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Simple Control Method to Limit the Spread of the New Zealand Mudsnail *Potamopyrgus antipodarum*

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Abstract.—The invasive New Zealand mudsnail *Potamopyrgus antipodarum* is now well established in rivers in the western United States and is rapidly expanding its range. *Potamopyrgus antipodarum* is most likely to be spread to new waters via contaminated equipment. To assess a possible method for controlling their spread, we conducted a desiccation and freezing experiment on seven size-classes of *P. antipodarum* to determine mortality at different temperatures and low or high humidity. Our results show that *P. antipodarum* does not survive freezing or desiccation at high temperatures with low humidity. At all temperatures, larger *P. antipodarum* generally survived desiccation longer than smaller ones, and for all size-classes mortality generally increased with increased exposure time. We recommend thoroughly freezing or drying potentially contaminated equipment to limit the spread of *P. antipodarum* to uninfected aquatic ecosystems.

The invasive New Zealand mudsnail *Potamopyrgus antipodarum* (family Hydrobiidae) has become well established in many river drainages throughout the western United States and is quickly spreading to new locations. Because of its rapid spread, little has been published concerning its ecological and economic impacts. Regularly updated maps of verified locations of *P. antipodarum* infestations in the western United States can be found at http://www.esg.montana.edu/aim/mollusca/nzms/ (Gustafson et al. 2003).

Simberloff (2003) and Allendorf and Lundquist (2003) suggested that early detection and eradication are key to reducing the impacts of invasive species on ecosystems because once established, invasive species are extremely costly and difficult to control (Byers et al. 2002; Simberloff 2003). Therefore, we suggest that preventing the spread and establishment of *P. antipodarum* into uninfected aquatic ecosystems is crucial.

Potamopyrgus antipodarum is a parthenogenic, live-bearing, prosobranch snail with high reproductive potential (Winterbourn 1970). Densities in infested waters in the western United States typically range from 10,000/m^2 to 40,000/m^2 but often exceed 300,000/m^2 (Richards et al. 2001) and have been estimated to be as high as 750,000/m^2 in rivers in Yellowstone National Park (R. Hall, University of Wyoming, personal communication). To date, there is only one published report (Richards et al. 2001) documenting the distribution, ecology, and impacts of *P. antipodarum* in waters in the western United States.

The dispersion of *P. antipodarum* into new habitats in the western United States is thought to be caused by anglers, recreationists, other river users, and perhaps waterfowl. Previous research suggests that *P. antipodarum* does not survive desiccation (Winterbourn 1970) or freezing (Hylleberg and Siegismund 1987; Siegismund and Hylleberg 1987). Many resource managers in the western United States recommend a dry-heat treatment for all potentially contaminated equipment (e.g., boots and aquatic sampling gear), although there are no published data to support the effectiveness of this control method. Winterbourn (1970) measured the mortality rates of *P. antipodarum* at low humidity on dry and damp substrata between 20°C and 25°C but did not report desiccation effects at different temperatures or for different size-classes. Our experience has been that with contaminated equip-

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ment, smaller *P. antipodarum* are harder to detect and remove than larger ones.

Because no data have been published on the desiccation mortality of *P. antipodarum* in the western United States, we conducted a desiccation experiment on seven size-classes using six different temperatures, low versus high humidity (for four of these temperatures), and dry versus saturated substrate (for one temperature); the variations in the experimental conditions were an effort to encompass a range of control conditions that might be used. Our general hypotheses were that desiccation-induced mortality of *P. antipodarum* would not be equal for different temperatures and size-classes.

Methods

We measured the desiccation-induced mortality of *P. antipodarum* reared in our laboratory from middle Snake River stock at six temperatures (−3, 9, 14, 21, 29, and 40°C) in August 2001. We placed *P. antipodarum* on dry substrata at 21, 29, and 40°C with low relative humidity (20–25%) in our laboratory. We selected these higher temperatures and low humidity to reflect the ambient summer conditions in the western United States and the conditions that anglers and other river users would most likely use in their control efforts. We also placed *P. antipodarum* on dry substrata at 9°C and 14°C with high relative humidity (90–100%) and on saturated substrata at 9°C with high humidity in our temperature−humidity control chamber. Our assumption was that these two cooler temperatures and higher humidity would represent the conditions under which anglers and researchers would use or store their equipment during the colder periods of the year. Additionally, we placed *P. antipodarum* on dry substrata at −3°C to determine mortality when frozen, which is another possible control. Temperature and humidity were monitored throughout the experiment with a calibrated mercury bulb thermometer and humidity meter.

We exposed five *P. antipodarum* from each of seven size-classes (1.50–1.99, 2.00–2.49, 2.50–2.99, 3.00–3.49, 3.50–3.99, 4.00–4.49, and >4.50 mm) to temperatures of 9°C and 14°C for 1, 2, 4, 6, 8, 16, 24, 32, 40, or 48 h; to temperatures of 21°C and 29°C for 1, 2, 3, 4, 5, 6, 8, 16, 24, or 48 h; and to temperatures of −3°C and 40°C for 1, 2, 3, 4, or 8 h (N = 2,450 snails). At the end of each desiccation period, snails were placed in 21-mm-diameter glass vials filled with aquaria water and allowed to recover for 24 h. We then recorded whether the snails were alive or dead, classifying them as alive if they were normally extended from their shells and active and as dead if they were withdrawn into their shells and inactive throughout the 5-min observation period. After working extensively with *P. antipodarum* for the last several years, we are certain that individuals that were withdrawn and inactive after 24 h of recovery were indeed dead.

