South Dakota) (Richards 1968) showed the highest percent germination rate with a mean of 10.2% (± 0.81% SE). The Woodworth WPA site 200 km to the east of NDSU had a percent germination mean of 6.5 (± 5.28% SE), which was not significantly different from the NDSU site ($p > 0.05$). The Strong WPA, located adjacent to the Woodworth WPA site had a percent germination mean of 2.8% (± 0.22% SE) which was significantly lower compared to the other sites ($p < 0.05$). Although seeds from Strong WPA had a lower germination rate, the fact that all the sites had some level of seed germination suggests that *R. pinnata* is capable of producing viable propagules to sustain itself hundreds of kilometers north of its range. Therefore, assuming that this native species when used in a restoration outside of its traditional range, but still within its native ecosystem, will have reduced ability to reproduce or expand is not valid. There is variability in the germination rate among the sites but studies reporting germination rates of *R. pinnata* within its traditional range also report high variability in germination rates (Greene and Curtis 1950, Halinar 1981).

In the field study, *R. pinnata* seeded into the weedy patch had an average of 1.5 plants established per plot (six plants total) while the native plots had no plants established. Therefore, *R. pinnata* is capable of establishing itself within an existing prairie planting. In this instance only the weedy patch had establishment, but this indicates that if there is any type of disturbance within a prairie planting *R. pinnata* can be expected to respond with new plants from seed.

As native species are considered for movement to mitigate climate change (Vitt et al. 2010) and augment prairie plantings, the lack of knowledge of how a species will interact with the local conditions (Gibson et al. 2016) and other species may lead to unintended consequences (Johnson et al. 2017). Even in its traditional range, restoration practitioners are now advising against using *R. pinnata* in restorations because of its competitive and easy to establish nature (Jessica Peterson, Minnesota Department of Natural Resources, pers. comm.). Therefore, the demonstrated ability of *R. pinnata* to be self-sustaining combined with its aggressive nature and the possibility of unintended consequences leads us to caution restoration practitioners on using this species outside of its traditional range.

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Japanese Knotweed Management in the Riparian Zone of the Bronx River

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Invasive species management is key to the preservation of natural riparian habitats, including along the Bronx River in New York City. Invasive plant management techniques include mechanical removal and herbicide application; these vary in their costs, non-target effects, and effectiveness (Weston et al. 2005, Hagen and Dunwiddie 2008, Delbart et al. 2012). Controlling invasive plants in an urban environment is challenging as urban natural resource managers have limited resources and often work with volunteers to address the constant issue of managing invasive plants. One such invasive plant is *Reynoutria japonica* (Japanese knotweed) and a hybrid, *Reynoutria × bohemica* (= *Reynoutria japonica* × *Reynoutria sachalinensis*).

Reynoutria japonica was introduced in the U.S. in the 1870s from eastern Asia and is now widespread in riparian and disturbed zones (Pyšek et al. 2003, Weston et al. 2005, Barney 2006, Gammon et al. 2010). It has large stems that can reach heights of over 5 meters and it primarily expands through rhizomes, which can grow to over 10 meters in length and extend up to 1 meter below the surface (Weston et al. 2005, Engler et al. 2011, Groeneveld et al 2014). *Reynoutria japonica* hybridized with *R. sachalinensis* to form *R.* × *bohemica*, which shares many of the same physical and growth traits as the other species (Pyšek et al. 2003, Gammon et al. 2010, Rouifed et al. 2011). Hereafter, "knotweed" will refer to *R. japonica, R. sachalinensis,* and *R.* × *bohemica*, which are all present on the Bronx River in New York City (Frankel et al. 1999, Yau et al. 2012, D. Atha and J. A. Schuler, New York Botanical Garden, New York, NY, pers. comm.).

The New York City Department of Parks & Recreation (NYC Parks), together with the Bronx River Alliance and the New York Botanical Garden (NYBG), produced the Bronx River Riparian Invasive Plant Management Plan (Yau et al. 2012), and initiated a study to try to improve knotweed control. The purpose of our study was to test the effectiveness of two common mechanical management techniques and to examine their effects on planted native *Quercus palustris* (pin oak) saplings and on the herbaceous layer in a knotweed dominated area in the Bronx River bank. We examined *Q. palustris* because it is a fast-growing species adapted to riparian soils and is a desired component of the canopy in these riparian forests (Sweeney and Czapka 2004).

We conducted a field experiment to answer the following questions:

- Are mechanical cutting and root and rhizome removal methods effective ways of managing Japanese knotweed populations?
- Does the reduction of Japanese knotweed affect the growth of *Q. palustris* saplings?
- How do the different Japanese knotweed management methods affect other plant species in the riparian herbaceous layer?

