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SHORT COMMUNICATION

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Calcium concentrations in the lower Columbia River, USA, are generally sufficient to support invasive bivalve spread

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Abstract

Dissolved calcium concentration [Ca^{2+}] is thought to be a major factor limiting the establishment and thus the spread of invasive bivalves such as zebra (*Dreissena polymorpha*) and quagga (*Dreissena bugensis*) mussels. We measured [Ca^{2+}] in 168 water samples collected along ~100 river-km of the lower Columbia River, USA, between June 2018 and March 2020. We found [Ca^{2+}] to range from 13 to 18 mg L^{-1} during summer/fall and 5 to 22 mg L^{-1} during the winter/spring. Previous research indicates that [Ca^{2+}] < 12 mg L^{-1} are likely to limit the establishment and spread of invasive bivalves. Thus, our results indicate that there is sufficient Ca^{2+} in most locations in the lower Columbia River to support the establishment of invasive dreissenid mussels, which could join the already widespread and abundant Asian clam (*Corbicula fluminea*) as the newest invader to an already heavily invaded Columbia River ecosystem. These new data provide important measurements from a heretofore undersampled region of the Columbia River and have important implications for the spread of invasive bivalves and, by extension, the conservation and management of native species and ecosystems.

KEYWORDS
Asian clam *Corbicula fluminea*, cation concentration, dreissenid mussels, shell formation, water chemistry

1 | INTRODUCTION

Calcium (Ca^{2+}) is a major inorganic constituent of freshwater systems globally. Major sources of Ca^{2+} in lakes and rivers include framework silicates, ferromagnesian minerals, and carbonate rocks (Tipper et al., 2010). The concentration of Ca^{2+} [Ca^{2+}] varies widely in the world's rivers, with an approximate range of 1–200 mg L^{-1} (ppm). In the Columbia River (CR), USA, early measurements of [Ca^{2+}] spanned 4.0–21.0 mg L^{-1} (Fuhrer, Tanner, Morace, McKenzie, & Skach, 1996).

Calcium plays an important role in freshwater biogeochemical cycling, both as a critical component of organismal physiology and biochemistry (e.g., neurotransmission) and as a resource necessary for shell formation in bivalve mollusks. The range expansion and establishment of several invasive bivalve species, including the Asian clam, *Corbicula fluminea*, the zebra mussel, *Dreissena polymorpha*, and the quagga mussel, *Dreissena bugensis*, have been linked to the availability of sufficient Ca^{2+} (Davis, Ruhmann, Acharya, Chandra, & Jerde, 2015; Lucy, Karatayev, & Burlakova, 2012; McMahon, 1996). Thus, the [Ca^{2+}] in a water body is of great interest to aquatic resource managers who are charged with preventing the establishment of invasive bivalves (Counihan & Bollens, 2017).

This short communication has three objectives: (1) measure [Ca^{2+}] in the lower CR during two different seasons (summer/fall 2018 and winter/spring 2020); (2) compare our lower CR measurements with basin-wide stream [Ca^{2+}] data; and (3) investigate the implications of these empirically determined [Ca^{2+}] values for the establishment of invasive bivalves (i.e., the Asian clam *C. fluminea* and the dreissenid mussels *D. polymorpha* and *D. bugensis*) in the CR.

2 | METHODS

Surface water samples were collected approximately monthly in the lower CR from 14 dock stations (11 in "summer/fall" [June–October] 2018 and 12 in "winter/spring" [February–March] 2020, with nine sampled during both seasons), for a total of 168 samples (Table 1). Water was collected using a sterile 60-mL syringe and filtered in the field via positive-pressure filtration through a 0.45-μm inline filter into a new 50-mL polypropylene bottle and immediately frozen.

In the laboratory, water samples were thawed for 2 days prior to acidification (final concentration of 1.5% HNO_3), then processed to determine [Ca^{2+}] using an Agilent ICP-MS. One standard was run for every 10 unknowns, with two blanks and conditioning and calibration standards included at the beginning and end of each run. Duplicate samples were always within the range of the standards. Analysis of internal standards indicated an analytical error of <2% for Ca^{2+}. Possible seasonal differences in mean [Ca^{2+}] between summer/fall 2018 and winter/spring 2020 were tested for each station separately and for the nine stations sampled both seasons, using a Welch's *t*-test (because of unequal variances; Zar, 1996). We then combined [Ca^{2+}] data we measured (168 measurements from 14 sites) with the 20-year (2000–2019) surface water [Ca^{2+}] dataset available from the - U.S. Geological Survey (USGS) National Water Information System (NWIS) online database (USGS, 2016) (4,778 measurements from 150 sites) in the lower CR. We then calculated mean concentrations for sites where both winter/spring and summer/fall [Ca^{2+}] measurements were available (63 sites). These values were subsequently imported into Arc Map 10.7 software for visualization.

