The Ecohydrology Of A Japanese Knotweed Invasion

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Abstract

Polygonum cuspidatum (Japanese knotweed) is an herbaceous, clonal invasive plant that can create a monodominant stand that outcompetes native species, particularly throughout riparian zones. To better understand how this species is so successful at invading, and why particular locations in riparian settings are more at risk, we investigated a variably invaded riparian valley site in the northeastern United States. We measured spatial variations in hydrologic and soil attributes (soil texture, depth profiles, volumetric water content) in relation to spatial variations in Japanese knotweed abundance (percent coverage). We also investigated how the arrival of this species alters hydrologic properties of the soil (e.g., infiltration rate) at a fine spatial scale (< 1 m). Across all variables observed, the strongest linear correlation ($p < 0.01$, $r = 0.70$) was found to be a positive relationship between mean percent coverage of Japanese knotweed and soils with a higher clay proportion. To understand causation in this relationship, and to better now how knotweed alters the physical environment it invades, we measured soil infiltration rates with stems present and absent ($n = 40$). We found that knotweed occurrence can create a significant ($p = 0.05$) decrease in infiltration rate, but only within finer soils. These results may elucidate new possible ecohydrologic feedback mechanisms between Japanese knotweed and soil properties that could promote a higher competitive advantage in finer soils. This new insight, along with other know mechanisms promoting knotweed growth, can help to better identify and prioritize conservation efforts around locations more at-risk of a successful invasion.

1. Introduction

One of the most damaging invasion species is *Polygonum cuspidatum* (syn. *Reynoutria japonica* and *Fallopia japonica*, herein Japanese knotweed, or knotweed (Jones et al. 2018; Vasquez-Valderrama et al. 2020). This clonal, herbaceous species has the ability to be the monodominant species in invaded areas and have community level changes. Even though this is one of the most studied invasive species (Vanderklein, Galster, and Scherr 2014), a previous literature review on Japanese knotweed found there is an existing need for more work on the ecohydrology and hydrogeomorphology of Japanese knotweed invasions (Vanderklein, Galster, and Scherr 2014; Lavoie 2017). To address this need for further understanding of any potential physical and ecohydrologic feedbacks associated with Japanese knotweed invasions, our study investigated if locations of Japanese knotweed invasion are associated with unique physical properties of the soil, and if this species can, in turn, also alter physical hydrologic properties of the soil it grows in. Specifically, we aimed to use a variably invaded riparian field site to investigate: 1) if there was any spatial correlation between knotweed abundance (percent coverage) and specific physical soil characteristics (texture, depth, volumetric water content, hydraulic conductivity, and porosity) and 2) if knotweed presence can alter a physical property of the soil relevant to the site's overall ecohydrological functioning (infiltration rate) to understand if any additional ecological feedbacks exist that may support the success of this particular biological invasion.

2. Methods

2.1 Site Selection

Marist College in Poughkeepsie, New York owns the 12-acre protected forest, Fern Tor Preserve. This site, shown in Fig. 1, was chosen due to the variable abundance of Japanese knotweed present there. In addition to being a forested area, Fern Tor is also a west-facing valley located on the east side of the Hudson River with a spring-fed, unnamed, 1st order tributary of the Hudson running through the valley, with its watershed entirely contained within the preserve. This site is a transition zone between aquatic and terrestrial habitats of the Hudson River Estuary. This transition contributes to the heightened levels of biodiversity in such ecosystems, but also makes them prone to invasion by competitive species (Fischer et al. 2015). All work involved in this investigation abided by the institutional, national, and international guidelines and legislation.

