W&M Ref: 791401

Invasive Species Management in Non-tidal Wetland and Stream Mitigation

2022 Annual Report

RPG Stream RFP #05

SUBMITTED TO:

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December 2022

EXECUTIVE SUMMARY

The report provides a progress-to-date summary of the research completed on Resource Protection Group (RPG) grant Stream RFP #05 and Amendment 01 as of December 31, 2022. The College of William & Mary (W&M) is leading the research team under Principal Investigator (PI) Doug DeBerry, with George Mason University (GMU) and Virginia Tech (VT) as collaborators. Below is a summary with a brief progress description for each task. As the project was initiated in the latter half of 2021, we are including 2021 milestones in this first progress report.

Task	Progress Summary
Literature Review	Draft completed February 2022; Annotated Bibliography provided as a separate document.
INU[1] Species Inventory and Mapping	Fieldwork completed by PI Aug-Sept 2021 with undergraduate research assistants from W&M and GMU providing detailed mapping June-Sept 2022; Summary Report for Northern Virginia Stream Restoration Bank (NVSRB) provided as Appendix A, and summary of Cedar Run Mitigation Bank (Cedar Run) mapping and inventory provided in Results section of this report.
Field Experiment	Graduate students recruited for NVSRB stream experiment (Robert Sullivan) and Cedar Run wetland experiment (Matthew Whalen). Site selection and existing conditions monitoring/mapping competed June-September 2022.
Guidance Document	To be completed
Reporting, Articles, and Presentations	Presentation to Reston Association completed January 2022

In addition to the above tasks, W&M added two related studies that were initiated by undergraduate students:

1) The first was seed bank study to evaluate the efficacy of different seed bank estimation protocols. This project was initiated in May 2022 and was carried through the end of the year. A brief description of the methods is provided here, and final results will be reported in 2023.
2) The second included an analysis of limiting similarity, an approach to modeling native species selections for ecological restoration based on specific plant traits and linear equations, with the goal of finding native species that would maximize competition against invasive plants. The final results of this research project pointed to the limitations of plant trait databases for both native species typically used in wetland and stream mitigation, and also for the invasive species that were being targeted in the study. A summary of the statistical code used in this process is provided here, along with some future research ideas.

[1] INU = Invasive, Nuisance, and Undesirable

INTRODUCTION

This report presents progress to-date as of December 31, 2022 covering the first full year[2] of the College of William & Mary (W&M) research project titled "Invasive Species Management in Non-tidal Wetland and Stream Mitigation." The grant supporting the stream mitigation component of this research was awarded by the Resource Protection Group (RPG) in July 2021 (Grant Stream RFP #05), and work on the grant was initiated in the fall of that year. An amendment covering the wetland mitigation aspect of the grant was issued in March 2022 and, since that time, the wetland and stream components of the research program have been executed in parallel.

The Principal Investigator (PI) for this project is Douglas A. DeBerry, a Research Assistant Professor in the Environment & Sustainability Program (ENSP) at W&M. George Mason University (GMU) and Virginia Tech (VT) were also awardees on the grant, and their roles and activities will be highlighted below.

Objectives: The overall objective of this project is to develop a research program with results that will fill important gaps in invasive, nuisance, and undesirable (INU) plant species management in compensatory non-tidal wetland and stream mitigation (mitigation). An equally important objective is to provide a scientific basis for improving the practice of mitigation through feasible recommendations – informed by research – that can be implemented by regulatory agencies, scientists, and managers. This project follows a 3-year W&M study funded by RPG under grant RFP #08 that identified important environmental drivers of plant invasion in mitigation, the conclusions of which have been instructive in implementing the current project.

The specific objectives include:

1. Prepare a detailed and fully annotated literature review focused on design, construction, management strategies, and techniques for prevention and/or control of INU species on wetland and stream mitigation sites.
2. Prepare an INU species inventory of the project sites for use in designing the field experiment to meet Objective #3.
3. Design and execute large-scale field experiments using a randomized block approach (or similar statistically valid method) to test the different strategies identified in Objective #1 and in RFP#08.
4. Prepare a guidance document on "proposed best practices" based on the findings obtained from completion of Objectives #1, #2, and #3 above.

In addition to the above goals, we added two research initiatives focused on: a) seed bank estimation procedures, and b) trait-based approaches for native species selections in ecological restoration.

[2] For brevity, progress made during the few months of active grant work in 2021 will be included here.

METHODOLOGY

Literature Review: We compiled peer-reviewed scientific research related to the objectives described above and summarized those references in an annotated bibliography, which has been submitted to RPG under separate cover. The literature review component of this research program was used to inform the experimental design, treatment techniques, and analysis aspects of the program.

Site Selection: The Northern Virginia Stream Restoration Bank (NVSRB) in Reston, VA was chosen as the site for the stream component of the study (Figure 1). The NVSRB includes restoration of nearly 12 miles of stream channels within The Glade and Snakeden Branch watersheds, an area that overreaches much of the adjacent floodplains and riparian corridors within this region.

The wetland study component was sited at the Cedar Run Mitigation Bank (Cedar Run) near Catlett, VA (Figure 1). This site includes two phases of a larger mitigation bank encompassing 715 acres in the Cedar Run watershed. Both phases were constructed in the early 2000s.

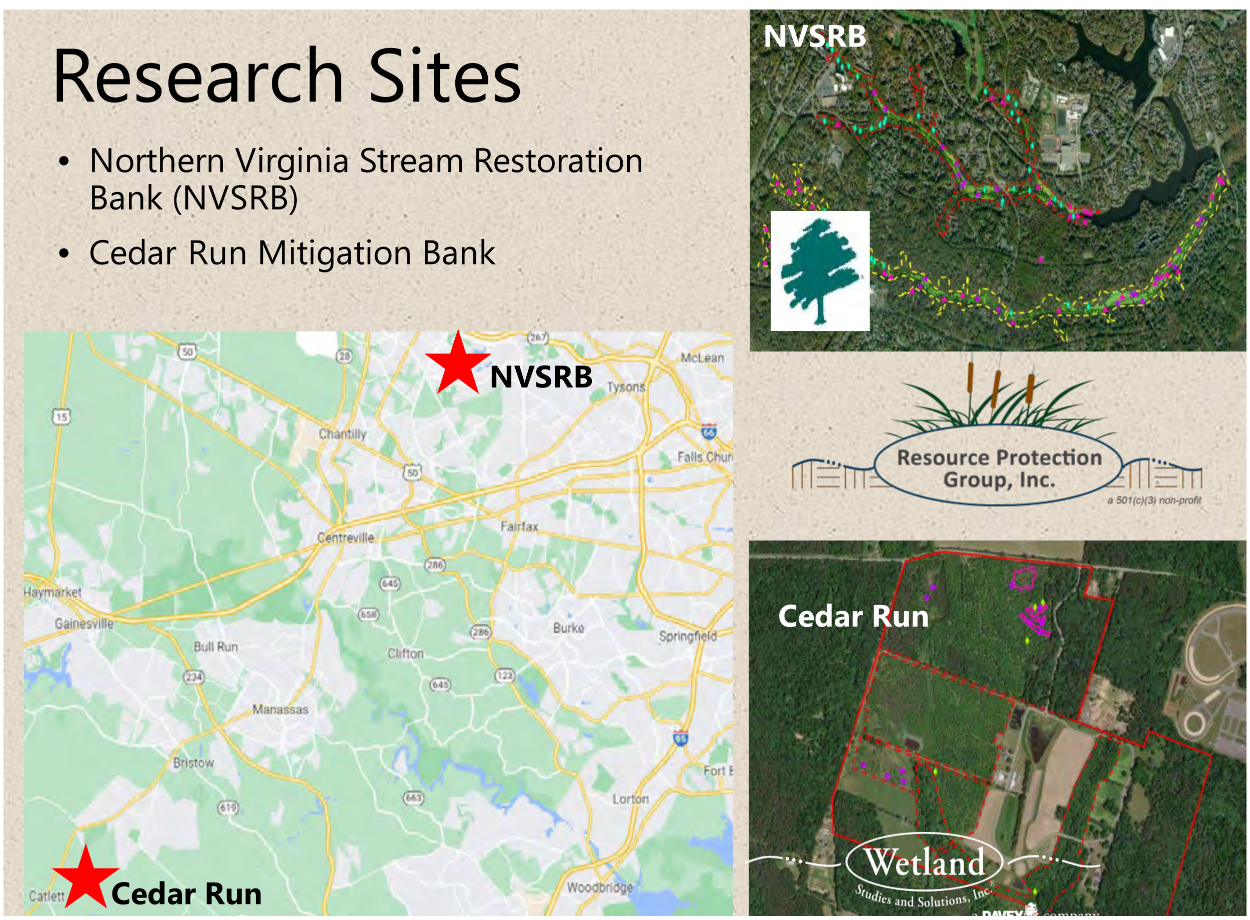


Figure 1: Research site locations.

Because the study areas are expansive, there was a significant effort invested in the initial field reconnaissance and invasive species inventory and mapping tasks to identify the best locations for staging the proposed field trials. The PI had already walked a significant portion of the overall NVSRB corridor for research previously completed under RPG RFP 08.