3 | RESULTS

Calcium concentrations in the lower CR ranged from 13 to 18 mg L^{-1} during summer/fall (mean [SE] = 15.80 [0.27] mg L^{-1}) and 5 to 22 mg L^{-1} during winter/spring (mean [SE] = 15.90 [0.97] mg L^{-1}) (Figure 1). There was no significant difference between seasons ($p >$ 0.05; *t*-statistic = 1.26) when pooling the nine sites sampled during both seasons. When each station was considered separately, however, one station showed a significant seasonal decrease in [Ca^{2+}], while five stations showed a significant seasonal increase in [Ca^{2+}] from summer/fall to winter/spring (Figure 1).

The data derived from the larger, regional USGS-NWIS database showed considerable spatial variability in mean annual [Ca^{2+}] across the lower CR Basin (Figure 2). Average concentrations ranged from 0.74 to 47.24 mg L^{-1}, with higher values occurring in eastern Washington (Figure 2).

4 | DISCUSSION

4.1 | Calcium concentrations in the lower Columbia River

The [Ca^{2+}] values for the lower CR that we report in this short communication fall within a range of mean annual concentrations reported for 315 globally distributed rivers and are similar to the median value amongst those rivers (mean: 27 mg L^{-1}; median: 14 mg L^{-1}; range 0.3–218 mg L^{-1}; Meybeck & Ragu, 1997). Our [Ca^{2+}] values are also similar to those for other, large temperate rivers in the UK (Neal & Robson, 2000) and China (Wu, Wang, Chen, Cai, & Deng, 2018), and generally fall within the range of the few other published values for the CR (4.0–21.0 mg L^{-1}; Fuhrer

TABLE 1 Location and number of water samples collected for [Ca^{2+}] in the lower Columbia River during 2018 and 2020

			2018					2020	
Sampling locations	Latitude	Longitude	June	July	Aug	Sept	Oct	Feb	Mar
Lower Celilo Pool	45.617542	−121.136062	1	2	2	4	4	2	2
Rowland Lake	45.709544	−121.381131						2	2
Bingen Harbor	45.708513	-121.457393	1	2	2	4	4	2	2
White Salmon	45.722746	−121.493679	1	2	2	4	4	2	2
Cook-Underwood Rd.	45.729416	−121.523418						2	2
Drano Lake	45.710801	−121.638799	1	2	2	4	4	2	2
Wind River	45.717913	−121.789161						2	2
Stevenson	45.694138	−121.877472	1	2	2	4	4	2	2
North Bonneville	45.633738	−121.965208	1	2	2	3	3	2	1
Beacon Rock	45.621675	−122.019967	1	2	2	3	4	2	1
Washougal Marina	45.577757	−122.381085	1	2	2	4	4	2	2
Vancouver	45.622235	−122.677263	1	2	2	2		2	2
Rainier City Park	46.094235	−122.943185	1	2	2	2			
Cathlamet, WA	46.201146	−123.386603	1	2	2	2			

