoil, is more prevalent in eastern Washington where the lakes tend have more alkaline waters. Smith and Barko (1990) reported that the optimal growth of Eurasian watermilfoil also takes place in alkaline waters, however Eurasian watermilfoil has been found to be abundant over a wide range of alkalinities (Madsen 1998). Potentially, plants of Eurasian and northern watermilfoil that grow in harder water conditions may have a higher nutritional value for *E. lecontei* than plants that grow in softer waters. Food quality (i.e., nutritional value) can impact fecundity, larval growth, pupation and adult emergence in aquatic insects (Resh and Rosenberg 1984).

Based on the logistic regression analyses at the statewide level, total alkalinity, pH and specific conductance were each positively correlated with weevil presence (χ^2_1 = 10.8, $P \leq 0.001$). In contrast, water depth showed a negative correla-

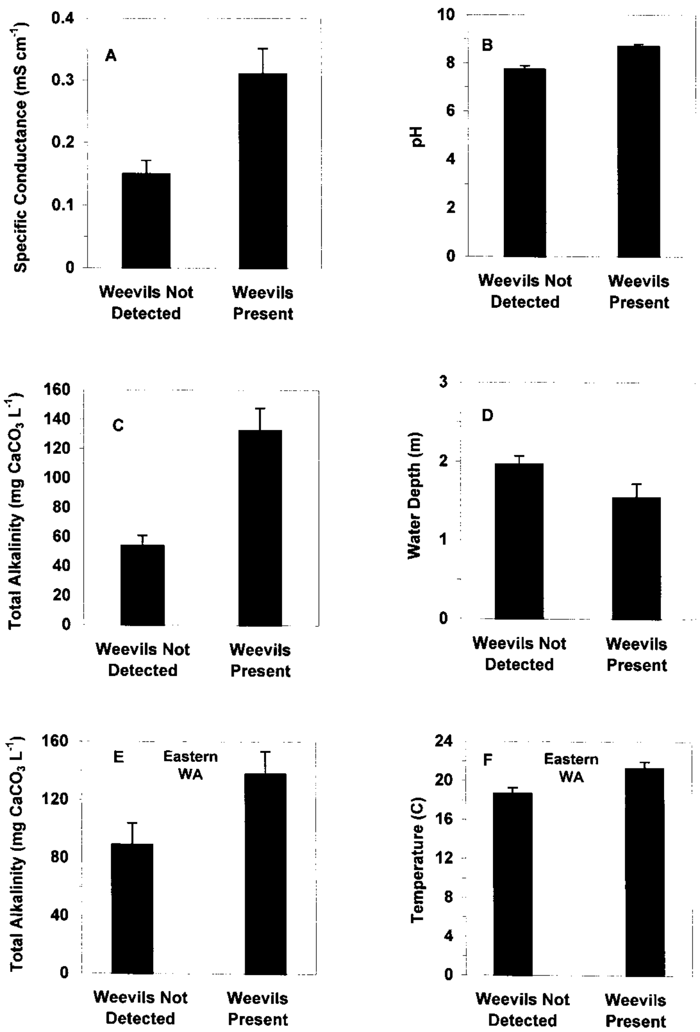

Figure 1. Water quality parameters that were significantly different at the statewide or regional level among waterbodies with *Euhrychiopsis lecontei* and those where *E. lecontei* was not detected. A) Statewide specific conductance (mS cm^{-1}); B) Statewide pH; C) Statewide total alkalinity (mg $CaCO_3$ L^{-1}); D) Statewide water depth (m); E) Total alkalinity (mg $CaCO_3$ L^{-1}) in eastern Washington; and F) Surface water temperature (C) in eastern Washington.

tion with weevil presence (χ_1^2 = 4.7, P = 0.03). Waterbody location (i.e., eastern versus western Washington) was also correlated with weevil presence (χ_1^2 = 14.9, P < 0.001). We found that total alkalinity, pH and specific conductance were highly correlated to each other (Pearson correlation ≥0.7) and therefore were not considered simultaneously in any multivariate model. Weevil presence also showed a significant relationship with surface water temperature and waterbody location (χ_2^2 = 24.3, P < 0.001). In fact, this multivariate model (water temperature + waterbody location) provided the best of fit of all six models (Hosmer-Lemeshow goodness-of-fit χ_8^2 = 4.0, P = 0.9) and was the most effective in describing weevil presence. The equation for this multivariate model is

$$\text{P(weevil presence)} = \frac{e^{-16.8 + 5(\text{location}) + 0.6(\text{water temperature})}}{1 + e^{-16.8 + 5(\text{location}) + 0.6(\text{water temperature})}},$$

where P(weevil presence) is the probability of finding weevils, location refers to whether a waterbody is in eastern (=1) or western Washington (=0), and water temperature is the average surface water temperature within the watermilfoil beds (all *Myriophyllum* spp.). The model suggests that both the surface water temperature and the location of a waterbody are related to the distribution of *E. lecontei* in Washington State, however the actual nature of this relationship is unknown and warrants further study.

