Using a landscape permeability metric to assess the impacts of different residential land development patterns on ecological connectivity in Chittenden County, VT

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ABSTRACT: Facilitating the movement of organisms across a landscape is a key aspect of land conservation. The ability of organisms to move within a region is important for organisms with large range sizes, organisms that migrate, or organisms that are experiencing range shifts due to climate change. Connectivity is also essential for retaining genetic diversity and preventing inbreeding depression, which can reduce the resiliency and health of species' populations. Patterns of residential development can have profound impacts on the connectedness of a landscape, making it imperative that development take place in an ecologically responsible manner. The state of Vermont has defined "smart growth" as development that takes the form of a central, high-density "village area" surrounded by largely intact agricultural, forestry, or undeveloped (or restored) land to combat the conversion of habitat areas to developed use. To combat development sprawl and keep rural lands intact, in the early 1990s Vermont passed Act 200, which aims to promote this smart pattern of development. This integrative thesis, which is focused in the subjects of biology and geography, attempts to determine the impacts of different residential zoning strategies implemented by four different towns in Chittenden County, Vermont, on landscape connectivity, using a landscape permeability metric as the main means of comparing the towns. This research provides tentative support for a pattern of high-density development in a town's central downtown area combined with limited development in residential clusters (rather than low-density development) in more rural districts.

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I. Introduction

Vermont and the Threat of Sprawl

Agricultural and undeveloped (or restored) lands are central to the economy and character of many towns in Vermont. Farming and forestry have long been central industries in the state, and outdoor recreation in rural areas serves as a draw for tourists and residents alike. Keeping lands that fall under these use categories largely intact is a primary statewide planning goal (Vermont Natural Resources Council, 2021). Preserving working or rural lands while keeping residential development mainly in a compact, walkable village area—a development strategy which the Vermont Natural Resources Council (2021) defines as “smart growth”—was historically the standard town development pattern in Vermont.

However, from the mid 20th century onwards, there has been a marked increase in residential sprawl in Vermont. A post-World War II population boom led to a high rate of low-density, single family residential development in the state. From 1950 to 1990, suburbs accounted for 60 percent of the state’s population growth (*Exploring Sprawl,* Number 6, 1999). Residential sprawl constitutes a very real threat to maintaining working and rural lands, and Vermont residents were concerned to see that rural residential development and agricultural subdivision were on the rise (*Exploring Sprawl,* Number 1, 1999).

Even to Vermonters who value the principles behind smart growth, there is great appeal to live outside of a town center on their own land. A survey of Vermont residents (a majority of whom reported supporting a pattern of “smart” land development) found that "respondents were also given a hypothetical choice between buying a $100,000 home in an urban or village area close to public transportation, work and shopping or a larger home in an outlying area with longer commutes and more yard space. Overall, 21% of the respondents chose the home in the urban or village area and 74% chose the home in the outlying area" (*Exploring Sprawl*, Number 1).

To combat sprawl, in 1988 the state passed Act 200, growth management legislation that encourages development in the form of compact village and urban centers surrounded by largely intact rural and agricultural landscapes (Vermont Natural Resources Council, 2021). The act prompted Vermont towns to develop plans that aligned with the goals of Act 200. However, the process of responding to sprawl and regulating development is complex and involves many factors, including attractive downtown living, municipal infrastructure availability, community opinion, and effective zoning and subdivision regulations. In some towns, high-density village center development has not been strongly incentivized or is not possible with current infrastructure (F. Ingulsrud, personal communication, January 26, 2021). In addition, many towns that adopted strong management techniques were affected by low-density development before stronger regulations were in place.

Population growth in the state has slowed over the past three decades, but one area of Vermont that continues to feel development pressure is Chittenden County: the county which includes the city of Burlington, Vermont’s largest urban center. From 1990 to 2000, Chittenden County’s population grew 11.2 percent, while Burlington's population declined -0.7 percent (Center for Rural Studies, 2003). Chittenden continued to grow in the 21st century. Chittenden County accounted for nearly 60 percent of statewide growth from 2000 to 2010 (Klyza and Trombulak, 2015). Statewide growth levels in Vermont between 2010 and 2018 were paltry, but growth *within* the state occurred mainly in towns within a 50-mile radius of Burlington (Petenko, 2019). This growth continues to threaten Vermont’s desire for traditional, village-style development patterns. Between 2000 and 2010, growth in rural communities outpaced growth in urban areas in the state of Vermont (Bolduc and Kessel, 2008).

As with the growth patterns that can be seen in the Burlington region, movement from urban centers to smaller bedroom communities within commuting distance to a city can lead to substantial land use change. Between 2000 and 2010, developed land in Vermont increased while the total amount of agricultural land declined (Bolduc & Kessel, 2008). The Forest Service reported that Chittenden County lost more than 5 percent of its forested lands between 1997 and 2008 (Bolduc and Kessel, 2008). Residential development that spreads outward from an urban center can steadily transform a landscape that represents a diverse mosaic of land use types into a largely developed region with only remnants of previous uses still present (Dupras et al., 2016). Growth in bedroom communities often correlates with substantial decrease in agricultural land (Hailu & Rosenberger, 2004), a trend currently exhibited in Vermont (Bolduc & Kessel, 2008). Development consisting of low-density, single-family houses has also been shown to correlate to significant decreases in the ecological functionality of forested landscapes (i.e. the ability of a forest to support or maintain the structure, stability, or productivity of an ecosystem, prevent secondary extinctions, and maintain its role in major biogeochemical cycles [Brodie et al., 2018]). These negative impacts are largely the result of development decreasing effective mesh size: the probability that two randomly chosen points on a landscape are within a connected patch of forest) and patch cohesion, while increasing patch density as patches are fragmented (Gounaridis et al., 2020).

Ecological Implications of Zoning Patterns

Residential development may be high-density or low-density in nature. Density of development involves the size of developable units and the number of dwellings per unit, with high-density zoning allowing smaller unit sizes with more dwellings per unit. In theory, low-density residential growth (generally, 1 unit per 2.5 - 10 acres, as defined by Robinson et al. (2005)) should keep homes few and far between, leaving large swaths of undeveloped land between dwellings, and low-density development has been used as a conservation strategy in the past. However, low-density zoning may actually encourage sprawl and highly fragment and convert habitat areas (Robinson et al., 2005). The potential risks of this type of development therefore clearly do not align with Vermont's "smart growth" principles.

Clustered development patterns provide an alternative to low-density development. Cluster development involves siting homes in a high-density arrangement, using a small amount of a total unit of developable land for building and road development, while preserving the rest of the land in a relatively undeveloped manner (Wilson & Appiah-Opoku, 2011). Cluster development is often used to provide a sense of community to residents through proximity and shared use of conserved open spaces (Wilson & Appiah-Opoku, 2011). Clustering homes often yields economic benefits to developers: clustered developments save on infrastructure costs such as roads, sewers, and utility lines (Pejchar et al., 2007). Proximity to open public spaces also typically leads to higher property values (Geoghegan, 2002), yielding financial benefits both residents and developers.

In addition, the preservation of open spaces due to clustering homes often has positive ecological implications and may facilitate species movement across landscapes (Pejchar et al., 2007). Research indicates that clustered developments conserve landscape connectivity better than low-density housing developments (Park et al., 2014), and putting homes nearer to one another reduces the area of a development's total zone of influence (ZOI). The ZOI is the zone around buildings in which only very human-tolerant species will move freely. In cluster-form zoning, the ZOIs of buildings typically overlap, which decreases the total area covered by ZOIs in a housing development (Odell et al., 2003). Clustering developments therefore results in less interrupted use of habitat and resources in areas nearer human settlements (Maletzke et al., 2017). Cluster development aligns well with the desire for a central developed area surrounded by working and rural lands in Vermont. This type of development resonates with the idea of largely limiting residential development to a central, high-density "village" while conserving land elsewhere in the town area and potentially represents the most acceptable form of residential development in more rural areas of a town (Theobald et al., 1997).

There are many benefits associated with a less interrupted habitat like that which can result from cluster development. This lower level of interruption results in a more ecologically connected landscape, meaning that animals can move across an area with greater ease. Facilitating the movement of organisms through a landscape is an essential facet of landscape conservation. Fragmentation of landscapes, or the reduction in habitat area and isolation of habitat patches due to human development, has deleterious impacts on biodiversity, gene flow, and overall persistence of species populations (Saunders et al., 1991).