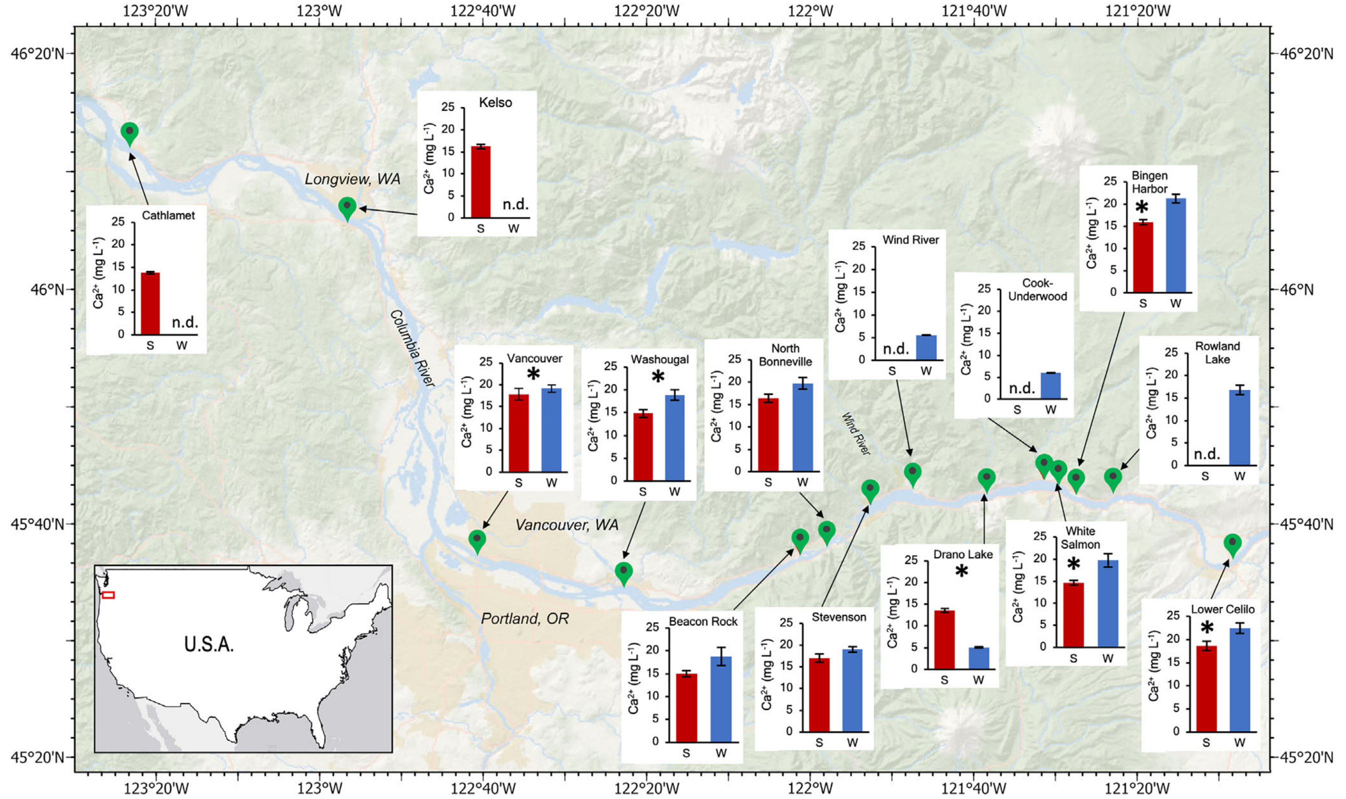

FIGURE 1 Mean [Ca^{2+}] during summer/fall 2018 (red bars) and winter/spring 2020 (blue bars) in the lower Columbia River, USA. Significant (two-tailed Welch's t-tests; $p < 0.05$) seasonal differences denoted by (*); "n.d." indicates no data were collected during that season; error bars represent 1 SE [Color figure can be viewed at wileyonlinelibrary.com]

et al., 1996); notably, however, they are consistently higher than the low-end values reported historically.

In temperate and high latitude freshwater systems, seasonal differences in [Ca^{2+}] might be expected to occur because of both physical and biological processes. Globally, limestone rivers show a seasonal increase in [Ca^{2+}] during high flow periods, while many other noncarbonate temperate and tropical river systems report a decrease in [Ca^{2+}] during peak flow (winter/spring) months (Rothwell et al., 2010; Tipper et al., 2010). Several (five of nine) of our stations showed somewhat higher [Ca^{2+}] during winter/spring than in summer/fall; these high values could be due to contributions of several calcium-rich magnesium carbonate-bearing upstream drainages and/or changes in the relative contribution from Ca^{2+}-rich waters during the wet season (Santos, 1965). Most of the basin-wide USGS stations upstream of our sampling (in the mainstem CR) show a similar pattern of increasing winter [Ca^{2+}] compared to summer (U.S. Geological Survey, 2016).

In contrast, three of our stations (Wind River, Drano Lake, Cook-Underwood Rd; Figure 1) showed quite low (<10 mg L^{-1}) [Ca^{2+}] during winter/spring, suggesting the possibility of site-specific, local dilution effects during high-precipitation, high-flow seasons in adjacent tributaries. For the basin-wide USGS-NWIS dataset, many stations in Oregon (south of the mainstem CR) show a trend of decreasing winter [Ca^{2+}] compared to summer (USGS, 2016), possibly due to the noncarbonate lithologies/sediments (e.g., Missoula flood deposits and Andesitic mudstone) and/or the more rain- (as opposed to snow-) dominated precipitation regime in this region.

