Identifying Key Areas to Improve Delaware Forest Connectivity Through Tree Plantings

By: Eric Reid

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Abstract

This paper explores the nexus between environmental change, particularly habitat fragmentation, and the need for connectivity and forest ecosystems. Investigating the impact of human-induced alterations to the landscape, the study focuses on the state of Delaware. The paper details the impacts of fragmentation across natural systems, delineating how deforestation, urban expansion, and land-use change adversely affect biodiversity, ecosystem services, and the integrity of forested landscapes.

Seeking to answer questions posed by the Delaware Forest Service, the study employs least-cost path analysis in ArcGIS Pro to identify and prioritize potential connectivity pathways for improving forest connectivity through strategic tree plantings. Developing a cost raster that considers both natural and anthropogenic factors allows the analysis to generate insights into the number of ideal locations, the prevalence of private land, and estimates the cost of tree plantings required to enhance connectivity.

The results exhibit 376 potential connectivity pathways traversing predominantly privately-owned lands. Prioritization criteria based on Forest Legacy Areas (FLAs), floodplains, and pathway length reveal high, medium, and low priority segments, aiding decision-making for tree planting initiatives. Assessments conducted on different corridor widths - ranging from 50 to 1000 feet (15.24 to 304.8 meters) - unveil varying planting area estimates and costs, offering flexibility and cost-efficiency to forestry planners.

While the analysis provides valuable insights into potential planting locations, it acknowledges limitations and highlights the need for ground-truthing and updated datasets for

data-driven decision-making. The study emphasizes the importance of ground-truthing to ensure optimal planting locations, addressing inaccuracies in the analysis, and fostering private landowner participation by minimizing disruptions to their activities and operations.

This research presents a robust framework for forest connectivity enhancement, enabling Delaware's Forest Service to strategically plan tree planting initiatives. It underscores the significance of understanding connectivity dynamics for effective conservation efforts, while also suggesting avenues for future research.

Introduction

Overview

Environmental change research has advanced significantly in recent decades, driven by the need to understand how human activities affect the environment and fragmentation, the impacts these changes have on anthropogenic and natural systems, and to evaluate potential solutions or mitigation strategies. Broad impacts have been documented in both natural and human environments. Severe flooding in atoll nations has forced thousands of people to migrate to more land-locked locations (Kench *et al*. 2018). Coastal communities have experienced an increased risk of infection from contaminated groundwater (Musacchio *et al*.,2021). Deforestation has reduced our capacity to remove greenhouse gasses, impairing air quality. Deforestation and fragmentation reduces flood buffers and, with rising precipitation levels, increases the frequency and severity of flooding events(Goff *et al*. 2022). Biodiversity in aquatic ecosystems has been impacted by reduced water quality, primarily from lack of chemical filters for the runoff as well as soil erosion (Allen 2004).

Fragmentation affects natural systems in multiple ways including a loss of ecosystem services, increased edge effects, and the addition of significant barriers to migration (Tapia-Armijos *et al*. 2015). Limited habitat and migration barriers lead to inbreeding and a loss of genetic diversity. This is compounded when considering small patch sizes limit maximum population sizes for many species (Willi *et al*. 2006; Cabarga-Varona *et al*. 2016).

The United States Forest Service (USFS) cites the 2018 report from the Mid-Atlantic Climate Change Response Framework on Mid-Atlantic Forest Ecosystem Vulnerability when stating fragmentation and land use change as one of the seven most significant threats to forest ecosystems (Butler-Leopold *et al*. 2018; Goff *et al.* 2022). The USFS began studying fragmentation after its relationship with the wildland-urban interface (WUI), the zone where human development and undeveloped vegetation meet, was understood. The WUI is the fastest growing land-use type in the United States and is related to loss and fragmentation of native species, the dispersal of nonnatives, and impaired air and water quality due to impervious surfaces and pollution. The USFS uses a spatial integrity index to analyze forest fragmentation based on core forest without WUI, High integrity forest without WUI, and WUI in core/high integrity forest. The Connecticut State Council on Environmental Quality's 2020 annual report defined core forest as interior forest at least 300 feet away from the forest/non-forest boundary. High integrity forests are those that provide vital ecosystem, climate, and biodiversity services (Wildlife Conservation Society, 2023). As of 2010, only six percent of forest land experienced no WUI and was classified as core forest. 168,000 acres of forest land in Delaware will have experienced WUI conditions for at least 30 years with additional acreage experiencing the same since 1990 (Goff *et al*. 2022). The Delaware Forest Service planned to use tree planting and forestry practices to reduce fragmentation and improve connectivity in the goals of its 2020 Forest Action Plan (Delaware Department of Agriculture (DDA) 2020: 86-89).

The best method for mitigating the impacts of fragmentation is to restore its counterpart: connectivity. Landscape connectivity is “the degree to which the landscape facilitates movement across its existing resources.” (García-Feced *et al*. 2011). Improving connectivity provides the landscape with several benefits. It increases habitat availability and biodiversity. Carbon storage increases, provided the reforestation efforts are not a monoculture (Hall *et al*. 2012). Water quality improves by increasing runoff filtration from agricultural lands adjacent to the waterways. Catchment soils, adjacent to waterways, have greater capacity to influence water quality than those further inland. Trees planted in floodplains, which grow in catchment soils, result in valuable timber harvests due to the nutrient rich water and soil (Hughes *et al*. 2012; Laudon *et al*. 2016). It is important to note that improving connectivity does not necessitate the cessation of forestry practices like timber harvests. Integrating forestry plantations into a landscape mosaic while positively modifying the physical and biological conditions of the forest can enhance natural restoration (Cabarga-Varona *et al*. 2016). Understanding the relationship between fragmentation and connectivity is crucial for conservation.