Loss of landscape connectivity and forest cover often leads to negative effects on biodiversity (Almeida-Rocha et al., 2020). Isolation of populations, which often results from fragmentation, can lead to reduced population growth rates (Fahrig & Merriam, 1985; Steffan-Dewenter & Tscharntke, 1999). Genetic drift and inbreeding depression within populations have been shown to correlate with degree of isolation from other populations (Delaney et al., 2010;

Richards, 2000), while maintaining connectivity facilitates gene flow between populations, enhancing the diversity of the gene pool and preventing inbreeding depression and genetic drift (Halsey et al., 2015).

Landscape connectivity is also an important facet of preparation for a warmer climate in the future. Increasing temperatures has already led to range shifts for many creatures (Devictor et al., 2012; Hickling et al., 2006), and a permeable matrix may aid access to new habitable territory as elevational or poleward shifts occur. Landscape connectivity paired with protected area coverage may spur community resilience in the face of climate change by allowing organisms to move to new suitable habitats.

Chittenden County: The Ecological Impacts of Four Towns' Development Decisions

This study compares the ecological implications of development patterns four towns from Chittenden County, using an ecological measure of landscape connectivity as the main means of comparison.

Fig. 1. An image of the four study towns from Chittenden county.

The four towns compared herein are Hinesburg, Jericho, Milton, and Williston (**Fig. 1**). All towns were impacted by Vermont's population boom in the late 20th century and are within reasonable commuting distance (less than a 20-mile drive) to Burlington. Each of these towns adopted or updated their town plans and zoning regulations in response to Act 200. However, their actions and capabilities in this regard differed significantly from one another (as detailed below in the following four sub-sections).

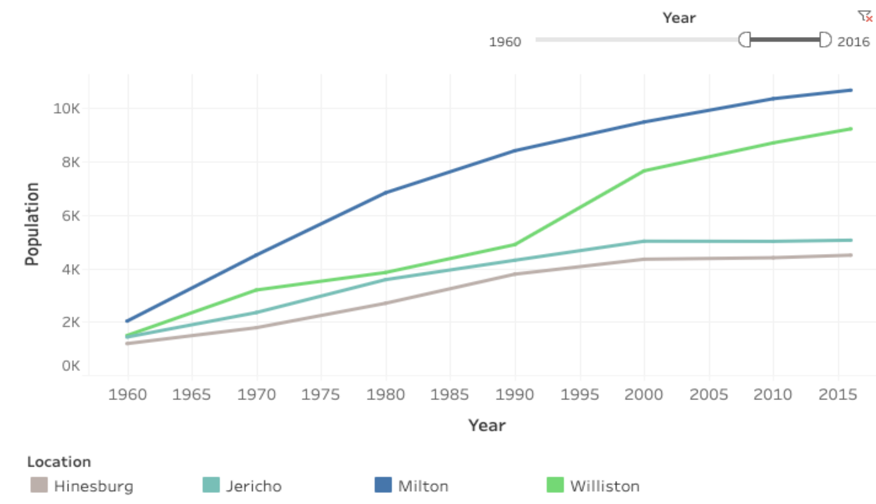


Fig 2a. A graph of the populations of the four towns compared in this study from 1960 to 2016. Source: https://www.housingdata.org/profile/population-household/population

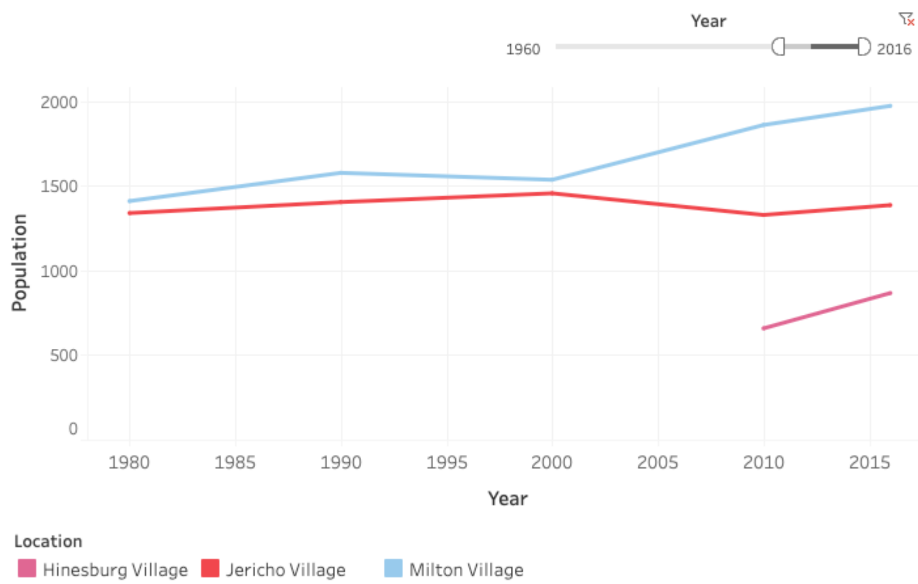


Fig 2b. A supplementary graph of the populations of the disincorporated villages associated with three of the four towns in this study (1960 to 2016). These villages fall within the area of the township and are counted as part of the town in this study. Source: https://www.housingdata.org/profile/population-household/population

a. Hinesburg (Moderate development pressure; offering incentives for high-density development in the village)

Hinesburg, VT, is located in the southern portion of Chittenden County, approximately 14 miles (by car) from Burlington. Hinesburg was included in a Growth Center Pilot Project in the mid-1990s, meaning that it received early and sustained state support and funding to develop a response to future development pressures (F. Ingulsrud, personal communication, January 26, 2021). From 2001 to 2008, most of the town's planning focus and funding went towards directing future growth towards the central, high-density zoning districts of the town. This effort seems to have been successful: during a spike in population increase between 2005 and 2008, 130 new dwelling units were approved in this area of the town, whereas between 1974 and 1980, only 80 new units were approved (Town of Hinesburg, 2013).

In May 2009, the high-density districts mentioned above were deemed the Village Growth Area (VGA), a 15.5-acre, high-density, mixed-use area in the heart of the village. The VGA was to serve as the town's primary growth area, and zoning regulations that provided guidelines for developing the VGA were adopted allowing developers to place 4 units on each acre of land in the Village district (Town of Hinesburg, 2009). These new regulations included density bonus incentives for criteria such as small dwelling size, green certification, renewable energy usage, and creation of public spaces or infrastructure to encourage high density development in Hinesburg, meaning that developers could build more than the base density on their acreage (Town of Hinesburg, 2020). As a purely hypothetical example, a developer with a 10-acre parcel of land with ¼-acre zoning who acquired a 100% density bonus could build 80 units on this land, rather than the base density of 40.

Available sewer capacity has also provided incentive for directing development to the VGA, especially since 2002, when a loophole exempting 10+ acre lots in rural districts from complying with state wastewater regulations was closed by the state (Environmental Protection Rules, n.d.), making rural development more difficult (Town of Hinesburg, 2013). (Availability of rural roads and the 10+ acre loophole, however, may have contributed to sprawl in Hinesburg prior to the loophole's closure.) All of these factors contribute to making the VGA an attractive option to developers.

After VGA zoning was adopted in 2009, the town's focus has shifted towards land use regulation revisions in the more rural areas of the town, and the process of regulating rural sprawl is ongoing (Town of Hinesburg, 2013). A focus on "open space" subdivision regulations currently exists in the town's zoning but arrived later than in Williston. A Planned Unit Development (PUD) provision—which allows (and often encourages) developers to design communities somewhat outside of existing zoning regulations, granting greater flexibility of development styles, mixed uses, and higher housing densities in rural districts to encourage growth that aligns with town goals in residential zoning districts—that exists in zoning bylaws has only been used sporadically (Town of Hinesburg, 2013). These PUDs can be used to encourage clustered development patterns in more rural districts (Vermont Planning Information Center, 2007).

b. Jericho (Moderate development pressure; lack of municipal infrastructure)

Jericho, Vermont, is 15.5 miles (by car) to the east of Burlington. The town has three state-designated village centers. Village center designation provides these towns with state assistance, priority for grant consideration, and other benefits from the state to assist with revitalizing their town centers (Vermont Agency of Commerce and Community Development, n.d.). These three town centers—Jericho Corners, Jericho Center, and Riverside— are spatially separated from one other.

In 2009, the Village Center District minimum density was changed from 1 acre zoning to ¼ acre zoning. However, Jericho Corners has been unable to significantly increase development density, in part due to a lack of sewer capacity. Similarly, in Jericho Center, a lack of public water supply and non-central location limit growth opportunities. However, as of 2015, the Riverside district has upgraded zoning regulations calling for character-based development in the vein of traditional and desirable village center growth patterns. Available undeveloped parcels in this district make it very promising for smart growth.