2.2 Transect Observations

The stratified 95 meter transect, as shown in Fig. 1, started at the edge of a walking path, and crossed the stream approximately 10 meters east of the pond located in the middle of the watershed. Along this transect, a one square meter quadrat was sequentially placed every five meters. Once the quadrat was placed down, Japanese knotweed plants were identified and quantified in comparison to other plant species to determine percent areal coverage (percent of area overlain by knotweed) within each quadrat. The sampling season (2018) contained multiple sampling periods during the growing season spanning from late spring through early fall, and results are presented as means of the observations for the entire year. Every quadrat location was also the location of a soil observation via an augured hole. Soil columns at 20 cm increments were extracted until the auger hit refusal and was recorded. A manual ribbon test was used to evaluate soil texture class, and the presence of roots, mottling, and saturated conditions in the augered hole for each extracted 20 cm depth increment of soil. The volumetric water content and temperature of each undisturbed soil depth layer was measured in place, prior to augering into that layer, with a portable frequency domain reflectometry probe (*Stevens Hydra Probe*) in a soil volume surrounding the 5 cm long sensing tines. Numeric geologic variables were then calculated along the transect for each quadrat location using these pedologic and hydrologic observations, which included: soil depth (cm), groundwater depth (cm, based on observed elevation of in-hole saturation), mean percentage clay (%, based on soil texture class), mean temperature (℃), mean volumetric water content (ratio of water volume to total volume of soil, air, and water), mean porosity (%, based on soil texture class), max depth of roots present (cm), and depth of first mottling (cm). Based on the determined soil texture of each 20 cm increment, mean soil hydraulic conductivity and mean porosity were also calculated using standards of these values by soil texture class provided by the United States Department of Agriculture (NRCS 2019) and *Geotech* data resources (Geotech 2013). The mean for each variable at the quadrat scale was determined using an integration of all 20 cm depth increments of soil data, and was also calculated for only the top 40 cm of soil depth increments for each site to isolate the impact of near-surface pedologic and hydrologic traits. The data found from these variables was overlaid with the ecological data in a data table summarizing all integrated quantitative values for each quadrat along the 95 m transect.

2.3 Soil Infiltration Tests

Plots A and B for infiltration studies were chosen because of their similar spacing of knotweed stem distribution, while being different in that Plot A is riparian, being directly adjacent to the stream and pond, while Plot B is farther upslope in a more terrestrial location. Within the plots, transects were created for the soil infiltration tests that contained alternating sampling locations (< 1 m spacing, across 40 locations) of Japanese knotweed stems present and stems lacking. Figure 2 shows these sites, which used an automated dual head infiltrometer, the *Meter Saturo (ISO 9001:2015)*, to measure the field saturated hydraulic conductivity (K_{fs}).

Short linear transects were created in these plots and the exact locations chosen for the 20 infiltration tests per plot altered between specific locations with Japanese knotweed stems present (n = 10 tests per plot) and Japanese knotweed stems absent (n = 10 tests per plot). When a plant's foliage intersected the transect line, it was chosen as a stem (with a threshold of 5 mm minimum diameter), and the midway point between successive stems along the transect were chosen as a non-stem locations. Infiltration tests reached full field saturation automatically before K_{fs} rates were automatically calculated. Two soil samples were taken via small shovel from each Plots A and B at depths of 0 to 10 cm (shallow) and 10 to 20 cm (deep) and were comprised of approximately a liter of wet soil per sample. The soil samples were oven dried overnight and measured for proportion size class using dry sieving.

3. Results

3.1 Ecologic and Pedologic Transect

After compiling all the field data under each site, the most relevant soil, hydrologic, and ecological data was compiled in Table 1 below. All the compiled data was used to make a linear correlation matrix represented in Fig. 3, below. This was done to visualize the data and systematically investigate which variables may have a relationship to one another, and the strength and direction of that relationship.

Table 1: Compiled data of soil depth (cm), estimated percent clay (based on soil texture class), volumetric water content (VWC), mean soil hydraulic conductivity (cm/sec) represented by K, mean porosity (% based on soil texture class), and mean percent coverage of knotweed (multiple observations over growing season). Each value is an integrated mean for the entire soil column, or the top 40 cm of soil – intended to represent near-surface conditions.

