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New Jersey Urban Development: Identifying Optimal Regions within New Jersey's Pine Barren Forest for Urban Development Based on Wildfire Risk and the Wildland-Urban Interface Theory

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Abstract – Population growth in New Jersey has led to increased use of land for residential purposes in the wildland-urban interface (WUI) of the south-central Pinelands region. Due to this increase in human activity, coupled with local environmental conditions, local authorities are concerned about an increased possibility of wildfires that could damage both the area's infrastructure and ecosystem. To counteract this risk, it is necessary to develop methods for accurate wildfire assessment and mitigation efforts. This project partnered with the New Jersey Pinelands Commission (NJPC) to develop a Fire Risk Assessment Tool that identifies areas with high fire risk based on land cover characteristics. We incorporated vegetation indices derived from Landsat 8 Operational Land Imager (OLI) and Sentinel-2 Multi-Spectral Instrument (MSI), land-use classification derived from LANDFIRE data and elevation into a Fuzzy Logic model to generate a 30 x 30 m Fire Risk Assessment Map. The map was used to analyze fire susceptibility in the Pinelands WUI and to identify optimal areas for urban expansion. Fifty-three percent of the total area within the Pinelands WUI was classified as having a moderate fire risk, while high and extremely-high fire risk accounted for 13%. An estimated 200,000 acres of land with a low to moderate risk of fire were identified as areas that would be suitable for development. The results and maps produced will be used by the New Jersey Pinelands Commission to guide urban development planning and decision making.

I. Introduction

Background Information

The region where human infrastructure and natural vegetation are adjacent or interspersed with each other is known as wildland-urban interface (WUI) (Radeloff et al., 2005; Theobald & Romme, 2007; Stewart, Radeloff, & Hammer, 2007). The WUI areas are widely increasing across the United States (Stewart, Radeloff, Hammer & Hawbaker, 2003). New Jersey is one of the most densely populated states within the U.S., and in recent decades, migration to the state's Pinelands region has increased due to the desire for privacy, space, natural beauty, and recreational opportunities. With the expansion of the WUI, there is increasing fear of higher wildland fire frequency and the threat to life and property due to fire (Fox et al., 2015). As a result, the wildland fire policy is dedicated to fire prevention and preparedness projects primarily in the WUI region (USDA, 2002).

The Pinelands lie in the south-central portion of New Jersey, covering 22% of the state's total land at 1.1 million acres in Ocean, Atlantic, Cape May, Camden, Gloucester, Burlington, and Cumberland counties (Forman, 1998; Clark, Skowronski, Gallagher, Renninger, & Schäfer, 2012). The gently sloping terrain has a vegetative cover mainly consisting of pine and oak stands, including "pygmy" stands, or trees at approximately 11 feet or less in height (New Jersey Pinelands Commission, 2015). The soil of the Pinelands region is sandy and porous, allowing for rainwater to swiftly infiltrate and filter through the ground, leaving the surface in drier conditions (Clark et al., 2012). This low water retention capacity results in an increased susceptibility to wildfires (DeBano, 2000). In addition to high permeability, Pinelands soil is acidic so the litter on the forest floor does not readily decompose causing fuel load to accumulate (Ludlum, 1983). The Pinelands ecologically depend on natural occurrences of wildfire in order for seeds to begin germination, and thus wildfire is a naturally occurring phenomenon of the region. However, with the expansion of the WUI, there is increased concern about higher risk of forest fires due to the increase in human recreational activities and changes in vegetation (Cohen, 2000). Therefore, thorough measures for wildfire mitigation and preparation are crucial for the community and the agencies overseeing the Pinelands region.

New Jersey experiences approximately 1,500 forest fires annually (State of New Jersey Department of Environmental Protection, 2017). Since 2008, the New Jersey Pinelands Commission (NJPC) has collaborated with the New Jersey Forest Fire Service to improve wildfire mitigation planning and execution. This collaborative study targeted the high risk areas of Stafford and Barnegat municipalities in Ocean County. However, there is a need for more updated and widespread methods for risk analysis and wildfire mitigation throughout the region. This project studied the Pinelands region using data from January to December of 2017 to create a Fire Risk Assessment Tool and map using Fuzzy Logic modeling in ArcGIS. The variables used in the model include vegetation type, fuel load, soil moisture, topography, and housing density of the WUI. Studies in spatial analysis of forests and human activity indicate that "areas with dense clusters of buildings surrounded by forestland have the highest density of fire ignition" (Chas-Amil, 2013). Certain vegetation types are more susceptible to wildfire, requiring thorough analysis of vegetation cover. Considering the effect of topography on vegetation distribution, a higher risk of ignition is associated with lower elevation areas which tend to have abundant vegetation, and thus increased fuel load (Calviño-Cancela, 2017).