Developing community infrastructure could increase the density of development in Jericho Center and Jericho Corners. Soils in the three village centers are favorable for on-site sewage disposal (Town of Jericho, 2020); however, neighboring wells limit the potential for such on-site disposal, and without municipal infrastructure, potential for dense development is limited. The town is currently looking into the development of a community wastewater system to encourage growth in the Village Center and mixed-use Commercial Districts.

In 2009, the town of Jericho began to offer high-density development for Planned Unit Developments (PUDs), for which a possible density bonus of up to 50 percent exists (Town of Jericho, 2020). However, PUD-style development, which allows was not made a requirement. The town also instilled permanently protected open space provisions for agricultural or rural PUD residential developments. Jericho has a great deal of land in its forestry districts and hosts the Ethan Allen Firing Range, which is a large area of contiguously forested and largely undeveloped land used for recreational purposes.

c. *Milton (High development pressure; lack of downtown, predisposition for sprawl)*

Milton, VT is approximately 12 miles (by car) from Burlington. Milton is the largest of these four Chittenden County towns, with a population of over 10,000 people. Milton has exhibited a more linear pattern of development largely along I-89, which runs north-south through the center of the town. Similar to Jericho, a limitation to dense development in a village center is a lack of centralized wastewater services to all areas of the intended growth center (Town of Milton, 2018). However, a Village Core Sewage Expansion project was completed in 2012, which will act as incentive for future development in the village area. In addition, the town has been subject to a great deal of automobile-oriented sprawl along Route 7 (Town of Milton, 2018).

Unlike Hinesburg, the zoning bylaws of Milton places less emphasis on incentivizing compact development, and unlike Williston (see below), Milton does not place an annual cap on the number of new residential developments that may be approved by the town. The town has a great deal of land that has good or fair potential for on-site waste disposal (Town of Milton, 2013), which is enticing for low-density residential developments in areas of the town away from municipal services. Additionally, the topography and soils of many of the districts are conducive to residential development.

Until recently, the town of Milton lacked a characteristic downtown. The would-be downtown area was without contiguous sidewalks, attractive wayfinding signs, or street lighting fixtures, and was subject to strip development (Freese, 2016). Within the past 5 years, efforts have been made to rectify this. Developing a "sense of place" and a downtown is one of Milton's main objectives for the future (Town of Milton, 2018), and in 2019 the town plan was amended to focus greater effort on revitalizing the village. In 2001, the town changed its zoning to increase density in the Town Core (similar to Hinesburg's VGA) area, but, as previously mentioned, water, wastewater, and transportation services need to be updated to take full advantage of these zoning changes.

The 2018 Town Plan mentions expanding the town's density bonus to incentivize clustering residential developments, and as of 2015, density bonuses were offered for residential developments based on dwelling size, green home certification, and renewable energy (Town of Milton, 2015). PUDs are "encouraged," but "Under no circumstances should clustering be mandatory" (Town of Milton, 2018). When PUD development occurs, the percent of land that must be left as protected open space is far lower than in Williston, with a minimum of 50% open land in the Agricultural/Rural Residential District.

d. Williston (High development pressure; permitting, regulation guided by availability of municipal infrastructure)

Williston, VT, is located approximately 9.3 miles (by car) to the east of Burlington. The town consists of largely commercial and industrial zoning in its western region. Its village and primary growth center, located in the portion of the town known as Taft Corners, comprises approximately 5 percent of the town's total area. Agricultural and rural residential districts are located further to the south and east.

In 1990, Williston was focused on encouraging high-density growth in Taft Corners. The town also wanted to encourage higher-density development in hamlet-style clusters and Planned Unit Developments in the rural and agricultural areas of the town. Land policy and sewer collection lines put into place earlier in the 20th century were already at work directing residential development to this area (Williston Planning Commission, 1990). The town had also already reviewed important open-space resources and committed to open-space preservation.

Like Hinesburg, Williston, Vermont, has made available community wastewater treatment services a factor in regulating development, and here, the guidelines for centering development in the village area are much more explicit. Since 2005, the town has only allowed a maximum of 80 new residential dwelling developments per year (Town of Williston, Vermont, 2017). In 2008, Williston received Growth Center Designation, which offers greater state support and funding for planning and development of mixed-use development in the smart-growth, traditional pattern of a compact town center surrounded by rural or working lands (Department of Housing and Community Development, 2017). The Growth Center, which is largely defined by the availability of municipal sewer service, contains 56 (70 percent) of those annual permits. Of the 565 new residential developments in Williston between 2005 and 2016, 412 units (73 percent) were located in the Growth Center, and 68 units (12 percent) were located in the municipal sewage area. Development in other areas of the town is discouraged through infrastructure availability and zoning specifications. In this way, the town has managed to control where its residential development is concentrated (Town of Williston, Vermont, 2017).

One key aspect of Williston's growth management is their requirement that residential developments in the Agricultural/Rural Residential District on parcels larger than 10.5 acres must designate at least 75% of the developed parcel as permanently protected open space. This requirement has been in place since 2004 and has greatly checked the pattern of development in the town's more rural areas (Town of Williston, Vermont, 2017).

Table 1. Important zoning differences between the 4 study towns.

Town	Hinesburg	Jericho	Milton	Williston
Distance from Burlington (mi)	14	15.5	12	9
Development Pressure	Moderate	Moderate	High	High
¼-acre Zoning in High Density Districts	Yes	Only in 1 of 3 of the town's Village Centers	Yes, post-2012	Yes

Clustering in Low-Density Districts	Clustering encouraged but not enforced	Clustering encouraged but not enforced	Clustering possible but not enforced	Consistent effort to encourage this style of development
Walkable, Compact Village/Downtown	Yes	Yes (3 spatially separate "village areas")	No; more linear pattern of development shaped by main roads	Yes
Factors Impacting Low Density District Development	10+ acre wastewater loophole closed 2002; high availability of rural roads	10+ acre wastewater loophole closed 2002	10+ acre wastewater loophole closed 2002; land favorable for development	10+ acre wastewater loophole closed 2002; permitted development process (only 30% annual development in rural residential districts)

Permeability: Measuring connectivity across the entirety of a landscape

This section discusses the metric used to measure the degree to which development has influenced the ability of organisms to move across the land contained within in the four towns detailed above. Ecological connectivity is the main means of comparison for the landscapes of these four towns. The connectivity of a landscape can be defined as "the extent to which a landscape facilitates the movements of organisms and their genes" (Rudnick et al., 2012, p.1). There are many ways in which connectivity can be measured, with the two most common measures being structural connectivity and functional connectivity (Calabrese & Fagan, 2004). Structural connectivity focuses mainly on landscape features and level of development and is defined as the connectivity of a landscape from the viewpoint of multiple motile species (meaning that it is assumed that many species would be impacted in a similar way by the features and characteristics of a landscape). Functional connectivity, on the other hand, typically takes a more specific view of movement across an area and is based on species-specific movement characteristics or even spatial tracking data of individual organisms.

Functional connectivity may provide a more accurate analysis of connectivity due to its basis in detailed knowledge of or tracking data pertaining to the specific movement tendencies of a species (Issii & Pereira-Silva, 2020). However, many connectivity models, especially regional models, analyze structural connectivity without considering traits specific to any one species (such as range size or dispersal ability) when seeking to characterize the general connectedness of a landscape, rather than the suitability of a landscape for a single species or small suite of species (Calabrese & Fagan, 2004). Structural models of connectivity can provide general insights about the connected nature of natural areas of a landscape.

One structural landscape connectivity metric, landscape permeability, aims to quantify the connectedness of an entire study area, with a greater focus on the quality of the matrix, or non-habitat areas, between habitat patches. Landscape permeability can be defined as a reflection of the degree to which a landscape allows the movement of many different types of organisms and sustains ecological processes (Anderson et al., 2012). Rather than focusing on linkages between specific habitat patches, permeability analysis considers connectivity to be a function of how the degree of resistance to movement ascribed to different land cover types influences the overall movement of organisms across the landscape in question (McGarigal et al., 2012; Theobald et al., 2012). This metric therefore essentially measures the connectedness of an entire landscape.

This research analyzes uses a permeability metric to analyze the ecological connectivity of the four Chittenden County towns discussed above (Hinesburg, Jericho, Milton, and Williston) in an attempt to quantify how residential development has impacted the ability of organisms to move across these four landscapes. When examined in the context of recent (past 20 years) of planning history, the results of this study may help identify development patterns that are conducive to organism movement. It was expected that Williston's heavily regulated development process, coupled with its early awareness of the implications of growth pressures and limitations imposed on development in rural zoning districts, would exhibit the most clustered patterns of development and have the most permeable landscape in its low-density residential districts, despite the heavy development pressures in the town due to its proximity to Burlington.