Quadrat Location	Soil Depth (cm)	VWC	Clay (%)	K (cm/sec)	Porosity (%)	Clay Top40cm (%)	K Top40cm (cm/sec)	Porosity Top40cm (%)	Mean % cover
0m	60	0.22	30	0.00001	44	30	0.00001	44	0
5m	120	0.19	30	0.00001	44	20	0.00001	44	0
10m	35	0.18	40	0.000001	22	40	0.000001	22	22
15m	50	0.12	100	0.0000001	62.5	100	0.0000001	62.5	11.5
20m	50	0.19	30	0.00001	44	30	0.00001	44	19.75
25m	70	0.18	50	0.000001	50	70	0.000001	50	50.5
30m	80	0.12	100	0.0000001	65	100	0.0000001	65	48.5
35m	34	0.22	30	0.00001	44	30	0.00001	44	20.5
40m	180	0.14	10	0.0001	37	30	0.00001	44	14
45m	113	0.08	0	0.001	35	50	0.00001	50	18.5
50m	175	0.19	30	0.00001	44	30	0.00001	44	29
55m	110	0.18	50	0.0001	50	50	0.0001	44	0
60m	80	0.23	10	0.0001	37	10	0.0001	37	0
65m	130	0.14	10	0.0001	50	10	0.0001	50	0
70m	190	0.14	10	0.0001	37	10	0.0001	37	0
75m	192	0.08	0	0.001	35	0	0.001	35	0
80m	70	0.14	10	0.0001	37	10	0.0001	37	0
85m	108	0.08	0	0.001	35	0	0.001	35	0
90m	40	0.08	0	0.001	35	0	0.001	35	0
95m	10	0.08	0	0.001	35	0	0.001	35	0

Based on the linear correlation matrix (Fig. 3), multiple significant relationships were discovered. A number of geologic and hydrologic variables strongly correlated with one another in ways that were expected based on their direct physically-based relationships. These variables that have this direct physical relationship are hydraulic conductivity (K, cm/sec) to VWC (cm^3 water/cm^3 of soil), K (cm/sec) to porosity (% void space), and clay (% by weight) to both K (cm/sec) and porosity (% void space). Each general variable integrated across the entire soil column, for example clay (clay %), also correlates to its mean value in the top 40 cm (clay % top 40 cm). The only variable that does not correlate to any other variable is soil depth (cm). The most important finding of this linear correlation matrix is how each variable relates to the mean percent cover of Japanese knotweed along the transect (right column, Fig. 3). Variables with strong correlations to mean cover of knotweed include: proportion clay with a positive linear correlation coefficient of 0.58 ($p < 0.01$), proportion clay in the top 40 cm with a positive linear correlation coefficient of 0.70 ($p < 0.01$), and porosity in the top 40 cm a positive linear correlation coefficient of 0.47 ($p = 0.04$)

3.2 Soil Infiltration

The infiltration rates (Fig. 4) showed a decreased rate and range of rates with Japanese knotweed stem present, shown in Plot A. The two-sample, two-tailed t-test showed that Plot A had a significant difference in infiltration rate based on stem presence ($p = 0.05$), while Plot B did not show a significant variation in infiltration rates based on the absence versus presence of stems ($p = 0.8$). The infiltration rates for Plot A with the Japanese knotweed stems present ranged from near zero to 0.03 cm/sec with an average of 0.005 cm/sec. For Plot A without Japanese knotweed stems present, the range was 0.001 cm/sec to 0.24 cm/sec with an average of 0.07 cm/sec. For Plot B with Japanese knotweed stems present, the range of infiltration rates was 0.006 cm/sec to 0.02 cm/sec with an average of 0.016 cm/sec. For Plot B without Japanese knotweed stems present, the range was 0.002 cm/sec to 0.04 cm/sec with an average rate of 0.016 cm/sec.

The soil texture of the two sites were taken at two depths. The results of the dry sieve measurements are shown below in Fig. 5. The mean percent of fine particles (< 0.02 mm) in Plot A was 7.3% by weight, as compared to Plot B with a mean of 2.1% fine particles by weight. Plot B also contained a larger mean percentage of coarse particles (ranging from 0.425 to 2.36 mm), comprising 56% of the soil weight.