Current connectivity research varies in scope, location, and methodology and mostly focuses on habitat connectivity as a whole rather than forests alone. Many geospatial tools have been developed to analyze habitat connectivity for species of conservation concern. In Indonesia, Conefor Sensinode software was used in conjunction with connectivity indices to determine the most important forest patches to connect for Javan hawk-eagle (*Nisaetus bartelsi*) breeding habitat (Nurfatimah *et al*. 2018). Conefor Sensinode is new software designed to support landscape planning. It measures the importance of habitat patches in the maintenance and improvement of landscape connectivity (Saura and Torné 2009). In Africa, cost surfaces were used to examine connectivity of African lion (*Panthera leo*) habitat and the impact of dispersal data on results. It found that cost surfaces could vary drastically based on the inclusion of dispersal patterns (Elliot *et al*. 2014). Carroll *et al.*, in a 2011 study of gray wolf (*Canis lupus*) habitat connectivity, explored the use of three different connectivity analysis methods; shortest-path, current flow, and minimum-cost-maximum flow. Centrality metrics, which evaluate paths between combinations of sites and assign a ranking based on its contribution to flow across the network, were then applied and the results between the methods were compared to look at the effects of centrality metrics. The use of centrality metrics could allow greater flexibility when used in planning. Belote *et al*. (2022) examined multiple species of conservation concern in an effort to better understand the variation of connectivity over different spatial scales and its connection to human-landscape modification sensitivity. The analysis used moving windows of different sizes to model spatial scale changes and used different resistance surfaces to model the gradient of a species sensitivity to anthropogenic change. For example, one resistance surface could represent the sensitivity of coyotes (*Canis latrans*) which adapt to different environments very well. Another resistance surface represents grizzly bears (*Ursus arctos*) which is significantly impacted by increased human presence.

Some studies examine specific land use classifications and their relationship with connectivity and fragmentation. Navarro-Cerrillo *et al*. (2022) used Land Use/Land Cover (LULC) data with mean patch edge (MPE) and mean patch size (MPS) as its metrics and found significant reductions in both MPE and MPS between the study years. Additionally, it indicated that afforestation of marginal agricultural lands improved connectivity.

Several studies have investigated new technology or methods for analyzing connectivity, such as the aforementioned Conefore Sensinode. Animal telemetry data can be analyzed to measure connectivity. Richard and Armstrong (2010) tracked 53 juvenile North Island robins (*Petroica longipes*) for 12 weeks and their tracking data was successfully used to compare models of functional landscape connectivity due to its status as dispersal data. Pelletier *et al*. (2017) produced an omnidirectional connectivity mosaic of the boreal region of Canada using the Circuitscape program. That study used imagery analysis to examine connectivity patterns across an entire region rather than a smaller species home range. Goicolea and Mateo-Sánchez (2022) looked to broaden the horizons of connectivity research by adding a new dimension: time. The authors argue that measuring connectivity statically may adversely affect the conservation measures suggested and implemented by planners. To make dynamic connectivity studies more efficient, Machado *et al*. (2020) introduces an new ArcGIS Python toolbox designed to assess land use changes between moments. The research being performed today will help produce better understanding of connectivity for conservation efforts being implemented across the globe.

Methods

Objectives

The 2020 Forest Resource Assessment, as part of the Forest Service's Forest Action Plan, has identified several strategies for improving forest quality in the state of Delaware. One strategy is reducing fragmentation by improving connectivity with tree plantings at desirable locations (DDA 2020). The Delaware Forest Service is interested in answering the following questions in pursuit of this goal.

- Where are ideal locations for the Forest Service to improve forest connectivity using tree plantings?
- How many high priority pathways exist?
- Of the parcels the pathways traverse, what percent of parcels are public vs private?
- Given possible corridor widths for connections between patches, how many acres of land will the pathways cover?
- How much would tree plantings in the corridors cost?

Connectivity Overview

Least-cost path analysis was used to answer the key questions and is one of the most common methods of analyzing connectivity (Elliot *et al.* 2014). The Optimal Region Connections tool, an ArcGIS Pro tool developed by the Environmental Systems Research Institute, Inc. (ESRI), creates a network of the most efficient pathways or corridors between origin locations. The tool's input is a feature class containing rasterized points or polygons that act as origin locations to be connected. The tool generates a line feature class connecting the origins to form an optimal route. By adding a cost surface, also called cost rasters or resistance surfaces, the tool will generate least cost paths between the origins based on the total cost of the line (Environmental Systems Research Institute, Inc. (ESRI) n.d.a). Resistance surfaces contain cell values which represent the cost of moving through each cell (Oliveira-Junior *et al*. 2020). The cell size for this analysis was 10x10 meters to precisely map forest boundaries. A resistance surface was compiled using both natural and anthropogenic factors, both of which are necessary in connectivity analysis for promoting biodiversity persistence (Pressey *et al*. 2007).

Origin Polygons

Origin polygons were generated by extracting forest blocks greater than 100 acres from Delaware Land Use Land Cover (LULC) data (Figure 1). The minimum polygon size was set at 100 acres as smaller land tracts may yield less profitability and could “devalue the larger polygons” (C. Miller 2023, personal communication, 4 October).

Cost Raster

A cost raster was created using an overlay of layers selected to account for specific variables (Figure 2). Costs were assigned based on a combination of factors such as the cost to plant in the area and the inverse of potential ecosystem services (Tables 1 & 2). LULC data is routinely used in least-cost path analysis of both connectivity and carbon storage (Sebastiani and Fares, 2023). The cost to plant trees is increased significantly by the cost to clear the land. Therefore, open water, industrial or commercial land, as well as impervious surfaces received the highest cost value of 100. In contrast, already forested land, idle fields, and clear-cut areas along with permeable lands received the lowest value of one. Distance between patches is extremely relevant when looking at forest connectivity through its relationship with the ability of propagules to disperse. This is vital to maintaining genetic and biological diversity (Oliveira-Junior *et al*., 2020). This also impacts planting cost so distances were assigned costs relative to the distance from the forest patch with distances under 0.25 miles equal one and greater than five miles equal five. Floodplains provide vital ecosystem services through runoff filtration and waterway width retention to preserve stream habitat. Floodplains received the lowest cost of one while areas outside floodplains received a cost of two to represent lower priority without impacting the cost raster significantly (Hughes *et al*. 2012). Floodplains were the Delaware Forest Service's most significant concern after timber harvests (C. Miller 2023, personal communication, 4 October). Protected lands owned by private organizations and government agencies represent lower costs to plant as well as beneficial to ecosystem services so they were assigned the lowest cost of one. The remaining layers of the cost raster focused on cost to plant over ecosystem services. Planting over impervious surfaces, likely requiring restoration work, would be expensive and may not be feasible, so impervious surfaces received the highest cost of 100. Permeable surfaces were assigned a cost of one. Delaware also maintains a Preliminary Land Use Service (PLUS) which tracks land use change proposals. Any planned land conversion to a tree planting friendly surface was given the lowest cost of one while the rest received the highest cost of 100. Cells not contained in the PLUS layer were assigned a value of two to limit the impact on the analysis. Together these datasets provide good coverage of both anthropogenic and environmental factors.