II. Methods

To determine degree of clustering in high- and low-density zoning districts of the four study towns, this analysis uses the Euclidean Nearest Neighbor (ENN) metric, which is commonly used in the landscape metric software FRAGSTATS to analyze degree of habitat patch isolation, to calculate the distance between a building and its nearest neighbor. The average ENN of high-density and low-density districts were calculated and compared between towns. This metric was used in an attempt to determine the relative amount of either sprawl or clustering in a developed area, with lower values of ENN expected to indicate clustered, high-density building development patterns that place buildings close together.

To assess the permeability of these four towns, this analysis used a methodology informed by Theobald (2012). This process involved creating cost surface rasters for each of the four towns. In these cost surfaces, pixel values were based the level of "cost" associated with organism movement across different land cover types (**Table 2**). These cost surfaces were then used to run 100 iterations of the Cost Distance tool in ArcGIS (with each iteration originating at one of 100 random source points in the forested areas of the town). Each iteration created a cumulative cost distance surface in which each pixel contained the value of the cost-weighted distance between itself and the source point used in the iteration, resulting in 100 cost distance raster outputs. Finally, the values of each pixel in these 100 cost distance rasters were averaged to generate a comprehensive "permeability surface" in which lower pixel values represent higher permeability to organisms moving across the landscape. All of the zoning districts in each town were then categorized as either high-density (3-acre zoning or lower) or low-density (>3-acre zoning) and the permeability values within the high- and low-density areas of the towns was assessed.

a. ZOI Percent Area and ENN

The total area covered by zones of influence (ZOIs) in the high-density development zoning districts were compared across the study towns. The ZOI of a building is an area of higher movement cost near a building due proximity to development and influence of development on habitat quality, and negatively influences an organism's willingness to move through an area (Theobald et al., 1997). The ZOI in this study was considered to extend to 100m away from a dwelling (as per Odell et al., 2013). Vermont e911 Building Footprint data, town boundary data, and town zoning data from Vermont Open Geodata Portal were used in this portion of the analysis.

The building footprint data were first clipped to each specific town boundary and a Euclidean kernel of 100 meters was run around each building. After running the kernel output, the area of each pixel was calculated and the areas of all pixels counted within the ZOI were summed, excluding all pixels 100m or further from the building footprints. The total area of all the high-density zoning districts in each town was then calculated. The ZOI results were normalized by area by dividing the ZOI area sum by the total high-density zoning district area to find the percent of the total area of the high-density zoning districts that fell within the zone of influence of buildings. This was done for high-density districts only because these were the areas of towns in which it was expected that an attempt to cluster development had been made.

To analyze development form, the Euclidean nearest neighbor (ENN) distance between building footprints in each town's high-density development districts and within rural/agricultural/lower density residential districts was calculated using the Near tool in ArcGIS Pro. The ENN metric is a measure of the distance between each housing point and its nearest neighbor. The average distance between houses for these zoning areas can then be compared to see how close together (or clustered) residences within developments in each zoning district are. The variance of the mean ENN values among high-density zoning districts and among low-density districts were compared across towns using a one-way ANOVA and Tukey-Kramer post-hoc test in Microsoft Excel.

b. Building the Cost Surface

Cost surfaces were created in Google Earth Engine using the 2016 0.5m^2 Vermont Land Cover and Vermont Agricultural Land Cover datasets from the Vermont Center for Geographic Information. The land cover layer, combined with the agricultural layer, was used to create a land cover classification raster layer for the four towns. The land cover types are classified as follows in **Table 2** and are ranked from 1-10, with a cost of 10 assigned to the most difficult land cover type to move across. This classification was based on Anderson et al. (2012) and reflects the cost of movement of large mammalian species common in the northeastern United States in the context of different land cover types. Conservation plans based on the needs of these organisms likely account for the habitat and land cover needs of other species present in the area (Anderson et al., 2012).

Table 2. Land cover types and corresponding movement cost assigned.

Land cover	Cost
Forest	1
Grass/Shrub	2
Agricultural Land	3
Barren	5
Water	6
Roads	9
Developed	10

The ZOI values from the kernel analysis detailed above were also used in this cost surface. The pixels within the kernel output were reclassified by decreasing the value of pixels as they increased in distance from the housing point, as shown in **Table 3**. Essentially, every 10m of distance away from the building resulted in a slightly lower cost of movement. Pixels with a distance of greater than 100m from the point had a value of 0. To account for easier movement across forests than across open spaces that are near developed areas due to greater cover (due to less exposure), the costs for forested areas within zones of influence was lower than for open areas within the zones (**Fig. 3**), with the cost values adjusted slightly based on the idea that forest cover within a building's zone of influence would offer slightly less resistance than open areas within the same zone (**Table 3**). then burned into the cost surface, with any underlying land use/land cover type that had a value less than that of the ZOI would be reassigned the higher ZOI value (**Table 3**). The cost surfaces were then clipped to an outline of each of the four towns that had been buffered by 500 m to account for edge effects.

Table 3. Land cover types and corresponding cost assigned (with ZOI specifications, where forested areas that fall within the ZOI are given modified values).

Land cover	ZOI Remap, Non-Forested (based on distance from building)	ZOI Remap, Forested (based on distance from building)	Final Cost
Forest	---	90 m	1
Grass/Shrub	---	---	2
Agricultural Land	100 m	70 m	3
---	---	---	4
Barren	80 m	40 m	5
Water	---	---	6
---	60 m	20 m	7
---	40 m	---	8
Roads	20 m	10 m	9
Developed	0 m	0 m	10

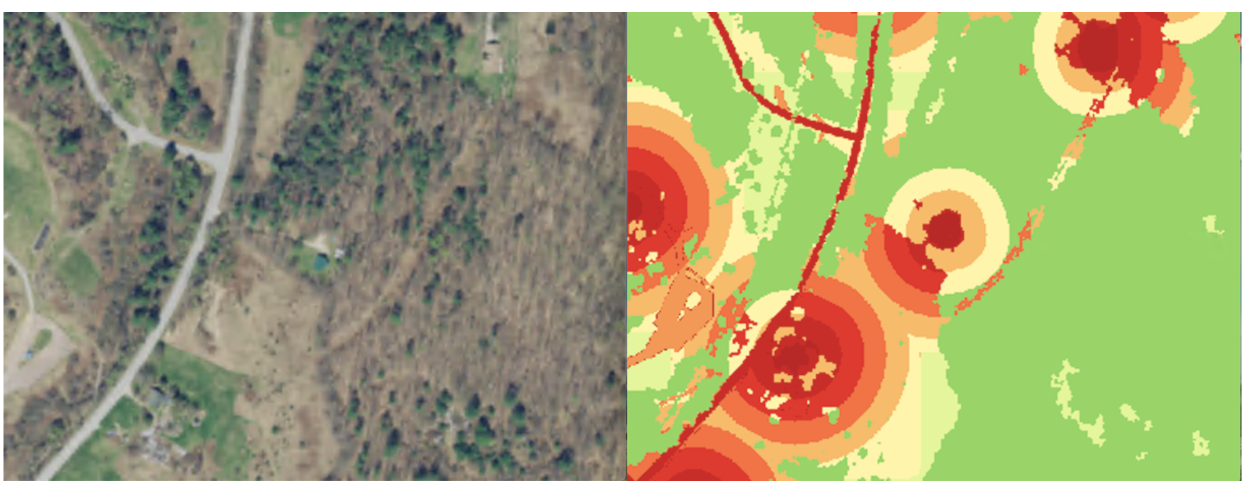


Fig. 3. Aerial imagery (left) and subsequent land cover classification incorporating ZOI metrics (right). Highest cost (max. value of 10) is shown in red, while lowest cost values are shown in green. The ZOI of the forested land on the

upper right side of the central building in the image is classified as lower resistance than the open land to the bottom left.

c. Permeability and Flow Accumulation

The cost surfaces were then exported from Google Earth Engine at a $1m^2$ resolution, loaded into ArcGIS Pro and used to run a landscape permeability model that was developed with assistance from William Hegman. This model creates a sample of 100 random start locations taken from natural (in this case, forested) land cover. The random starts were visually determined to be well distributed across the landscape and are located within the town boundary. In this way, there is relatively complete coverage of the town's landscape matrix, and the cost surface was extended beyond the boundary of the town by 500m to reduce edge effects. Start points were located within (presumably) suitable habitat or movement areas, as they are located within areas of forested cover.