In April of 2010, we established 60 2m × 2m plots in the Bronx River Forest (BRF). An additional 60 plots were also established in the NYBG for a total of 120 plots across the two sites. We positioned plots approximately 1m upland from the edge of the riverbank of the Bronx River (Figure 1) with a half meter buffer between each plot. We planted one *Q. palustris* sapling in the center of each plot in mid-April 2010; all of the planted *Q. palustris* saplings were approximately the same size. We planted the *Q. palustris* saplings before treatment occurred to capture initial conditions in the plots. We randomly assigned plots to one of three treatments with an equal number of plots per treatment type. The knotweed removal treatments were: A) cutting three times during the growing season (May, July, and September), hereafter referred to as the "cutting" treatment; or B) cutting once (May) and then root and rhizome removal twice (July and September), hereafter referred to as the "rhizome removal" treatment. Cutting is defined as cutting all non-woody vegetation within the plot with hand pruners, hedge trimmers or loppers as close to the ground as possible. Rhizome removal involved digging out all roots and rhizomes to at least 15 cm below the surface during each treatment event. We applied the treatments in 2010, 2011, and 2012.

We measured percent cover, stem density, and height of knotweed; caliper, height, and crown spread of the planted *Q. palustris* saplings; and the cover of the herbaceous layer at the end of August each year prior to the application of the last treatment. We identified herbaceous plants and assigned them a midpoint from percent cover classes (< 5, 5–10, 11–25, 26–50, 51–75, or 76–100%). We measured stem diameter 15 cm above the soil surface with calipers. We measured sapling height from the soil surface to the terminal bud of the leader stem. We estimated crown spread by calculating the average of the longest line across the crown, and the longest perpendicular line.

We used the program R (R v. 3.0.2, R Foundation for Statistical Computing, Vienna, Austria) to perform data analysis and visualization. We tested the data for statistical significance using the repeated measures analysis of generalized linear mixed models, specifically using the R functions glmmPQL from the MASS (Venables and Ripley 2002) and nlme packages (Pinheiro et al. 2013). We analyzed the data to determine if the independent variables of knotweed abundance, sapling size, and the herbaceous layer metrics were significantly different across the dependent fixed effects variables of treatment, year, and site, and if there was an interaction between treatment and year, and treatment and site. We used Plot ID as the random effects variable. We compared the control plot data to the root removal and cutting treatments in the model summary output. We used a separate post-hoc model summary (R function glht from the multcomp package (Hothorn et al. 2008) with designated treatment comparisons) to test for significance between the cutting and root removal treatments.

After the final data collection in 2012, we found that knotweed stem densities generally increased following cutting and the response of stem density to rhizome removal varied between sites (Figure 2A). Knotweed average stem height was significantly higher—at least 60%—in control plots compared to cutting and rhizome removal treatments in both NYBG and BRF across all years (Figure 2B; Generalized Linear Mixed Model (GLMM), Cutting vs. Control, $t = -6.52$, $DF = 118$, $p < 0.001$; Rhizome removal vs. Control, $t = -5.99$, $DF = 118$, $p < 0.001$). In 2011, rhizome removal reduced knotweed percent cover (38% NYBG, 16% BRF) relative to the control plots (69%

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Figure 1. Locations of treatment plots in the Bronx River Forest and New York Botanical Garden, New York City, New York, USA.

