

Demystifying the Fuzz: Building a Flexible Fuzzy Logic Tool

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Abstract

GIS professionals use their skills to acquire and analyze data to solve myriad questions that are either brought to them or they ask themselves. While some of these questions have cut and dry answers, many do not, including those related to site selection. The site selection process in general is complicated, and while there are definite wrong answers, there can also be several correct answers, all dependent on different factors with both spatial and nonspatial components. These factors include the quality of the ever-changing criteria GIS professionals consider for their analysis, the diverse sets of preferences and opinions of colleagues and stakeholders involved in the decision-making process, and the navigation of an overabundance of tools and knowledge available to solve the question at-hand most effectively. What follows is my capstone project of building a single, flexible tool for use in ArcGIS Pro version 2.9 that combines the powers of fuzzy logic and automation to ease the burden GIS professionals face when performing such site selection analyses. By reviewing the literature, I demonstrate why fuzzy logic is well-suited for performing site selection analysis, how it has been applied to previous analyses, and why there is a need for this tool to be created. I then showcase the flexibility of this fuzzy logic tool by solving problems in two scenarios in two locations and discuss my next steps for further refining and sharing the tool with a wider audience to make fuzzy logic accessible to GIS professionals outside academia.

Keywords: Fuzzy logic, automation, multi-criteria decision analysis, suitability analysis, geoprocessing tools

Demystifying the Fuzz: Building a Flexible Fuzzy Logic Tool

GIS professionals are lifelong learners who serve unique roles in their organizations with their ability to acquire and analyze data to answer a wide array of questions across numerous disciplines. Some questions GIS professionals attempt to answer have clear answers; however, those related to site selection are much more subjective and dependent on various factors, both spatial and nonspatial in nature. One of these factors is the ever-changing criteria GIS professionals include in their analyses. Through improvements in technology and access to open data portals, GIS professionals can incorporate data that is newly created or updated every month [13], every week [34] or even every five minutes [33]. The data considered for analyses may also change as priorities shift within an organization or at the direction of external stakeholders. Once GIS professionals select the best data at any point in time, they must determine each criterion's importance with regard to the diverse opinions of decision-makers involved, and in relation to the other criteria included, in the analysis. GIS professionals must then distill this wealth of information down to its core to make it easily digestible by audiences through clean tables and cartographically pleasing maps. To do so, GIS professionals face the daunting task of navigating an overwhelming sea of knowledge and learning the applications of an overabundance of tools available to them, such as the approximately 200 Spatial Analyst tools available in ubiquitous Esri software [20, 21], all while adhering to deadlines that draw ever closer. To ease these burdens GIS professionals face when performing site selection analysis, I built a flexible fuzzy logic tool, configured to allow users to select the data and set parameters for various scenarios, while keeping the more in-depth technical processes automated in the background in a less daunting, black box configuration.

Multi-criteria decision analysis is a powerful way to leverage the combination of numerous, conflicting datasets with expert knowledge to reach an outcome more methodically than relying on intuition alone [30], and its use in GIS is not new [29]. By defining which attributes are desirable in each layer, and stacking each layer on top of the next, as seen in Fig. 1, GIS professionals have a way to define

the most suitable locations in a study area, based on the parameters they have set. Binary, or Boolean, logic is one way to define an attribute's desirability in site selection analysis and is based on defined, crisp membership of either being in or out. Because natural phenomena like personal behaviors can be governed more by cultural norms than rules set by arbitrary boundaries, there are analytic processes, such as weighted overlay, that aim to explore this gray region between the black and white areas of otherwise binary logic [25].

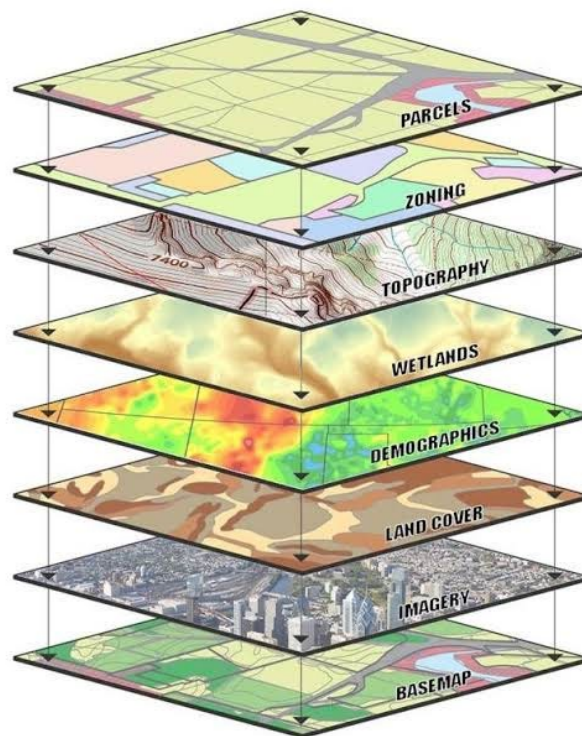


Fig. 1 – Example of using multi-criteria decision analysis to perform site selection. By defining the desirable attributes of each layer, and aligning each layer on top of the next, GIS professionals can identify regions of the study area that meet all, some, or none of the attributes to determine suitable locations in the analysis. Image obtained from Ryan & Nimic [40]. Reproduced here for educational purposes only.

To overcome the strict classifications and arbitrary boundaries of binary logic, GIS professionals can instead utilize fuzzy logic to classify their data and define an attribute's desirability in site selection analysis. According to Esri [22], fuzzy logic assumes there are inaccuracies in the attributes and geometry of spatial data, and the sources of these inaccuracies lead to imprecision in assigning cell values to classes, especially when boundaries between classes are not clear. A nonspatial example of fuzzy logic is applied when defining heights for classifying a person as "short" or "tall". This may be easy in the beginning, but such classifications become even more subjective when introducing classes with modifiers, such as "somewhat short" or "kind of tall", and the problem is further compounded when relying on others to classify the same data, as personal and cultural differences and backgrounds also influence opinions of the classes to which an object or attribute belongs. Fuzzy data has values ranging from 0 to 1 with values of 0 being excluded as members of the dataset and values of 1 being included as members, with the uncertainties falling in between [23]. The degree to which the values change from 0 to 1 is defined through one of seven fuzzy membership functions [23], and the resulting fuzzy data layers can be combined into a final suitability layer through one of five fuzzy overlay types [24].

Fuzzy logic and the fuzzy data within it allow GIS professionals to explore the edge areas of their data and include them in analyses, especially since boundaries may be arbitrary to being with. Considering Fig. 2, it is clear using crisp data that the star is not in any green polygon, but it is close to one. Because personal behaviors are often not guided by arbitrary boundaries, fuzzy data allows GIS professionals to explore if "somewhat close" is somewhat acceptable and assign membership values to cells that may lie beyond the boundary of a crisp dataset. The fuzzy data in Fig. 3 allows the star to possibly be a member of the green polygon to the left of the image.

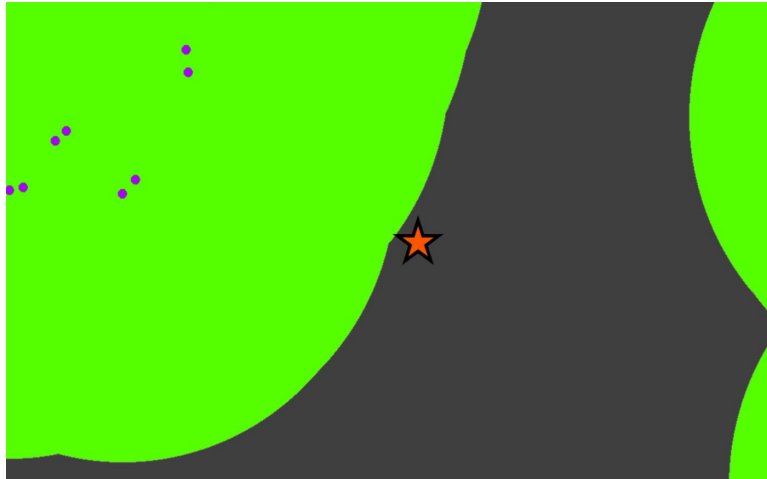


Fig. 2 – Using crisp data with defined boundaries, the star is not located within any green polygon. Data obtained from Port Authority of Allegheny County [38]. Reproduced here for educational purposes only.