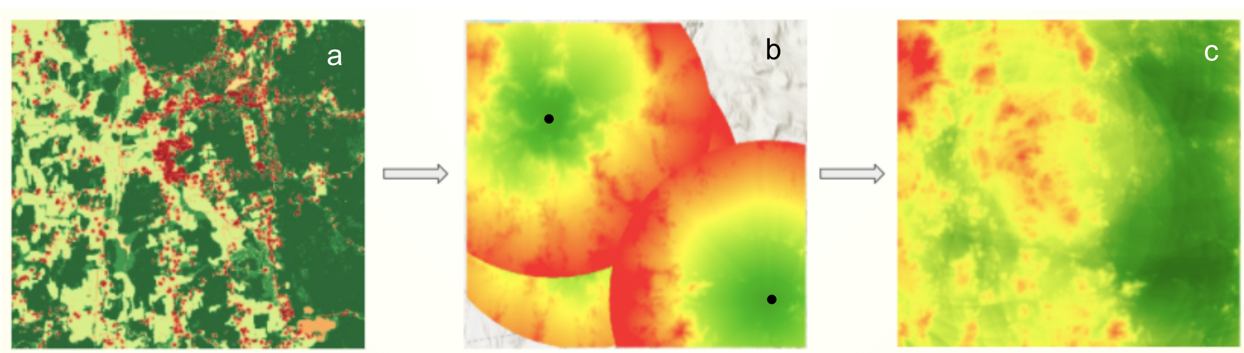


Fig. 4. Visual representation of the Cost Distance model process. **Fig. 4a** represents the initial cost surface. **Fig. 4b** represents a subset of 3 of the 100 Cost Distance outputs, created using versions of the cost surface that are buffered by 6000m from the source pixel used in the given iteration of the model. Locations of source pixels are represented by the black dots. **Fig. 4c** represents the final output of all the cost surface outputs averaged together to create a final cost surface (red = low permeability, high resistance; green = high permeability, low resistance).

The model then uses the start pixels and cost surface to run Cost Distance, a tool which generates a cumulative cost of moving across a landscape that is weighted by the pixel values in a cost surface. One hundred iterations of the model were run, based on iteration variance results reported in Theobald et al. (2012). Each iteration was run on a version of the cost surface (**Fig. 4a**) that was clipped to a 6,000m-diameter buffer around the source point that was to be used in the given iteration of the model. This buffer was created to reduce centrality effects (i.e. reduce the potential that areas in the center of the town would be classified as more permeable simply due to the fact that more pixels would have to pass through them to move across the entire town landscape, meaning that these pixels would generally be closer to *all* source points if the entire cost surface were included in each run of the model). The 6,000m buffer size (3,000m radius) was based loosely on the area of convex hulls created around raw bobcat range tracking data from the State of Vermont (raw data provided by William Hegman).

The Cost Distance model process generated 100 rasters representing the cost of moving from every pixel in the buffered cost surface to the single source pixel used each given iteration (**Fig. 4b**). The values in the pixels of the 100 resulting Cost Distance output rasters were then averaged together to generate a mean 'permeability' score in each pixel, where a higher permeability index value indicates greater resistance to movement and therefore lower permeability (**Fig. 4c**).

All of the zoning districts in each town were then categorized as either high-density (less than 3-acre zoning) or low-density (3+ acre zoning). The pixels in the comprehensive permeability value surface that fell within the forested areas within each district were then selected and an average of the permeability values of the forested pixels in each zoning district was taken. The variance among the means of high-density districts between towns and low-density districts between towns were then analyzed using a one-way ANOVA and Tukey-Kramer post-hoc test in Microsoft Excel.

III. Results

The zone of influence analysis by high density zoning districts showed that Milton has the largest total area covered by the zones of influence caused by development (**Fig. 5**). Hinesburg had the largest percent coverage of zone of influence in its high-density zoning districts, though percent coverage of high-density zoning districts for all towns were relatively similar (**Fig. 6**).

Figure 5. The total zone of influence coverage for the high-density development areas of each town.

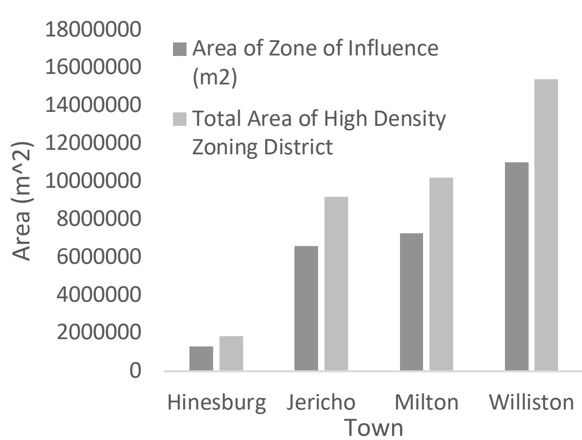
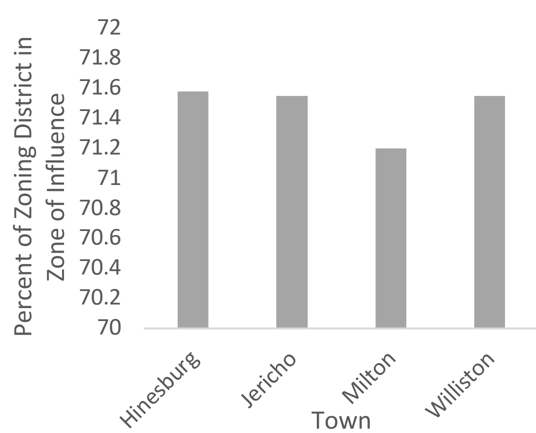


Figure 6. The percent coverage of the zoning districts included in high-density development areas covered by zone of influence areas in each town.



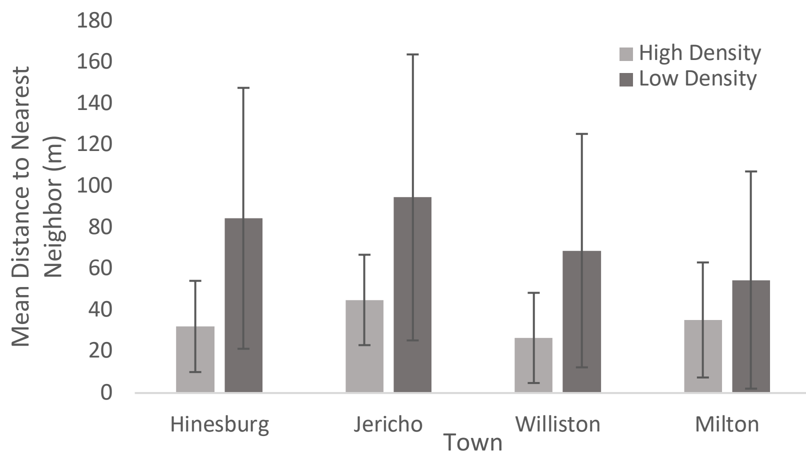


Fig. 7. Mean distance (in meters) to nearest neighbor (ENN) for each of the four study towns (±SD), broken up by high-density and low-density zoning districts. There was no significant difference in ENN values of the high-density districts between the towns, nor between any of the low-density districts of the towns. Statistical significance was determined using a one-way ANOVA ($p > 0.05$ for both tests).

The high-density areas of Jericho have the largest distance to nearest neighbor values, while the other three towns' high-density areas have relatively similar ENN values (**Fig. 7**) There was no significant difference in ENN values of the high-density districts between the towns. There was also no significant difference in ENN between the low-density districts of the study towns. Statistical significance was determined using a one-way ANOVA ($p > 0.05$). When broken down to a district level, the ENN analysis revealed that there was a great deal of variation in distance to nearest neighbor values within and across the four towns (**Fig. 8**).

The average permeability values reported for the low-density development areas of these towns were consistently lower than those of high-density development areas. Areas of higher resistance to movement were generally concentrated near high density development areas (**Fig. 9, Fig. 10**). Milton and Williston contain areas of higher total maximum resistance to movement than Jericho and Hinesburg. Jericho had the lowest maximum permeability index value (**Fig. 10**). In the high-density zoning districts, there was a significant difference in mean permeability values for Jericho and Milton ($F\ [4,26] = 3.880$, $p = 0.05$). In the low-density zoning districts, there was a significant difference between the means of Hinesburg and Jericho, Hinesburg and Williston, Jericho and Milton, Jericho and Williston, and Milton and Williston ($F [3,20] = 3.880$, $p < 0.05$) (**Fig. 10**).

