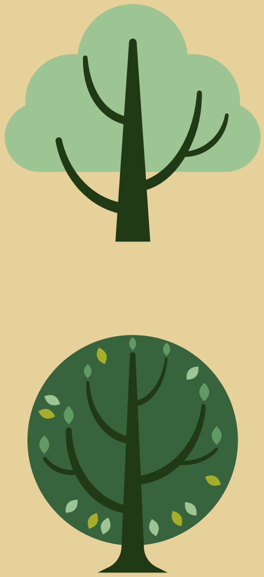
Applied Nucleation for Forest Recovery in the Mid-Atlantic



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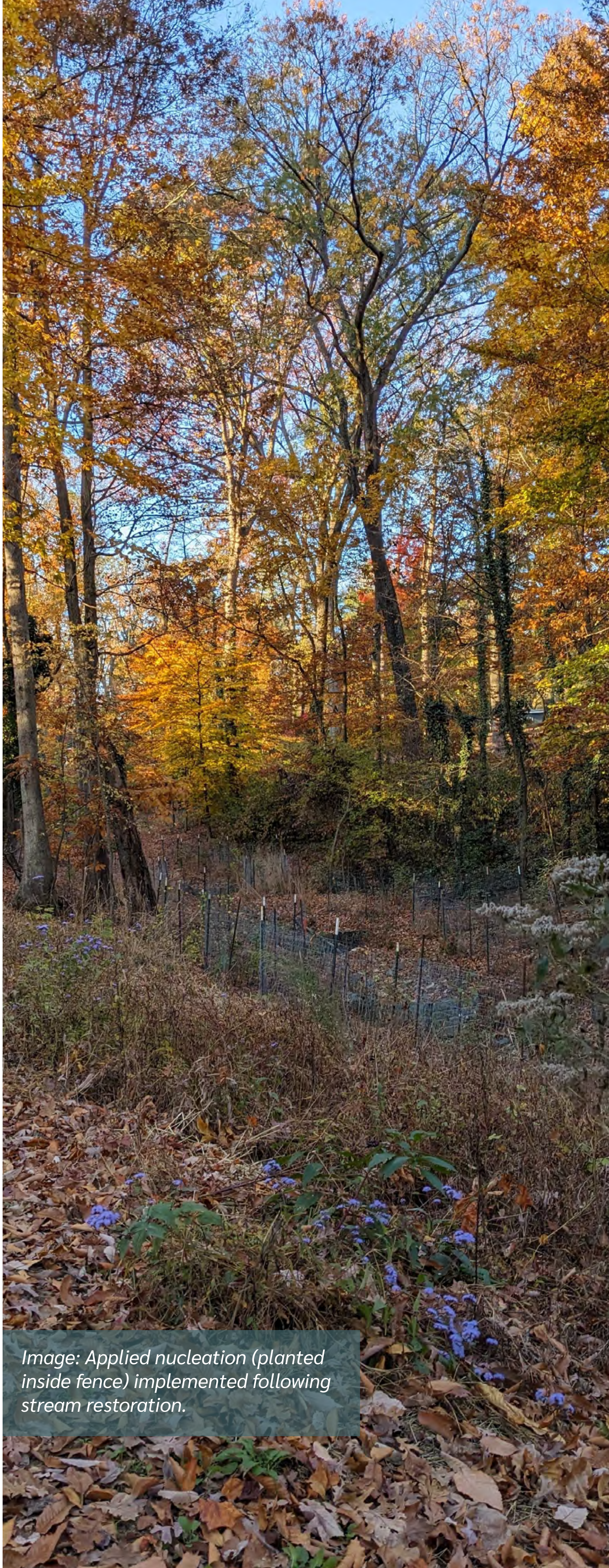
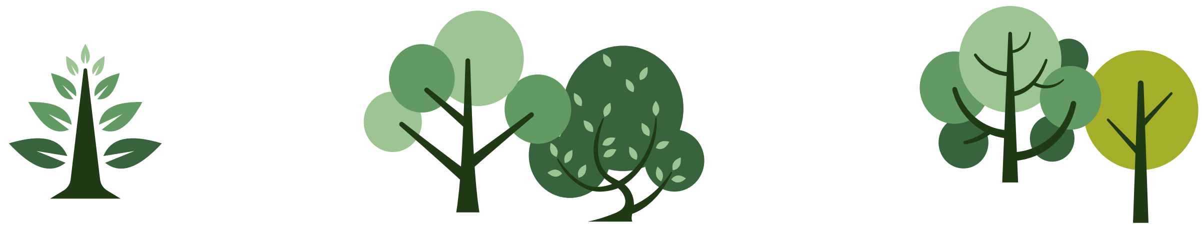


Image: Applied nucleation (planted inside fence) implemented following stream restoration.



“The superficial appearance of vegetation restoration should be avoided.” SCHIRONE ET AL. 2011.

This resource guide is in two parts, first a “how to” implement applied nucleation, and second, how to measure if a high-quality forest has been restored.