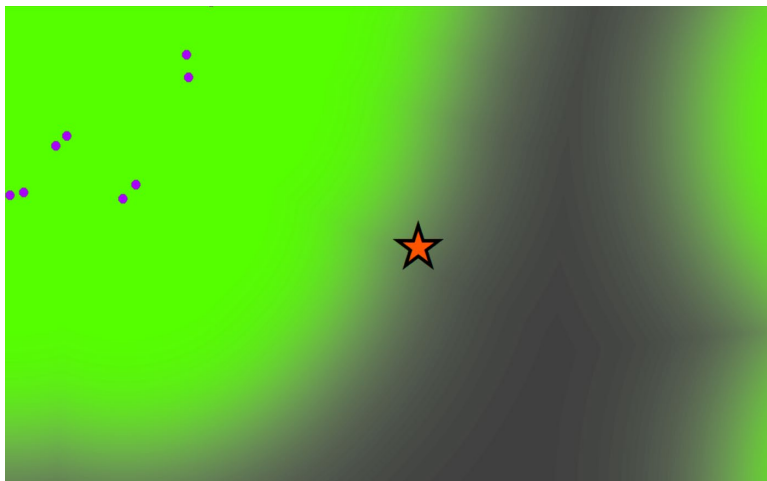


Fig. 3 – Using fuzzy data without defined boundaries, the star could be considered a member of the green polygon to the left of the image. Data obtained from Port Authority of Allegheny County [38].

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In the literature, there are innumerable site selection suitability analyses across a range of disciplines that have made use of these advantages of fuzzy logic. A small subset of these analyses includes assessing groundwater suitability for consumption [31], landslide hazard susceptibility [10], land suitability for redevelopment [11], winter storm damage risk [1], wind turbine site selection

optimization [12], and seismic activity vulnerability [32]. This variety of applications indicates that fuzzy logic is quite flexible and can be applicable to the needs of more general GIS professionals outside academia, such as those working in municipal planning offices.

Automation can add further efficiency to a site selection analysis based on fuzzy logic. Data technicians of any skill level benefit from tools that save time and remove as many potential risks of human error as possible. Using Microsoft Excel as a nonspatial example, automation can be used for something as simple as changing a field's string to all uppercase characters or something more convoluted like concatenating cell values or performing lookups to retrieve data from other workbooks. GIS professionals work with automation quite often when using native and custom geoprocessing tools in GIS software. GIS professionals interact with panels, such as the one shown in Fig. 4, that allow them to select data and set parameters but ignore the inner workings of the tools—so long as all goes according to plan. These processes are hidden in a black box that makes the entire process of using the complex tools more accessible, especially to novice users.

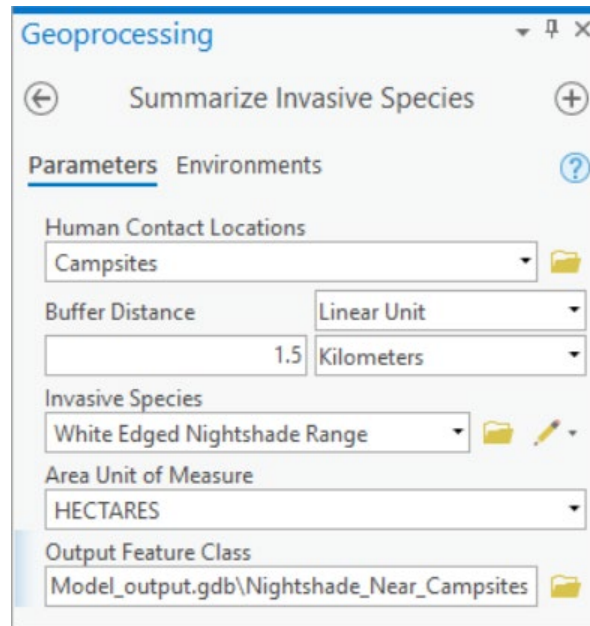


Fig. 4 – Example of a custom geoprocessing tool panel in ArcGIS Pro. The panel only displays the information necessary for a GIS professional to operate the tool—the inner workings of the automated processes are hidden from the user. Image obtained from Esri [26]. Reproduced here for educational purposes only.

Goal, Objectives, and Results

This combination of multi-criteria decision analysis, fuzzy logic, and automation brings me to my goal and objectives. My overarching goal was to make fuzzy logic more accessible to GIS users outside academia. My objectives to accomplish this goal were to develop a flexible fuzzy logic tool and then apply this tool to answer real-world questions in scenarios that a municipal GIS employee may encounter.

Objective #1 – Develop a Flexible Fuzzy Logic Tool

The flexible fuzzy logic tool combines the preprocessing steps necessary for spatial analysis with fuzzy membership and a final overlay function. Combining these processes allows users to run multiple

iterations of the same analysis, while reducing instances of human error along the way. This tool allows users to choose their own layers for the analysis and set membership domains and weights for each layer to incorporate the numerous, sometimes conflicting, preferences of multiple stakeholders and decision makers involved.

Objective #1 – Technology

The technology I used to complete my project was ArcGIS Pro version 2.9. Esri products are ubiquitous in the GIS world [28], and ArcGIS Pro is their new standard. Keeping in mind my audience is a municipal GIS employee, I wanted help organizations that have already invested in this proprietary software—and especially the additional cost of extensions like Spatial Analyst—benefit from wider application of the software available to them.

I constructed my tool using Python 3.7, the scripting language of choice for ArcGIS Pro. Scripting a custom tool in Python affords developers the greatest amount of flexibility and control, especially when the tool is to have a varying number of inputs and parameters. Because this was a key component of the tool I was looking to construct, I deviated from my original proposal to construct a tool in ModelBuilder, Esri’s “visual programming language for building geoprocessing workflows” and documenting processes and decisions made along the way [27]. ModelBuilder is well suited for such purposes, but it is not possible to construct a tool in it with the amount of flexibility I needed.

Objective #1 – Results

After writing the Python script for my fuzzy logic tool, I configured the tool’s parameters for use as a custom geoprocessing tool that combines the preprocessing steps necessary for spatial analysis with fuzzy membership and a final overlay, conveniently packaged in a toolbox that can be added to ArcGIS Pro. Fig. 5 shows the interface of the tool. Due to the varying number of input layers a user can enter, the interface panel can grow to be quite long. On the left of the image in Fig. 5 is a closeup of the

top of the panel where users select the layers and workspace for the analysis. On the right is a closeup of the bottom of the panel, where users choose the parameters for each layer and the name of the final output raster. To assist users, I configured the tool's metadata to display information for every parameter, readily available to the user by hovering over each parameter's respective blue "i" icon on the panel, as exemplified in Fig. 6. The information text also links directly to ArcGIS Pro documentation online where appropriate.