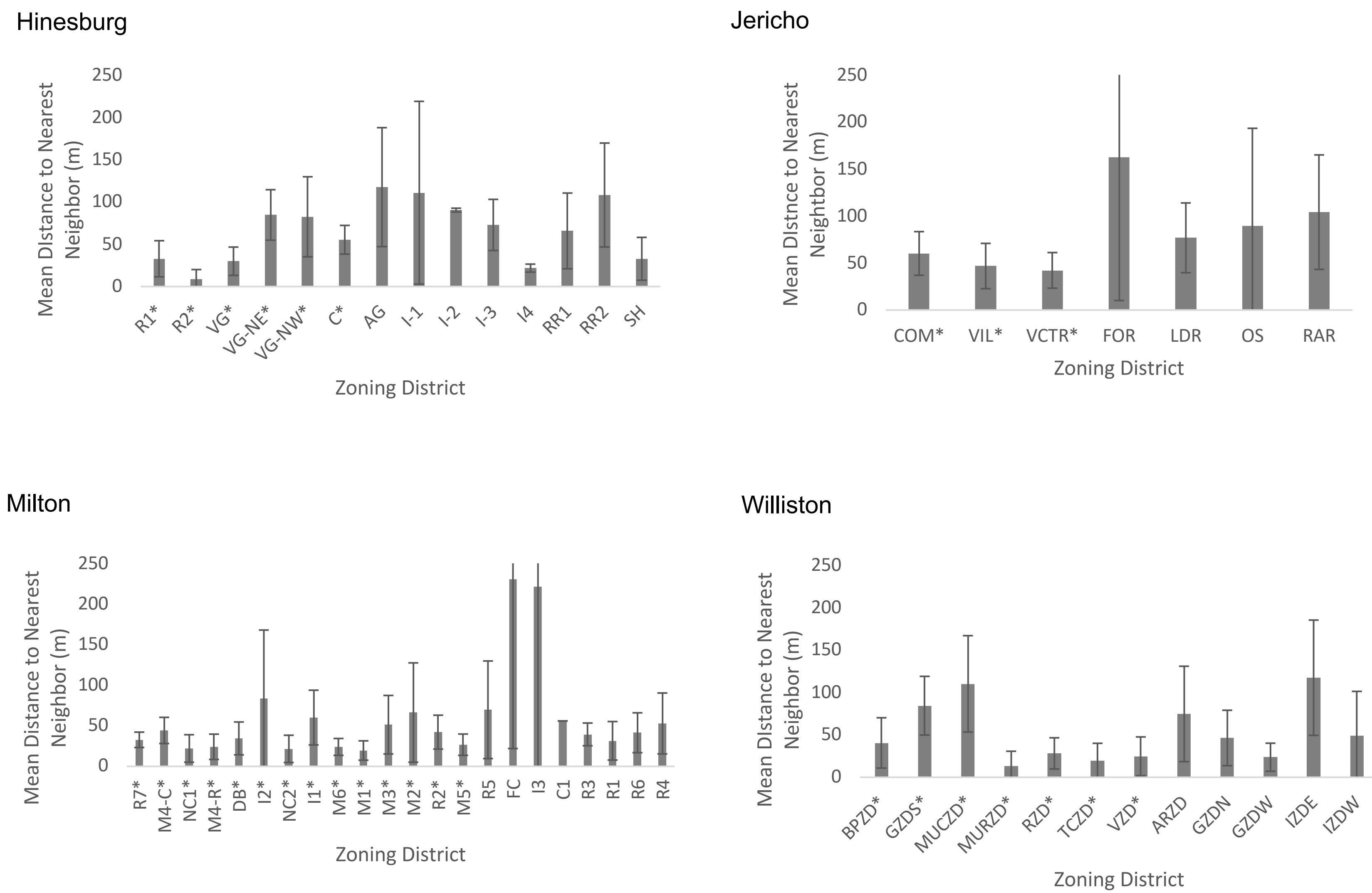


Figure 8. Mean distance (in meters) to nearest neighbor, broken up by zoning district. Asterisks indicate a zoning district classified as "high density."

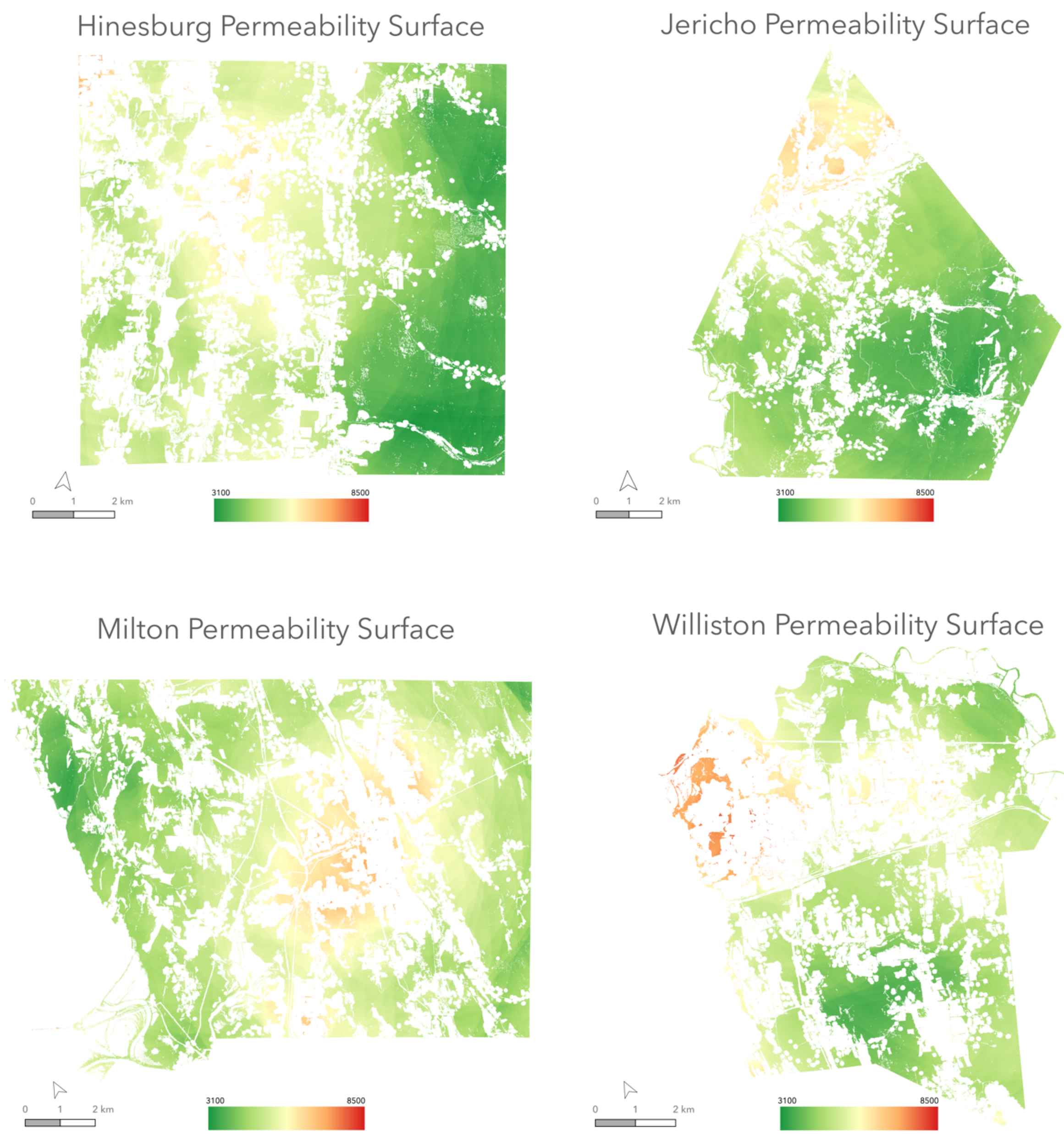


Fig. 9. Cost surfaces for each of the four study towns. Green indicates greater permeability (less resistance to movement) while red indicates low permeability (high resistance to movement). Permeability index values range from 3100 to 8500.