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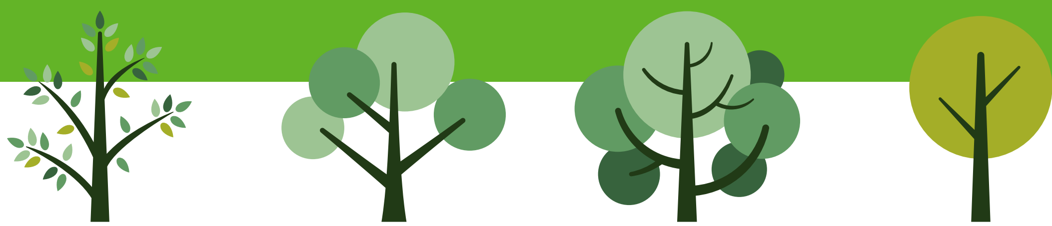
A Simple Approach to Measure Reforestation Quality



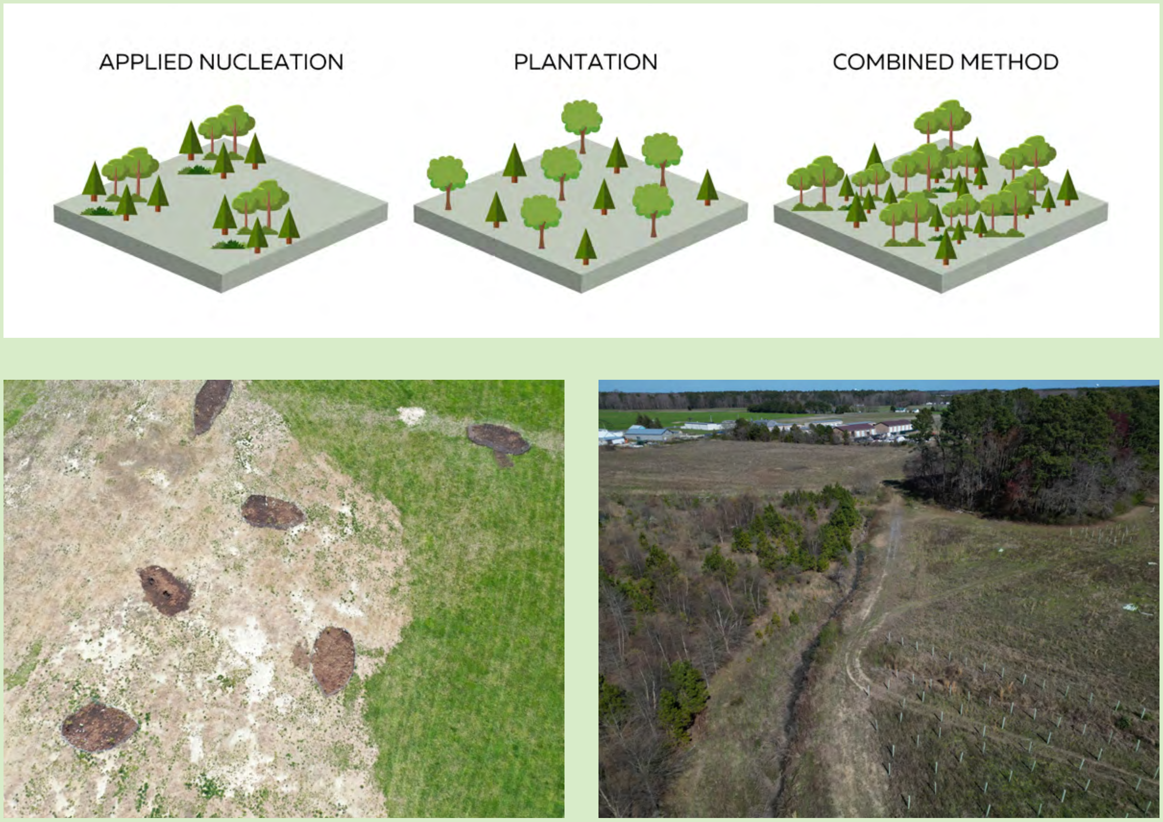
Reforestation as a water quality best management practice (BMP) has been widely adopted (Chesapeake Bay Program 2018 - BMP Reference Sheet D-7: Urban Tree Practices). Nuances between results of tree canopy over turfgrass, impervious surface, and position in the watershed (upland vs. buffer) have been addressed and continue to be reviewed (Chesapeake Bay Forestry Workgroup, Claggett et al. 2014). Beyond establishing tree cover, reforestation potential is less well understood. The effects of forest quality on water quality also requires further study: individual metrics of forest function such as stem density, standing carbon, soil health and soil microbial community, and coarse woody debris have been documented as leading to different water quality outcomes.

Timelines to achieve a functional forest range from three to 300 years, depending on the definition of functional forest, however, as a practice for water quality crediting forest function is granted at the time of implementation. This crediting is considered conservative and accounts for variability in the practice (Claggett et al. 2014). Recent work on a stream restoration chronosequence in Fairfax County (Napora, Noe, Ahn and Fellows 2023) found floodplain total soil carbon responsive to riparian corridor restoration, including improved hydrology and forest planting, after just three years. But where restoration is limited to planting only, soil and species responses may begin to be detectable only after six years in the absence of constraints (Yarranton and Morrison, 1974). However, achieving a functional forest from a traditional, row-based tree plantation may not be possible (Schirone et al. 2011) or take multiple decades.

This study tests both the effect of multiple reforestation techniques as well as the efficacy of available metrics to measure forest function five-years after planting.

Applied nucleation plants more species, more closely together, in small areas, leaving gaps between plantings (Figure i, Holl et al. 2020). This resultant effect creates pioneer colonies of pocket forests across the restoration area. Whereas, plantation reforestation is based on tree plantations where trees are established in rows, ideally spaced across the entire site, to create healthy, large trees. This is the predominant style of reforestation in the Mid-Atlantic.