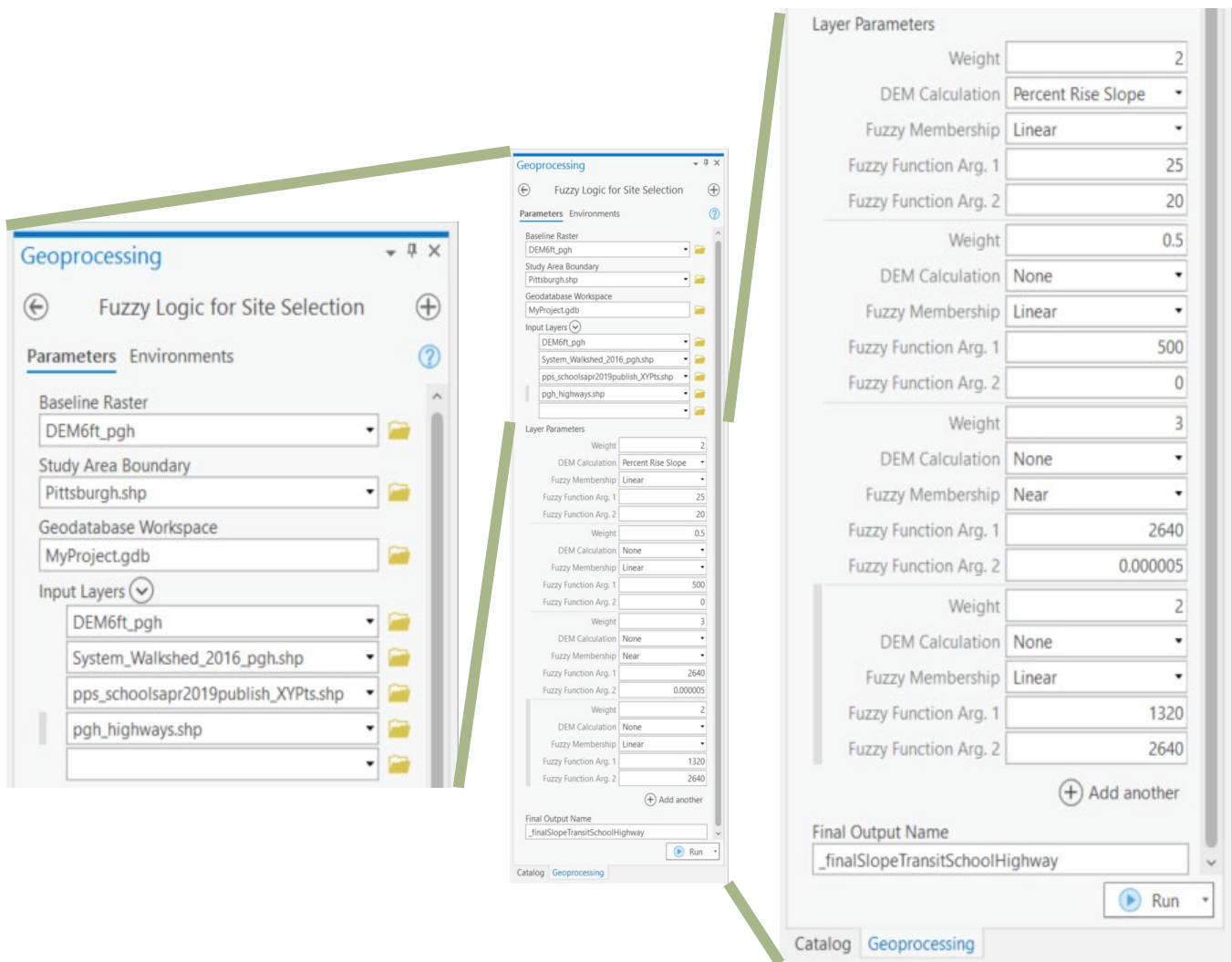


Fig. 5 – The user interface of my custom fuzzy logic tool in ArcGIS Pro. Due to the varying length of the panel, dependent on the number of layers used in an analysis, the left of the image shows a closeup of the top of the panel. Here, users enter the layers and workspace for the analysis. On the right is a closeup of the bottom of the panel where users enter each layer's parameters and the name of the final output raster.

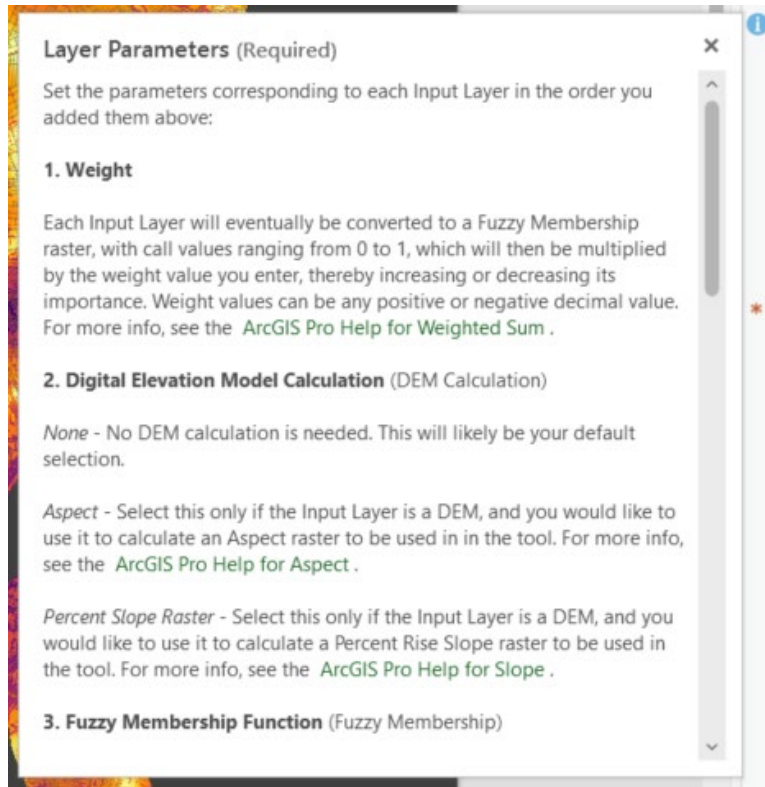


Fig. 6 – Example of my tool’s parameter information in ArcGIS Pro. Help text is readily available to users by hovering over each parameter’s respective blue “i” icon on the interface panel. Where appropriate, the information text also links directly to ArcGIS Pro documentation online.

The following is a walkthrough of the parameters and how the tool functions in the background. First, users select a baseline raster. This raster defines the geoprocessing environment settings—including the snap raster, cell size, and projection to be used for all other layers—and determines the linear unit for distances that can be entered as parameters for the vector input layers. Next, users select a study area boundary. This polygon serves as the analysis mask, and the final output raster will have values for all cells within it. Thirdly, users choose a geodatabase workspace where all intermediate layers and the final output raster will be saved. From there, users select the input layers for the analysis and their corresponding parameters. These layers can be raster data, vector data—such as points, lines, or polygons—, or a combination of the two. The parameters include the option to calculate an aspect or

percent rise slope raster from an input digital elevation model raster, the type of the fuzzy membership function for each layer, the two arguments for said membership function, and the weight of the importance by which to multiply the membership raster. Finally, users enter a name for the final output raster that can be retrieved from the geodatabase workspace after the tool has successfully run.

Once the user clicks “Run”, the tool reprojects any study area boundary and input layers not in the same projection as the baseline raster. If a reprojection is necessary, the tool reprojects any input raster layers with a bilinear resampling algorithm, as users are likely to be working with continuous data, such as an elevation, temperature, or precipitation raster. In the event a user is working with discrete data, such as a land cover raster, the fuzzy membership functions that follow in the processing chain will still incorporate values near those in the original raster.

With all input layers in the same projected coordinate system as the baseline raster, the tool then creates intermediate rasters. For a raster input layer, this could be a calculated aspect or percent rise slope raster, if selected as a parameter. The tool then uses the values of this calculated raster, or the original input raster layer, as input for a fuzzy membership function, given the membership type and argument parameters entered. Fig. 7 shows an example of a calculated percent rise slope raster and its conversion into a fuzzy membership raster. For vector layer inputs, such as school location points, highway polylines, and watershed polygons, the tool instead creates intermediate Euclidean distance rasters that have cell values as distances from the vector features in the linear units of the baseline raster’s projected coordinate system. The Euclidean distance raster values are then used as inputs for the fuzzy membership function. Figs. 8–10 show examples of Euclidean distance rasters and their conversions to fuzzy membership rasters for points, polylines, and polygons, respectively.