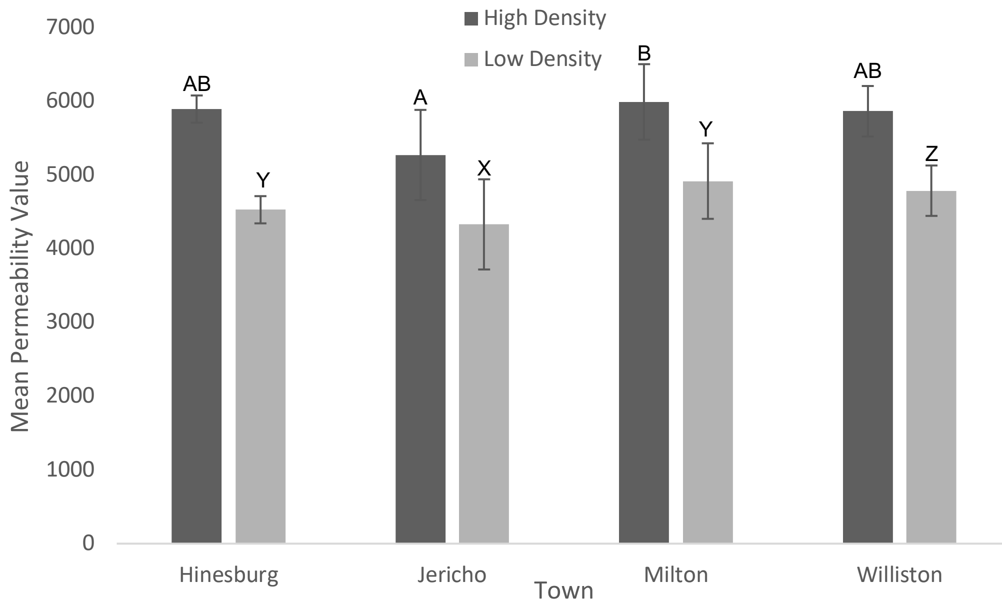


Fig. 10. Mean permeability values for zoning districts classified as "high density" and "low density" for each of the four towns. Higher values indicate greater resistance to movement. Error bars indicate standard deviation from the mean value. In the high-density zoning districts, there was a significant difference in mean permeability values for Jericho and Milton ($F [4,26] = 3.880$, $p = 0.05$) (significant differences indicated by letters A and B). In the low-density zoning districts, there was a significant difference between the means of Hinesburg and Jericho, Hinesburg and Williston, Jericho and Milton, Jericho and Williston, and Milton and Williston (ANOVA and Tukey-Kramer post-hoc) ($F [3,20] = 3.880$, $p < 0.05$) (Significant differences indicated by X, Y, and Z).

IV. Discussion

The results generated by this analysis indicate that ZOI coverage, when normalized by total district area, is relatively similar across the high-density districts of the towns. They also indicate that Jericho had the highest ENN values in its high-density districts, but no ENN values in either low- or high-density districts across the towns were significantly different from one another. Finally, the permeability analysis found several significant differences across both low- and high-density districts (**Fig. 10**).

Zone of Influence and Euclidean Nearest Neighbor Analysis

Based on the high degree of development and lower level of development regulation in Milton, ZOI coverage in the high-density development districts of Milton was expected to a) encompass a larger total area because of the high level of development and b) cover a larger total area of the town, as less-regulated development would allow for non-clustered housing formations, meaning there would be less overlap of ZOIs. This lower amount of ZOI overlap was also expected in Jericho because of the lack of municipal water and sewage services leading to an inability to reduce zoning acreage in high-density districts from 1 acre to ¼-acre zoning.

The town of Milton did indeed have the highest overall ZOI coverage, and Jericho, with a population trajectory similar to Hinesburg's (**Fig. 2a**) had a higher total ZOI coverage than Hinesburg. This would indicate that the ZOIs in Jericho may not be overlapping due to the inability to develop at ¼ acre zoning (**Fig. 5**). However, when normalized by area, this data shows that the percent coverage of high-density zoning district by ZOIs is similar across all four towns (**Fig. 6**). This may have to do with the number of buildings in the high-density zoning districts of the four towns, so normalizing by total number of residential buildings per town could potentially lend some insight into the drivers of the results of **Fig. 6.**

The Euclidean Nearest Neighbor (ENN) analysis showed no significant difference in the ENN values of the high-density zoning districts of the four towns (**Fig. 7**). This is a surprising finding, especially in the context of comparing towns with similar population trajectories (Hinesburg and Jericho, Milton and Williston) to one another. In the case of Hinesburg and Jericho, the availability of municipal sewer and water infrastructure in Hinesburg was expected to lead higher density and greater clustering of housing and therefore to lower ENN values. This trend is reflected in the data, but the difference in means is not significant. Similarly, the development regulations in Williston's high-density areas are more stringent than those of Milton, but the ENN values in the high-density areas of these two towns are not significantly different from one another (**Fig. 7**).

An analysis of the ENN values for the low-density zoning districts in the towns showed that none of the values in any of the towns are significantly different from one another (**Fig. 7**). This finding is also surprising when considered in the context of the zoning histories of these four towns. Williston has made a concerted effort in its low-density zones to enforce hamlet-style clustering of homes (Williston Planning Commission, 1990) an area of planning where the other three towns in this study have historically fallen short, and it is surprising that the ENN values do not reflect this difference. Like Williston, Hinesburg was an early and informed actor on the importance of high-density development in town centers. However, the Hinesburg zoning plan lacked a focus on low-density development in its non-central zoning districts (Hinesburg 2013 Town Plan; F. Ingulsrud, personal communication, January 26, 2021), and it was expected that Hinesburg may be different from Williston in its low-density ENN values. Similarly, Milton's less rigorous rural residential development density requirements were expected to lead to significantly higher ENN values than those seen in Williston, but the data indicate that this may not be the case (**Fig. 7**).

Milton and Jericho differ in their respective population size and population increase rates, and the town of Jericho contains the largely intact, undeveloped Ethan Allen Firing Range, which may be contributing to the high ENN values in Jericho's rural districts. These factors may be the cause of the large (but non-significant) difference in low-density district ENN values in these two towns.

Permeability Analysis

Average permeability values in low-density zoning districts were consistently lower than the permeability values in the high-density districts across all four towns (**Fig. 10**). These lower permeability index values in low-density districts indicate lower resistance to movement across the landscape. In the high-density district analysis, Jericho was significantly more permeable than Milton. There were several significant differences in mean permeability values between the low-density districts of the towns: Hinesburg was significantly less permeable than Jericho, but significantly more permeable than Williston; Jericho was significantly more permeable than both Milton and Williston, and Milton was significantly less permeable than Williston (**Fig. 10**).

Once again, the difference between Jericho and Milton's high-density districts' permeability values may possibly be attributable to the degree of development within each of the towns. It is also possible that Jericho's apparent strength in preserving low resistance to movement even in its high-density areas may in fact be the inability to place homes close to one another by reducing high-density zoning to ¼ acre in all its village centers (**Table 1**). Similarly, when considered in the context of high-density minimum lot size (**Table 1**), is not surprising that Hinesburg had fairly high resistance values in its high-density districts; the clustering of development that occurs therein means that buildings are close together and likely have overlapping ZOIs between them, leading to high resistance in these areas.

Considering the permeability values of the low-density zoning areas, the data show that Jericho and Hinesburg have lower mean permeability index values than the other two towns (which indicates that they have higher permeability in their low-density districts) (**Fig. 10**). When considering degree of development and proximity to Burlington, it stands to reason that these two smaller towns would be more permeable than Milton and Williston. However, Hinesburg does not differ significantly from Milton in terms of low-density district permeability. The development loophole exempting 10+ acre lots in Vermont's rural districts from complying with state wastewater regulations in low-density residential districts was only closed in 2002 (Hinesburg 2013 Town Plan). While the loophole remained open, its existence and the high density of rural roads in Hinesburg (Inguslrud, personal communication, January 26, 2021) constituted a large draw for development in these districts, and the similarity between Hinesburg and Milton may be partially due to the combined effects of high land availability, the wastewater loophole and availability of rural roads that made land in rural districts more accessible. However, when looking at **Fig. 9**, this finding is still somewhat surprising, as it is apparent that Hinesburg contains more large, continuous, highly permeable areas (i.e. areas with low permeability index values) than does Milton. This indicates that permeability may not be the optimal way to analyze landscape quality from an ecological, structural connectivity perspective. Incorporating patch characteristics (e.g. size and compactness) of habitat areas or areas of natural cover would make this analysis more robust. Indeed, da Silva et al. (2015) found that both a matrix permeability metric and forest fragment characteristics metrics were needed to accurately predict the occurrence of a study organism in a moderately- to highly-degraded forested landscape.

Williston performs well in its retention of permeability in its low-density districts. Although development rates and pressures in Milton and Williston are comparable, especially since the year 2000 (**Fig. 2a, 2b**), Williston's low-density district resistance to movement value is significantly lower than Milton's (**Fig. 10**). As mentioned before, this may be because Williston enforces hamlet-style clustering of homes in its low-density zoning districts (Williston Planning Commission, 1990; F. Ingulsrud, personal communication 26 January 2021).