II. Project Partners & Objectives

We partnered with the NJPC, which oversees fire suppression and prevention within the New Jersey Pineland Reserve. A Fire Risk Assessment Map for the Pinelands area was developed in 1981, but with the influx of development that has occurred over the past 40 years, updated maps are necessary for proper management. In efforts to obtain updated information on the fire risk potential, the NJPC performs expensive and time consuming field assessments of vegetative conditions. While government funding for wildfire suppression has increased, the cost of fire suppression due to changes in climatic conditions and urban growth has increased as well, limiting the NJPC's ability to consistently monitor wildfire risk within the area (USFS, 2007).

The objectives of this project included identifying optimal areas within the WUI for urban development and locating areas where fire mitigation efforts should be allocated. The end products developed in this project will allow the NJPC to examine and update existing policies to better accommodate the changing environment in the pinelands region as population growth continues to increase.

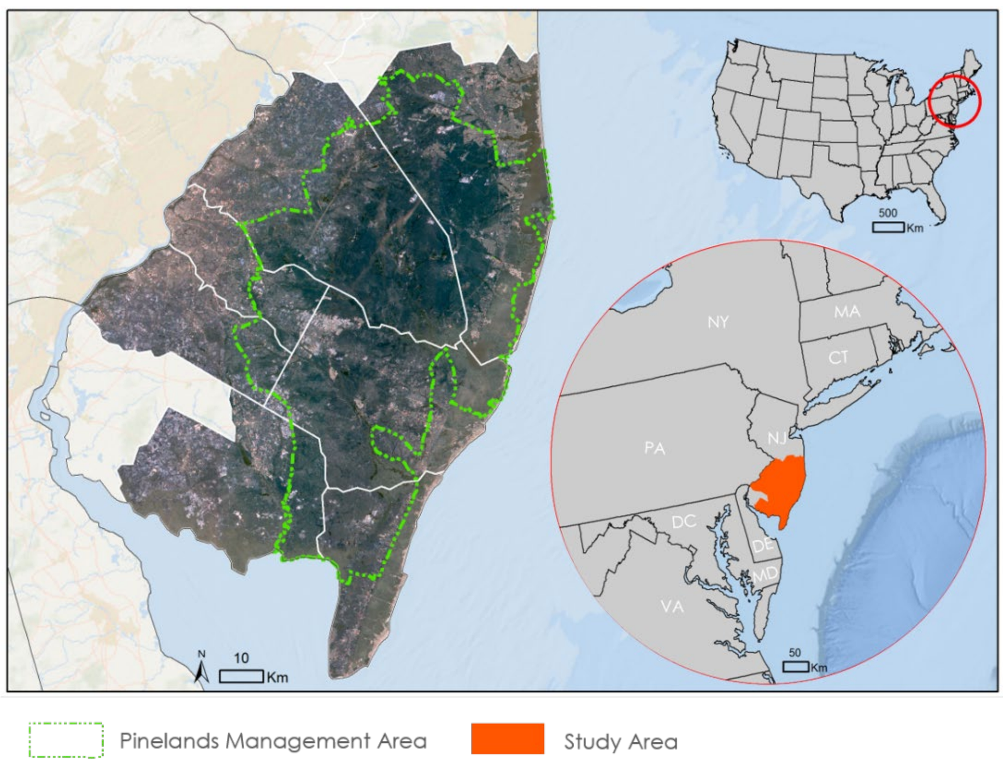

Figure 1. *New Jersey and Pinelands Management Areas*

III. Methodology

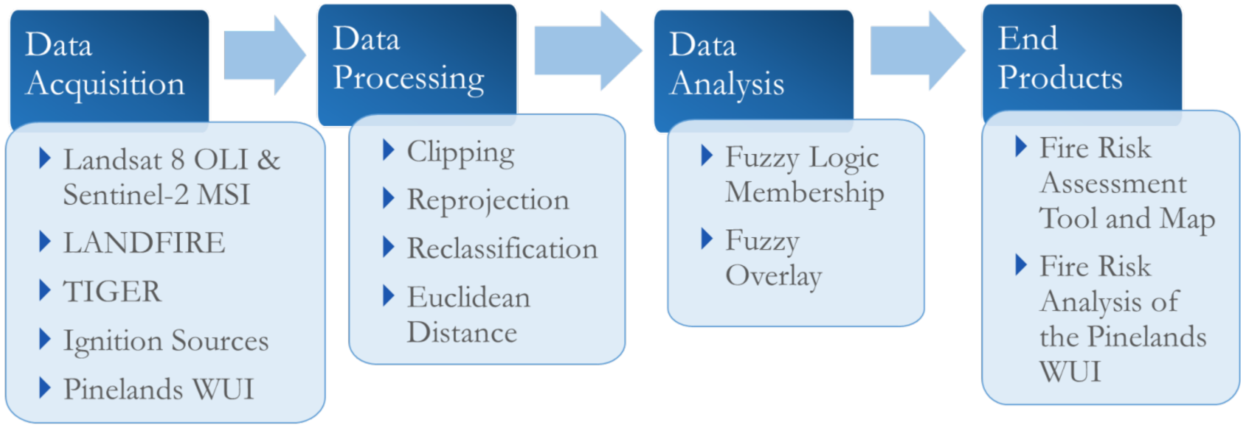

Figure 2. *Methodology for developing the fire risk in the New Jersey Pinelands*

Data Acquisition

We incorporated Sentinel-2 MultiSpectral Instrument (MSI) and Landsat 8 Operational Land Imager (OLI) data into this project. We acquired Sentinel-2 MSI Level 1C cloud free data for the year 2017 (April - November) from the United States Geological Survey (USGS) GloVis data portal. This included four tiles, T18SWJ, T18SVJ, T18TVK, and T18TWK, of Copernicus Sentinel-2 data 2017 covering the study area each with 13 spectral band layers. The data has a spatial resolution of up to 10 meters and a revisit time of 5 days. We also acquired cloud free Landsat 8 OLI data for several months (Feb/Jun/Jul/Oct/Dec) throughout 2017 in order to have a more complete understanding of the vegetation in the study area during the year. The data acquired from Landsat 8 OLI has a spatial resolution of up to 30 meters and a revisit time of 16 days. The data were collected from the GloVis data portal for the path (14)/row (32, 33) corresponding to the study area of southern New Jersey. We then used these data to derive vegetation and soil moisture indices for each month.