4. Discussion

The results of the ecologic and pedologic transect suggest a significant ($\alpha = 0.05$) linear relationship exists between the prevalence of clay in the soil and percent cover of Japanese knotweed ($p < 0.01$), and that this is a strongly positive relationship ($r = 0.7$). Other properties of the soil were also found to relate to the proportion of clay, such as porosity (Fig. 3). Since porosity values were calculated from soil texture, and porosity is inversely proportional to grain size, this porosity percentage increase as clay percentage increases is well understood and expected (Fennell, Wade, and Bacon 2018). Due to this connection, the relationship between porosity percentage in the top 40 cm of soil and the mean percent Japanese knotweed coverage is also found to be a significant ($p = 0.04$) and positive relationship ($r = 0.47$).

Results on infiltration rate indicate that Japanese knotweed stem presence correlates with a longer average infiltration rate (Fig. 4). This was shown for both Plot A (riparian site) and Plot B mid-slope terrestrial site), but there was only a significant difference ($p = 0.05$) shown in Plot A between the infiltration rates with and without the stems present (Fig. 4). Plot B did not show a significant difference ($p = 0.88$) between infiltration rates of sampling locations with knotweed stems present or absent. The riparian site (Plot A) also had a higher proportion of fine sediment when compared to the other location (Fig. 5) and the mid-slope terrestrial site (Plot B) had a higher percentage of coarse-grained particles (Fig. 5).

These findings showed the potential for this invasive species to relate to physical changes in the soil and its hydrologic properties.

Past studies have also investigated infiltration rates, and have attributed lower infiltration rates for invasive species to physical disturbances (Vanderklein, Galster, and Scherr 2014) but have not examined the relationship between soil texture as closely. As stated in the Lavoie (2017) literature review, there have been very few studies that have looked at the physical changes to the environment due to knotweed invasions. Our study also demonstrates that knotweed plots had increased amounts of the fine-grained soil component, common in the organic-rich soil A horizons, showing a strong similarity to Maurel et al. (2010). Together, these findings suggest physical changes to the soil under Japanese knotweed are a feature of this particular invasive.

In the finer-textured riparian site (Plot A), knotweed appeared to drastically change infiltration rates between areas with or without stems. Due to Japanese knotweed growth influencing soil properties, finer-grained soils (such as in our riparian Plot A) may allow this invasive to have a higher competitive advantage. By creating a more sub-optimal soil pore environment via the introduction of extensive subsurface biomass, Japanese knotweed can continuously compact pore space, which can limit infiltration rates and deplete water storage capacity for competitors. Through our findings, and knowing they are in relative similarity to others, we believe a previously unidentified positive feedback mechanism is likely occurring to support the competitive expansion of knotweed invasions in finer-textured soils (Fig. 6).

Known mechanisms that allow for a successful Japanese knotweed invasion are shown on the right in Fig. 6. Alongside these known feedback mechanisms, we have illustrated our own newly proposed positive feedback mechanism demonstrating the uniquely competitive advantage knotweed has in fine-grained soils. Starting at the first stage (A), Japanese knotweed is introduced to a new area. From here, the extensive rhizome network of large rhizomes (the ‘knots’ of the knotweed root system) causes the soil to compact, limiting water holding capacity in fine-textured soils (B), whereas in coarser soils containing a lesser proportion of flat clay and organic particles comprising the soil matrix, this compaction would not have the same impact in removing soil pore space due to the higher proportion of spherical soil particles, and therefore would not limit soil water holding capacity as greatly. This soil pore compaction also causes a decrease in infiltration capacity, limiting the ability for additional water to enter these fine-tectured soils as easily. Because of the soil compaction and decreased infiltration in organic and clay-rich soils, knotweed has a competitive advantage and can outcompete other plants (C) because native plants are no longer able to as easily acquire the needed soil moisture from the newly compacted clay-rich soil matrix, whereas knotweed has its ‘knots’ to store and release water from within its own rhizome network. Through this (and other feedback mechanisms), knotweed outcompetes the other vegetation and the abundance increases in the soils that have a finer texture and higher percentage of clay (D). The knotweed then continues in this loop where it invades an area with clay-rich soils, changes the soil water holding capacity, and outcompetes the other vegetation struggling to survive in the surface soils, forming a successful invasion (E).