__Figure i.__ Below. Graphic depiction of reforestation techniques. Bottom left aerial photo of six applied nucleations just after planting (Lewes, Delaware, photo by D. Morrow). Bottom right, aerial photo of plantation style planting, one year after planting (Frankford, Delaware, photo by E. Janssen).



Site: Fairfax County, VA, implemented reforestation in the applied nucleation style in four parks between 2017 and 2018, as well as concurrent traditional or plantation-style planting techniques. Paired reforestations were also implemented based on a plantation planting approach.

Fairfax County, VA is in the Potomac River Watershed of the Chesapeake Bay Watershed. The Mid-Atlantic Piedmont physiographic province is the dominant geology and encompasses six of the eight reforestations. Two reforestations were in the Triassic Basin, a subset of the Piedmont characterized by sedimentary rock and higher ratios of *Carya sp.* (hickories) in the predominantly Eastern North American Forest and Woodland (NatureServe, 2024).

Methods: Research plots (N=161) were established in eight recent (five-year old) reforestations. Where at least two of four treatments existed, unplanted (U), natural forest (F) (combined subcategories of forested buffers (B) or tree saves (S)), plantation

(P) or applied nucleation (N) three to six paired replicates were evaluated. An additional treatment, nucleation adjacent (NA) was implemented immediately outside the dripline of trees installed in a nucleation.

How to determine if forest function is recovering? The suite of functional metrics was chosen that can be completed quickly with limited staff/staff training and commercially available resources (Table i).

Discriminant Function Analysis (Appendix B) examined which metrics were most influential in differentiating between the treatments to detect differences across sites. For recommendations on which metrics to use, we also evaluated correlated results, ease of sampling, and any required additional analysis and cost.

How to determine if forest function differs between reforestation techniques? The selected metrics did not have established target values to indicate forest function in the Mid-Atlantic. Therefore, measurements in the reforestation practice (applied nucleation (N) or plantation (P)) were compared with unplanted (U) and nearby best available forest (represented by tree saves, tree buffers around the disturbance, or adjacent undisturbed forest (F)). We had previously measured growth of climax species, including height and diameter at breast height (DBH).

Analysis compared results of the responsive metrics in the first phase with directional change towards the more desirable function, e.g. greater total soil carbon was determined to be the higher forest function. Where there was not a social value to guide decision-making, undisturbed forest was used as a reference condition.

Table i. *Metrics used to detect change in forest condition.*

Sample Metrics	
Soil Bulk Density	Tree Canopy (Spherical Densiometer) (averaged 12 measurements per plot)
Soil Organic Matter (% Loss on Ignition) (three samples per plot, combined for analysis)	Shrub Number (two m2 circular plot)
Soil Total Nitrogen	% Non-Native Invasive Plant Cover (ground cover) (one m2 square plot)
Soil Total Carbon	% Native Plant Cover (ground cover) (one m2 square plot)
Soil Total Phosphorus	% Leaf-Litter (including woody deciduous and *Juniperus virginiana* needles) (one m2 square plot)
Soil pH	Soil Moisture (average of three measurements)
Survivorship	Diameter Breast Height and Total Height

Results: ***Can forest recovery be detected at five years?*** Yes. The low-tech metrics successfully detected change between unplanted (U), reforested (P or N), and forested (F) conditions, however, the percent change varied between metric (Table ii).

Some techniques required more skill in the field than others (plant identification, soil bulk density) or expensive follow-up processing in the lab, while a third group had expensive start up costs (soil moisture meter) (Table iii).

Even though the metric could detect change, does not mean it is appropriate at all stages of forest recovery. After five years, change in the reforestation area, including spread from the initial planting at the nucleation is visible in aerial photography (Figure ii). Tree canopy and woody leaf-litter in a young reforestation may not have developed and may require multiple years to be a useful metric. Other metrics are correlated, e.g. total organic matter and total soil carbon, with total organic matter being a relatively simple test, and not requiring clean chemistry techniques, it is much more efficient.

Table ii. *Recommended metrics to evaluate forest function post-restoration. The Discriminant Function Analysis (Appendix B) classification success rate (separation of measured metrics of forest function along treatment categories) was 64%.*

Sample Metrics	Absolute Value of Standardized Scoring Coefficients – Discriminate Function Canonical Axis 1	Included in Final Recommendation
Soil Organic Matter	0.66	Yes
Tree Canopy	0.55	Yes
Soil Total Nitrogen	0.47	Highly corelated with Soil Organic Matter
Soil Total Carbon	0.36	Correlated with Soil Organic Matter
% Leaf-Litter	0.34	Yes
Soil Moisture	0.34	Dependent on weather condition
Shrub Number	0.33	Dependent on planting palette
% Non-Native Invasive Plant Cover (ground cover)	0.25	Not predictive enough
Soil Total Phosphorus	0.18	Not predictive enough
% Native Plant Cover (ground cover)	0.09	Not predictive enough
Soil Bulk Density	0.05	Not predictive enough
Soil pH	0.01	Not predictive enough

Is there a difference between Applied Nucleation and Plantation forest recovery? Yes. We detected differences in tree canopy cover, soil organic matter, and percent cover of leaf-litter. These metrics showed consistent forest quality (either higher values or near the reference condition) in applied nucleation plantings as compared to same age/same site plantation plantings, unplanted areas, and adjacent forests (Figure iii). Plots adjacent to nucleations, but outside the planting zone were similar to both unplanted and plantation areas, where as nucleations were the most similar to reference forest conditions.