Invasive Species Inventory and Mapping: The invasive species inventory and mapping component of the project was initiated at NVSRB in late summer 2021 and concluded in late summer 2022. This work was completed by the PI and supported by undergraduate research assistants from W&M (Kent Codding) and GMU (Ryan McIntyre). A summary of the methods used is provided in Appendix A (note that mapping at Cedar Run used similar methods).

Seed Bank Study: A seed bank study was initiated by the PI and an undergraduate research assistant (Sam Dutilly) in May of 2022. The purpose of the study was to evaluate different methods of estimating seed bank composition and determine which would be most practical during the planning stages of a wetland mitigation project. This study involved several phases, including field sampling; a pilot study involving in-house seed extraction trials, greenhouse emergence trials, and an offsite laboratory extraction trial; and a full-scale study using both the greenhouse emergence and offsite lab approaches. A summary of the methods used and work completed through 2022 is included at the following link: Using Soil Seed Banks for Wetland Mitigation Planning: Comparison of Seed Bank Estimation Methods

Limiting Similarity Study: An additional study was undertaken by an undergraduate research assistant (Kari Eskeland) to evaluate the potential for using trait-based linear equations to solve for ideal native species to compete with targeted invasive plants. The concept is referred to as "limiting similarity," a name that alludes to the assumption that native plants will be most competitive with non-native invasive plants if the natives have similar traits (e.g., leaf area index, root:shoot ratio, growth rate, crown diameter, etc.; Laughlin 2014). The methods used involved a review of the literature and identification of available plant trait databases, as well as incorporation of the existing statistical code into a workable format.

RESULTS

Literature Review Results: As noted, the literature review task was delivered as an annotated bibliography and can be found on the RPG website at the following link: Invasive Species Management in Non-tidal Compensatory Mitigation: Annotated Bibliography

Invasive Species Inventory and Mapping Results – NVSRB: The results of the invasive species mapping task for the NVSRB project site are summarized in Appendix A. In addition to the mapping study, the PI conducted a pilot study to determine the feasibility of using both stream corridors (Glade and Snakeden) for the intended field trials. This involved collecting randomized plot data to document the overall vegetative cover of the target invader (*Microstegium vimineum*) and the dominance of other plant species in the community. Pilot plot locations are shown on Figure 2, and the data are summarized in Table 1.

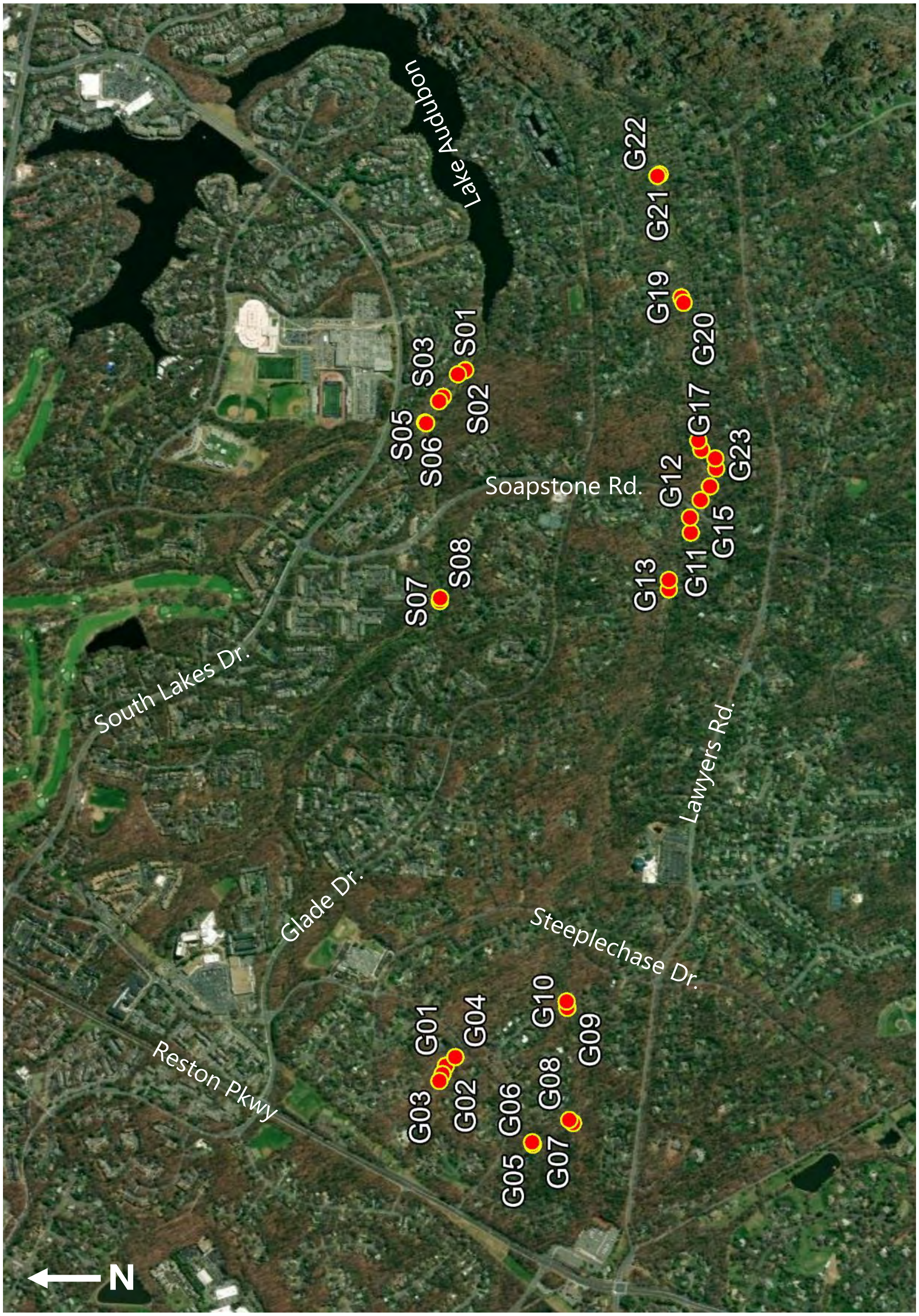


Figure 2: Microstegium *pilot plot locations at NVSRB. See Appendix A for more information on study area.*

Table 1. Data from feasibility study of potential *Microstegium* field trial locations at NVSRB in Reston, Viriginia. Yellow and orange columns represent pilot plots sampled in The Glade and Snakeden Branch, respectively. The target invasive species is annotated in bold typeface. This pilot study demonstrated that all sites reviewed were suitable for the field experiment. Data were collected by D. DeBerry between September 11 and September 20, 2022.

	G01	G02	G03	G04	G05	G06	G07	G08	G09	G10	G11	G12	G13	G14	G15	G16	G17	G18	G19	G20	G21	G22	G23	G24	S01	S02	S03	S04	S05	S06	S07	S08
Acer negundo																															3	
Amphicarpaea bracteata															3	3		3	15	15		3										
Apocynum cannabinum															3				3	15												
Arisaema triphyllum									3																							
Arthraxon hispidus																											3					
Athyrium asplenioides	15															15												3				
Bidens frondosa																			3													
Boehmeria cylindrica				1							3			3							1	1	3			1			3	3	1	1
Carex lurida																										1						
Cephalanthus occidentalis																											3					
Cinna arundinacea					1		38	15	1	3	15	3	3	15		1	3			3		3	3		15	15	3	15			3	3
Dichanthelium clandestinum											1											3								3		
Elymus virginicus											3																		3		1	
Hedera helix						1		1																								
Ilex opaca var. opaca						1																										
Juncus effusus																												3				
Leersia oryzoides																			1													
Lindera benzoin								1								1								3						3		
Lonicera japonica											1				1	3					3				1		3		1	15		
Microstegium vimineum	**98**	**98**	**98**	**98**	**98**	**85**	**98**	**85**	**98**	**85**	**98**	**98**	**98**	**85**	**98**	**85**	**98**	**85**	**98**	**85**	**98**	**98**	**98**	**85**	**98**	**98**	**98**	**98**	**98**	**85**	**98**	**85**
Mimulus alatus												1		3													3					
Mimulus ringens																			3													
Osmundastrum cinnamomeum	3																															
Parathelypteris noveboracensis										1	15							15														
Parthenocissus quinquefolia								1		1														1								
Persicaria hydropiperoides	3			3					1					1	15		15	3		3	15		3	1								
Persicaria longiseta										1		1		1			1	1		1			1				1				1	
Persicaria perfoliata																					15	3	15	15								
Persicaria punctata																											3	3	15			
Persicaria sagittata				1											1						3				1							
Persicaria virginiana		3	1		1				1	1																						
Pilea pumila												1																				
Rosa multiflora																15			1		1								3			
Rubus pensilvanicus										1																		1		1		
Rumex crispus																								3								
Scirpus atrovirens														3																		
Smilax rotundifolia	3																							1								
Solidago rugosa																						1										
Symphyotrichum racemosum		1		1															1						3	1		1			1	
Toxicodendron radicans																										1						
Vaccinium pallidum			3																													
Vernonia noveboracensis																														1		
Viburnum dentatum								3																								
Viburnum prunifolium																											1					
Vitis labrusca							3									1																
Zizia aptera								1																								
Total cover in plot:	122	102	102	104	100	87	139	107	104	93	136	104	101	111	121	124	117	107	125	122	136	112	123	109	118	117	118	124	123	111	108	89

The data collected in the NVSRB pilot study demonstrated that all potential sites had sufficient cover of *Microstegium* to move forward with field trials (Table 1). In addition, to separate potential shade sites from open canopy sites for field trials, canopy cover data were collected by taking a skyward photograph at each plot using a hemispheric lens and converting the imagery into a binary map (see procedure described in Rueden et al. 2017). The images were stored for future analysis, the results of which will be included in subsequent reporting.