We obtained the Digital Elevation Model (DEM) data derived from high quality light detection and ranging (LiDAR) for the study area from USGS in the National Map-3D Elevation Program (3DEP) Data portal. The elevation data has a high spatial resolution of 1/9 arc second (3.4 meters). The total of 72 tiles of elevation datasets covering the study area dated from 2006 to 2011.

Table 1. *Summary of attributes of the acquired data*

Data Summary		
	Spatial Resolution	Temporal Resolution
Landsat 8 OLI	30 m	16 days
Sentinel-2 MSI	10 m	5 days
DEM	3.4 m (1/9 arc)	

We acquired vegetation data from the USGS LANDFIRE (LF) data portal. These data provided existing vegetation incorporating 89 different vegetation types. Vegetation type classifications were primarily derived from NatureServe Ecological Systems classification, alliances of the U.S. National Vegetation Classification, the National Land Cover Database and LF specific types.

The NJPC provided us with the zoning and management area shapefiles for the Pinelands. These data contained the Pinelands WUI extent. Similarly, the New Jersey Forest Service provided shapefiles of ignition sources and fire history for the Pinelands. This data included point locations of ignition sources for approximately five thousand fires over a 10-year period from 2008 through 2017 in the study area. The ignition source dataset detailed the location, acreage burned, and year of the fire. From the United States Census Bureau Topologically Integrated Geographic Encoding and Referencing System (TIGER)/Line Shapefiles data portal, we obtained NJ Roadway Network shapefiles. This dataset depicted the primary and secondary roads throughout the study area.

Data Processing

We mosaicked the USGS 3DEP data together to cover southern New Jersey and then clipped by the study area boundary to obtain the elevation for the area. This elevation layer was further processed to derive other topographical variables such as slope and aspect in ArcGIS.

The Euclidean distance tool calculated the distance from roads using the primary and secondary road shapefile. This tool provided how far away one road in the study area lies from others, so as to depict the area between major crossing roads. Within the area between roads, we assumed an increasing risk of wildfire with increasing distance from these major roads. Hereby, fire susceptibility increases with distance from major roads.