Regional comparisons (i.e., eastern versus western Washington) showed that in western Washington there were no significant differences in water quality and watermilfoil frequency of occurrence between lakes with *E. lecontei* and lakes in which we did not detect weevils. Similarly, weevil presence was not correlated with water quality, watermilfoil frequency of occurrence or watermilfoil species. The latter may be attributed to fact that we only found weevils in one western Washington lake in 1997, therefore providing a small sample size and making it harder to detect any significant differences or correlations. In comparison, eastern Washington lakes and rivers with *E. lecontei* had significantly higher surface water temperature (21.3 ± 1.4 C) (mean ± 2SE), pH (8.7 ± 0.2) and total alkalinity (137.8 ± 31 mg of $CaCO_3$ L^{-1}) (P < 0.05). Also, weevil presence was positively correlated with surface water temperature (χ_1^2 = 7.7, P = 0.005). This model provided a good fit (Hosmer-Lemeshow goodness-of-fit χ_6^2 = 7.9, P = 0.2) and its equation is

$$\text{P(weevil presence)} = \frac{e^{-10.8 + 0.5(\text{water temperature})}}{1 + e^{-10.8 + 0.5(\text{water temperature})}},$$

where P(weevil presence) is the probability of detecting weevils, and water temperature represents the average surface water temperature in the watermilfoil beds (all *Myriophyllum* spp.) of a waterbody. The model suggests that as the surface water temperature increases, the more likely one is to detect weevils. The latter may be explained in part by the role of water temperature on the developmental rate of *E. lecontei*. Mazzei et al. (1999) tested the effects of water temperature on the developmental times of *E. lecontei* and the rate of stem damage to Eurasian watermilfoil plants. Their experiments revealed that developmental times decreased with increasing water temperature; there was a linear relationship between developmental rate and temperature up to 29C. In addition, Mazzei et al. (1999) found that the daily stem damage per larva increased with temperature, but the total extent of larval damage was the same for all the temperatures tested (approximately 15 cm per larva). We were probably more likely to detect weevils during our snorkeling surveys if the weevils were present in lakes with higher water temperatures (>20C), because the number of summer generations and larval damage increase with increasing water temperature, therefore making weevil abundance and damage more evident.

Our study suggests that the distribution *E. lecontei* in Washington State appears to exhibit a pattern where the weevil is more prevalent in eastern Washington among hard water lakes and rivers. Furthermore, surface water temperature may indirectly play a role in weevil distribution. Other factors that may also explain the distribution of *E. lecontei* in Washington State, but have yet to be examined, include over-win-

Table 2. Statewide comparisons of water quality and watermilfoil frequency of occurrence between waterbodies with *Euhrychiopsis lecontei* and those where *E. lecontei* was not detected. The number of waterbodies (n) with weevils and those where weevils were not detected, as well as mean measurements, standard errors (SE) and results from the t-tests, are shown.

Measurement	Weevils not detected n = 36		Weevils present n = 14		P- value
	Mean	SE	Mean	SE	
Total alkalinity (mg $CaCO_3$ L^{-1})	53.9	7.0	132.4	15.4	0.00
Temperature (C)	21.1	0.4	21.5	0.6	0.59
pH	7.7	0.1	8.7	0.1	0.00
Dissolved oxygen (mg L^{-1})	11.7	0.3	11.9	0.5	0.68
Specific conductance (mS cm^{-1})	0.2	0.0	0.3	0.0	0.00
Secchi depth (m)	2.9	0.3	2.8	0.3	0.83
Water depth (m)	2.0	0.1	1.5	0.2	0.04
Watermilfoil (*Myriophyllum* spp.) frequency of occurrence (%)	49.9	5.3	60.0	6.5	0.29
Eurasian watermilfoil frequency of occurrence (%)	54.8	6.4	77.3	10.8	0.13
Northern watermilfoil frequency of occurrence (%)	50.4	6.4	59.3	9.4	0.45

tering survival and habitat quantity and quality, and predation (e.g. fish community composition) (Sutter and Newman 1997, Newman et al 1996).

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