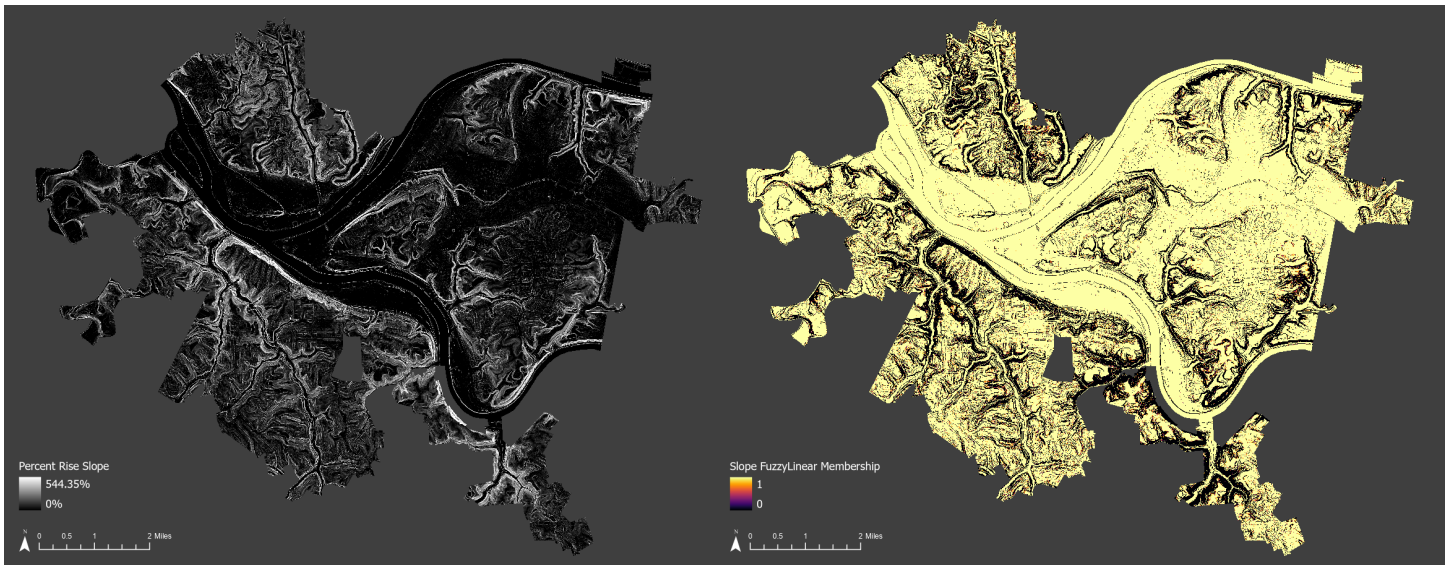


Fig. 7 – Example of a calculated percent rise slope raster and its conversion into a fuzzy membership raster using the Fuzzy Linear function. Data obtained from Allegheny County Division of Computer Services Geographic Information Systems Group [6, 7]. Reproduced here for educational purposes only.

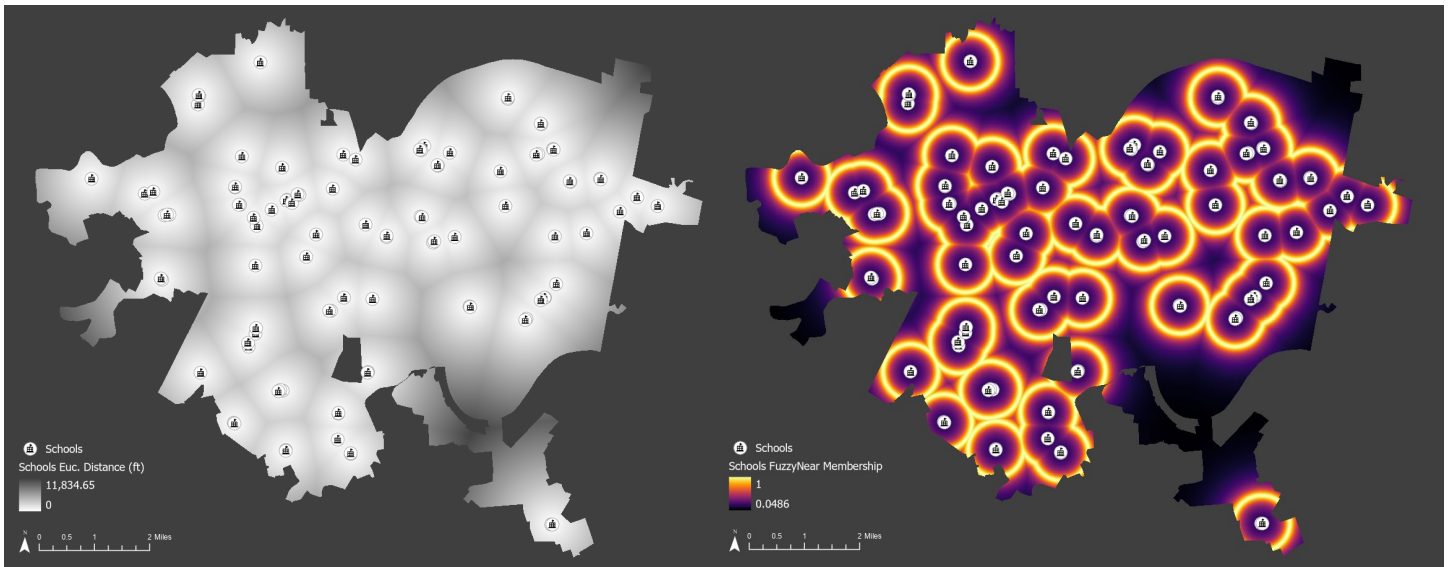


Fig. 8 – Example of a Euclidean distance from point features raster and its conversion into a fuzzy membership raster using the Fuzzy Near function. Data obtained from Allegheny County Division of Computer Services Geographic Information Systems Group [7] and Pittsburgh Public Schools [36].

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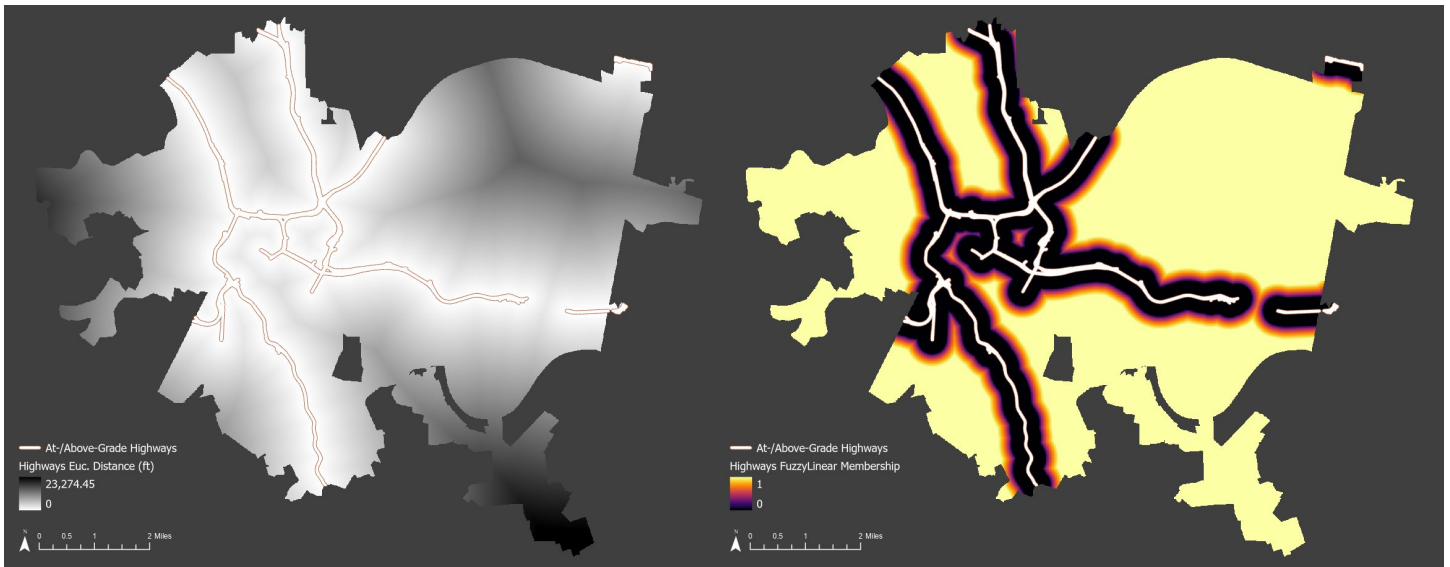


Fig. 9 – Example of a Euclidean distance from polyline features raster and its conversion into a fuzzy membership raster using the Fuzzy Linear function. Data obtained from Allegheny County [2] and Allegheny County Division of Computer Services Geographic Information Systems Group [7]. Reproduced here for educational purposes only.