Declarations

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Conflicts of Interest

Not applicable

Availability of Data and material

Data was uploaded to Springer Nature's Data Support Services.

Code Availability

Not applicable

Author's Contributions

JA, GD, and ZK conceived the ideas and methodology. Data collection was principally done by JA and GD. JA and GD contributed to the writing of the manuscript, with direction and editing from ZK.

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Figures

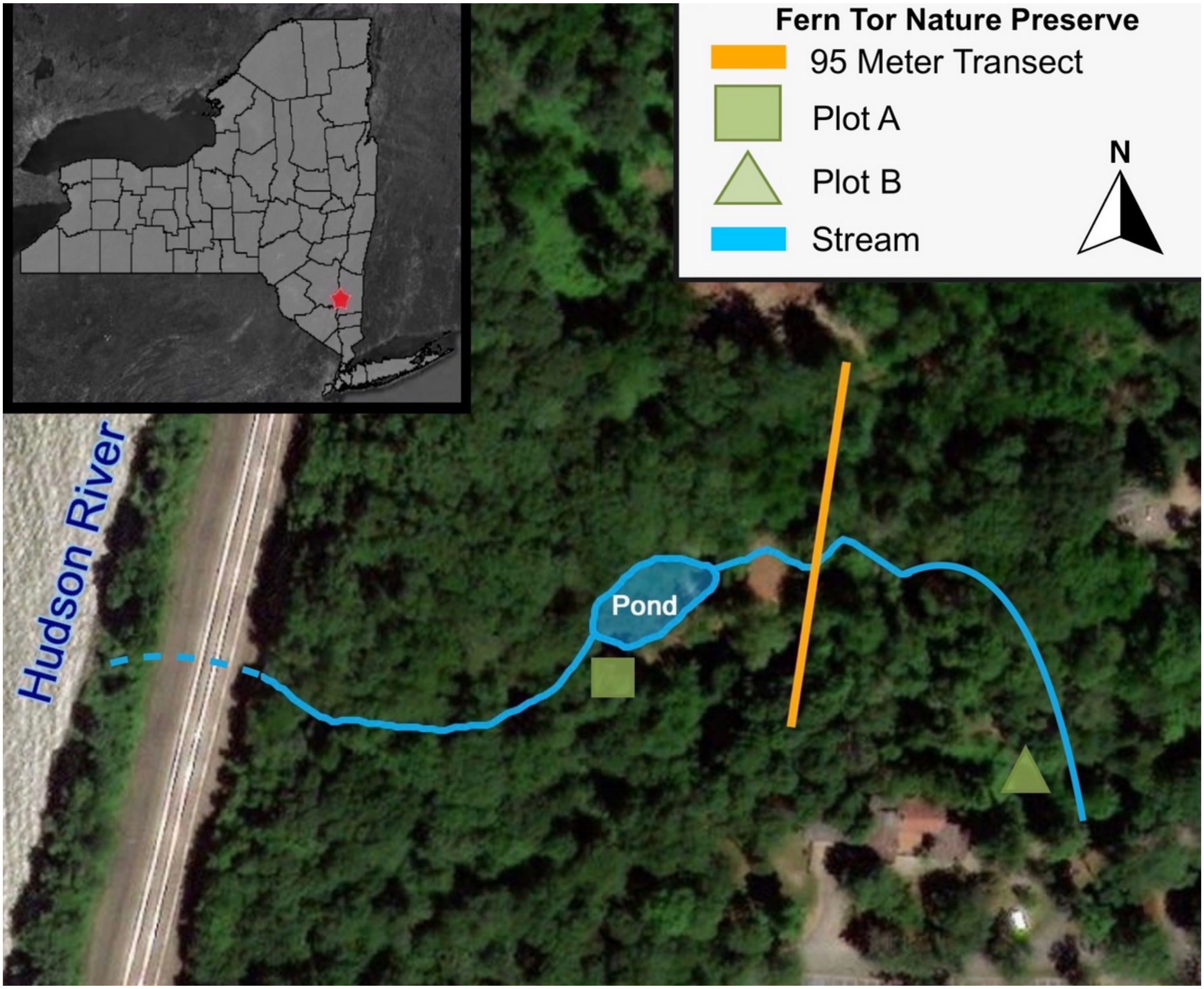

Figure 1

Site map showing the locations for the 95 m ecological-pedologic observational transect, as well as the two plots used for high-resolution soil infiltration testing.

Figure 2

The Plots A and B for the soil infiltration tests. Plot A is riparian, being directly adjacent to the stream and pond, while Plot B is farther up-slope in a terrestrial mid-slope location.