Invasive Species Inventory and Mapping Results – Cedar Run: At Cedar Run, two sections of the site were selected to carry forward to the field trials, one for *Arthraxon hispidus* and one for *Phalaris arundinacea*. The site locations area shown on Figure 3.

Figure 3. Geographic position of study sites at Cedar Run wetland mitigation site, built ~ 2003. P = Phalaris *and A =* Arthraxon.

Similar to the approach used at NVSRB, the PI added a pilot study to the mapping project at Cedar Run to determine the feasibility of using both sites ("A" and "P" on Figure 3) for the intended field trials. Data were collected as described above in both mapped polygons to document the overall vegetative cover of the target invaders (*Arthraxon* and *Phalaris*) and the other species in the community.

The results of this analysis demonstrated two important characteristics of both sites: 1) there was sufficient cover of the target invaders to conduct the experiments, and 2) there were no other highly competitive invaders at either site, allowing the team to target each individual invader without the confounding effects of competition from other invasive species. The pilot plot locations are shown in Figures 4a and 4b, and the data are provided in Table 2. Example photographs are included in Appendix C.

In addition to the abundance data, the PI also collected hemispheric canopy photos to evaluate whether existing tree cover could be used as a variable in the experiment. The results showed that both sites lacked a sufficient canopy for shade trials, so the *in situ* canopy photo analysis was not carried forward into future phases of the study.

Figure 4a. Arthraxon *pilot study plot locations at Cedar Run.*

Figure 4b. Phalaris *pilot plot study locations at Cedar Run.*

Table 2. Data from feasibility study of *Phalaris* (blue columns) and *Arthraxon* (green columns) potential experimental sites at Cedar Run. The two target species are annotated in bold typeface. This pilot study demonstrated that both sites were suitable for the field experiment. Data collected by D. DeBerry on September 23, 2022.

	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11	P12	A01	A02	A03	A04	A05	A06	A07	A08	A09	A10	A11	A12
Acer rubrum							1																	
Ambrosia artemisiifolia	1																							
Amphicarpaea bracteata															3	3		3	15	15		3		
Apocynum cannabinum															3				3	15				
Arthraxon hispidus						**3**				**3**			**98**	**98**	**98**	**98**	**98**	**98**	**98**	**98**	**98**	**98**	**98**	**98**
Asclepias incarnata var. *pulchra*																						1		
Bidens aristosa			1	1	1		3				3	1						3						
Bidens connata														3										
Bidens frondosa																			3					
Carex lurida													1		3									
Echinochloa muricata														3	1	3	1	15	15	3		1	1	3
Erechtites hieraciifolius													3			1	1	1	3					1
Fraxinus pennsylvanica					1		1																	
Juncus dichotomus					3																			
Juncus effusus			1							3												15		
Juncus tenuis	1																							
Leersia oryzoides																					3		3	
Leersia oryzoides																			1					
Lonicera japonica							3		3															
Mimulus alatus												1		3										
Mimulus ringens																			3					
Panicum virgatum													1		1		3	3		1		3	3	
Persicaria hydropiperoides						1				1								1						
Persicaria perfoliata																					15	3	15	15
Phalaris arundinacea	**85**	**98**	**85**	**98**	**85**	**98**	**85**	**98**	**85**	**98**	**85**	**98**												
Pilea pumila												1												
Rosa multiflora																15			1		1			
Rubus pensilvanicus									3															
Rumex crispus																								3
Salix nigra																	3							
Scirpus atrovirens															1									
Scirpus atrovirens														3										
Scirpus cyperinus		3	3	3	3	3		3					3	1			15		1		15	3	15	3
Solidago rugosa																						1		
Symphyotrichum racemosum	1				1		1				1													
Typha latifolia																		1		3				
Verbena hastata										1														
Total cover in plot:	**88**	**101**	**90**	**102**	**94**	**105**	**94**	**101**	**91**	**106**	**89**	**101**	**106**	**111**	**110**	**120**	**121**	**125**	**143**	**135**	**132**	**128**	**135**	**123**

Seed Bank Study Results: Detailed results of the seed bank study through the end of 2022 are described in a separate report included at the following link: Using Soil Seed Banks for Wetland Mitigation Planning: Comparison of Seed Bank Estimation Methods

Limiting Similarity Study Results: At the time of this study, we found that existing plant trait databases were insufficient to develop reliable trait profiles for the native species that are typically used in wetland and stream restoration projects in the Mid-Atlantic Region. Further, we were not able to find reliable trait data on any of the targeted invaders. We attempted to "fill the gaps" using information researched from native floras, systematic literature, other relevant published work, and information provided by native growers and horticulturalists in addition to our own measurements taken in the field or on harvested plant material, but the information was often conflicting, making trait selection somewhat arbitrary. Overall, the study was useful because we were able to acquire the statistical code in R and get it to run with some sample data sets. We believe that the theoretical basis for the technique is sound, and recommend that it be considered for future research in wetland and stream mitigation as plant trait databases become more inclusive.

NEXT STEPS

Both the stream and wetland field experiments will be staged and initiated in the spring of 2023. We will also engage an undergraduate research team from GMU to assist with plot maintenance and data collection over the 2023 growing season. Data collection will be executed during the peak growing season (late summer), to include plant community properties and environmental variables. The latter will include soil physiochemical data from samples taken and submitted to the VT Soil Testing Lab. We will also be collecting canopy cover data using the hemispheric photo methods noted above.

REFERENCES CITED

Laughlin, D.C., 2014. Applying trait-based models to achieve functional targets for theory-driven ecological restoration. *Ecology Letters 17*(7), pp.771-784.

Rueden CT, Schindelin J, Hiner MC, DeZonia BE, Walter AE, Arena ET, Eliceiri KW. 2017. ImageJ2: ImageJ for the next generation of scientific image data. BMC Bioinformatics 18:1-26.

Appendix A

NVSRB Invasive Plant Species Inventory and Mapping Report

Invasive Plant Species Inventory Project

Northern Virginia Stream Restoration Bank (NVSRB)
Reston, Virginia

Doug DeBerry[1], Kent Codding[1], Ryan McIntyre[2]

[1]College of William & Mary, Environment and Sustainability Program
[2]George Mason University, Environmental Science and Policy Program

Introduction

Over the course of the 2022 growing season, we mapped the relative dominance of invasive plant species within the boundaries of the Northern Virginia Stream Restoration Bank (NVSRB), a 12-mile stream restoration project in the town of Reston, Virginia. The project area encompasses the conservation easement that surrounds the stream restoration corridor, which includes the riparian corridors of both Snakeden Branch and The Glade, the two principal stream systems within the bank, as well as some secondary tributaries. The mapping methodology is provided below, followed by the results of the mapping project.

Mapping Techniques

Mapping was completed using the "Field Maps" ESRI application in combination with Survey123 to collect abundance data on invasive plant species. The entire project area was divided into management compartments. Compartments were designated based on the following criteria:

1. Proximity to the 100-year floodplain.
2. Ease of access (i.e., roads, paths, bridges, etc.).
3. Overall plant community properties.