When running the Optimal Region Connections Tool, the cost raster was selected as the "Input Cost Raster" and the processing extent set to the cost raster's extent to ensure all areas of the state were covered in the analysis. The distance method was set to planar due to Delaware's relatively small size being an indicator that running a geodesic distance method, which accounts for the earth's curvature, would not significantly impact the study results while drastically increasing processing power and time. Similarly, the option to generate "Connections Within Regions," which generates pathways through the origin regions, was not selected as the regions are already forested and would increase processing power and time (ESRI, n.d.b). The results of the analysis were manually reviewed for quality and the final results are detailed in the section below.

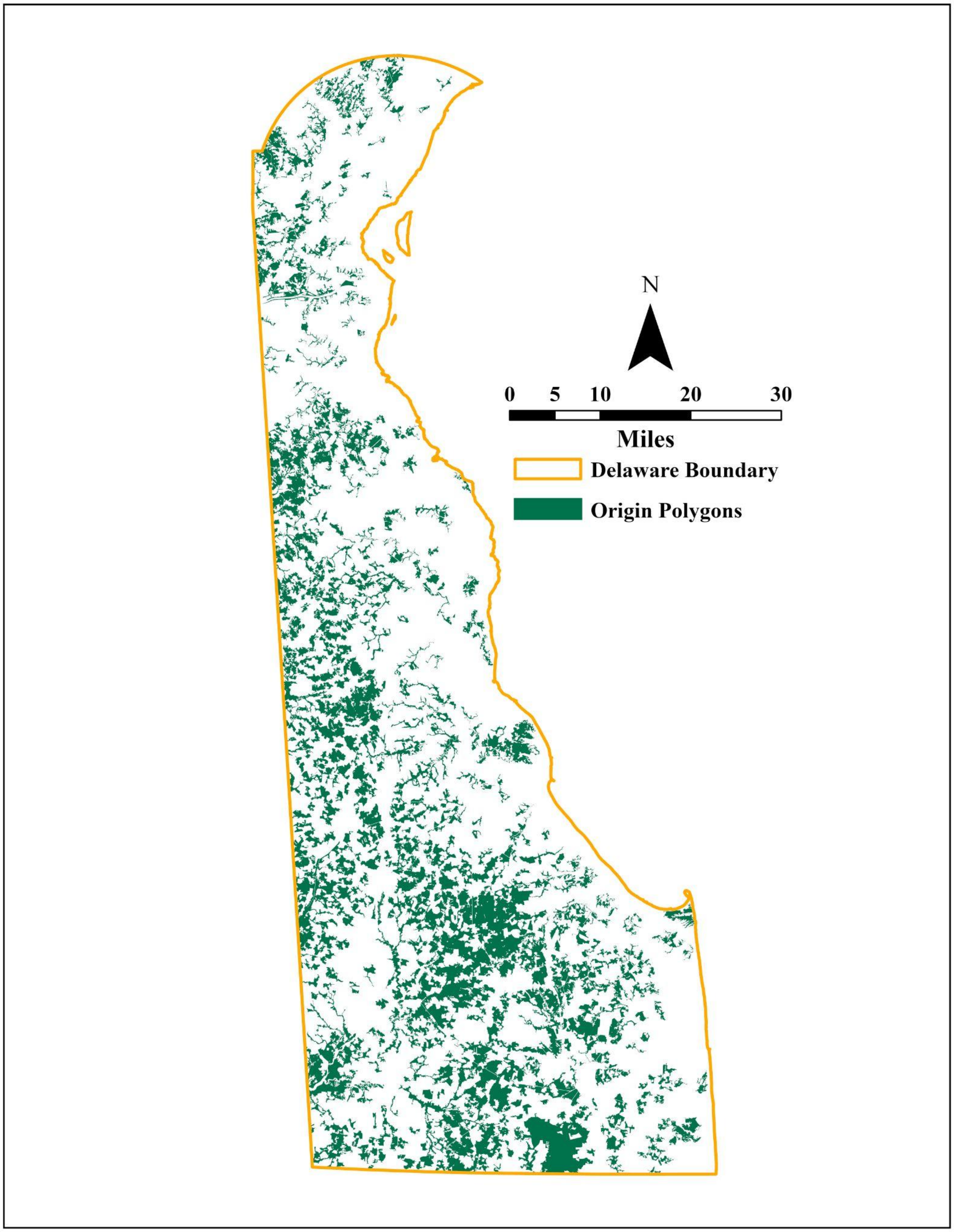
Prioritization

A cost connectivity tool may create hundreds of pathways, making a method of prioritization beneficial for choosing planting projects. The Delaware Forest Service has selected high value areas to preserve called "Forest Legacy Areas" (FLA). Further discussion with Forest Service representatives indicated a high priority should be given to floodplains as well. The final priority was the length of the connection as planting cost would increase proportional to connection length. Each segment was scored based on the prioritization criteria. Ten points were assigned to segments in FLAs and five points to segments in floodplains. Segment lengths were scored from one to five based on the total length in meters. The scores for each section were then combined for a total priority score (Table 3). Land ownership type was considered but determined to be irrelevant. State owned land was not prioritized because any state-owned land not already planted on would not be reserved for planting purposes in most cases. Replanting on private land is characteristic of the east coast of the United States where the public domain is small (Bowers and Mcknight 2012).