As a separate matter, biological productivity in the CR would be expected to be highest in summer and fall, when temperatures are highest. For instance, in the invasive Asian clam *C. fluminea*, both feeding (Rollwagen-Bollens et al., 2021) and growth (Henricksen & Bollens, In Review) are temperature-dependent and highest during summer in the lower CR. Bivalve shell formation, and thus Ca^{2+} uptake, would also be expected to be temperature-dependent and thus highest during summer. The relative importance of these physical and biological processes in controlling [Ca^{2+}] is poorly understood and in need of further research.

4.2 | Implications for invasive bivalves

Aquatic invasive species pose a growing threat to freshwater ecosystems worldwide (Dexter & Bollens, 2020; Havel, Kovalenko, Thomaz, Amalfitano, & Kats, 2015; Lodge et al., 2006). Indeed, the lower CR is now a highly invaded ecosystem, hosting several species of invasive copepods (Connelly, Rollwagen-Bollens, & Bollens, 2020; Cordell, Bollens, Draheim, & Sytsma, 2008; Dexter et al., 2018; Dexter, Bollens, Cordell, & Rollwagen-Bollens, 2020; Rollwagen-Bollens

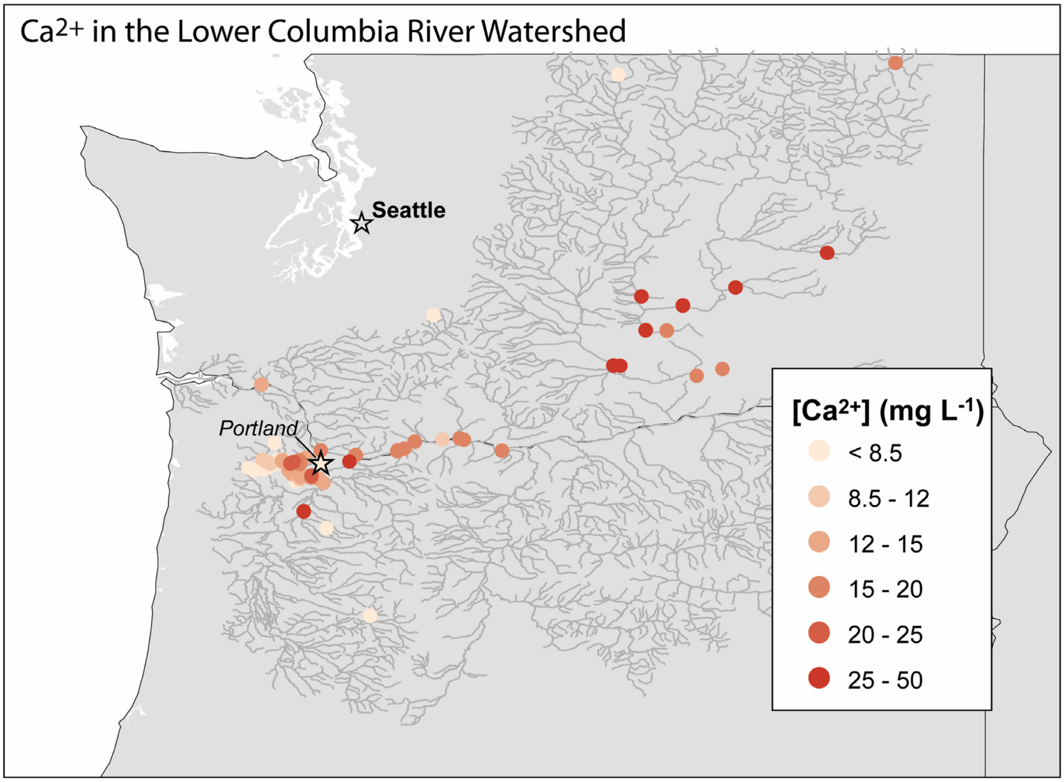

FIGURE 2 Mean $[Ca^{2+}]$ in the lower Columbia River Basin using data from the USGS NWIS (2,132 data points collected from 54 sites between 2000 and 2019), and this study (142 data points from nine sites collected in 2018 and 2020) for which both winter/spring and summer/fall measurements were available [Color figure can be viewed at wileyonlinelibrary.com]