Each band from four tiles of Sentinel-2 MSI data and two tiles of Landsat 8 OLI data were mosaicked and processed to derive a Normalized Difference Vegetation Index (NDVI) and Tasseled Cap Wetness (TCW) for the leaf-on (Apr/May/Jun/Jul/Aug) and leaf-off (Feb/Sep/Oct/Dec) periods. NDVI is a graphical indicator of vegetation presence/abundance and vegetation health; TCW provides an indication of vegetation albedo and moisture content, which are additionally informative about vegetation health of the study area. Leaf-On refers to the growing season of the region during the aforementioned months, whereas Leaf-Off refers to the time period in which growing is minimal to nonexistent and deciduous trees are bare of leaves. The two time periods accounted for variation in fuel load availability as deciduous forests lose their leaves during the winter months and thereby provide a greater fuel load to burn. During the summer when deciduous forests regain their leaves, the increase in fuel load at both the surface and canopy leads to higher fire risk. We chose to use NDVI to analyze vegetation because it reflects the vegetation condition and health for the area, while TCW is associated with vegetation and soil moisture. Since soil moisture, and vegetation cover and condition play significant roles in wildfire occurrence, these variables had critical implication for the study. For NDVI, red (RED) and near infrared (NIR) bands were used from each earth observation data in raster calculator using **Equation 1** (Rouse, Haas, Schell & Deering, 1974; Deering, 1975). Similarly, TCW was derived using **Equation 2** which incorporated BLUE, GREEN, RED, NIR, and Shortwave Infrared (SWIR) bands (Baig, Zhang, Shuai & Tong, 2014).

$$(\mathbf{1})\ NDVI = (NIR - RED)/\ (NIR + RED)$$

$$(\mathbf{2})\ TCW\ =\ 0.1509(BLUE) + 0.1973(GREEN) + 0.3279(RED) + 0.3406(NIR) - 0.7112(SWIR1) - 0.4572(SWIR2)$$

After the calculations of NDVI and TCW, the indices were clipped to the study area. Then NDVI and TCW data for leaf-on and leaf-off periods were averaged using the respective months for each period. This process resulted in four final NDVI and TCW layers, one for each earth observation (Landsat 8 and Sentinel-2) and each time period.

We reclassified the LANDFIRE vegetation type data from 89 to 12 land classes. These classes included open water, sparsely vegetated, developed, exotic herbaceous, exotic tree-shrub, grasslands, conifer-hardwood, riparian, agricultural land, hardwood, conifer, and conifer-hardwood. Then we aggregated these vegetation types and ranked each from 1 to 9 based on fire susceptibility (**Table 2**). All of the input layers were re-projected to the North America Albers Equal Area Conic coordinate system for further analysis.

Table 2. *Land Use classifications from the LANDFIRE Vegetation Type dataset*

Land Use Classification (In Order of Fire Susceptibility)
Conifer
Conifer-Hardwood
Hardwood
Grassland
Exotic Herbaceous/Exotic Tree-Shrub
Sparsely Vegetated/Agriculture
Riparian
Developed
Open Water/Quarries/Gravel Pits/ Roads/Barren

Data Analysis

Fuzzy Logic uses the Fuzzy Membership to reclassify the data into values between 0 and 1 to which determine how the data impacts the associated risk. Fuzzy Logic recognizes that binary classifications of 0 and 1 are extreme cases, and there exist variations of the truth in between such extremes (for example, 0.45 as opposed to strictly 0 or 1). To ensure the proper Fuzzy Membership and midpoint (median) assignments, we examined the frequency of ignition sources occurring in several input variables, including NDVI, TCW, vegetation type, and elevation. Specifically, all of the layers were overlaid with ignition source point data to understand the relation between fire occurrences and the respective variable layers. We then identified the frequency of ignition sources occurring within a given range for each variable, and the range with the highest number of ignition sources was determined to be the midpoint for the variable. The analysis between the NDVI and ignition sources showed that a majority of ignition sources occurred at Sentinel-2 MSI's leaf-on NDVI value of 0.47, Sentinel-2 MSI's leaf-off NDVI value of 0.35, Landsat 8 OLI's leaf-on NDVI value of 0.70, and Landsat 8 OLI's leaf-off NDVI value of 0.58 (Figures A1-A4). These values were used as midpoints when assigning Fuzzy Membership. Similarly, the examination between the elevation and ignition sources showed that a majority of ignition sources occurred in the range of 10 – 30 meters above sea level, with a sharp decline in ignition sources as the maximum elevation exceeds 30 meters (Figure B1). This result is likely due to increased vegetation abundance in lower elevation areas, and thus an increased fuel load in these low-lying areas. As elevation increases and vegetation abundance decreases, the risk for ignition decreases.