Potential Planting Area

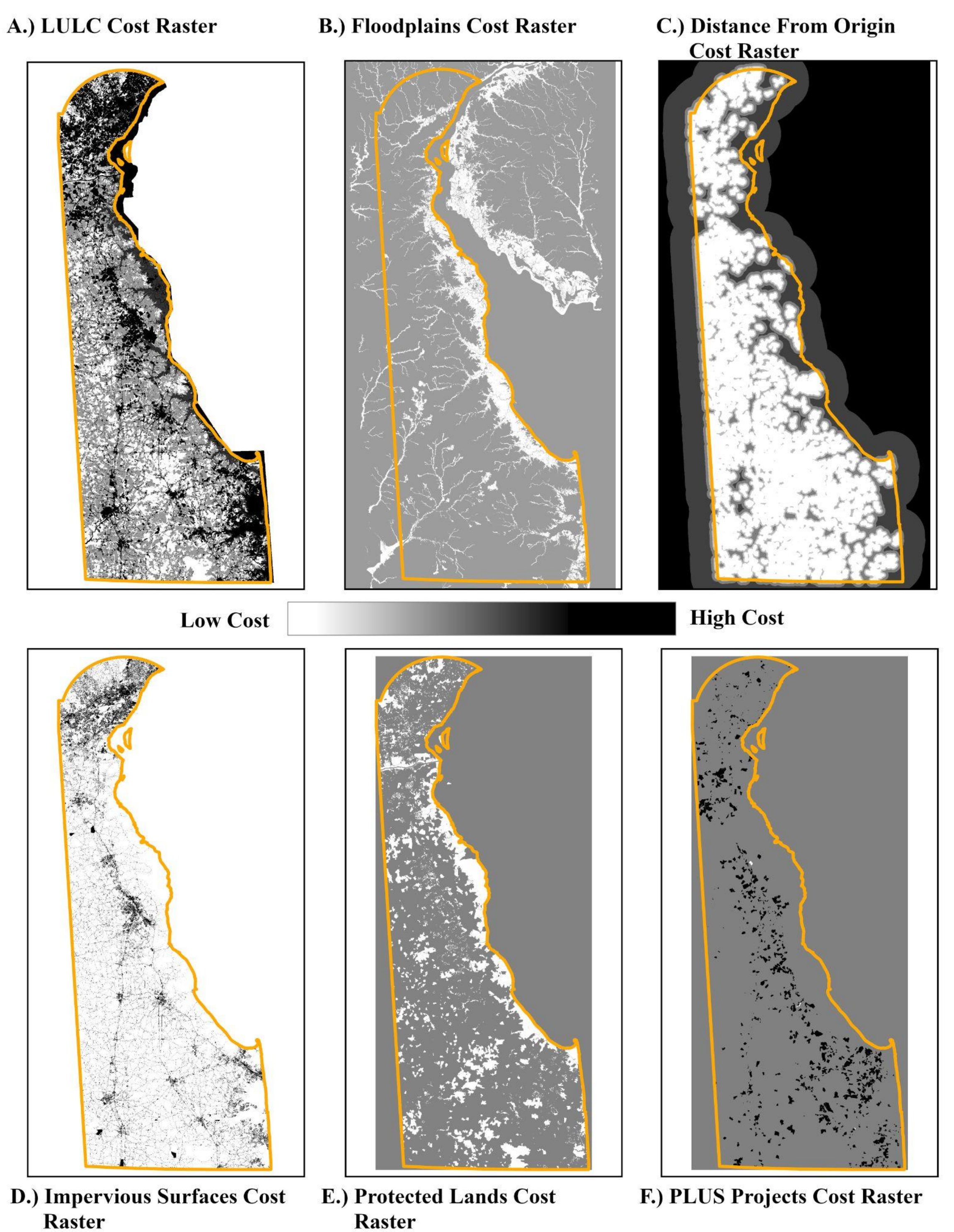
Determining corridor width is necessary to facilitate the Forest Service's required estimate on the cost of tree planting. Minimum corridor width estimates vary wildly and range from meters to kilometers in length and width (Pouzols and Moilanen 2014). Indiana's Division of Fish and Wildlife suggests 50 feet (15.24 meters) and 200 feet (60.96 meters) are sufficient minimum and maximum corridor widths to facilitate travel, nesting, or escape cover. Bond (2003) with the support of the Center for Biological Diversity, suggests corridors should be as wide as possible but that 1000 feet (304.8 meters) is a sufficient minimum. Loro *et al.*, 2015, used a wider 600 meter (1968.5 feet) corridor to prevent bottlenecks. Based on these estimates and the length of the connection pathways, the "Buffer" tool in ArcGIS pro created buffer polygons around the connection pathways at 15.24 meters, 60.96 meters, and 304.8 meters. The buffer area was measured in acres. Hardwood plantings are spaced out in a 10x10 foot grid and support 400 trees per acre whereas softwood plantains are spaced out in an 8x9 foot grid and support 600 trees per acre. Multiplying the acres per buffer, the trees per acre, and the cost to plant per tree generates cost estimates for each buffer width.

Figure 1



Depiction of the origin polygons that will be connected through the connectivity tool. The Delaware boundary was included to give context to the study location.

Figure 2



This matrix displays the individual cost rasters which, when combined, make up the total cost surface used in the analysis. Lighter colors correspond to lower costs. Delaware boundary included in orange for context.

Table 1: A classification of the LULC category costs for use in the cost surface.

Land Use	Cost	Land Use	Cost
Mixed Single and Multi-Family Residential	100	Farmsteads and Farm Related Buildings	100
Single Family Dwellings	100	Other Agriculture	3
Multi-Family Dwellings	100	Herbaceous Rangeland	2
Mobile Home Parks/Courts	100	Shrub/Brush Rangeland	2
Retail Sales/Wholesale/Professional Services	100	Mixed Rangeland	2
Vehicle Related Activities	100	Deciduous Forest	1
Junk/Salvage Yards	100	Evergreen Forest	1
Warehouses and Temporary Storage	100	Mixed Forest	1
Other Commercial	100	Clear-cut	1
Industrial	100	Waterways/Streams/Canals	100
Highways/Roads/Access Roads/Freeways/Interstates	100	Natural Lakes and Ponds	100
Parking Lots	100	Man-made Reservoirs and Impoundments	100
Railroads	100	Bays and Coves (Tidal)	100
Airports	100	Non-tidal Open Water	100
Communication Antennas	100	Non-Tidal Forested Wetland	1
Marinas/Port Facilities/Docks	100	Non-tidal Scrub/Shrub Wetland	4
Other Transportation/Utilities	100	Non-tidal Emergent Wetland	5
Utilities	100	Tidal Forested Wetland	1
Mixed Urban or Built-up Land	100	Tidal Scrub/Shrub Wetland	4
Other Urban or Built-up Land	100	Tidal Emergent Wetland	5
Institutional/Governmental	100	Beaches and River Banks	100
Recreational	100	Inland Natural Sandy Areas	100
Cropland	3	Extraction	100
Pasture	2	Transitional (includes cleared, filled, and gravel)	100
Idle Fields	1	Tidal Shoreline	100

Orchards/Nurseries/Horticulture	3	Non-tidal Shoreline	100
Confined Feeding Operations/Feedlots/Holding	3		

Table 2: A breakdown of the costs assigned to the other layers in the cost surface.