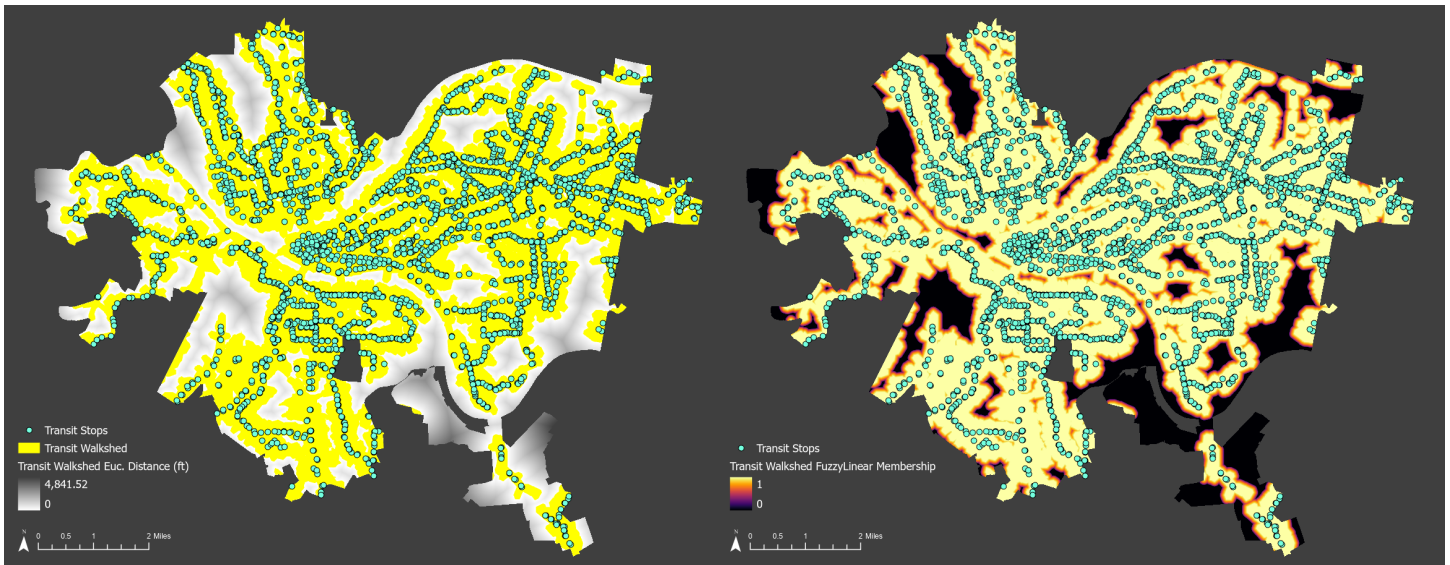


Fig. 10 – Example of a Euclidean distance from polygon features raster and its conversion into a fuzzy membership raster using the Fuzzy Linear function. Data obtained from Allegheny County Division of Computer Services Geographic Information Systems Group [7] and Port Authority of Allegheny County [38, 39]. Reproduced here for educational purposes only.

Finally, to combine the powers of both fuzzy logic and the weighted sum function in ArcGIS Pro, the tool multiplies each fuzzy membership raster by its weight parameter, sums the weighted fuzzy membership rasters together, and normalizes the values to a scale of 0–100 for better comparison between multiple iterations of the same analysis. Fig. 11 shows an example a normalized weighted sum output from the fuzzy membership rasters in Figs. 7–10. Using the “Inferno” color scheme in ArcGIS Pro, the areas most meeting the example criteria appear to be “glowing” with suitability.

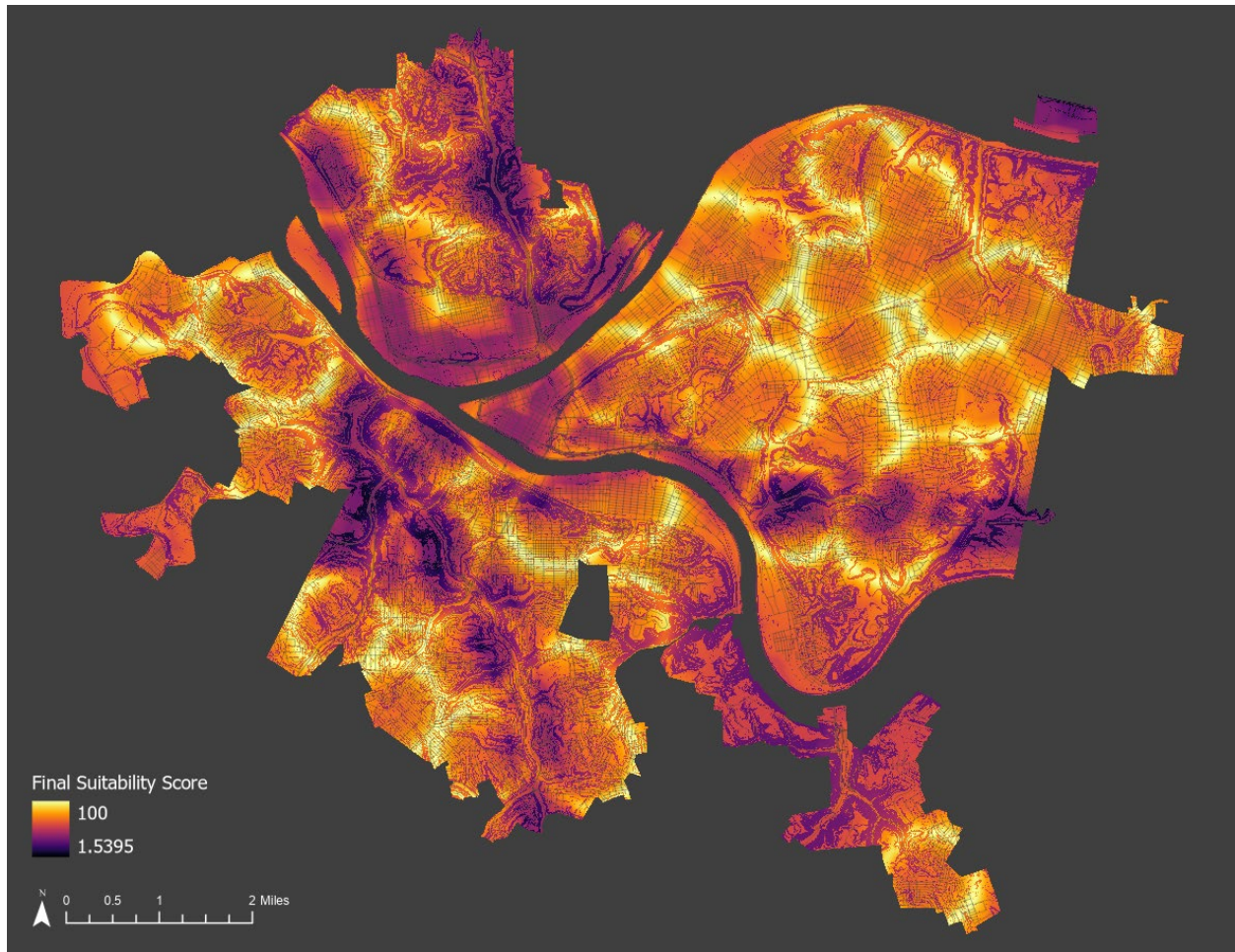


Fig. 11 – Example of the tool’s final, normalized weighted sum output raster, using the fuzzy membership rasters from Fig. 7–10. The areas that appear to be glowing yellow are those with the highest scores and thereby meet the example criteria the most. Data obtained from Allegheny County [2], Allegheny County Division of Computer Services Geographic Information Systems Group [5, 6, 7], Pittsburgh Public Schools [36], and Port Authority of Allegheny County [39]. Reproduced here for educational purposes only.