We used the fuzzy memberships "Near" and "Linear" based on the relation of variables with ignition sources and expert opinion from NJPC (**Table 3**). The NDVI and elevation were assigned "Near" memberships, while TCW, vegetation types, and distance to roads were assigned "Linear" memberships as their relationship with ignition sources were directly proportional. The "Near" membership demonstrated that the NDVI and elevation had the highest risk of fire at the midpoint value, and the risk decreased as values deviated from the midpoint. For elevation, values closest to 20-30 meters had a high fire risk, with a sharply decreasing fire risk for higher or lower elevations. High fire risk was assigned to the low TCW values that correspond to very dry areas, and low fire risk was assigned to the high TCW values that correspond to areas rich in moisture. Vegetation types received the "Linear" membership considering the ranking of fire susceptibility for class, as was shown in Table 1. For example, conifer forests were properly designated as high fire risk area and open water/barren/roads as low fire risk area.

Table 3. *Variables, and their assigned Fuzzy Membership, that were incorporated into Fire Risk Assessment Map*

Variable	Data Source	Spatial Resolution	Temporal Resolution	Date Published	Fuzzy Membership
Elevation	NLCD 3DEP	3.4m	-	2006-2011	Near (29)
NDVI Leaf On	Landsat 8 OLI	30m	16 Days	2017	Near (0.7)
NDVI Leaf On	Sentinel-2 MSI	10m	5 Days	2017	Near (0.47)
NDVI Leaf Off	Landsat 8 OLI	30m	16 Days	2017	Near (0.58)
NDVI Leaf Off	Sentinel-2 MSI	10m	5 Days	2017	Near (0.35)
TCW Leaf On	Landsat 8 OLI	30m	16 Days	2017	Linear
TCW Leaf On	Sentinel-2 MSI	10m	5 Days	2017	Linear
TCW Leaf Off	Landsat 8 OLI	30m	16 Days	2017	Linear
TCW Leaf Off	Sentinel-2 MSI	10m	5 Days	2017	Linear
Vegetation Types	LANDFIRE	30m	-	2014	Linear
Distance from Roads	TIGER	Line	-	2017	Linear

Understanding how roads affect the wildfire risk was challenging given that it is assumed to have both positive and negative associations with fire risk. One of the most common ignition sources was cigarette butts being tossed from primary and secondary roads, landing in relatively dry shrubbery along road sides, and igniting. This would lead to the assumption that closeness to roads has a higher fire risk than being further away, but these types of fires are generally not likely to spread due to the ease of access and containment by fire services. On the contrary, the increase in distance from roads increases the difficulty for fire rescue workers to access and combat potential wildfires. Based on this concept, distance from roads was assigned a "Linear" membership, where areas farther away from the road had a higher fire risk than areas near roads.

With all the datasets assigned a Fuzzy membership, we used the Fuzzy Overlay tool in ArcMap to incorporate each dataset into the model. The model weighed each variable based on its fire risk susceptibility, as determined by the assigned fuzzy memberships. In the Fuzzy Overlay tool there are various overlay types or methods which combine the Fuzzy data layers based on a given set theory analysis for each method. We selected the Gamma function method as it is an algebraic product of the Sum and the Product functions, each raised to the power of gamma (ESRI, 2016). As a result, is it a compromise between the increasing effect of sum and the decreasing effect of Product. By incorporating all of the variables into the Fuzzy Overlay tool, a Fire Risk Assessment Map was generated for the study area. The final map produced had a scale of 0 to 1, with 0 being the lowest fire risk and 1 being the highest fire risk. We classified the scale into five equal intervals, extremely low, low, moderate, high, and extremely high. The ModelBuilder in AcGIS incorporated all of these variables and/or processes to develop a Fire Risk Assessment Tool for NJPC to generate updated fire risk maps in future.

We used the Fire Risk Assessment Map for analyzing the fire risk of the Pinelands WUI. Based on the needs of the NJPC, four categories of the Pinelands Management Area that are more capable of accommodating development were selected for this analysis. This Pinelands WUI included the regional growth areas, pinelands villages, pinelands towns, and rural development areas. We clipped the Fire Risk Assessment Map to the Pinelands WUI to analyze the different fire risk classifications within the area.

IV. Results & Discussion

Analysis of Results

The Fuzzy Logic Model generated a 30-meter resolution Fire Risk Assessment Map for the year (**Figure 3**). Of the study area, 13% was classified at high and extremely high fire risk, while 52% was classified moderate fire risk, 20% at low fire risk, and 15% at extremely low fire risk. The extremely low fire risk areas included the open water, barren lands, mine gravel pits, roads, and some of the developed regions. The extremely high fire risk category included the pine barren forest, which lies mostly in the preservation area of Pinelands.