Layer	Variable	Costs
Floodplain Raster		
	0.2% Annual Chance Flood Hazard	1
	1% Annual Chance Flood Hazard	1
	Regulator Floodway	1
	Other	2
	No Data	2
PLUS Raster		
	Agricultural Research Farm	1
	Residential/Woods	1
	Botanic Gardens	1
	Open Space	1
	Agriculture	1
	Farmland	1
	All other categories	100
	no data	2
Impervious Surfaces Raster		
	Impervious Surface	100
	Permeable Surface	1
Distance From Origin (Meters) Raster		
	<402.336	1
	402.336-804.672	2
	804.672-1609.34	3
	1609.34-8046.72	4
	>8046.72	5
Protected Lands Raster		
	Yes	1
	No	2
	no data	2

Table 3: An explanation of how priority was scored based on specific criteria.

Priority Type	Priority Variable	Score
Forest Legacy Area (FLA)		
	Inside FLA	10
	Outside FLA	0
Floodplain		
	Within Floodplain	5
	Outside Floodplain	0
Segment Length (in meters)		
	<100	5
	100-200	4
	200-300	3
	300-500	2
	>500	1

Results

Connectivity Pathways

The connectivity analysis identified 471 connection pathways throughout the state (Figure 3). After manual editing, 95 pathways were removed because the current land use is already forest or due to obstructions (bodies of water or major highways) resulting in 376 potential connectivity pathways. Pathways traversed 1,022 tax parcels of which 93.46 percent were privately owned (Table 4).

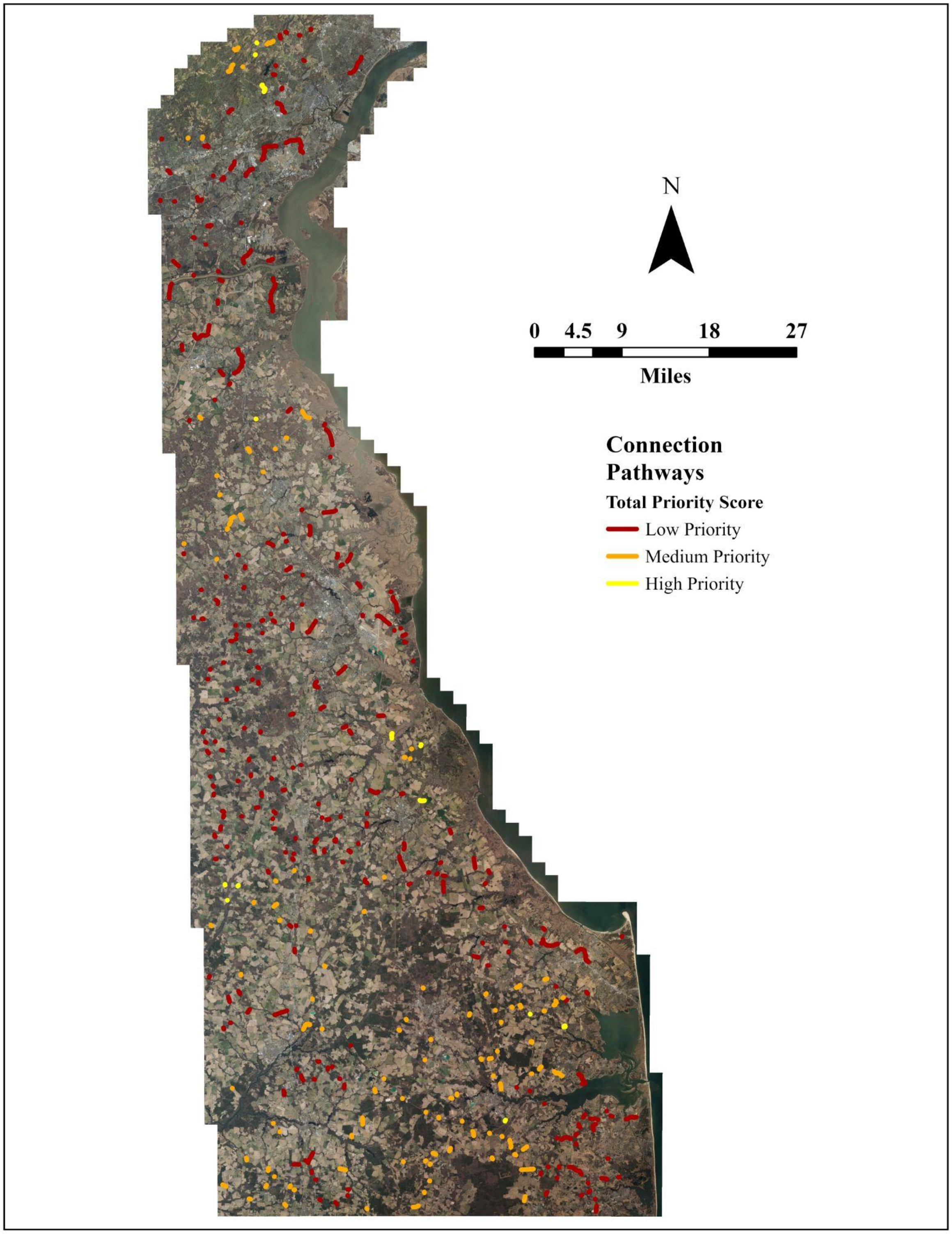
Prioritization

The prioritization process resulted in five pathways attaining a perfect priority score of 20. Scores over 16 indicated the pathways were located in both an FLA and floodplain and were considered high priority. There were 13 high priority pathways (Figure 4). Scores between 11 and 15 were considered medium priority and 108 connection pathways were found at this level (Figure 5). There were 255 pathways that scored a low priority of ten or lower (Figure 6). The mean score was 7.57 while the median score was slightly lower at six. The low mean and median is consistent with the larger number of low priority pathways.

Potential Planting Area

Creating connection pathways at different widths yielded important area and cost estimates for the Delaware Forest Service (Table 5). Using the smallest pathway width of 50 feet (15.24 meters), the total area to be planted for all priority levels was 919.9 acres and would cost an estimated $717,000 for hardwood planting or $1,100,000 for softwoods. Planting only high priority pathways would cover 23.6 acres and cost an estimated $18,500 for hardwoods and $27,500 for softwoods. The total area to be planted using pathway widths of 200 feet (60.96 meters) was 4,159.8 acres and would cost an estimated $3,200,000 for hardwoods or $4,900,000 for softwoods. Planting all high priority areas would cover 110.4 acres and cost approximately $86,000 for hardwoods and $129,000 for softwoods. When creating 1000 feet (304.8 meters) pathways, the total planting area was 33,709.1 acres and would cost an estimated $26,300,00 for hardwoods or $39,400,000 for softwoods. Only planting high priority areas would cover 987 acres and cost an estimated $770,000 for hardwood trees and $1,150,000 for softwood trees.