The correlation of visual cues, e.g. canopy cover, and forest health, especially in the early stages of reforestation, suggests quantitative testing can be an infrequent occurrence during monitoring – e.g. if the planting looks like a forest, it likely is developing the qualities of one, although testing of metrics such as soil organic matter and the development of a forest cover of woody leaves could begin at five years.

Tree canopy, percent soil organic matter, and percent leaf-litter consistently detected a difference between treatments. Total soil carbon replicated patterns found in percent soil organic matter, while soil pH and soil moisture failed to detect a consistent pattern between reforestation techniques. Presence of shrubs was strongly correlated with reforestation technique (nucleation), as they were virtually absent from forested areas, plantation plantings, and unplanted areas.

Table iii. *Sample metrics by cost effectiveness.*

Sample Metrics	Specialized Field Tools	Expertise	Field Time	Cost
Soil Bulk Density	Soil Hammer/ Lab Work	Medium	Medium	$15/each, tool cost ~$400
Soil Organic Matter	Soil Probe/Lab Work	Low	Medium	$10/each
Soil Total Nitrogen	Soil Probe/Lab Work	Low	Medium	$30/each
Soil Total Carbon	Soil Probe/Lab Work	Low	Medium	Incl. with total nitrogen
Soil Total Phosphorus	Soil Probe/Lab Work	Low	Medium	$30/each
Soil pH	Soil Probe/Lab Work	Low	Medium	$10/each
Soil Moisture	Soil Moisture Probe/Drying oven and balance	Low	Low	Tool cost ~$1200, reusable
Tree Canopy	Spherical Densiometer	Medium	High	Tool cost ~$100, reusable
Shrub Number	Quadrat/Tape Measure	Low	Medium	0
% Non-Native Invasive Plant Cover (ground cover)	Quadrat	High	Low	0
% Native Plant Cover (ground cover)	Quadrat	High	Low	0
% Leaf-Litter	Quadrat	Low	Low	0
Plant Survivorship	Method of tracking individuals	Medium	Low	0
Height	Rod, Clinometer or Laser	Medium	Low	Rod, $80, Clinometer, $200, Laser $400
Diameter Breast Height (DBH)	DBH tape	Low	Low	DBH tape, ~$60

__Figure ii.__ Aerial photographs from just after planting and after four years showing canopy closure and expansion into nucleation adjacent areas at Lewinsville Park. Aerial photography courtesy of Fairfax County, Virginia.

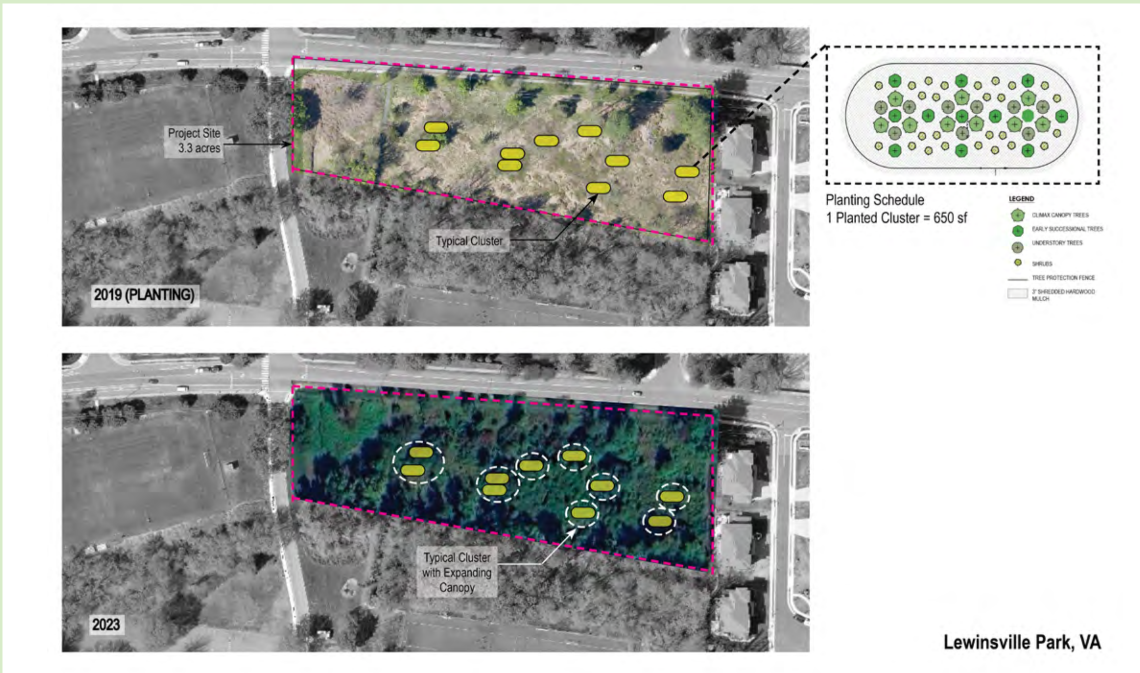


__Figure iii.__ Significant, repeatable metrics of ecosystem health: tree canopy cover, % cover of leaf-litter and % soil organic matter show significant differences between reforestation techniques at five years. These three metrics were the "easiest" to measure and explained most of the differences across planted and control treatments at the Fairfax County, VA sites. Graphs show mean (solid line), +/- 95% confidence interval (blue box) and distribution of all measurements.

