DEVELOPMENT OF A MODEL TO QUANTIFY AND MAP URBAN GROWTH

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ABSTRACT

There is widespread concern about urban sprawl in the United States, yet there is no consensus on how to define urban sprawl, what its effects are, and how it can be controlled. Central to these questions is the measurement and quantification of urban sprawl over time. Digital imagery from sensors based on satellite platforms has provided an extensive archive of historic and current data with high spatial integrity that are well suited to change applications. Researchers at NASA's Regional Earth Science Application Center (RESAC) at the University of Connecticut have developed a model that quantifies and characterizes urban growth while maintaining the spatial detail of the source satellite imagery. The urban growth model, which has its origins in a forest fragmentation model developed by EPA and USGS, is based on two dates of satellite-derived land cover. Our modified version of this landscape fragmentation model produces an output map identifying five types of urban growth: in-fill, expansion, isolated, linear branching, and clustered branching. The resulting map presents a powerful visual and quantitative assessment of the type of urban growth occurring across the landscape. Such information will allow local land use decision makers to see clearly the results of past land use choices as well as the potential effects of future decisions. This paper presents the basis for the development of our urban growth model and examples of its application.

INTRODUCTION

The University of Connecticut is home to a NASA Regional Earth Science Applications Center (RESAC) called NAUTILUS. NAUTILUS stands for Northeast Applications of Useable Technology in Land planning for Urban Sprawl. One mission of NAUTILUS is to make the power of remote sensing technology available, accessible, and useable to land use planners and decision makers concerned about the impacts of urban sprawl on their communities. Central to this mission is quantifying and describing urban sprawl in a useful and objective manner. But can urban sprawl be defined *objectively*? A thorough literature review revealed many ways, subjective and objective, qualitative and quantitative, to describe urban sprawl. Because of the bias present in many definitions, as well as the shear number of definitions, researchers at NAUTILUS decided to focus on an urban *growth* model that allows the end user to decide what kinds of growth should be considered sprawl and what kinds should not, further maintaining the objective nature of the urban growth model.

Even with a wealth of literature surrounding urban sprawl, no method previously existed that simultaneously is quantifiable, displays the emergence of growth over time, has historical depth, displays spatially detailed data, maintains spatial pattern and configuration, examines the whole landscape and is broadly available, avoids spatial averaging, and does not require much data input. Remote sensing is an ideal tool for meeting these objectives and quantifying urban growth over time due to the availability of temporal images, landscape-wide coverage, and high spatial integrity. This paper describes the urban growth model developed by NAUTILUS.

Urban Growth Types

Theoretically, the existing road network connects all current urban development creating one large and complicated urban patch. Jaeger (2000) describes how the patchwork development of sites, all connected by a linear infrastructure, causes landscape fragmentation and produces a series of isolated segments of habitat, ecosystems, or land-use type. This concept is used throughout the definitions of urban growth types because the relation (or distance) to the existing urban patch is important when determining what kind of urban change is occurring or has occurred. It must be noted that 30m pixels do not always identify all roads on the landscape. This model identifies five types of urban growth: infill, expansion, isolated, linear branch, and clustered branch. Note that urban means developed and includes residential as well as commercial and industrial areas.

An *infill* type growth is characterized by a non-urban pixel surrounded by at least 40% urban being converted to urban. Ellman (1997) defines infill policies as the encouragement to develop vacant land in already built-up areas. Infill development usually occurs where public facilities such as sewer, water, and roads already exist.

An *expansion* type growth is characterized by a non-urban pixel surrounded by some urban but no more than 40%, being converted to urban. This conversion represents an expansion or "spreading out" of the existing urban patch. Humphrey Carver (Harvey and Clark, 1965) states that the growth of cities will continuously have a belt of land on the outskirts that will be undergoing the conversion from rural to urban uses. Expansion-type development has also been called *urban fringe development* (Heimlich and Anderson, 2001;Theobald, 2001).

Outlying growth is characterized by a change from interior non-urban to urban. In order for a pixel to be classified as interior non-urban, it inherently does not border any urban pixels (in fact there are no urban pixels in the 5x5 roving window). This type of change indicates an area of development that is some distance from existing urban areas. Outlying growth can be further divided into three growth types: isolated, linear branch, and clustered branch. *Isolated* growth is characteristic of a new house or construction generally surrounded by non-urban and some distance from an existing urban area. Forman (1995) calls this type of spatial process *perforation*, and defines it as "the process of making holes in objects such as habitat or land type." The second is *linear branching* which represents a new road or new linear development surrounded by non-urban and some distance from existing urban areas. A linear branch is different from an isolated growth in that the interior-to-urban pixels are connected. The third type of outlying growth is *clustered branching*, which is characteristic of a new neighborhood or large complex. Harvey and Clark (1965) define *leap-frog development* as the "settlement of discontinuous, although possibly compact, patches of urban uses."