Figure 3



This aerial map depicts the results of the connectivity analysis, showing the connectivity lines generated by the ArcGIS Pro tool. Aerial imagery was included as the background to give context to the connections.

Figure 4

An aerial photographic map exhibiting an example of a high priority pathway. It is considered high priority because it is located in a floodplain and an FLA and covers a short length. This example is not representative of every feature categorized as high priority.

Figure 5

An aerial photographic map exhibiting an example of a medium priority pathway. It is assigned medium priority status due to its location in an FLA and short pathway length. It is not located in a floodplain. This example is not representative of every feature categorized as medium priority.

Figure 6

An aerial photographic map exhibiting an example of a low priority pathway. It is designated a low priority pathway because it does not reside in an FLA or floodplain and has a longer pathway length. This example is not representative of every feature categorized as low priority.

Table 4: A breakdown of land ownership by type and subtype.

Owner Type	Owner Subtype	Percent
Public		6.55%
	United States of America	0.63%
	State of Delaware	3.79%
	Counties and Municipalities	2.13%
Private		93.46%
	Private Owner	92.90%
	Conservation Organization	0.55%

Table 5: Analysis results of the total cost to plant new connectivity pathways. The average cost to plant a tree is $1.95 per tree. Multiplying this the number of trees per acre (400 hardwoods or 600 softwoods) and the total acres per priority level results in the estimated costs.

Corridor Width	Priority Level	Total Acres	Estimated Hardwood $ Cost	Estimated Softwood $ Cost
50 Feet (15.24 Meters)				
	High Priority	23.61620	$18,420.64	$27,630.96
	Medium Priority	185.56334	$144,739.40	$217,109.11
	Low Priority	710.68927	$554,337.64	$831,506.45
	Totals:	**919.86882**	**$717,497.68**	**$1,076,246.52**
200 Feet (60.96 Meters)				
	High Priority	110.40817	$86,118.37	$129,177.56
	Medium Priority	881.78790	$687,794.56	$1,031,691.83
	Low Priority	3,167.56048	$2,470,697.17	$3,706,045.76
	Totals:	**4,159.75655**	**$3,244,610.10**	**$4,866,915.15**
1000 Feet (304.8 Meters)				
	High Priority	987.01648	$769,872.84	$1,154,809.28
	Medium Priority	8,154.72021	$6,360,681.73	$9,541,022.61
	Low Priority	24,567.35987	$19,162,540.64	$28,743,810.97
	Totals:	**33,709.09656**	**$26,293,095.21**	**$39,439,642.86**

Discussion

This study demonstrates the potential to improve the connectivity of Delaware's forests through tree plantings that generate connection pathways resulting in better health for Delaware's forest ecosystems. The analysis successfully generated a number of prioritizable pathways used to estimate area and costs for tree plantings. However, it should be noted that this analysis is not a guarantee and that ground truthing will be required at the sites. The least cost path is not necessarily the optimal path. In Figure 7, the recommended pathway impinges upon a farm field. Moving the planting area west where the trees are sparse and filling in the gaps could be a better option. Several pathways connect forest patches that are separated by utility lines (Figure 8). While maximum tree height would be limited, allowing successional growth to develop could help connect those patches to provide wildlife cover and food. Data inaccuracies in the underlying cost raster components can also lead to suboptimal pathways. Figure 9 shows a pathway that is already forested and does not need planting. Similarly, Figure 10 shows a pathway across an open field but a connection pathway would be easier to create near the houses to the forest across the street that is not recognized as forest. This would avoid splitting a farmer's field while still connecting forests as well as lower planting costs due to a shorter pathway. This is valuable insight since most of the land to be planted will be privately owned and avoiding disruptions to the owner's activities will increase the likelihood of their participation. Despite these instances and few others like them, this analysis is accurate enough to give foresters valuable planting locations.

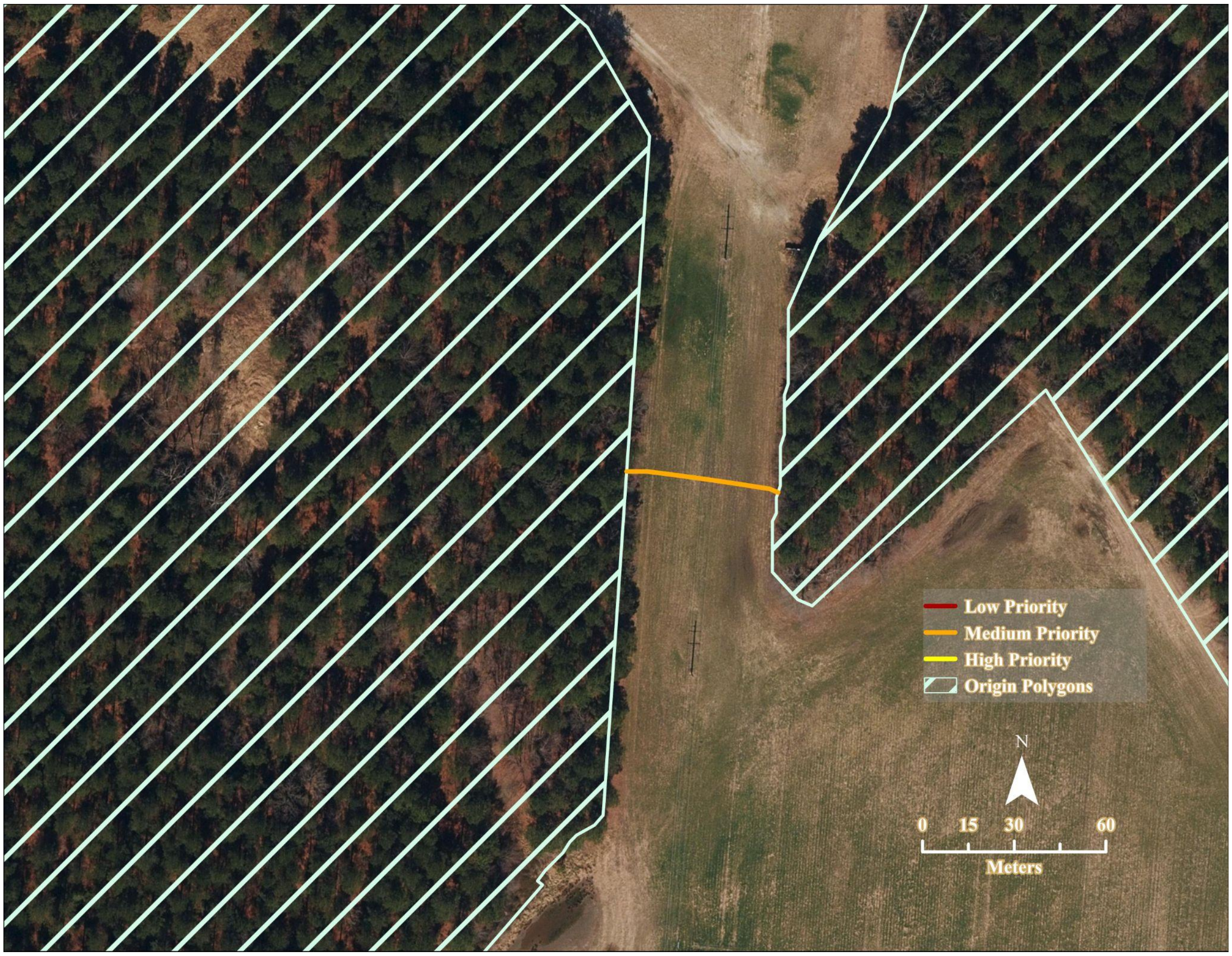
Understanding the relationship between priority level, pathway width and planting cost will allow the Delaware Forest Service to plant pathway widths according to need. The majority of the funding required to plant comes from the low priority pathways due to the high number of these pathways. Planting all the low priority pathways will cost from $850,000 to $29 million depending on the pathway width. Combining widths based on priority level can lead to both high quality and high numbers of connectivity pathways. For example, planting 1000 feet (304.8 meters) pathways for high priority areas, 200 feet (60.96 meters) pathways for medium priority areas, and 50 feet (15.24 meters) pathways for low priority areas will cost a combined estimate of $2.3 million. This is a compromise of quality and quantity for potential connectivity pathways across the state.