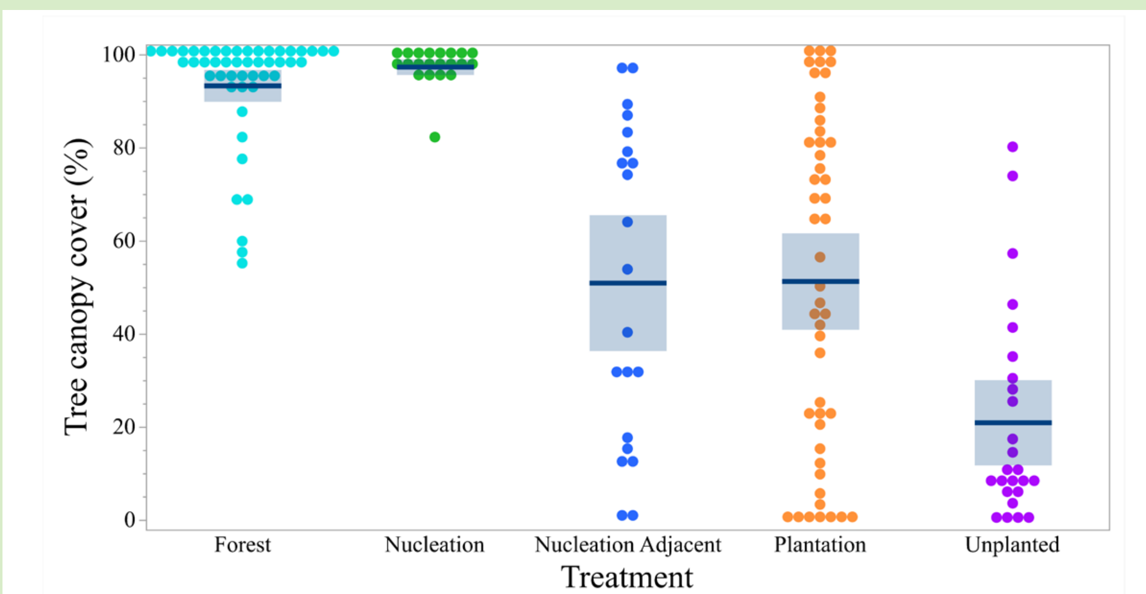
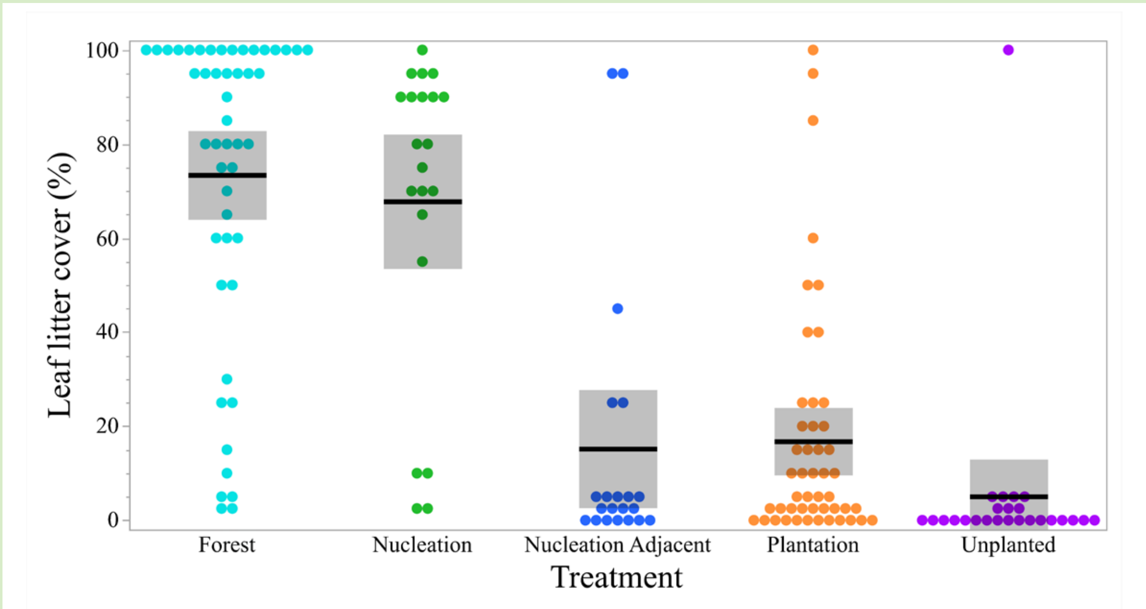
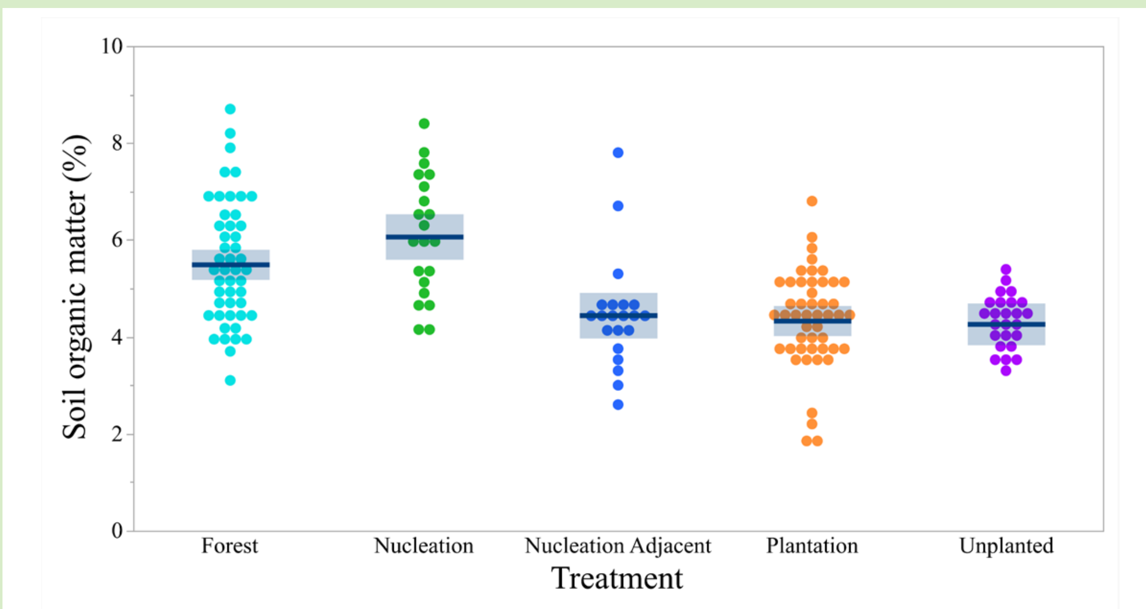