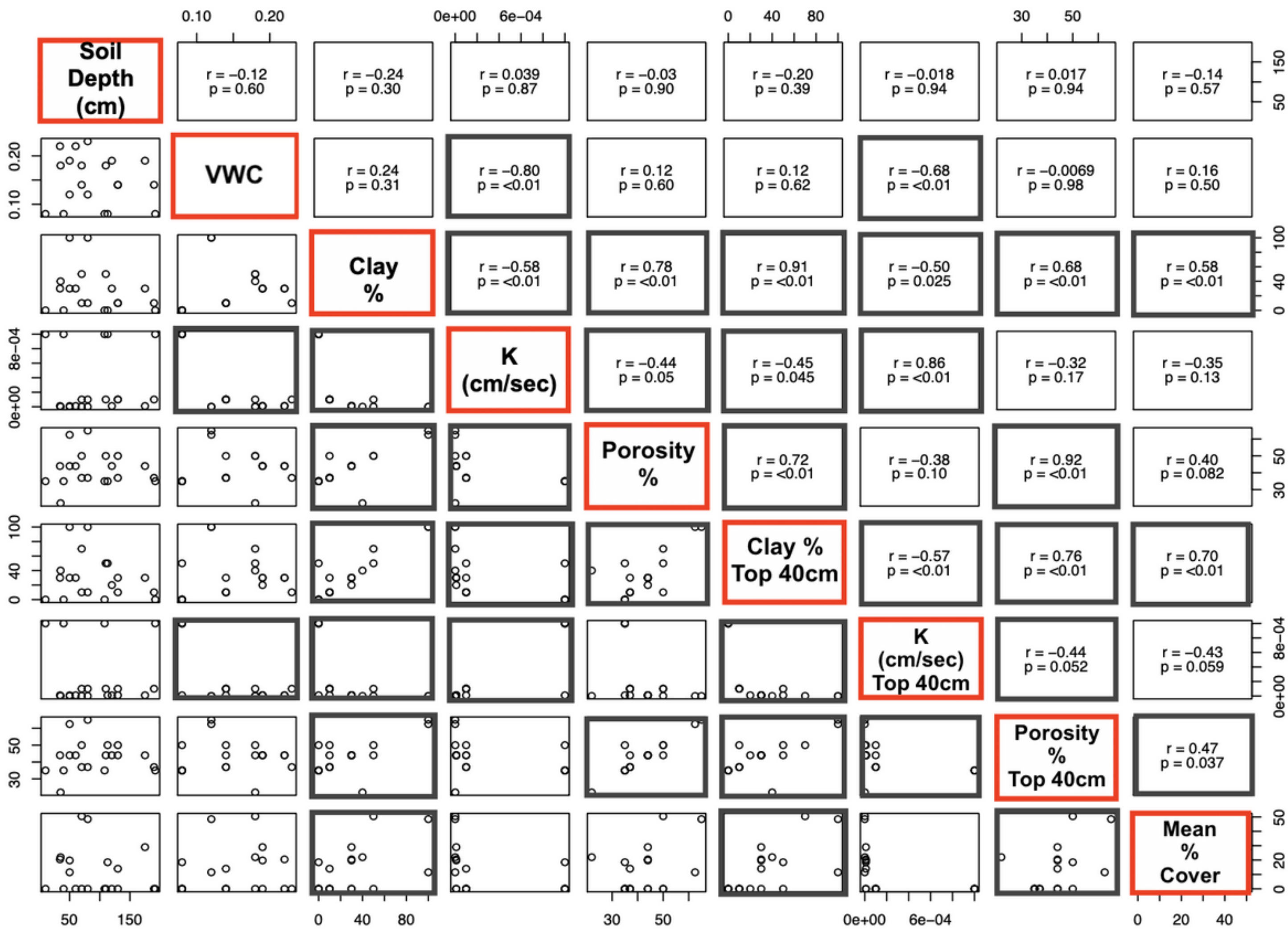

Figure 3

Compiled data from Table 1 was combined into a Pearson's linear correlation matrix. Significant correlations ($p \leq 0.05$, gray boxes) were found between hydrological features, geological features, and mean percent cover of Japanese knotweed along the 95 m transect. Note, K denotes hydraulic conductivity.

Figure 4