In summary, this analysis highlights the significance of addressing forest fragmentation through strategic connectivity improvements in Delaware. By employing GIS analysis, the study identified 376 potential pathways, emphasizing the need for collaboration between state agencies and private landowners. The prioritization framework created offers a systematic approach to resource allocation but requires ground-truthing to validate results due to potential data inaccuracies. Despite limitations, the study provides valuable insight into cost-effective tree planting strategies across different pathway widths and priority levels. By optimizing these approaches, the Forest Service can maximize the quantity and quality of connectivity pathways while managing resources efficiently. Overall, this research offers a crucial foundation for enhancing forest connectivity. It provides a structured roadmap for forestry agencies to strategically plan tree plantings, fostering ecosystem resilience. Embracing these findings and addressing their limitations will enable more informed conservation efforts and better land management practices for Delaware's forests.

Figure 7

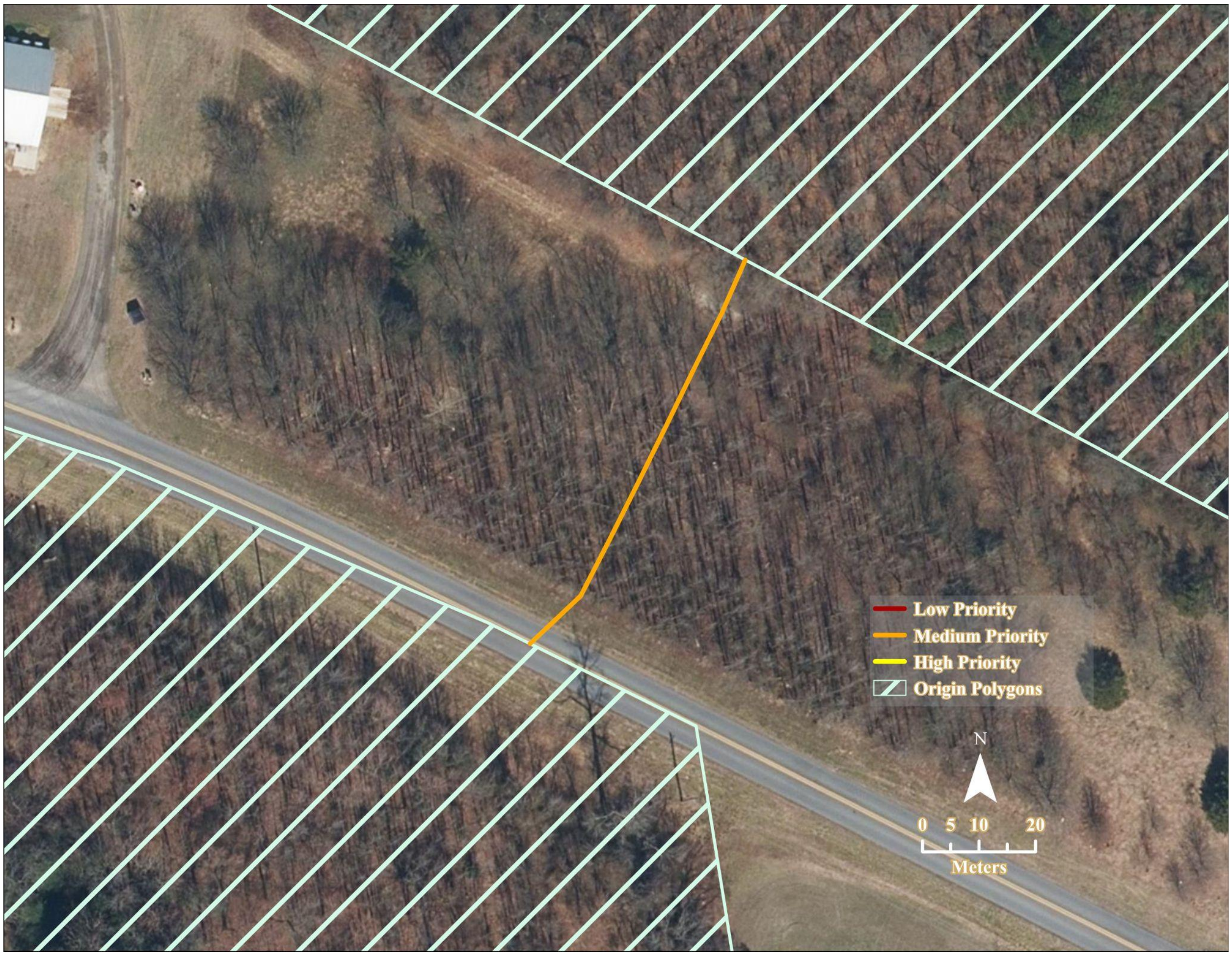
The pathway depicted in this aerial image crosses a farm field. Planting in the area to the west would cost less due to the shorter pathway and would reduce disruption to the landowner's farming operation.