METHODS

Background

The roots of the urban growth model lie in a forest fragmentation model developed by Riitters *et al.* (2000). After adapting the method for use with 30-meter Landsat-derived land cover data as opposed to 1-kilometer land cover data, it was applied to four dates of land cover for the Salmon River Watershed in eastern Connecticut, USA (Hurd *et al.,* 2001). Viewing multiple dates of fragmentation images prompted the creation of a rule-based system to create a change map too highlight areas that had experienced development between the two image dates. Although the entire fragmentation model is not necessary for the urban growth model, one idea is essential – that of *Pf*, or proportion of forest. This is a value created from a moving window that quantifies the number of forest pixels in the window, as compared to the number of non-water pixels. Ritters *et al.* (2000) used a *Pf* of 0.6 to separate perforated and edge forest types from transitional forest, and a *Pf* of 0.4 to separate transitional forest from patch forest. For the sake of the urban growth model, perforated and edge were combined to one class ($Pf > 0.6$) and transitional and patch were combined to one class ($Pf < 0.6$). One other major adaptation was made to Riitters *et al.* (2000) model. The input image to the forest fragmentation model is a binary forest vs. nonforest image. Because urban areas are of interest in the urban growth model, the input image is a binary image of non-urban versus urban. Classes such as agriculture that originally occurred in the nonforest class, now appear in the non-urban class. Because of this change, the *Pf* value is referred to as the proportion of non-urban.

Creation of the Urban Growth Map

An area slightly greater than the Salmon River watershed in eastern Connecticut was used as a test site for development of the urban growth model due to the large number of available images. The examples in the following paper are taken from this area, which includes at least part of the towns of Bolton, Glastonbury, Hebron, Marlborough, East Hampton, Colchester, Haddam, and East Haddam. Only the town of Marlborough is fully covered.

An overview of the steps in the urban growth model is shown in Figure 1. First, the user creates a land cover map for at least two dates to be used as input into the urban growth model. The urban growth model calculates the proportion of non-urban and creates the non-urban fragmentation maps. Next, the two non-urban fragmentation maps are used to create a change map, which is used to create the urban growth map. A contiguous pixel grouping (referred to as clumping) procedure is performed and the final urban growth map is produced.

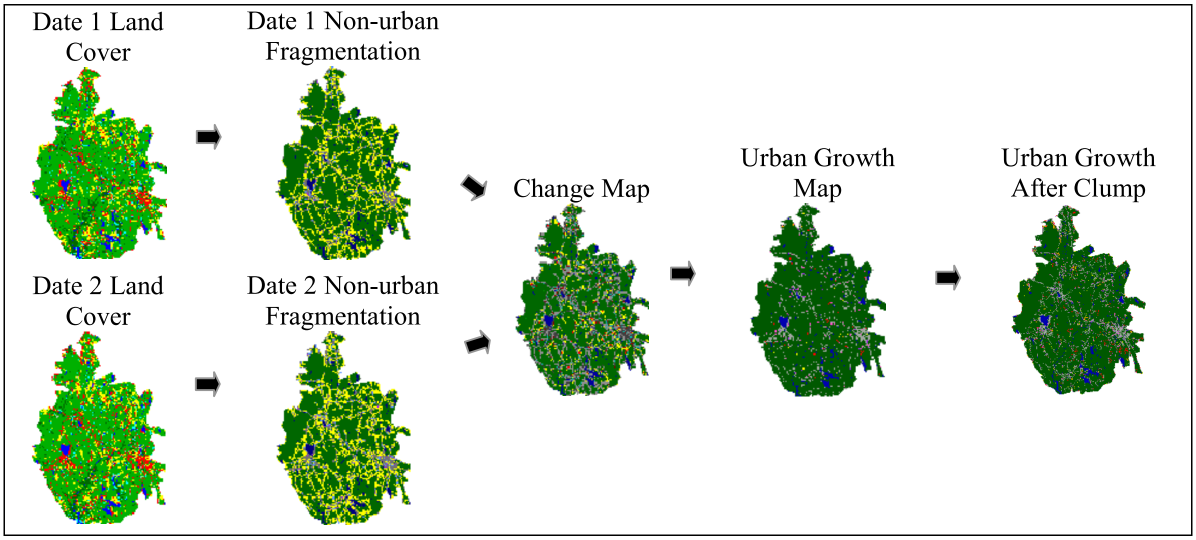


Figure 1. An overview of the steps involved in the urban growth model.

Land Cover Maps. The first step in the urban growth map is creation of land cover maps from satellite data. The model was developed using 30-meter Landsat TM data. Land cover with varying pixel sizes could also be employed, however, use of the 5x5 pixel window could result in more or less fragmentation on the fragmentation images, ultimately influencing the final urban growth map. Here, land cover maps were created using two seasons of imagery and cross correlation analysis (Koeln and Bissonette, 2001), however, it is thought that any pixel-based classifier would be adequate for creating the land cover map.