The range of soil infiltration rate for the two sites, Plot A and Plot B, are shown. For Plot A, there was a t-value of -1.8 ($p = 0.05$) between stem and non-stem measurements. For Plot B, a t-value of 0.15 ($p = 0.88$) was calculated between stem and non-stem measurements.

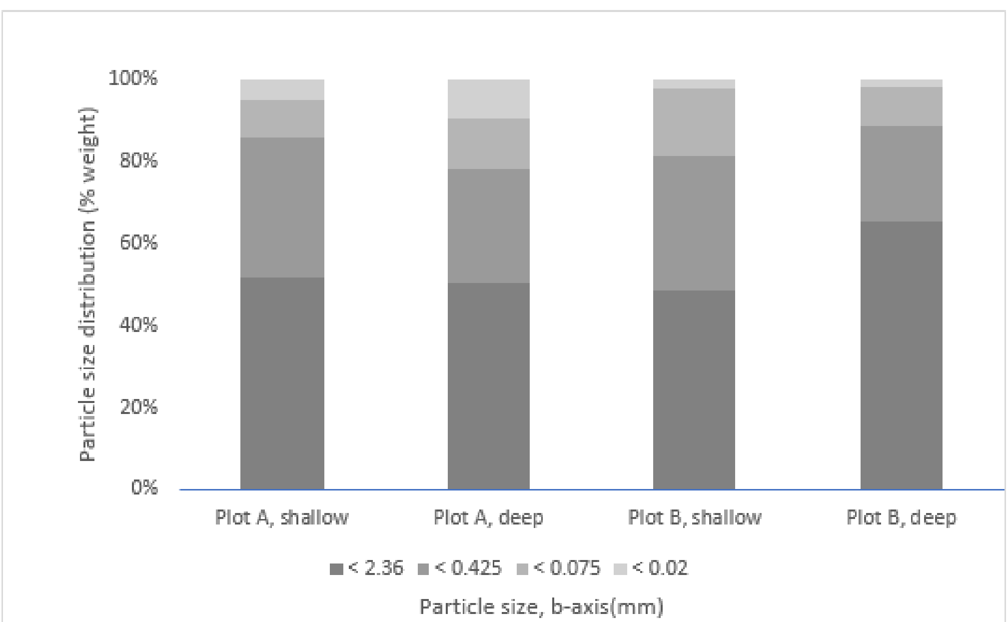

Figure 5

Soil texture make up by % dry weight. Each plot was sampled for a shallow measurement at 0-10 cm depth and a deep measurement at 10-20 cm depth.