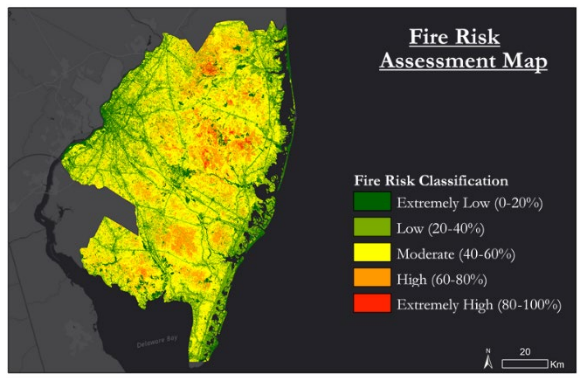

Figure 3. *Fire Risk Assessment Map for southern New Jersey classified in five equal intervals from low to high (on a scale of 0 to 100 from the original scale of 0 to 1 used in the Fuzzy Overlay).*

The analysis of Pineland WUI showed that all four regions have a majority of their areas in low and moderate fire risk (**Table 4**; **Figure 4**). The extremely high fire risk areas in the Pinelands WUI accounts for less than 0.5% of the total area.

Table 4. *Fire risk analysis of the Pinelands WUI*

Pinelands WUI	Total Area(acres)	Fire risk Area within Pinelands WUI (acres)				
		Extremely Low	Low	Moderate	High	Extremely High
Regional Growth Area	126028.9	25197.3	29767.5	59672.8	11284.3	107.0
Rural Development Area	125245.9	10789.9	17679.5	78170.1	18499.2	107.2
Pinelands Villages	26128.5	3069.5	4603.6	12295.1	6012.4	147.9
Pinelands Town	24524.3	5388.4	5707.1	10825.9	2579.8	23.1