et al., 2021), an invasive cladoceran (Dexter, Bollens, Rollwagen-Bollens, Emerson, & Zimmerman, 2015; Smits, Litt, Cordell, Kalata, & Bollens, 2013), and the invasive Asian clam *C. fluminea* (Bolam, Rollwagen-Bollens, & Bollens, 2019; Hassett et al., 2017). Some of these invasive taxa seem to be increasing in abundance along with long-term (decadal) increases in water temperature (Dexter, Bollens, & Rollwagen-Bollens, 2020). Thus, there is increasing interest—and indeed, urgency—in predicting when and where further invasions might occur, and what management actions, such as early detection monitoring and watercraft inspections, might be undertaken to reduce or mitigate their spread. This is especially true of dreissenid mussels, which are global invaders (Nalepa & Schloesser, 2014; Strayer et al., 2019) that have crossed the North American continental divide into the western U.S. (Wong et al., 2010) and now threaten the CR Basin, amongst other regions.

Bivalve mollusks require calcium for the formation of their shells, and several studies have indicated that $[Ca^{2+}]$ is often an important environmental predictor of the presence of freshwater bivalves (Davis et al., 2015; Lucy et al., 2012; McMahon, 1996). However, the minimum $[Ca^{2+}]$ required for dreissenid growth and survival is poorly constrained and may vary between species and even between life stages within a species (Davis et al., 2015). Applying the reported $[Ca^{2+}]$ needed for growth and survival of dreissenid mussels, Neary and Leach (1992) defined a waterbody's risk of establishment as: low (<12 mg L^{-1}), medium (12–20 mg L^{-1}), and high (> 20 mg L^{-1}). More recently, Counihan and Bollens (2017) defined risk as very low (≤ 12 mg L^{-1}), low (>12 and ≤ 15 mg L^{-1}), medium (>15 and ≤ 25 mg L^{-1}), and high (>25 mg L^{-1}). Based on these previous studies, as well as our observations of $[Ca^{2+}]$ reported herein, the lower CR is at risk of invasion by dreissenids, though perhaps at only a moderate level.

The $[Ca^{2+}]$ requirements for the Asian clam, *C. fluminea*, are not well understood (McMahon, 2002), and in fact, there are somewhat conflicting reports in the literature. For instance, Karatayev, Padilla, Minchin, Boltovskoy, and Burlakova (2007), citing Boltovskoi (unpubl.), reported that *C. fluminea* can survive in waters with $[Ca^{2+}]$ as low as 3 mg L^{-1}, whereas Zhao, Schöne, and Mertz-Kraus (2017) stated that "*C. fluminea* appears to be less tolerant to low Ca^{2+} concentrations than *D. polymorpha*," implying a substantially higher minimum $[Ca^{2+}]$ requirement. But, as noted above, *C. fluminea* has become widespread in the CR (Bolam et al., 2019; Hassett et al., 2017), and thus it appears that $[Ca^{2+}]$ as low as 5–22 mg L^{-1} (our results) can support populations of *C. fluminea*. If Zhao et al. (2017) are correct that dreissenids are more tolerant of low $[Ca^{2+}]$ than *C. fluminea*, then this would suggest that regions already invaded by *C. fluminea* (like the CR) may also be at risk of invasion by dreissenids.

5 | CONCLUSIONS AND IMPLICATIONS

Our observations of $[Ca^{2+}]$ ranged from 5 to 22 mg L^{-1}, with most (74.4%) values in the 15–22 mg L^{-1} range. Previous research in other waterbodies indicates that low [Ca^{2+}] (e.g., <12 mg L^{-1}) is likely to limit the establishment and thus the spread of invasive bivalves (Davis et al., 2015; Oliveira, Calheiros, Jacobi, & Hamilton, 2011; Strayer et al., 1996). Therefore, the results we report in this short communication indicate that there is usually sufficient [Ca^{2+}] in the lower CR to support the establishment of invasive dreissenid mussels, which could join the currently widespread and abundant Asian clam (*C. fluminea*) as the newest bivalves to invade an already heavily invaded CR ecosystem. Understanding the suitability of the lower CR to support invasive bivalves will help managers direct the limited resources available for early detection monitoring and watercraft inspections to areas that are at risk of invasion.

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DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the findings of this study are available within the article.

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