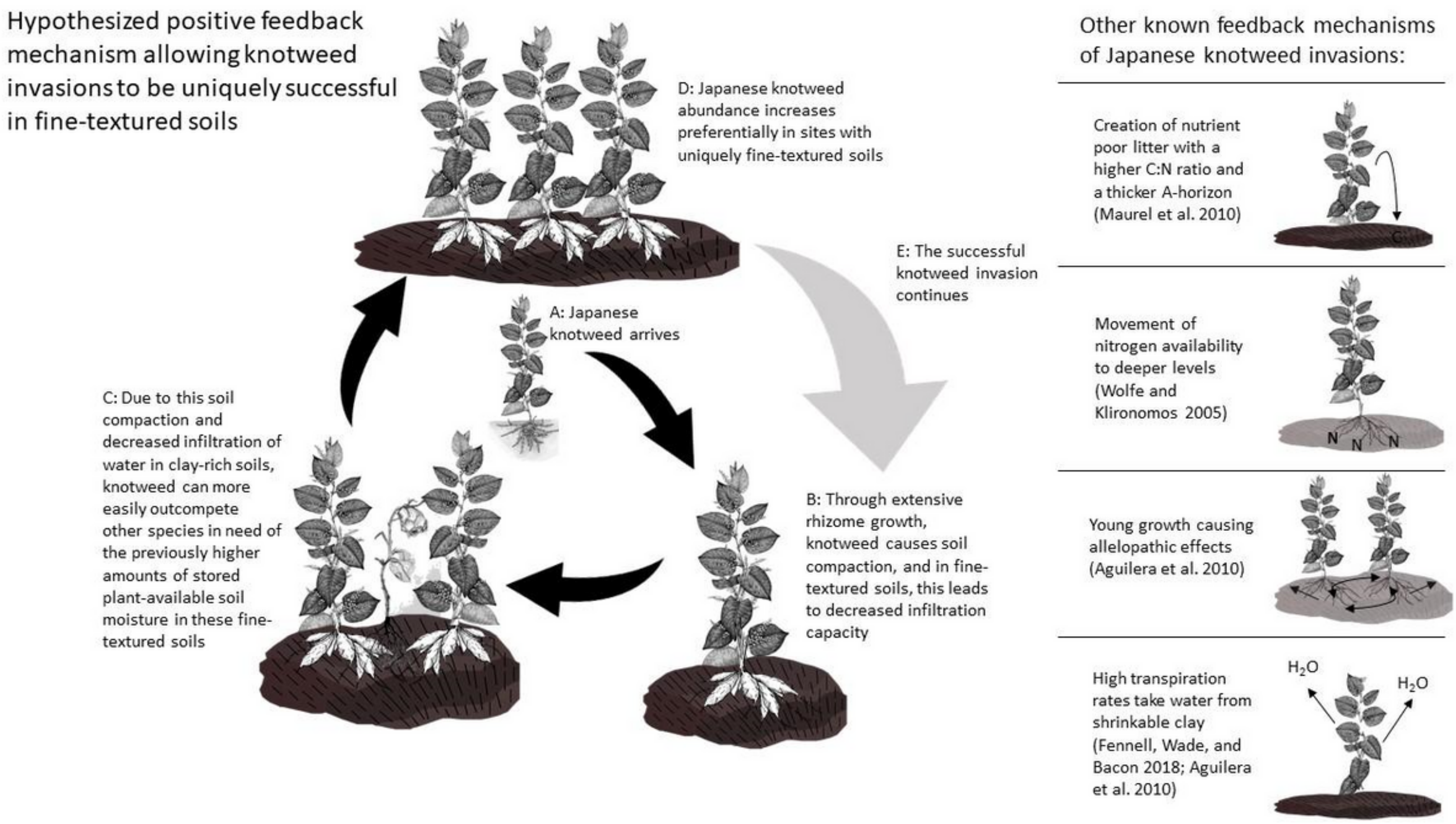

Figure 6

A newly hypothesized positive feedback mechanism, along with known feedback mechanisms, supporting Japanese knotweed invasions.