Statistical analyses.—We developed a probit regression model of mortality for the 10 time periods and each of the size-classes and temperatures except −3°C, 9°C on saturated substrate with high humidity, and 40°C. For this purpose, we used the probit analysis program in the computer statistical software package MINITAB (Minitab 2000). This program generated estimates of the time (h) required to achieve 99% mortality among the test organisms (LT99) as well as 95% confidence intervals for each of the four regression models. We conducted chi-square goodness-of-fit tests to determine whether the models were appropriate and whether the regression slopes were equal. Our best-fit model for 9°C with high humidity and a dry substrate was a logistic model; models with $\log_{10}$ transformed data were best for exposures to 14, 21, and 29°C. As none of the Pearson goodness-of-fit tests were significant (at the 0.05 level), we considered the probit models appropriate. Because none of the goodness-of-fit tests for equal slopes were significant, comparisons were made between size-classes within the four temperature treatments.

Results

All *P. antipodarum* in all size-classes died within 1 h in the −3°C and 40°C treatments except for one in the 2.0–2.5-mm size-class at −3°C, which survived for 2 h. As 80−100% of the *P. antipodarum* in all size-classes on saturated substrata at 9°C with high humidity were still alive after 48 h, we could not generate a probit model for this treatment. To summarize the results from the probit models for the other four temperature treatments, (1) larger *P. antipodarum* survived desiccation longer than smaller ones; (2) for all size-classes, mortality rates were greatest at the higher temperatures and lowest at 14°C; and (3) in general, mortality increased with increased exposure time (Table 1).

Many (54%) of the eventual mortalities in our experiment would float on the water surface when put in the vials after desiccation and were unable to sink for several hours (if at all), even after we

TABLE 1.—Mean (confidence limits in parentheses) time (h) to mortality of 99% of *P. antipodarum* in seven size-classes subjected to dessication at four different temperatures, as determined by probit regression. The 9°C and 14°C treatments were at high humidity, the 21°C and 29°C treatments at low humidity. A logistic probit model was used for the 9°C treatment, a $\log_{10}$ probit model for the other treatments. Five individuals of each size-class were desiccated at each temperature over 10 time periods ($N = 5 \times 7 \times 4 \times 10 = 1{,}400$).

Size-class (mm)	Temperature (°C)			
	9	14	21	29
1.50–1.99	41.67 (34.24, 49.09)	42.97 (34.44, 53.61)	11.04 (7.52, 16.19)	8.35 (5.43, 12.85)
2.00–2.49	46.60 (39.07, 54.13)	53.50 (43.31, 66.08)	11.48 (7.85, 16.78)	11.15 (7.40, 16.79)
2.50–2.99	48.40 (40.91, 55.89)	52.61 (42.68, 64.86)	21.15 (14.13, 31.67)	10.36 (6.87, 15.62)
3.00–3.49	50.22 (42.85, 57.60)	52.61 (42.68, 64.86)	32.21 (21.30, 48.71)	11.57 (7.57, 17.68)
3.50–3.99	50.22 (42.85, 57.60)	49.35 (39.38, 61.85)	33.81 (21.74, 52.58)	16.26 (10.55, 25.02)
4.00–4.49	58.39 (51.46, 65.32)	61.69 (50.19, 75.82)	43.94 (27.83, 69.37)	18.45 (11.93, 28.53)
≥4.50	59.85 (52.84, 66.86)	67.52 (54.64, 83.43)	44.53 (28.55, 69.46)	20.93 (13.44, 32.62)

vigorously stirred the water. Of the floating mortalities, 72% did not exceed 2.5 mm.

Discussion

We attribute the large increase in mortality between 14°C and 21°C to the large differences in relative humidity (90–100% versus 20–25%). Lower humidity apparently contributes to quicker desiccation. Snails probably did not sink in recovery tubes after desiccation because they became less dense than the water and were unable to break through the surface meniscus. This, we presume, was due to evaporative loss of extracellular water held in the mantle cavities by the closed opercula and the fact that more extracellular water was lost as the snails retracted further into their shells during desiccation. Eventually, at the highest temperatures and longer desiccation durations, the snail body tissue may have become desiccated.

Freezing or desiccation at high temperature and low humidity appear to be good ways to minimize the human-caused spread of *P. antipodarum* via contaminated equipment. Hylleberg and Siegismund (1987) and Siegismund and Hylleberg (1987) also reported that *P. jenkinsi* (Smith), which is synonymous with *P. antipodarum*, had low tolerance to freezing, both in estuaries and under laboratory conditions. Under damp and nonfreezing conditions, however, *P. antipodarum* can survive for very long periods of time and can easily be transported to new locations. Winterbourn (1970) reported that *P. antipodarum* from New Zealand were able to remain dormant and survive desiccation for up to 50 d on a wet substratum at 20–25°C, and our results showed that in the western United States these snails can survive dessication for at least 48 h on a damp substratum at 9°C.

From this and other laboratory experiments and our field work with *P. antipodarum* in infested waters, we suggest that any heat−drying treatment of potentially infected equipment be at a temperature of no less than 29–30°C and a low humidity level for a minimum of 24 h or, alternatively, at a temperature of at least 40°C and a low humidity level for at least 2 h to ensure a high kill rate. Freezing for several hours is also effective. It has been our observation that commonly used lace-up wading shoes are good transport mechanisms for *P. antipodarum*, which often get wedged in between the laces and the shoe. As felt-bottomed soles can also house *P. antipodarum*, we recommend a thorough visual inspection and removal of snails in addition to desiccation or freezing treatments. Fortunately, as the results from this experiment demonstrate, smaller, less detectable snails (<2 mm) are more susceptible to freezing and desiccation.

The spread of *P. antipodarum* is not inevitable. Unlike some aquatic invaders, *P. antipodarum* has no resistant stage, does not have any adhesive structures, and does not tolerate prolonged freezing conditions in the environment. With some effort, the invasion of *P. antipodarum* into new ecosystems can be restricted.

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