For curious or more experienced users, the Python code behind the tool also contains comments to describe nearly every line’s purpose. In addition, there are functions to validate layer names and change them as necessary, as well as print success, warning, and error messages to the tool’s

Messages window so users may see the tool's progress and determine where an error may have occurred.

Objective #2 – Apply the Tool to Answer Real-World Questions

To test my tool's flexibility, I applied it to two real-world scenarios a municipal GIS employee may face in their daily work in two locations: Pittsburgh, Pennsylvania, and Fayetteville, Arkansas. I chose these two cities as I currently live in and am familiar with Pittsburgh, where I have local knowledge and could subjectively assess the validity of the tool's outputs. I chose Fayetteville, a less populated city, as it covers nearly the same area as Pittsburgh, but it is in a different region of the United States, and I have no experience in or local knowledge of it [42, 43].

Objective #2 – Data Sources

I retrieved all my project data from open data portals, namely the Western Pennsylvania Regional Data Center and Pennsylvania Spatial Data Access for local data in Pittsburgh. I retrieved data for Fayetteville from the City of Fayetteville, Arkansas, and Arkansas Department of Transformation and Shared Services' Arkansas GIS Office websites. In addition, I also retrieved data on job centers for both cities from the U.S. Census Bureau's *OnTheMap* platform.

Objective #2 – Results

Determining Where to Hang Traps to Detect the Emerald Ash Borer

My first scenario was determining where to hang traps to detect the invasive, highly destructive emerald ash borer (EAB). It can be quite costly for municipalities to remove dead trees that have been infested by EAB [14], but hanging traps requires time, equipment, and personnel—all of which equal money—so identifying where vulnerable ash trees may be located, especially if an extensive tree inventory is not available, can save costs upfront. Table 1 shows the criteria, three layers, and

parameters I used for this test scenario that makes use of two of the seven total fuzzy membership functions. Pittsburgh's baseline raster was in the Pennsylvania State Plane South (Feet) projection and thereby required distance parameters to be entered in feet, whereas Fayetteville's baseline raster was in a Universal Transverse Mercator projection and required distance parameters to be entered in meters. Before using this tool in an actual trap placement exercise, one should consult subject matter experts to determine the best criteria for this purpose.

Table 1 – Criteria, layers, and parameters used to determine where to hang traps to detect the emerald ash borer.

Criteria	Layers	Function, Arg. 1, Arg. 2, Weight
Potential ash tree locations	Parks	Linear, 0.25 mi, 0 mi, 0.5
Near transit corridors	Streets with speeds \geq 45 mph	Small, 0.75 mi, 2.0, 2.0
Near other freight corridors	Railroads	Small, 0.75 mi, 2.0, 2.0

Figs. 12 and 13 show the results for Pittsburgh and Fayetteville, respectively. In both cities, the tool highlights areas that are proximate to highways and rail lines, while adding additional consideration for nearby parks, thereby reducing much of the costly legwork needed to examine the entire study area. A logical next step for the user would be to incorporate this final suitability raster as input in a zonal statistics calculation to determine exact properties that score well and would be worth investigating further.

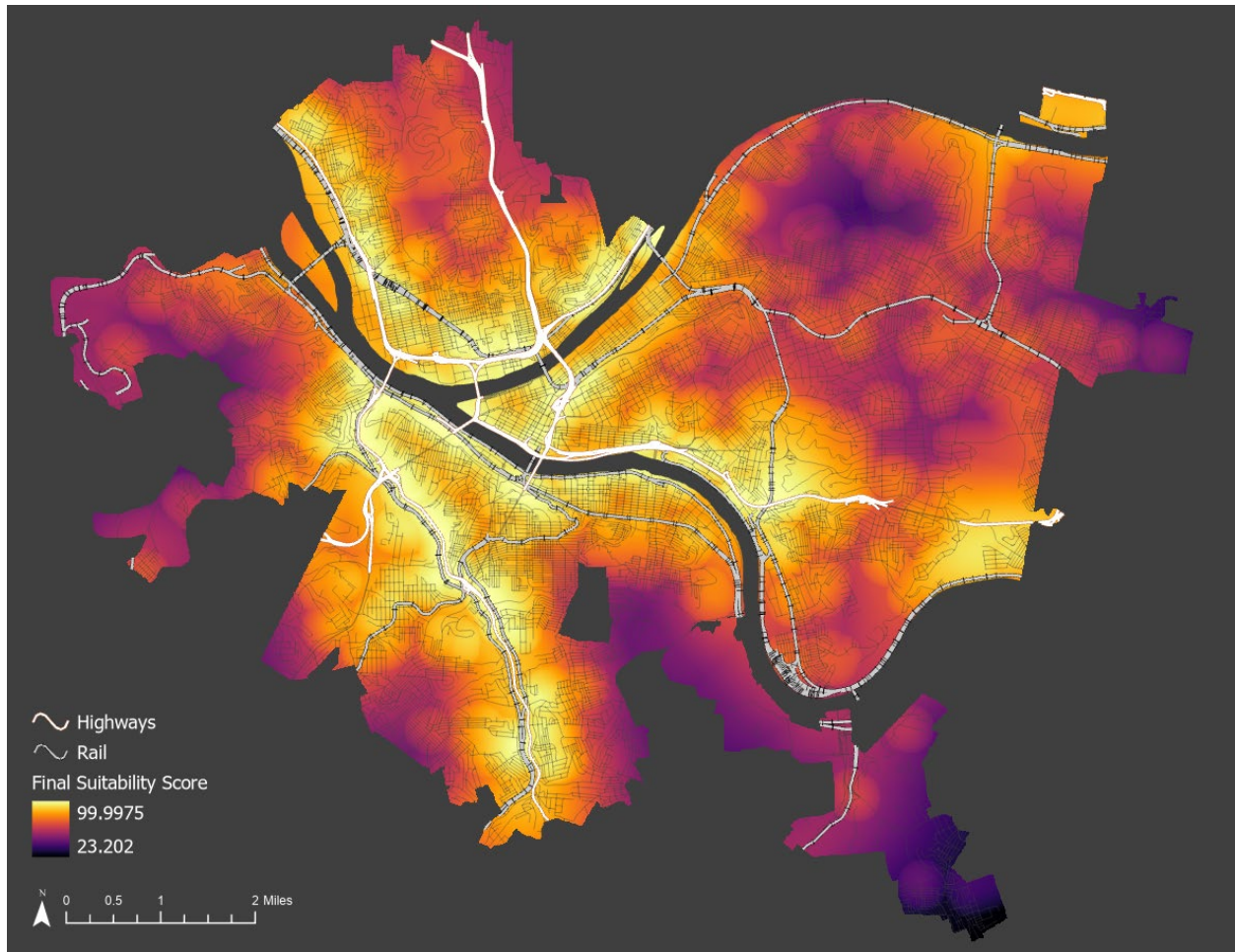


Fig. 12 – The tool’s final suitability raster of locations to consider for hanging traps to detect the emerald ash borer in Pittsburgh, Pennsylvania. Data obtained from Allegheny County [2], Allegheny County Division of Computer Services Geographic Information Systems Group [4, 5, 7], and City of Pittsburgh [19]. Reproduced here for educational purposes only.