***Figure iii.** continued*





Do initial conditions matter?

Plant palettes varied by site, but the process of nucleation was implemented as consistently as possible. Separating out if initial site condition affected the success of the planting technique, meaning, would some sites be more suited to one reforestation technique or another, was an initial subgoal, but was overwhelmed by the general success of the nucleations across all four sites compared to same site plantations.

Survivorship and Growth of Individual Trees

Survivorship by species was not uniformly better in applied nucleation after four years, however, survivorship was high in all nucleations (Table iv). This may hold true across initial plant size - when nucleation was implemented with bare root seedlings, greater than 50% of the stems were still alive at year one. Generally, DBH and height were lower in nucleations than in plantations, although the two treatments had similar growth rates for species other than willow oak *(Quercus phellos)* which had higher growth in plantations. Overall, fewer trees survived in the plantation plots, combined with the lower initial planting density, most of the canopy trees on the restoration site were found within a nucleation.

Survivorship studies show that individual species have variable survivorship depending on a planting site, e.g. "Right Plant, Right Place." Site-specific planting plans prevented mortality, however, nucleations generally helped survivorship and did not, as was hypothesized, hurt survivorship at four years.

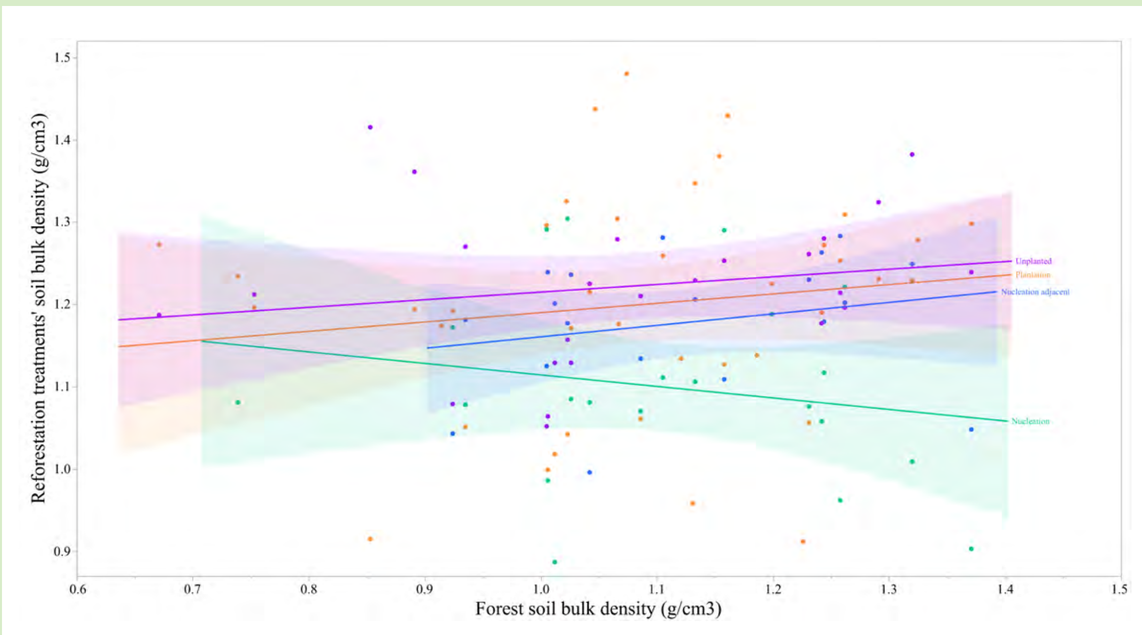
Table iv. *Survivorship of measured species at four years in plantation style vs nucleation style plantings. (L)ewinsville, (C)hurchill, (R)ock Hill.*

Species	Site	Deer protection	Plantation	Nucleation
Liriodendron tulipifera	L	Shelter	0.57	0.82
Nyssa sylvatica	L	Shelter	0.63	0.81
Quercus phellos	L	Shelter	0.62	0.95
Quercus phellos	C	Shelter	0.86	0.9
Quercus alba	C	Shelter	0.96	0.95
Platanus occidentalis	R	Fence	0.1	0.92
Robinia pseudoacacia	R	Fence	0.15	0.89

Bulk Density on poor quality vs high-quality sites

Lower bulk density is associated with other valued ecosystem services, such as increased root production, rainfall infiltration, and soil health. Soil bulk density was lowest in the existing forest saves and buffers (1.08 g/cm^3) and in nucleation (1.10) and highest in plantation-style restorations (1.2) and in areas that were unplanted (1.20). At locations with higher underlying soil bulk density (e.g. worst conditions), the nucleation technique lowered bulk density better than other treatments; lower underlying soil bulk density (e.g. better starting conditions) did not have as great of a difference between reforestation treatments (Figure iv).