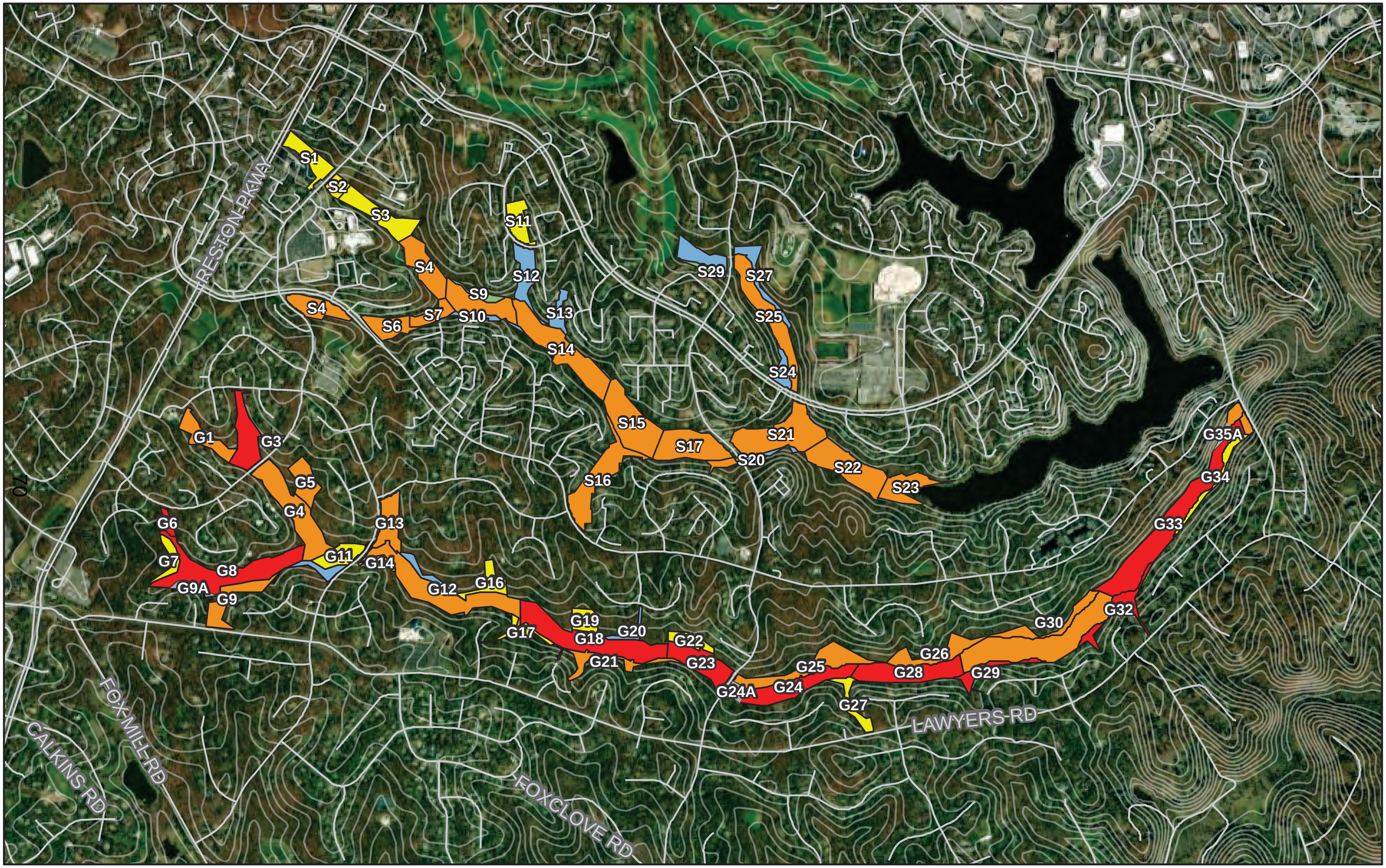
Compartments were labeled "G1, G2, etc." for The Glade, and "S1, S2, etc." for Snakeden Branch. For each compartment, a visual inspection of the field conditions was conducted in which the assessor noted overall cover of invasive species within the compartment, as well as any individual invasive plant species present along with their relative abundance in the compartment. This information was recorded in a Survey123 form, along with the following data fields:

1. Current date and time
2. Compartment ID
3. Braun-Blanquet cover classes: 0-5%, 5-25%, 25-50%, 50-75%, 75-100%.
4. Invasive species present in compartment, along with each species' relative cover in the compartment using one of four qualitative abundance values: Dominant (>20% of compartment), Common (5-20% of compartment), Scattered (1-5% of compartment), Occasional (<1% of compartment).
5. Representative photos
6. Any additional notes or observations that may be relevant to the inventory (e.g., deer prevalence, human disturbance, etc.).

Results

We mapped 36 compartments in The Glade and 29 in Snakeden Branch (see attached mapping and tables). During the 2022 growing season, there were 25 invasive plants found The Glade and 22 in Snakeden. The overwhelming dominant was Japanese stiltgrass (*Microstegium vimineum*) (see attached charts). The overall invasive cover by compartment is shown on the attached map.

NVSRB Invasive Plant Mapping 2022



11/25/2024

Snakeden_Floodplain_Inventory
- 50-75%
- 25-50%
- 5-25%
- 0-5%

Glade_Floodplain_Inventory
- 75-100%
- 50-75%
- 25-50%
- 5-25%

Elev Contour clipped

Roadway Centerlines clipped

World Imagery

Low Resolution 15m Imagery

High Resolution 60cm Imagery

High Resolution 30cm Imagery

Citations

4.8m Resolution Metadata

Maxar

1:24,477

0 0.15 0.3 0.6 mi

0 0.25 0.5 1 km

The Glade Invasive Species Mapping Project - Summary by Compartment

Overall Cover codes: 1=0-5%, 2=5-25%, 3=25-50%, 4=50-75%, 5=75-100%

Invasive Species Relative Dominance codes: O=Occasional (<1%), S=Scattered (1-5%), C=Common (5-20%), D=Dominant (>20%)

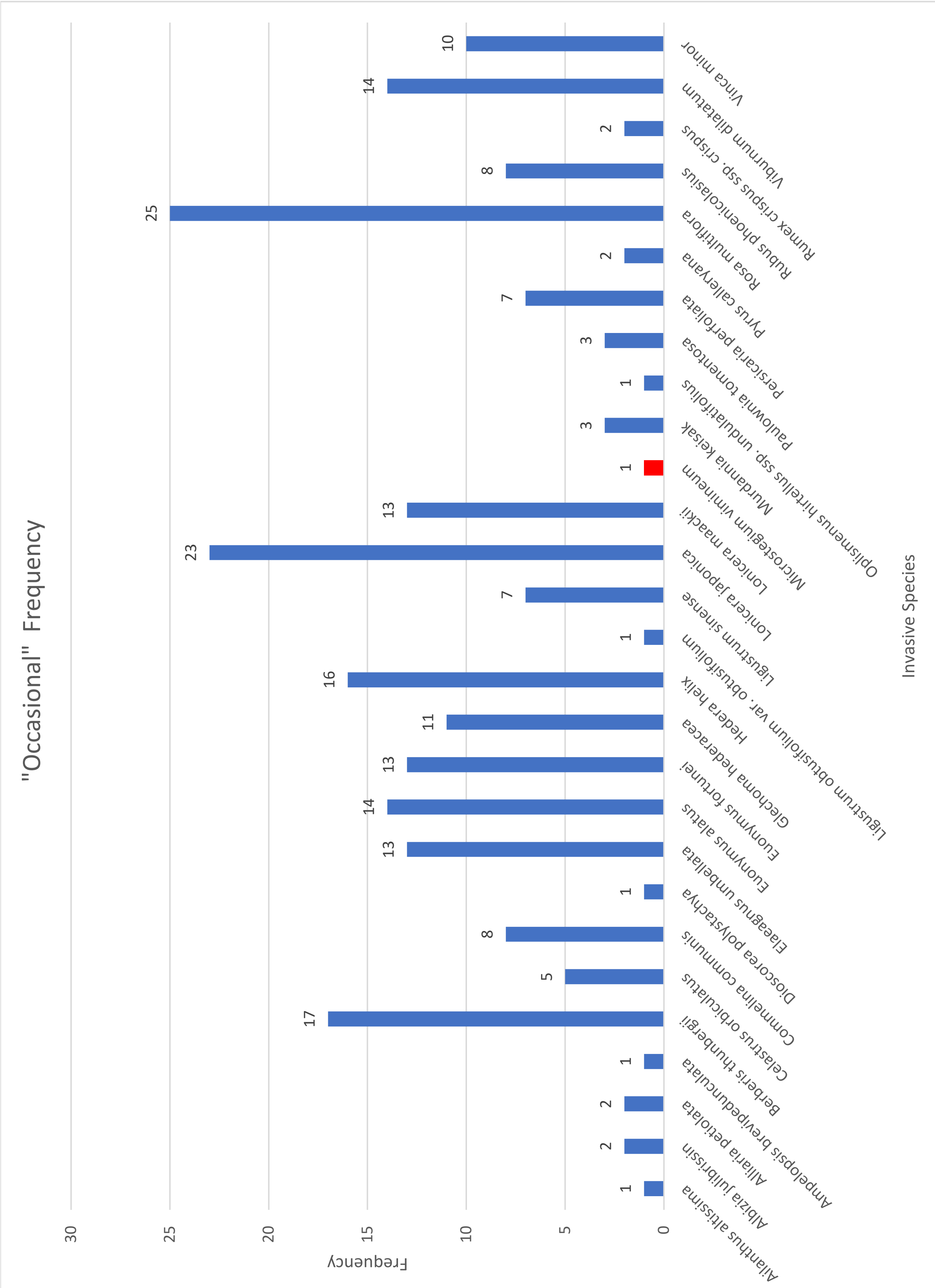
Compartment	OVERALL COVER	*Ailanthus altissima*	*Albizia julibrissin*	*Alliaria petiolata*	*Ampelopsis brevipedunculata*	*Berberis thunbergii*	*Celastrus orbiculatus*	*Commelina communis*	*Dioscorea polystachya*	*Elaeagnus umbellata*	*Euonymus alatus*	*Euonymus fortunei*	*Glechoma hederacea*	*Hedera helix*	*Ligustrum obtusifolium*	*Ligustrum sinense*	*Lonicera japonica*	*Lonicera maackii*	*Microstegium vimineum*	*Paulownia tomentosa*	*Persicaria perfoliata*	*Rosa multiflora*	*Rubus phoenicolasius*	*Rumex crispus*	*Viburnum dilatatum*	*Vinca minor*
G01	4					O							O	S			O		D			O			S	
G02	5					O				O	O	O	O	S			O		D	O		O			S	S
G03	2											O		S					C						S	
G04	4					O					O		O				O	O	D			O			C	O
G05	4			O		O						O							D			O			C	O
G06	5													S		O	O		D			S			S	S
G07	3													O			O		D			O			S	S
G08	5					O					O	O	O	O		O	O		D			S			S	O
G09	4			O							O		O	O			O		D			O			S	O
G10	2										O						O		C						O	
G11	3					O						O		O			O		D			S			O	O
G12	4					O						O		S			O		D			O				
G13	4									O				O					C			O				S
G14	4																		D	O		O				S
G15	2																O		C			O				
G16	3					O						O							D							
G17	3										O						O		D							S
G18	5																		D			C				
G19	3																O		C							O
G20	2					O				O		O		O			O		S							
G21	4									O	O			S			O		D			O	O			O
G22	3																		C			O				O
G23	5							O		O		O	O	S		O	C		D	O		C	O	O	O	
G24	5					O				O				O			S	O	D		S	O	O			
G25	4					O						O		O			O	O	D		O	S	O			S
G26	4					S				O		S	O	S			O	S	D			C				S
G27	3					O							O	O			O		D			S	S		O	
G28	5												O	O			O	O	D			C		O	O	S
G29	5					O				O		O		S		O	O		D		O	S			O	S
G30	4		O			O	O					O	O	S	O		S	O	D		O	S			O	O
G31	4	O					O				O	S	O	O			O		D		O	S			O	O
G32	5				S	O	S			O	O	O		S		S	S	O	D		O	C			S	S
G33	5						O		O	S		S		O			S	O	D		S	O				S
G34	3					O	S			O	O						S		D			O	O		O	
G35	4						S			O	S			S			S	O	D			C			O	
G36	4		O		O		S			S	S					O	C	O	C			C			O	