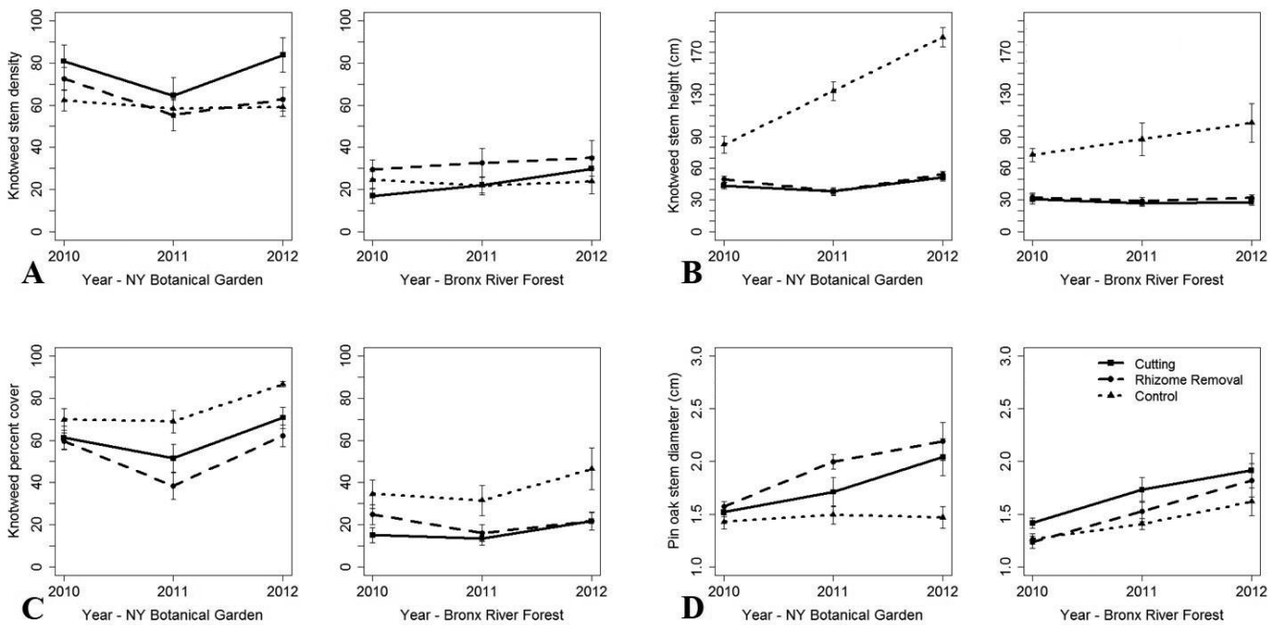

Figure 2. Effect of knotweed treatment on: A) knotweed stem densities (stems per 4 m2), B) knotweed stem height (cm), C) knotweed percent cover, D) *Quercus palustris* stem diameter (cm) at the New York Botanical Garden and the Bronx River Forest. Error bars represent standard error.

NYBG, 31% BRF; Figure 2C; GLMM, Rhizome removal vs. Control in 2011, t = –2.94, DF = 206, $p = 0.004$). *Quercus palustris* stem diameter increased over time across all plots in both NYBG and BRF (Figure 2D; GLMM, *Q. palustris* stem diameter 2010 vs. 2012, t = 2.17, DF = 193, $p = 0.03$). *Quercus palustris* sapling height and crown spread had similar growth trends as stem diameter. In 2012, cutting treatments supported greater cover of other herbaceous vegetation (all species excluding knotweed, 16% NYBG, 53% BRF) compared to control plots (7% NYBG, 42% BRF; GLMM, Cutting vs. Control in 2012, t = 2.06, DF = 193, $p = 0.04$).

Controlling established invasive species is a global challenge that requires a large amount of resources and time, and the result is often temporary reduction that requires repeated application to maintain (Vitousek et al. 1997, Maxwell et al. 2009, Martin and Blossey 2013, Hazelton et al. 2014). The mechanical removal of invasive species is an accessible management technique that can temporarily improve the success of riparian restoration (Sweeney and Czapka 2004, Simmons et al 2015). In our study, cutting and rhizome removal resulted in similar reductions in knotweed abundance. There was no difference in impact on knotweed stem densities, average heights, or percent cover between the two treatment types; neither treatments greatly reduced the stem density and percent cover of the knotweed. However, the treatments were equally effective at reducing knotweed height over the course of our study.

Other studies have found that cutting and rhizome removal are equally effective at reducing invasive species. Esmaeili and colleagues (2009) found that stem clipping negatively impacts rhizome biomass in the clonal plant species *Carex divisa* (separated sedge), *Eleocharis palustris* (common spikerush), *Juncus articulatus* (jointleaf rush), *Juncus gerardii* (saltmeadow rush), and *Elymus repens* (quackgrass). Francis and colleagues (2008) found that viable fragments of knotweed rhizome can grow at varying depths underground, which means that root removal does not stop growth of clonal plant species when rhizome fragments remain to reinitiate growth. These studies show that cutting aboveground tissues has an indirect impact on roots and rhizomes that is equally as effective as root and rhizome removal. Based on these findings, we recommend cutting knotweed repeatedly rather than digging out roots and rhizomes.

Quercus palustris growth was higher in treatment plots, however, treatments did not facilitate the return of robust native herbaceous communities. The most frequently encountered species across treatment and control sites from 2010 to 2012 included *Urtica dioica* (stinging nettle), *Viola sororia* (common blue violet), *Persicaria pensylvanica* (Pennyslvania smartweed), *Parthenocissus quinquefolia* (Virginia creeper), *Alliaria petiolata* (garlic mustard), and others. Most herbaceous species found across treatment plots were disturbance-adapted colonizers that do well in riparian soils. Seven of the top ten most frequently encountered species overlap between the two treatment types. Therefore, treatments did not have a major impact on community composition of the herbaceous layer, but did impact the growth of larger woody species.

We often work with volunteers to remove and help manage invasive plants along the Bronx River. Only

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mechanical removal is used with volunteers, as there is strict permitting, licensing, and training needed to apply herbicides. Throughout this project in 2010–2012, 2100 volunteer hours were spent managing knotweed along the river banks. This greatly supplemented the 530 hours of paid staff time devoted to knotweed management. Due to the similar impacts of cutting and rhizome removal treatments on knotweed abundance, we recommend that cutting alone be used as a mechanical management technique, and that the hard-work of digging out roots and rhizomes may not be necessary. However, on this short-term time scale we were not able to eradicate knotweed, nor recover the herbaceous community. Further studies are required to understand the long-term impacts of these control and restoration techniques.

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