Figure iv. *Bulk density results, the negative slope of the nucleation measurements (in green) shows that bulk densities in high initial conditions are lower in nucleations than the unplanted, plantation or nucleation adjacent treatments.*



What does this mean for the future of riparian buffer restoration?

The applied nucleation technique in Fairfax County was developed to increase performance of reforestation following forested stream buffer disturbance associated with stream restoration. This source of tree loss appears especially irksome, as one environmental benefit – water quality - is prioritized over another – forest quality. The tree loss associated with stream restoration remains one of the most controversial aspects of stream restoration in the Mid-Atlantic. Without replanting, forest loss can be persistent, delaying water quality improvements due to increased solar heating, lag in regenerating woody debris and leaf-litter and aesthetics. However, as stream restorations usually include tree saves or buffers that could provide for future seed rain, the potential for a forest seedbank, mycorrhizal bank, and a relatively ‘natural’ soil community, reforestation under these conditions is entirely possible, and as shown here, can occur in a relatively short time.

The technique has been applied repeatedly in Fairfax County, Virginia for this purpose. However, most of those applications are less than three years old and not included in this analysis. For the oldest four sites, including both stream-side and upland reforestation, applied nucleation, after five years, outperformed traditional plantation reforestation across all sites, and, for some metrics, outperformed tree saves. Additionally, where nucleation was applied, resident/stakeholder feedback was positive. **Applied nucleation should be considered as a technique in stream buffer forests as well as large-acreage upland tracts in suburban and urban areas.**

The main drawback of nucleation may be in the limited initial planted area. Generally, costs and social acceptance hurdles increase when planting densely. As an unfamiliar technique to practitioners and landowners alike, the benefits of nucleation plantings may not be immediately recognized. Elsewhere, the idea of pocket-forests has sparked several voluntary plantings from New York City to Iowa, even before the data was available to show success in temperate climates.

The inconsistent survivorship, slow canopy coverage, and inability to replicate natural forest architecture of plantation-style reforestations, that were the initial drivers in finding an alternate planting practice, were also found in this study. Additional gaps in soil organic matter, leaf-litter, soil moisture, and total nitrogen between plantations and adjacent forests emphasize that traditional reforestation approach may not be sufficient to create a functioning forest in suburban areas. However, if the immediate area around the reforestation is devoid of seed source, there is a long lapse between when the site was last forested and/or site constraints require an even distribution of plant material, an applied nucleation approach may not be the preferred choice. Finally, we were unable to detect trees or improvements in the metrics in the unplanted sites (a passive restoration strategy).

Reforestation may take years to mimic the functions of a mature, high-quality forest. At five-years, the applied nucleation technique does not produce mature forests. However, the nucleation technique more closely mimics the succession process than a traditional plantation style restoration. Five-year or older plantation style forests resemble plantations with limited understory or diversity. Incorporating an applied nucleation technique in buffer re-establishments and for narrow or small (<10 acre) upland sites should be given consideration if a functional forest is the restoration goal.

Abstract: The modified applied nucleation technique in the mid-Atlantic forest

Applied nucleation for reforestation is a concept developed and refined by Miyawaki in Japan and Holl in Costa Rica, as well as others throughout the tropical and Mediterranean climates. Referred to as Miyawaki forests, pocket-forests, nucleations, or superclumps, a variety of plant materials from herbaceous to overstory trees are planted densely (closer than 1.25 meters) on prepared soils. In Fairfax County, we planted four groups of species, fast-growing early successional species like *Robinia pseudoacaia*, deer-resistant species like *Amsonia triloba*, overstory canopy trees like *Quercus phellos*, and shrubs like *Viburnum prunifolium*. Trees were specified between ½”- ¾” caliper and shrubs were a minimum 3-gallon container. Each site had one or two site-specific palettes to increase diversity and test species tolerance of the dense planting. Plantings were mulched with hardwood mulch and invasive species control was contracted for at least three-years following planting. Generally, 65 stems were included in each nucleation which was between 200 and 650 square feet, approximately 15 feet wide and 33 feet long. Deer protection ranged from individual tree shelters to a single four-foot wire fence around the entire planting. Applied nucleations provided higher tree canopy cover (92%), percent soil organic matter (6%), and percent area of leaf-litter (65%) which matched or exceeded onsite reference forests. Areas adjacent to the nucleations, but unplanted, performed nearly as well as areas planted in traditional plantation-style forest. These metrics were inexpensive, reproducible (the patterns held across all four nucleations), and at five-years, good predictors of forest health.