Conservation Implications:

Based on the reviewed zoning documents, it was expected that, relative to its population size, Williston would have the most permeable landscape in its low-density zoning district due to a) a strong control on containing development to the town's designated growth area that is served by municipal water and sewer services, and b) its efforts to develop in clustered, hamlet-style formations in its low-density districts. Interestingly, Williston does not have significantly lower ENN values than the other three towns in its low-density districts, a finding which neither supports nor refutes the expectations for this study (**Fig. 7**). (It would be useful to visualize both development compactness scores and the spatial characteristics of habitat patches or areas of natural cover in these low-density districts to see what may be causing such similar ENN values in the low-density districts of the towns.) However, from the results displayed in **Fig. 10**, it appears that the expectations for this study may be supported by the findings of the permeability analysis. Williston's average low-density district permeability is significantly lower than Milton's, the town to which it is most similar in terms of population (**Fig. 2a**). It is also significantly higher than Hinesburg and Jericho, but differences in degree of development and in development pressure may explain the difference in permeability values between the larger and more developed Williston and the two smaller towns.

This analysis therefore provides tentative support for the development style used by Williston in its residential town planning. This conclusion aligns with the findings of Theobald et al. (1997), who found that clustering subdivisions in low-density development residential areas can reduce total disturbance area, resulting in conservation of more intact habitat areas. Similarly, Robinson et al. (2005), who found that unregulated or non-cluster low-density development can increase sprawl and lead to high conversion of habitat areas and corridors to states of lower ecological quality. A focus on highly regulated and concentrated residential development in designated high-density areas of a town, while allowing for minimal but also highly regulated and preferably clustered development in low-density districts may therefore be a sensible tactic for maintaining the connectedness of the permeability of low-density zoning districts.

Interestingly, the lowest permeability index values for high-density zoning areas were found in Jericho. The town is functionally unable to reduce lot sizes to ¼ acre zoning in its high-density districts due to municipal water and sewer availability. This inability to reduce acre size may actually be an asset in terms of retaining permeable areas in the matrix of the high-density zoning districts. However, the benefit of the lower resistance to movement values in Jericho's high-density districts ultimately depends on species' willingness to use natural areas that are near high levels of human activity and development. It is probably unrealistic to assume that many species (especially human-avoidant species) would consistently utilize the high-density zoning areas of these towns.

When discussing the permeability of the high-density zoning districts and whether or not the higher permeability in Jericho's high-density districts is truly an asset, there are other benefits of higher-density residential development that must be considered. For instance, Stone (2004) found that high-density residential development patterns are associated with lower levels of impervious surface coverage per unit. Likewise, Kim & Zhou (2012) found that smaller lot sizes smaller lot frontages resulted in higher (yet perhaps more fragmented) vegetation cover in high-density residential areas, and vegetation cover (especially native vegetation cover) often positively correlates with important ecological characteristics, such as prevalence of native bird species (Germaine et al., 1998). Therefore, smaller minimum lot size may ultimately be more beneficial than retaining higher permeability in high-density districts.

In addition, as mentioned above, one core benefit of concentrating and largely restricting development to high-density areas nearer the center of a town is the conservation of open space in other areas of the town. Conversion of agricultural or forested lands to residential developments should be minimized, as rural residential development can have more pronounced effects on biodiversity and ecological processes than agricultural or forestry activity (Marzluff & Ewing, 2001). One sustainable development strategy may therefore be to sacrifice permeability in a small, concentrated area of a town in order to prevent the conversion of working or undeveloped land outside the area of development to residential use. A flow accumulation model was attempted in this analysis to analyze mobility "bottlenecks" (i.e. areas where movement across a landscape is very constricted to a single possible corridor), but results were highly inconclusive. This could be a track for future research.

Ultimately, it must be acknowledged that this is a relatively simple permeability model, relying mainly on land cover types and distance from development (i.e. "naturalness"). However, Krosby et al. (2015) found that using a "naturalness" score to determine landscape connectivity provided a reasonably efficient proxy for focal species connectivity modeling. The metric of landscape permeability used in this study may be a simple and effective method to determine the relative permeability values of different areas of a town and inform conservation aspects of future planning efforts. With that said, it would be beneficial to incorporate other factors (species movement and land use characteristics, patch characteristics, distance from roads, etc.) into this model.

Finally, comparison of permeability results with location data of species of interest can be beneficial to validate the results of studies like this one. For instance, Gray et al. (2016) used puma tracking data characteristics to validate the results of a largely structural permeability model and found that their permeability analysis was largely accurate with regard to the movement patterns of at least one species of interest. As bobcat are a human avoidant species native to Vermont, it may be possible to use the bobcat tracking data used in this analysis (or a similar dataset regarding another species of interest) to determine buffer areas for the different cost surfaces used in iterations of the cost distance model to validate the results of this study to some degree. Gray et al. (2016) also raise an interesting point about the failure to include slope in their model and how this inclusion could explain some of the areas where their model does not match with puma movement patterns. Similarly, this permeability analysis of Chittenden towns could benefit from the inclusion of higher movement costs in steeper areas. Additionally, as mentioned above, the non-significant difference in low-density zoning district permeability between Milton and Hinesburg indicates that incorporating patch characteristics (e.g. size and compactness) of habitat areas or areas of natural cover would benefit this analysis in terms of determining what areas of a landscape to prioritize for conservation.

As Vermont's population continues to expand, conserving permeable and habitable areas in a landscape should be considered a key priority in development planning. Based on the results of this study and a thorough consideration of the existing literature, the idea of concentrating development in one core area while limiting development in other areas of the town may be a favorable tactic to achieve this goal. However, linkages across high-density development areas and habitat patch characteristics are key factors to consider when implementing this strategy, and a flow accumulation model or least-cost path analysis could be included to make this analysis more robust. Future work should also focus on permeability between towns (perhaps even on a regional level), especially in the face of climate-necessitated range shifts or altered migration patterns.

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Glossary:

Act 200: 1988 Vermont legislation that aimed to, among other things, encourage development in the form of compact village and urban centers surrounded by largely intact rural and agricultural landscapes

Clustered Development: Siting homes in a high-density arrangement, using a small amount of a total unit of developable land for building and road development, while preserving the rest of the land in a relatively undeveloped manner

Connectivity: "The extent to which a landscape facilitates the movements of organisms and their genes" (Rudnick et al., 2012, p.1).

Functional Connectivity: A measure of landscape connectivity that typically takes a more specific view of movement across an area and is based on species-specific movement characteristics or even spatial tracking data of individual organisms.

Structural Connectivity: A measure of landscape connectivity that focuses mainly on landscape features and level of development and is defined as the connectivity of a landscape from the viewpoint of multiple motile species (meaning that it is assumed that many species would be impacted in a similar way by the features and characteristics of a landscape).

Cost Surface: Raster surface with pixel values that reflect the level of "cost" associated with organism movement across different land cover types.

Euclidean Nearest Neighbor (ENN): Measure of Euclidean distance between a building and its nearest neighbor.

Fragmentation: The reduction in habitat area and isolation of habitat patches due to human development.

Growth Center: The area of a study town that is designated as the "village" in the smart growth planning practices, with high-density, mixed use planning.

Growth Center Designation: Vermont designation which offers greater state support and funding for planning and development of mixed-use development in the smart-growth, traditional pattern of a compact town center surrounded by rural or working lands.

High-Density District: In this study, a zoning district with a minimum density of less than 3 acres.

Landscape Permeability: A reflection of the degree to which a landscape allows the movement of many different types of organisms and sustains ecological processes, with a greater focus on the movement values in all areas of a landscape, rather than habitat patches and essential corridors.

Low-Density Development: A zoning tactic that keeps homes few and far between, leaving large swaths of undeveloped land between dwellings.

Low-Density District: In this study, a zoning district with a minimum density of 3 acres or greater.

Planned Unit Development (PUD): A provision in zoning regulations which allows for greater flexibility of allowed housing types and layouts, higher housing densities, and the designation of common space within a development to encourage clustered development patterns in rural residential zoning districts. PUDs can be used to encourage clustered development patterns and are typically pedestrian-oriented and allow developers to bypass existing zoning regulations to meet adapted overarching density and conservation goals (Vermont Planning Information Center, 2007).

Smart Growth: Vermont Natural Resources Council defines this as clustered village-style town centers surrounded by largely intact agricultural, forestry, or undeveloped lands

Town Core: See "Growth Center."

Village Growth Area (VGA): See "Growth Center."

Village Center: See "Growth Center."

Village Center Designation: Provides Vermont towns with state assistance, priority for grant consideration, and other benefits from the state to assist with revitalizing their town centers.

Zone of Influence (ZOI): The zone around buildings in which only very human-tolerant species will move freely. In cluster-form zoning, the ZOIs of buildings typically overlap, which decreases the total area covered by ZOIs in a housing development.