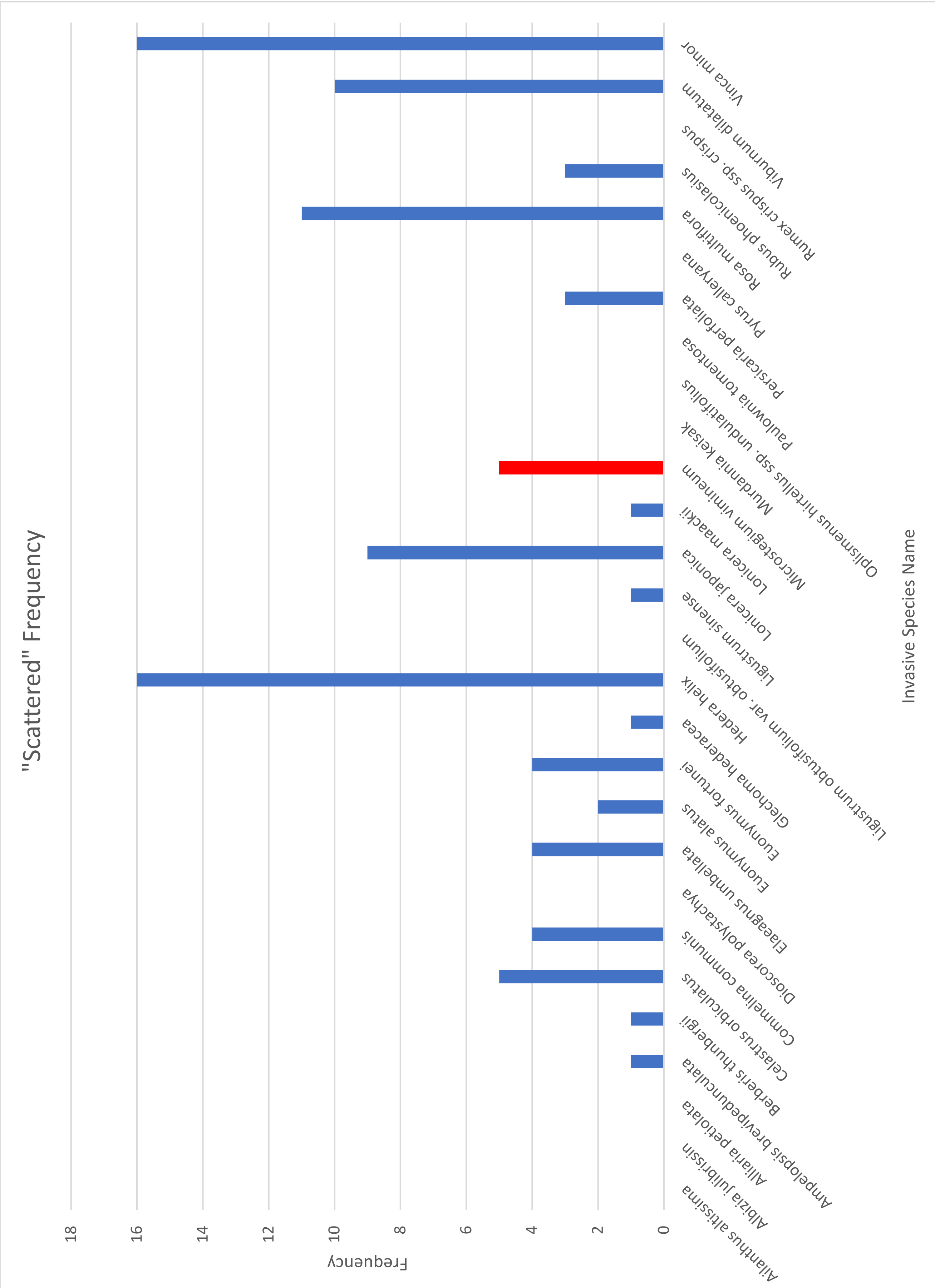
Snakeden Branch Invasive Species Mapping Project - Summary by Compartment

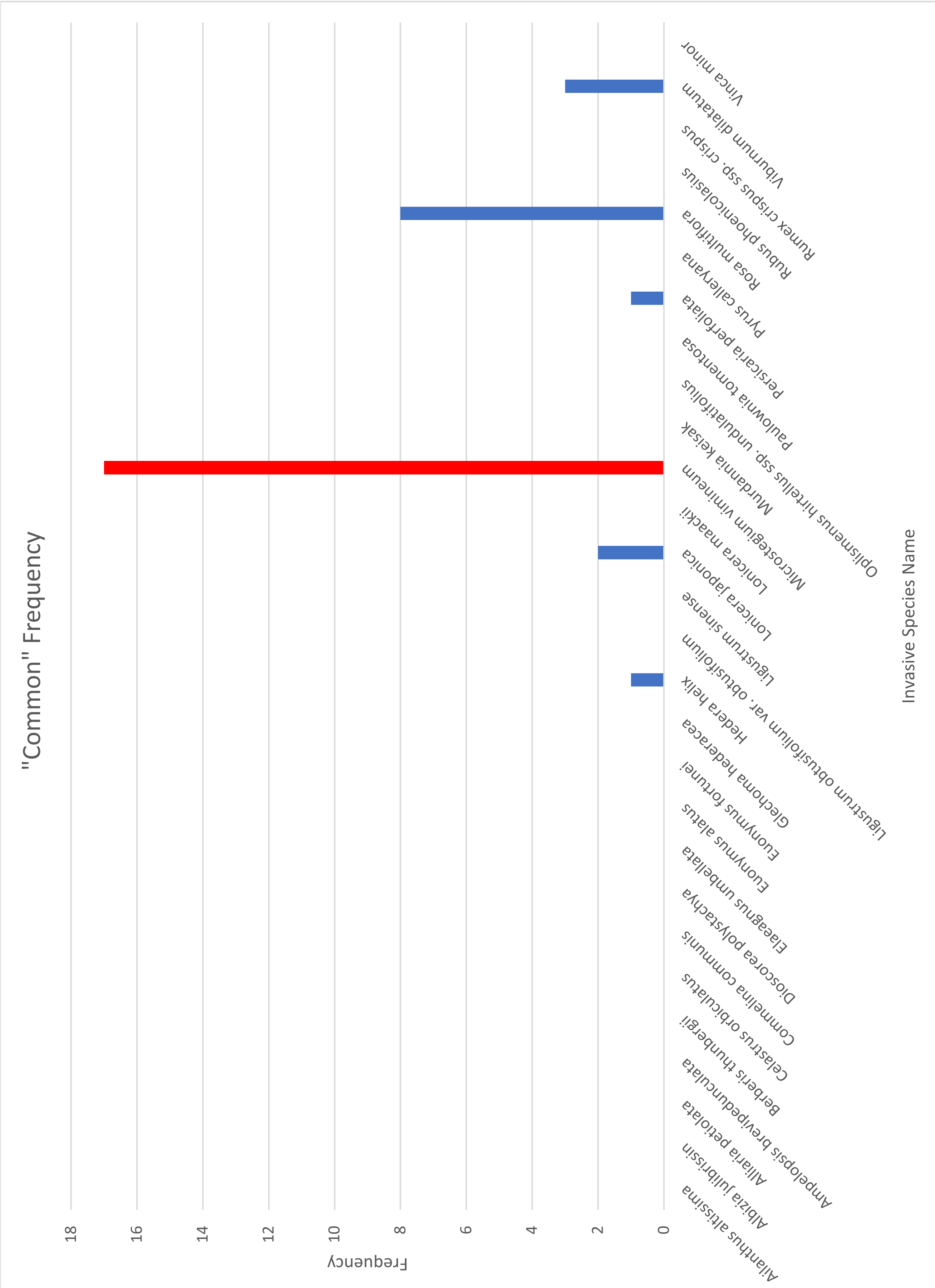
Overall Cover codes: 1=0-5%, 2=5-25%, 3=25-50%, 4=50-75%, 5=75-100%