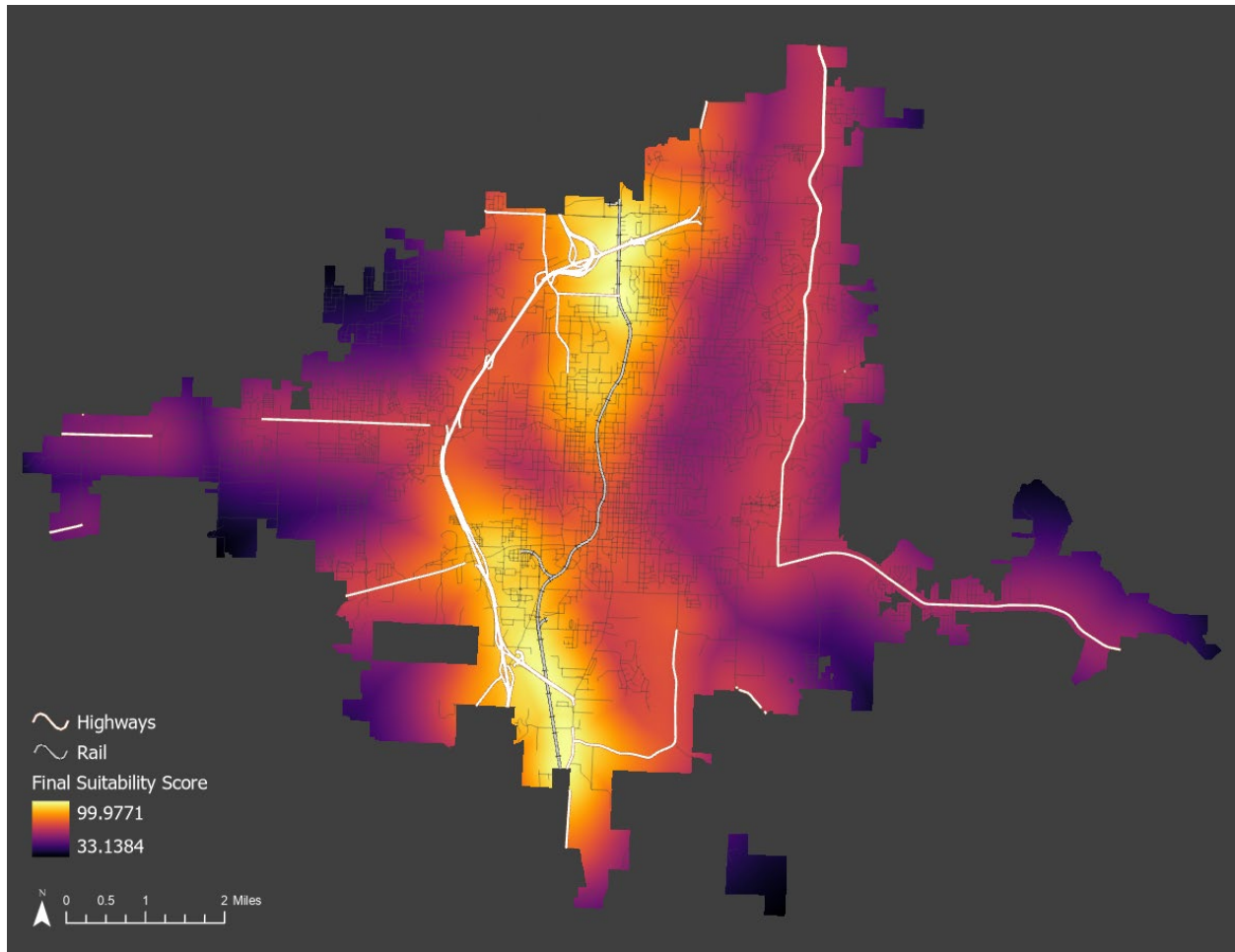


Fig. 13 – The tool’s final suitability raster of locations to consider for hanging traps to detect the emerald ash borer in Fayetteville, Arkansas. Data obtained from Arkansas Department of Transformation and Shared Services [9] and City of Fayetteville, Arkansas [15, 16, 18]. Reproduced here for educational purposes only.

Selecting Sites for an Affordable Housing Development

My second scenario was selecting sites for an affordable housing development. This is important as cities move such developments that were previously “out of sight, out of mind” into multi-use developments—mixing residential and commercial uses—and whose residents would be better served by incorporating cooling greenspaces [37]. Table 2 shows the criteria, seven layers, and parameters I

used for this test scenario that makes use of three of the seven total fuzzy membership functions. The same parameter unit conversions mentioned in the previous scenario also apply here. Before using this tool to guide any development, one should consult subject matter experts and the local community to determine the best criteria for this purpose.

Table 2 – Criteria, layers, and parameters used to select sites for an affordable housing development.

Criteria	Layers	Function, Arg. 1, Arg. 2, Weight
Near, but not in, major job centers	Top 10 job centers	Gaussian, 1 mi, 0.000005, 1.0
Accessible to transit	Transit stops/stations	Linear, 500 ft, 0 ft, 0.5
Near, but not next to, schools	Schools	Near 0.5 mi, 0.000005, 2.5
Not in food deserts	Grocery stores	Linear, 0.5 mi, 0 mi, 1.0
Buildable topography	Elevation (percent rise slope)	Linear, 25, 20, Weight: 2.0
Proximate to parks/greenspace	Parks	Linear, 0.75 mi, 0.25 mi, 1.0
Accessible to, but not along, major highways	Streets with speeds \geq 45 mph	Linear, 0.25 mi, 0.5 mi, 1.0

Figs. 14 and 15 show the results for Pittsburgh and Fayetteville, respectively. Pittsburgh appears to show areas of high suitability across the city, with some of the highest scores in the East End neighborhoods where such affordable housing development has already been underway. In Fayetteville, the areas of highest suitability are near the city center. As previously mentioned, an appropriate next step would be to apply these suitability rasters in a zonal statistics calculation to determine which properties, block groups, or neighborhoods warrant further local stakeholder engagement and on-the-ground investigation for potential development.