Abbreviations:
C – Churchill Road Park Planting Site
DBH – Diameter Breast Height
H -Huntsman Lake Park Planting Site
L -Lewinsville District Park Planting Site
OP -Olney Park Planting Site
R -Rock Hill District Park Planting Site
SB -Silas Burke Park Planting Site

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Appendix A. *Is applied nucleation right for me?*

1. Do you want a natural area/wildlife habitat?
NO – STOP
YES – 2

2. Do you want the entire area to be a wildlife habitat?
NO – 3
YES – 5

3. Where do you want the non- habitat area?
OPEN PLAY SPACE SURROUNDED BY HABITAT – 4
MOSTLY WILDLIFE, MAYBE SOME TRAILS – 5

4. Native Meadows are a great choice - pollinator benefits, water quality benefits and they preserve sight lines – and they are compatible with open play space
GO TO **www.xerces.org** FOR AN INTRODUCTION TO MEADOWS

5. Don't forget to look at 4 as part of your site could be meadow
DO YOU WANT TO MAINTAIN MEADOW IN THE LONG TERM? Pick a mix with more grasses – at least 50-70% grasses –then 6
DO YOU WANT THE MEADOW FOR SHORT TERM GROUND COVER AS THE TREES FILL IN? Pick a mix with more flowers, and only 20-35% grasses –then 6

6. Great! You want trees! What kind of trees?
INDIVIDUAL SPECIMENS – 7
ROWS – 8
MINI FORESTS – 9

7. Specimen trees blend in with typical single family or community landscaping, you'll be looking at fewer species, planted larger with longer care cycles.
LARGE CANOPY TREES
SPECIMEN FLOWERING TREES

8. Rows of trees are a quick way to fill up a large space, typically planted 8-10 foot on center, you usually need to go smaller because you need a lot of trees
BARE ROOT TREES

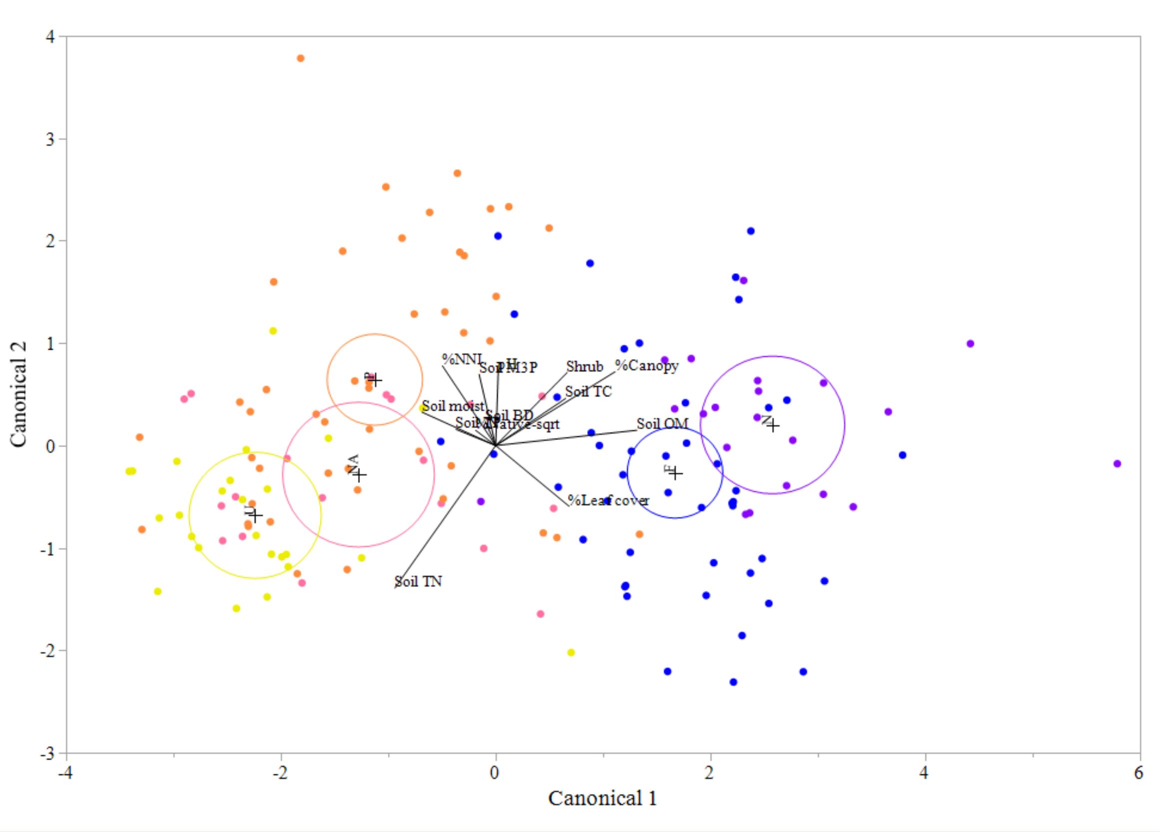
9. Mini forests
START SMALL – 10
GO BIG – 11

10. Plan on 8-10 per acre; aim for 12-16 different species of tree and shrub, about 50-60 individuals multiple starting size classes

11. Plant one giant acre of dense plantings, or 14 mini-forests per acre, explore the techniques, ask questions and try something new.

Appendix B. *Discriminant Function Analysis*

Discriminant Function Analysis helps identify metrics that separate out the treatments. Nucleations ("N", purple) and adjacent forest (tree saves and buffers ("F", blue)) separate out on the x axis (which represents the most important differences among plantings) with higher percent leaf-litter (%Leaf cover), higher soil % organic matter (Soil_OM) and higher tree cover (%Canopy) than adjacent to nucleations ("NA", pink), plantation ("P", orange), or unplanted ("U", yellow) treatments. Total nitrogen (Soil_TN), phosphorus, pH, bulk density and shrub number do not vary along the x axis, whereas soil moisture (Soil moist) is higher outside of the forest and nucleations as is percent non-native species (%NNI). The classification success rate (separation of measured metrics of forest function along treatment categories) was 64%.



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Maryland Department of Natural Resources

Anne Arundel County Maryland

DPW Baltimore City Department of Public Works

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Image: Scientists explore a soil sample from a plantation style plot, the paired applied nucleation plot in the background.