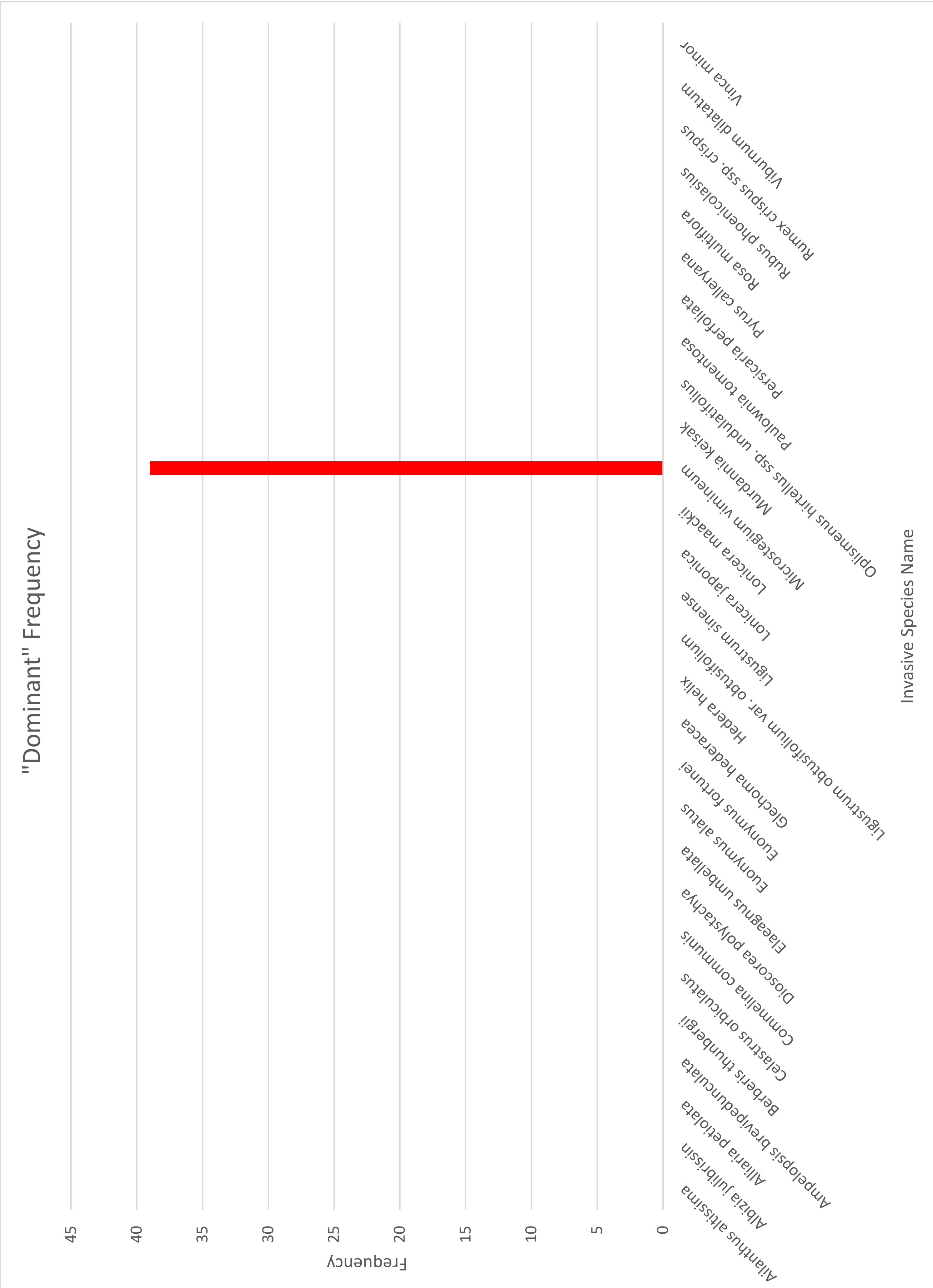
Invasive Species Relative Dominance codes: O=Occasional (<1%), S=Scattered (1-5%), C=Common (5-20%), D=Dominant (>20%

Compartment	OVERALL COVER	*Alliaria petiolata*	*Berberis thunbergii*	*Celastrus orbiculatus*	*Commelina communis*	*Dioscorea polystachya*	*Elaeagnus umbellata*	*Euonymus alatus*	*Euonymus fortunei*	*Glechoma hederacea*	*Hedera helix*	*Ligustrum sinense*	*Lonicera japonica*	*Lonicera maackii*	*Microstegium vimineum*	*Murdannia keisak*	*Oplismenus hirtellus* ssp. *undulatifolius*	*Persicaria perfoliata*	*Pyrus calleryana*	*Rosa multiflora*	*Rubus phoenicolasius*	*Viburnum dilatatum*	*Vinca minor*
S01	3										S				S					C			
S02	3														C				O	S		O	
S03	3		O	O				O						O	C			O		S			
S04	4				S										D							O	
S05	3														D					O			
S06	4				S										C	O		S		O			
S07	4			S	O			O			S		O		D	O		C					
S08	4				S									O	D					O			
S09	1										O				O					O			
S10	2										C		S		C								
S11	3														C						S		
S12	2				O										S						S		
S13	2														C					O			
S14	4				O										D	O						O	
S15	4				S							O		O	D				O	O		S	
S16	4							O		S	O				C					O	O	S	
S17	4				O										D					S	O	C	
S19	4						S	O			O				C								S
S20	2														C						O		S
S21	4										S			O	D								
S22	4														D					O			
S23	4			O							O	O			D		O			O			
S24	2						S		S														
S25	4				O		O						O		D			O		O			
S27	2				O		O						S		S								
S28	2				O						S		S		C								S
S29	1														S								S


"Occasional" Frequency
Frequency
Invasive Species
0
5
10
15
20
25
30
Ailanthus altissima 1
Albizia julibrissin 2
Alliaria petiolata 2
Ampelopsis brevipedunculata 1
Berberis thunbergii 17
Celastrus orbiculatus 5
Commelina communis 8
Dioscorea polystachya 1
Elaeagnus umbellata 13
Euonymus alatus 14
Euonymus fortunei 13
Glechoma hederacea 11
Hedera helix 16
Ligustrum obtusifolium var. obtusifolium 1
Ligustrum sinense 7
Lonicera japonica 23
Lonicera maackii 13
Microstegium vimineum 1
Murdannia keisak 3
Oplismenus hirtellus ssp. undulatifolius 1
Paulownia tomentosa 3
Persicaria perfoliata 7
Pyrus calleryana 2
Rosa multiflora 25
Rubus phoenicolasius 8
Rumex crispus ssp. crispus 2
Viburnum dilatatum 14
Vinca minor 10


"Scattered" Frequency
Frequency
0
2
4
6
8
10
12
14
16
18
Ailanthus altissima
Albizia julibrissin
Alliaria petiolata
Ampelopsis brevipedunculata
Berberis thunbergii
Celastrus orbiculatus
Commelina communis
Dioscorea polystachya
Elaeagnus umbellata
Euonymus alatus
Euonymus fortunei
Glechoma hederacea
Hedera helix
Ligustrum obtusifolium var. obtusifolium
Ligustrum sinense
Lonicera japonica
Lonicera maackii
Microstegium vimineum
Murdannia keisak
Oplismenus hirtellus ssp. undulatifolius
Paulownia tomentosa
Persicaria perfoliata
Pyrus calleryana
Rosa multiflora
Rubus phoenicolasius
Rumex crispus ssp. crispus
Viburnum dilatatum
Vinca minor
Invasive Species Name


"Common" Frequency
Frequency
0
2
4
6
8
10
12
14
16
18
Invasive Species Name
Ailanthus altissima
Albizia julibrissin
Alliaria petiolata
Ampelopsis brevipedunculata
Berberis thunbergii
Celastrus orbiculatus
Commelina communis
Dioscorea polystachya
Elaeagnus umbellata
Euonymus alatus
Euonymus fortunei
Glechoma hederacea
Hedera helix
Ligustrum obtusifolium var. obtusifolium
Ligustrum sinense
Lonicera japonica
Lonicera maackii
Microstegium vimineum
Murdannia keisak
Oplismenus hirtellus ssp. undulatifolius
Paulownia tomentosa
Persicaria perfoliata
Pyrus calleryana
Rosa multiflora
Rubus phoenicolasius
Rumex crispus ssp. crispus
Viburnum dilatatum
Vinca minor


"Dominant" Frequency
Frequency
0
5
10
15
20
25
30
35
40
45
Invasive Species Name
Ailanthus altissima
Albizia julibrissin
Alliaria petiolata
Ampelopsis brevipedunculata
Berberis thunbergii
Celastrus orbiculatus
Commelina communis
Dioscorea polystachya
Elaeagnus umbellata
Euonymus alatus
Euonymus fortunei
Glechoma hederacea
Hedera helix
Ligustrum obtusifolium var. obtusifolium
Ligustrum sinense
Lonicera japonica
Lonicera maackii
Microstegium vimineum
Murdannia keisak
Oplismenus hirtellus ssp. undulatifolius
Paulownia tomentosa
Persicaria perfoliata
Pyrus calleryana
Rosa multiflora
Rubus phoenicolasius
Rumex crispus ssp. crispus
Viburnum dilatatum
Vinca minor

Northern Virginia Stream Restoration Bank Invasive Plant Inventory
Representative Photographs*
August 7 to September 15, 2022


G1.