Figure 8



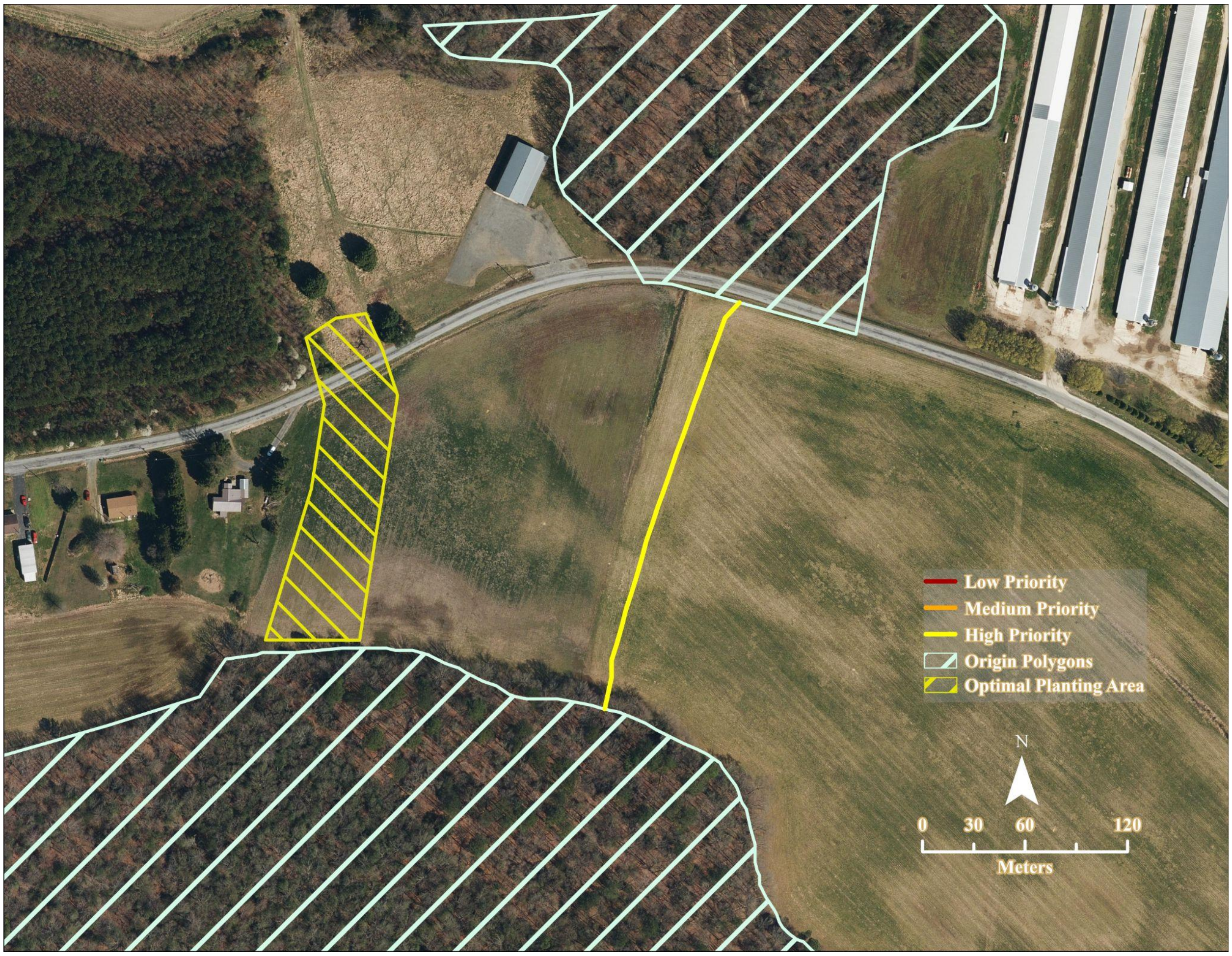
The pathway in this exhibit connects two forest patches separated by power lines. Allowing successional growth would give shelter to wildlife traversing the distance between forest patches. While this does not receive the full benefit of a tall canopy, it will still promote improved water filtration and habitat.

Figure 9



This pathway shows the limitations of the analysis. With incomplete or inaccurate data comes pathways created unnecessarily. The pathway crosses entirely forested land, with the exception of a highway, therefore, planting will not occur here.

Figure 10



Similar to figure 7, this pathway crosses a farm field. However, due to data inaccuracy, the tool did not register the forest ecosystem to the northwest. Planting the pathway alongside the private homes would avoid dividing the farm field and disrupting their operations while lowering planting costs due to shorter pathways.

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Conflict of Interest Statement

None declared.

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Data Availability

- Upon approval from the Delaware Forest Service, the data generated during this project will be released in the form of WebMaps available on the FirstMap Hub site: https://de-firstmap-delaware.hub.arcgis.com/. Once published, searching "Forest

Connectivity Planting" in the search box on the hub site will provide the user with the WebMap.

- The underlying data for US Flood Hazards are available in ESRI's Living Atlas at ID: 2b245b7f816044d7a779a61a5844be23.
- The underlying data for NRCS Easements are available in ArcGIS REST Services Directory at https://nrcsgeoservices.sc.egov.usda.gov/arcgis/rest/services/easements/easements/MapServer/1.
- The underlying data for several layers can be found on FirstMap's HUB Site at https://de-firstmap-delaware.hub.arcgis.com/ and can be accessed with the following ID numbers:
    - Delaware LULC: 4c21a2b79352453a9a8446195302dea7
    - Delaware PLUS: b138b2dc71a9493ba1ae3ba0c5ef401e
    - Delaware Protected Natural Resources: 93f84280fdb1479eb7a9f1aca94e4ff8
    - Delaware Road Inventory: 445d6a18b20144a2bbbb8ba2e92f8ed0
    - Delaware State Forest: b138b2dc71a9493ba1ae3ba0c5ef401e
- The underlying data for Forest Legacy Areas and Impervious Surfaces cannot be shared publicly due to its location on a private server. The data will be shared upon reasonable request to the corresponding author.

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