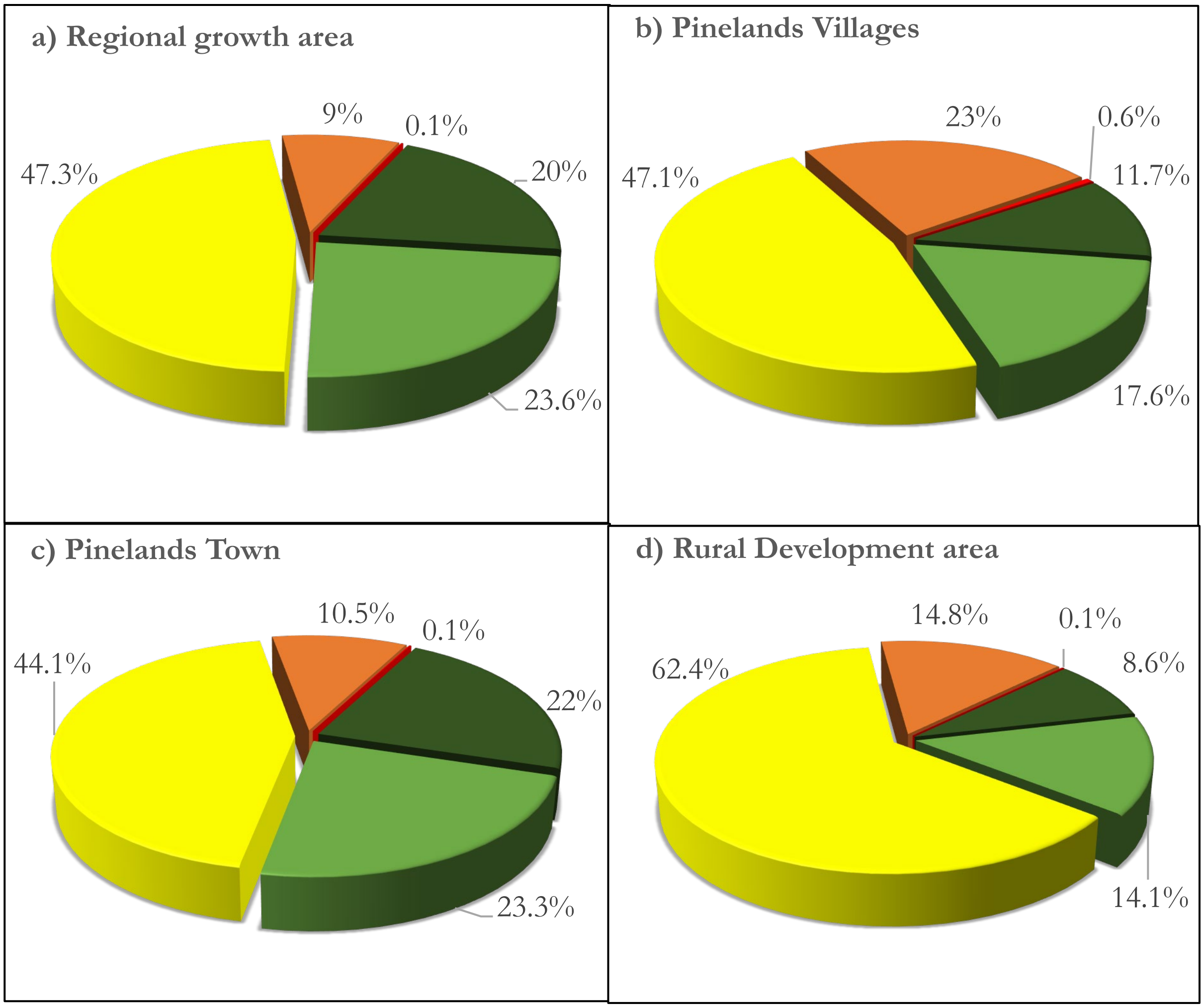

Figure 4. *Fire risk analysis of the regional growth area **(a)**, Pinelands villages **(b)**, Pinelands town **(c)**, and rural development area **(d)** within the pinelands management area. This shows that less areas are under higher fire risk and more areas in low and moderate fire risk.*

Future Work

In this paper we report the calibration of the Fire Risk Assessment model but not its validation. In the future, ignition source data from 2018 (and years following) can be overlaid with the Fire Risk Assessment Map to validate its accuracy in predicting areas of high and extremely high fire risk. The Pinelands WUI boundary data were from 2014, making the extent of the current Pinelands WUI unknown. A fire risk analysis of the Pinelands WUI should be updated once current WUI boundaries become available. Higher resolution climate data, and other edaphic or topographic variables can be incorporated to more accurately assess the wildfire risk of the Pinelands. As more updated data become available in the following years, the project partner can input it into the Fire Risk Assessment Tool and generate updated Fire Risk Assessment Maps. Moreover, the NJPC can utilize this fire risk analysis of the Pinelands WUI to identify areas within the Pinelands to expand urban development.

V. Conclusions

A majority of the Pinelands WUI lie in low and moderate fire risk zones, which are considered to be suitable areas for development. The areas in the high and extremely high fire risk zones primarily lie in the Pinelands Preservation Area. However, within the Pinelands Preservation Area development is not permitted.

The most recent fire risk analysis of the New Jersey Pinelands was conducted in 1981 by the NJPC. Given the 36 year time difference, we discovered discrepancies in fire risk between the 1981 map and the newly generated 2017 map. The 2017 map displayed considerably more areas lying in moderate fire risk than the 1981 fire risk map. The latter map showed the majority of the Pinelands in moderate to extreme fire hazard zones, with moderate zones outlining the northwestern region of the Pinelands. In the 2017 map, the majority of the study area lies in moderate risk zones, with high and extreme fire risks in isolated areas of the Pinelands. Reasons for these discrepancies are uncertain, but it could be due to changes in vegetation cover of the Pinelands area, expansion of the roadway network, and perhaps the lack of data in 1981 displaying false levels of high fire risk.

As population in the region continues to grow the areas of each fire risk area may change, becoming more or less severe than in recent years. The NJPC can use the end products provided by this project for decision making in planning and developing areas within the Pinelands WUI. The Fire Risk Assessment Map will help the NJPC to target areas for increased wildfire mitigation and to determine areas most suitable for urban development based on low fire risk. Moreover, the project partner will be able to produce updated ire risk assessments maps by using the Fire Risk Assessment Tool as new data becomes available.

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References

Baig, M. H. A., Zhang, L., Shuai, T., & Tong, Q. (2014). Derivation of a tasselled cap transformation based on Landsat 8 at-satellite reflectance. *Remote Sensing Letters*, *5*(5), 423-431.

Calviño-Cancela, M., Chas-Amil, M. L., García-Martínez, E. D., & Touza, J. (2017). Interacting effects of topography, vegetation, human activities and wildland-urban interfaces on wildfire ignition risk. *Forest Ecology and Management*, *397*, 10-17. doi:10.1016/j.foreco.2017.04.033

Chas-Amil, M. L., Touza, J., & García-Martínez, E. (2013). Forest fires in the wildland–urban interface: a spatial analysis of forest fragmentation and human impacts. Applied Geography, 43, 127-137.