G3.


G2.


G4.

* Note: “G” and “S” series denote management compartments in The Glade and Snakeden Branch, respectively.

Northern Virginia Stream Restoration Bank Invasive Plant Inventory
Representative Photographs
August 7 to September 15, 2022


G5.


G7.


G6.


G8.


G9.


G11.


G10.


G12.


G13.


G15.


G14.


G16.


G17.


G19.


G18.


G20.

G21.

G23.

G22.

G24.


G25.


G27.


G26.


G28.


G29.


G31.


G30.


G32.


G33.


G35.


G34.


G36.

Northern Virginia Stream Restoration Bank Invasive Plant Inventory
Representative Photographs
August 7 to September 15, 2022


S1.


S3.


S2.


S4.

S5.

S7.

S6.

S8.

Northern Virginia Stream Restoration Bank Invasive Plant Inventory

Representative Photographs

August 7 to September 15, 2022

S9.

S11.

S10.

S12.


S13.


S15.


S14.


S16.

Northern Virginia Stream Restoration Bank Invasive Plant Inventory
Representative Photographs
August 7 to September 15, 2022


S17.


S20.


S19.


S21.

Northern Virginia Stream Restoration Bank Invasive Plant Inventory

Representative Photographs

August 7 to September 15, 2022

S22.

S24.

S23.

S27.


S28.


Typical dominant infestation of *Microstegium vimineum* in floodplain.


S29.


Bush honeysuckles (*Lonicera* spp.) and invasive viburnums (*Viburnum* spp.).

Rosa multiflora, a prevalent invader throughout the study area.

Multiple invaders growing together at one location (pictured: *Lonicera* spp., *Rosa multiflora*, *Microstegium vimineum*, *Hedera helix*, *Celastrus orbiculata*).

Vinca minor, a secondary dominant that is listed as moderately invasive in Virginia but was problematic in several areas throughout the study site.

S/A above, with *Berberis thunbergii* and *Elaeagnus umbellata* pictured left.

Appendix B

Exploring the Limiting Similarity Concept Statistical Code

Exploring Invasive Species Data

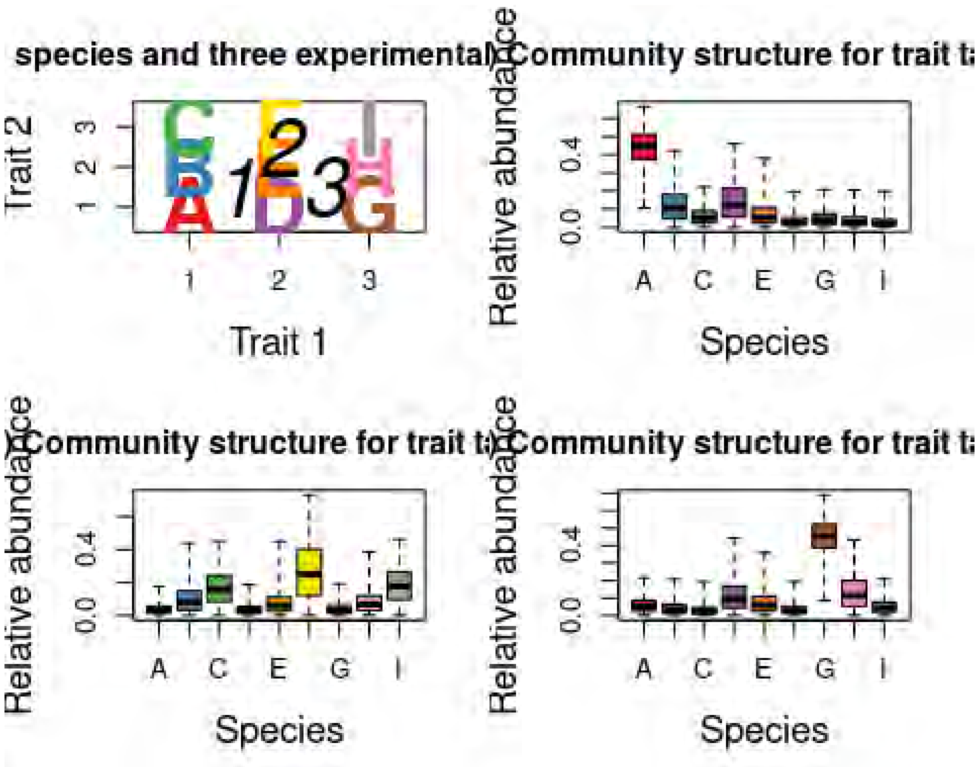
Kari Eskeland
December 2022

Exploring the Paper: Laughlin D, 2014, Applying trait-based models to achieve functional targets fortheory-driven ecological restoration. Ecology Letters. pp. 771-784. doi: 10.1111/ele.12288

```
# install.packages("limSolve")
# install.packages("limSolve", repos="http://R-Forge.R-project.org")
# install.packages("MASS")
# install.packages("mclust")
#The ‘mclust’ library of R can be used to develop probability density functio
ns for any desired multimodal trait distribution
# install.packages("FD")
# install.packages("RColorBrewer")
# install.packages("vegan")

#load libraries
library("limSolve")
library("MASS")
library("mclust")

## Package 'mclust' version 5.4.10
## Type 'citation("mclust")' for citing this R package in publications.

library("FD")

## Loading required package: ade4

## Loading required package: ape

## Loading required package: geometry

## Loading required package: vegan

## Loading required package: permute

## Loading required package: lattice

## This is vegan 2.6-2

library("RColorBrewer")
library("vegan")

#define species mean trait values for each of nine species

spp <-matrix(nrow = 3, byrow = TRUE, data = c(1,1,1,1,1,1,1,1,1,1,1,1,2,2,2,3
```