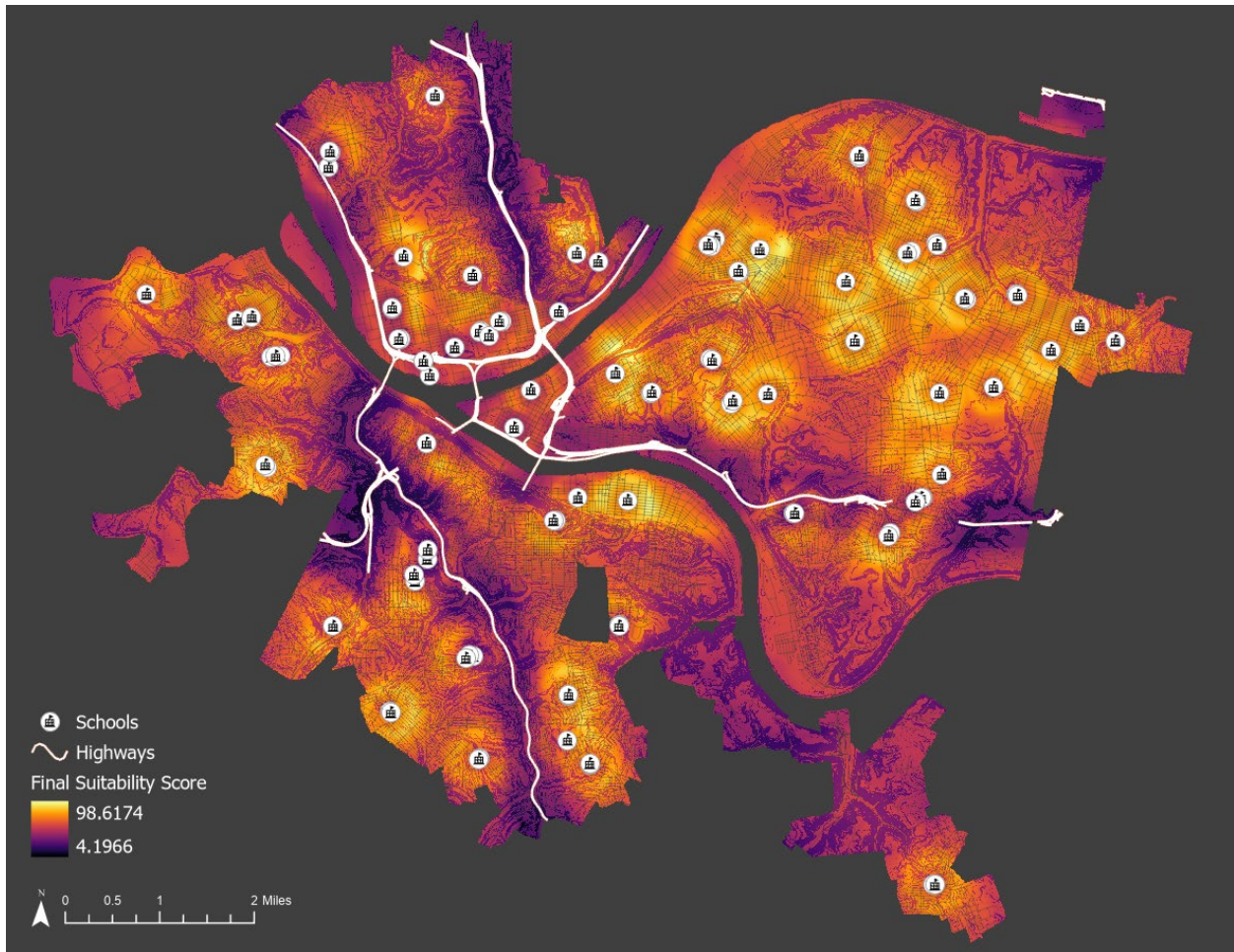


Fig. 14 – The tool’s final suitability raster of locations to consider investigating further for an affordable housing development in Pittsburgh, Pennsylvania. Data obtained from Allegheny County [2, 3], Allegheny County Division of Computer Services Geographic Information Systems Group [5, 6, 7], City of Pittsburgh [19], Pittsburgh Public Schools [36], Port Authority of Allegheny County [39], and U.S Census Bureau [41]. Reproduced here for educational purposes only.

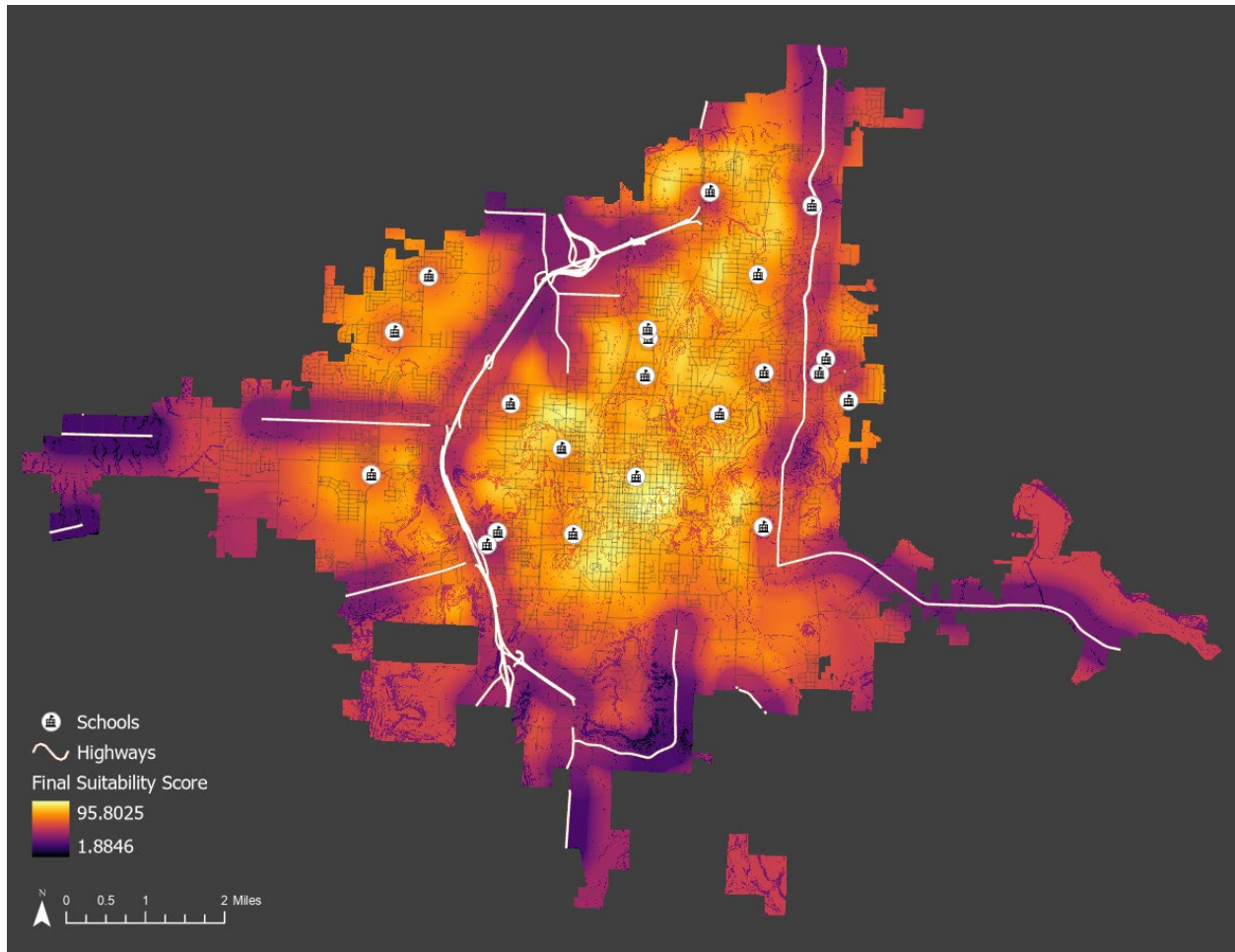


Fig. 15 – The tool’s final suitability raster of locations to consider investigating further for an affordable housing development in Fayetteville, AR. Data obtained from Arkansas Department of Transformation and Shared Services [8, 9], City of Fayetteville, Arkansas [15, 17, 18], Ozark Regional Transit [35], and U.S. Census Bureau [41]. Reproduced here for educational purposes only.

Challenges and Limitations

The challenges and limitations I faced in executing this capstone project were related to the tool’s integration into proprietary software. As previously mentioned, my original intent was to build this tool in ArcGIS Pro’s ModelBuilder to make it more easily decipherable by more novice users; however, that interface is not well suited for allowing a flexible number of inputs and parameters.

Instead, I scripted the tool in Python and included comments in the code to help curious users learn the purpose of each code block. Once the code was ready for configuration as a custom geoprocessing tool in ArcGIS Pro, I had to work within the confines of my own knowledge and the limitations of how a script tool's panel and input parameter types can be configured to allow a varying number of inputs. Because of this, the input layers are separate from their corresponding parameters on the tool's interface. To work around this limitation and make certain users enter the same number of layers and parameters, I configured the tool's metadata to show information on every parameter and added appropriate error messages in the Python script to be displayed in the tool's Messages window.

Next Steps

My next steps for this project are to engage with others interested in conducting user testing to identify and address any errors or tool validations I may have overlooked. Following my capstone presentation to my Penn State MGIS peers and faculty, two individuals have already reached out stating their interest, and I will be connecting with them in short order. Though the tool's interface can grow to be quite long depending on the number of input layers users enter, I would like to add an optional zonal statistics calculation. With this, users could select, e.g., a parcel layer and associate the tool's final output raster values with actual properties. Following this tool expansion and user testing, I would like to share the tool more widely with a broader audience through word of mouth, additional conference presentations, and potentially hosting it on GitHub if that is indeed an appropriate platform for this. If possible, I would like to share the tool with appropriate Esri staff for consideration in having it formally adopted into a future ArcGIS Pro update.

Conclusion

GIS professionals face an array of challenges when performing spatial analyses such as site selection. These challenges begin with the quality and overabundance of data and exist throughout the

decision-making process when determining each layer's importance in the analysis, incorporating stakeholder feedback, and navigating the expanse of knowledge and applicable tools that can help GIS professionals synthesize the information and make it accessible to their audiences. My project was to build a flexible, custom geoprocessing tool that combines the powers of fuzzy logic and automation in ArcGIS Pro version 2.9. I tested this tool in two scenarios in two different cities to demonstrate its ability to handle an array of analyses, for which fuzzy logic is suitable. By sharing my tool with a larger audience, I will fulfill my goal of making fuzzy logic more accessible to GIS professionals outside academia.

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