Clark, K. L., Skowronski, N., Gallagher, M., Renninger, H., & Schäfer, K. (2012). Effects of invasive insects and fire on forest energy exchange and evapotranspiration in the New Jersey pinelands. *Agricultural and Forest Meteorology*, *166*, 50-61. Retrieved from https://www.sciencedirect.com/science/article/pii/S0168192312002419

DeBano, L. F. (2000). The role of fire and soil heating on water repellency in wildland environments: a review. *Journal of Hydrology*, *231*, 195-206. Retrieved from https://www.sciencedirect.com/science/article/pii/S0022169400001943

Deering, D. W. (1975). *Measuring" forage production" of grazing units from Landsat MSS data*. In Proceedings of the Tenth International Symposium of Remote Sensing of the Envrionment, 1169-1198.

ESRI. (2016). ArcGIS for Desktop: How Fuzzy Overlay works. Retrieved from http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/how-fuzzy-overlay-works.htm

European Space Agency. (2015). Sentinel-2 Data [Data set]. Geoscience Australia. https://doi.org/10.4225/25/566a407cd2e2b

Forman, R. T. (Ed.). (1998). Pine Barrens: Ecosystem and landscape. Rutgers University Press, New Burnswick, New Jersey.

Fox, D. M., Martin, N., Carrega, P., Andrieu, J., Adnès, C., Emsellem, K., & Fox, E. A. (2015). Increases in fire risk due to warmer summer temperatures and wildland urban interface changes do not necessarily lead to more fires. *Applied Geography*, *56*, 1-12.

Ludlum, D. M. (1983). *The New Jersey weather book*. New Brunswick, NJ: Rutgers University Press. Retrieved January 31, 2018, from https://climate.rutgers.edu/stateclim_v1/njclimoverview.html.

Martinuzzi, S., Stewart, S. I., Helmers, D. P., Mockrin, M. H., Hammer, R. B., & Radeloff, V. C. (2015). The 2010 wildland-urban interface of the conterminous United States. *Research Map NRS-8. Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station. 124 p. [includes pull-out map]. 8*, 1-124.

New Jersey Pinelands Commission (NJPC). (2015). The Pinelands National Reserve. Retrieved January 24, 2018, from http://www.nj.gov/pinelands/reserve/

New Jersey Department of Environmental Protection. (2017). Wildfire Danger Levels & Restrictions. Retrieved from http://www.state.nj.us/dep/parksandforests/fire/firedanger-restrictions.htm

Radeloff, V. C., Hammer, R. B., Stewart, S. I., Fried, J. S., Holcomb, S. S., & McKeefry, J. F. (2005). The wildland–urban interface in the United States. *EcoLogical applications, 15*(3), 799-805. doi:10.1890/04-1413

Rouse, J. W., R. H. Haas, J. A. Schell, and D. W. Deering (1973) *'Monitoring vegetation systems in the Great Plains with ERTS',* Third ERTS Symposium, NASA SP-351 I, 309-317.

Stewart, S.I., Radeloff, V.C., & Hammer, R.B. (2003). *Characteristics and location of the wildland urban interface in the United States*. In Proceedings of the Second International Wildland Fire Ecology and Fire Management Workshop, November 16–20. Orlando, FL. Retrieved from https://www.researchgate.net/publication/237434606

Stewart, S. I., Radeloff, V. C., Hammer, R. B., & Hawbaker, T. J. (2007). Defining the wildland–urban interface. *Journal of Forestry*, *105*(4), 201-207. Retrieved from http://fpf.forestry.oregonstate.edu/system/files/Stewartetal_definingWUI.pdf

Theobald, D. M., & Romme, W. H. (2007). Expansion of the US wildland-urban interface. *Landscape and Urban Planning*, *83*, 340e354. Retrieved from http://dx.doi.org/ 10.1016/j.landurbplan.2007.06.002.

US Department of Agriculture, US Department of the Interior, National Association of State Foresters, And National Association of Counties. (2002). *National Fire Plan Memorandum of Understanding for the Development of a Collaborative Fuels Treatment Program*. Available at www.fireplan.gov.

US Forest Service. 2007. Fiscal Year 2007 Budget Justification. Available online at www.fs.fed.us/publications/budget-2007/fy2007 - forest-service-budget-justification.pdf; last accessed Dec. 27, 2008.

U.S. Geological Survey Earth Resources Observation and Science Center. (2014). Provisional Landsat OLI Surface Reflectance [Data set]. U.S. Geological Survey. https://doi.org/10.5066/f78s4mzj