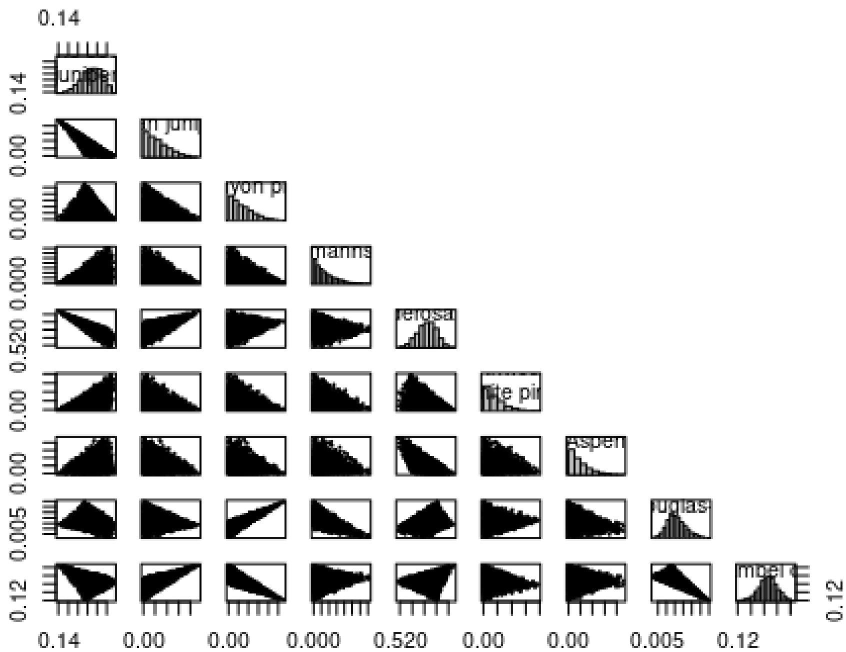
```
,3,3,1,2,3,1,2,3,1,2,3))
#define the chosen functional trait targets
t1=c(1,1.5,1.5)
t2=c(1,2,2.5)
t3=c(1,2.5,1.5)

#set up plot window
par(mfrow=c(2,2),mar=c(5,4,3,2))

#create plot to see where each species resides in trait space
#and where the functional trait targets occur in trait space
plot(c(0.5:3.5),c(0.5:3.5),col="white",xlab="Trait 1",
ylab="Trait 2",
main="(A) Nine species and three experimental trait targets",
cex.lab=1.4,xaxp=c(1,3,2),yaxp=c(1,3,2))
cols <-brewer.pal(9, name="Set1"); cols[6]="gold"
text(1,1,"A",col=cols[1],font=2,cex=3)
text(1,2,"B",col=cols[2],font=2,cex=3)
text(1,3,"C",col=cols[3],font=2,cex=3)
text(2,1,"D",col=cols[4],font=2,cex=3)
text(2,2,"E",col=cols[5],font=2,cex=3)
text(2,3,"F",col=cols[6],font=2,cex=3)
text(3,1,"G",col=cols[7],font=2,cex=3)
text(3,2,"H",col=cols[8],font=2,cex=3)
text(3,3,"I",col=cols[9],font=2,cex=3)
text(1.5,1.5,"1",col=1,font=3,cex=3)
text(2,2.5,"2",col=1,font=3,cex=3)
text(2.5,1.5,"3",col=1,font=3,cex=3)

#plot the generated experimental communities for each of three trait target
xs1 <-xsample(E = spp, F = t1, G = diag(9), H = rep(0,9), iter=3000)

## Warning in lsei(E = E, F = F, G = G, H = H): No equalities - setting type
= 2

boxplot(xs1$X[,1],xs1$X[,2],xs1$X[,3],xs1$X[,4],xs1$X[,5],xs1$X[,6],xs1$X[,7]
,xs1$X[,8],xs1$X[,9],
main="(B) Community structure for trait target 1", xlab="Species",ylab="Relat
ive abundance",range=0,
names=c("A","B","C","D","E","F","G","H","I"),col=cols,cex.lab=1.4)

xs2 <-xsample(E = spp, F = t2, G = diag(9), H = rep(0,9), iter=3000)

## Warning in lsei(E = E, F = F, G = G, H = H): No equalities - setting type
= 2

boxplot(xs2$X[,1],xs2$X[,2],xs2$X[,3],xs2$X[,4],xs2$X[,5],
xs2$X[,6],xs2$X[,7],xs2$X[,8],xs2$X[,9],
main="(C) Community structure for trait target 2",
xlab="Species",ylab="Relative abundance",
```

```
range=0,names=c("A","B","C","D","E","F","G","H","I"),col=cols,cex.lab=1.4)

xs3 <-xsample(E = spp, F = t3, G = diag(9), H = rep(0,9), iter=3000)

## Warning in lsei(E = E, F = F, G = G, H = H): No equalities - setting type
= 2

boxplot(xs3$X[,1],xs3$X[,2],xs3$X[,3],xs3$X[,4],xs3$X[,5],
xs3$X[,6],xs3$X[,7],xs3$X[,8],xs3$X[,9],
main="(D) Community structure for trait target 3",
xlab="Species",ylab="Relative abundance",
range=0,names=c("A","B","C","D","E","F","G","H","I"),col=cols,cex.lab=1.4)
```

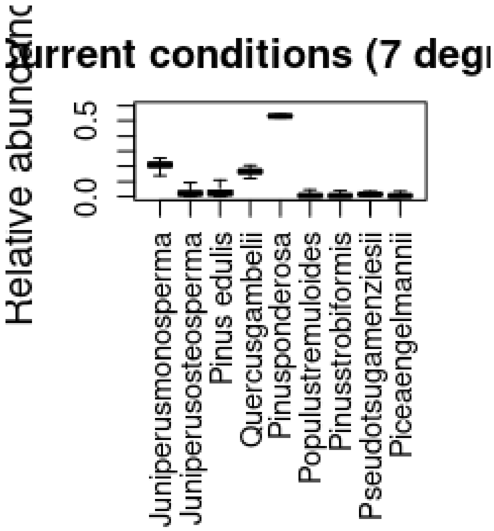



```
T <-matrix(c(0.04,90,8.4,0.576,1,0.028,90,9.6,0.486,1,0.031,120,11.2,
0.562,1,0.008,151,28.1,0.329,1,0.041,166,31.8,0.448,1,0.014,166,25,
0.407,1,0.02,151,25.7,0.404,1,0.03,120,28,0.448,1,0.039,130,13.8,0.634,1),
ncol=9)

constraints<-c(0.039,140,22.6,0.508,1)

xs  <- xsample(E=T,F=constraints,G=diag(9),H=rep(0,9),iter=3000)

## Warning in lsei(E = E, F = F, G = G, H = H): No equalities - setting type
= 2

#Plot the samples
panel.hist <-function(x, ...)
```

```
{
  usr <-par("usr"); on.exit(par(usr))
  par(usr = c(usr[1:2], 0, 1.5) )
  h <-hist(x, plot = FALSE)
  breaks <-h$breaks; nB <-length(breaks)
  y <-h$counts; y <-y/max(y)
  rect(breaks[-nB], 0, breaks[-1], y, col="gray", ...)
}
pairs(xs$X,diag.panel=panel.hist,upper.panel=NULL, cex=0.1,labels=c("One-seed
juniper","Utah juniper","Pinyon pine",
"Engelmannspruce","Ponderosa pine","Southwestern
white pine","Aspen","Douglas-fir","Gambel oak"),cex.labels=1)

## Warning in par(usr): argument 1 does not name a graphical parameter

## Warning in par(usr): argument 1 does not name a graphical parameter

## Warning in par(usr): argument 1 does not name a graphical parameter

## Warning in par(usr): argument 1 does not name a graphical parameter

## Warning in par(usr): argument 1 does not name a graphical parameter

## Warning in par(usr): argument 1 does not name a graphical parameter

## Warning in par(usr): argument 1 does not name a graphical parameter

## Warning in par(usr): argument 1 does not name a graphical parameter

## Warning in par(usr): argument 1 does not name a graphical parameter
```



```
par(mar=c(6,4,3,2),cex.axis=1.1, las=3)
boxplot(main="A) Current conditions (7 degrees C)",
ylim=c(0,0.6),xs$X[,1],
xs$X[,2],xs$X[,3],xs$X[,9],xs$X[,5],xs$X[,7],xs$X[,6],xs$X[,8],
xs$X[,4], cex.lab=1.5, cex.main=1.5, ylab="Relative abundance",
range=0, names=c("Juniperusmonosperma","Juniperusosteosperma",
"Pinus edulis","Quercusgambelii","Pinusponderosa","Populustremuloides",
"Pinusstrobiformis","Pseudotsugamenziesii","Piceaengelmannii"),
ylab="Relative abundance",font=3)

## Warning in (function (z, notch = FALSE, width = NULL, varwidth = FALSE, :
## Duplicated argument ylab = "Relative abundance" is disregarded
```



Conclusions of Data

The Figures perationalise the response-and-effect trait framework for theory-driven restoration ecology experiments. The hypothetical species abundance distributions were generated using underdetermined systems of linear equations.

Step 1. Set targets by selecting relevant traits and trait values to optimise the response or effect of interest. For experimentation, select multiple trait values as trait targets to test their effectiveness.

Step 2. Define the species pool, and determine the mean (and possibly variance-covariance) of the traits of each species.

Step 3. Apply quantitative trait-based models to derive species abundance distributions.

Step 4. Establish experimental communities and maintain species abundances within the range of variability set by the models to keep trait targets at desired level.

Step 5. Monitor community response or ecosystem effect by trait target and treatment to test effectiveness of trait targets and community assemblages. **The error bars** that do not overlap in this data set show that the Juniperus monosperma and the Pinus ponderosa are statistically different.

Ultimately, these mathematical models could be used to determine ranges of species abundances that meet functional trait constraints in the application of the theories of environmental filtering, limiting similarity, competitive hierarchies, and mass ratio theory.

Appendix C

Cedar Run Pilot Study
Representative Photographs

Cedar Run Mitigation Bank Invasive Plant Inventory

Representative Photographs*

September 2022


A1.


A3.


A2.


A4.

* Note: “A” and “P” series denote plots in the Arthraxon and Phalaris study areas, respectively.

Cedar Run Mitigation Bank Invasive Plant Inventory
Representative Photographs
September 2022


A5.


A7.


A6.


A8.

Cedar Run Mitigation Bank Invasive Plant Inventory
Representative Photographs
September 2022


A9.


A11.


A10.


A12.

Cedar Run Mitigation Bank Invasive Plant Inventory

Representative Photographs

September 2022

P1.

P3.

P2.

P4.

Cedar Run Mitigation Bank Invasive Plant Inventory

Representative Photographs

September 2022

P5.

P7.

P6.

P8.

Cedar Run Mitigation Bank Invasive Plant Inventory
Representative Photographs
September 2022


P9.


P11.


P10.


P12.

Cedar Run Mitigation Bank Invasive Plant Inventory
Representative Photographs
September 2022


Representative canopy photo at Arthraxon study site.


Representative canopy photo at *Phalaris* study site.