Non-urban Fragmentation Maps. After the land cover maps are created, the next step is to calculate the proportion of non-urban for each center pixel of a 5x5 roving window. Water pixels are excluded from the analysis, so the proportion of non-urban is the number of non-urban pixels in a 5x5 window divided by the number of non-water pixels in the same 5x5 window. The resulting image contains urban pixels, transitional/patch non-urban pixels, perforated/edge non-urban pixels, and interior non-urban pixels.

Change Map. Next, the non-urban fragmentation maps are used to create a change map. The change classes are outlined in Table 1 and are separated into three types: no change, regrowth classes, and changes that indicate urban growth. The *changes that indicate urban growth* (Table 1) are of relevance to the urban growth model.

Urban Growth Map. The urban growth model produces an output map with no-change classes and five types of urban growth including infill, expansion, isolated, linear branching, and clustered branching. Changes that indicate each of the urban growth types are shown in Table 1. Outlying growth is separated into isolated, linear branching, and clustered branching using a set of rules.

Table 1. Change classes resulting from two dates of non-urban fragmentation maps. The type of growth indicates which changes are significant to the urban growth map. Note that most of cases of regrowth classes are not real changes and are due to classification error.

CHANGE CLASS	DATE 1	DATE 2	TYPE OF GROWTH
NO CHANGE CLASSES			
Urban - No change	Developed	Developed	
Water - No change	Water	Water	
Interior - No change	Interior	Interior	
Fragmentation class - No change	Perforated/edge or Patch/transitional	Same fragmentation class as first date	
REGROWTH CLASSES (many cases are classification errors)			
Change within fragmentation class	Perforated/edge or patch/transitional	Fragmentation class different from first date	
Developed to fragmentation class	Developed	Perforated/edge or Patch/transitional	
Change to Interior	Developed	Interior	
CHANGES THAT INDICATE URBAN GROWTH			
Interior to Perforated/edge	Interior	Perforated/edge	Used for clump
Interior to Patch/transitional	Interior	Patch/transitional	Used for clump
Patch/transitional to Developed	Patch/transitional	Developed	Infill Growth
Perforated/edge to Developed	Perforated/edge	Developed	Expansion Growth
Interior to Developed	Interior	Developed	Outlying Growth ∗ Isolated ∗ Linear Branching ∗ Clustered Branching

Clumping Growth Types to Create Final Map. Due to the nature of a pixel-by-pixel roving window, any area of growth often consisted of at least two types even though it was all part of the same development. Common problems included that all clustered branching areas were bordered by linear branch pixels (Figure 2) and most linear branch areas contained some isolated and/or cluster pixels (Figure 3). To remedy this, each area of growth was grouped. Each group, or clump, was determined by all adjacent pixels that experienced either a non-urban to urban change, or an interior non-urban to fragmented non-urban change (Table 1). All *outlying* pixels within each clump were changed to only one type of outlying growth. The determination is made by a set of rules as well as a user-defined variable of the percentage of cluster pixels necessary to make the area a clustered branching growth as opposed to a linear branching growth.

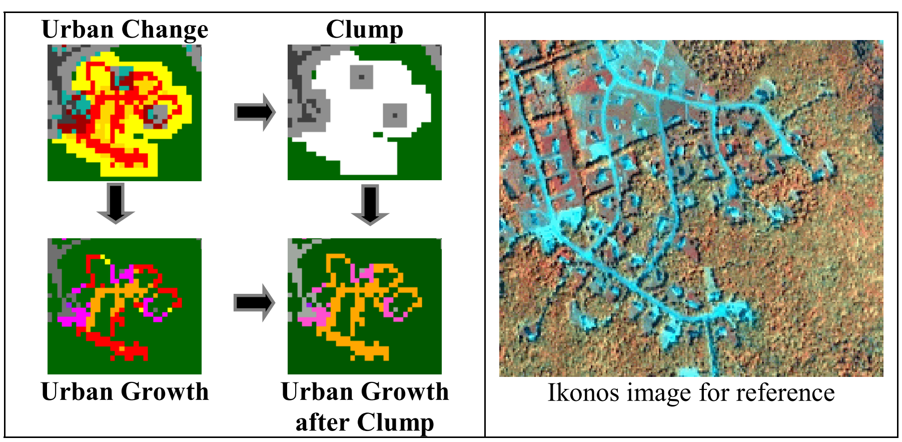


Figure 2. An example of the result of the "clump" step. In the original urban growth map, the area of growth included a number of linear branching pixels, clustered branching pixels, and some isolated pixels. The clumping procedure changed all outlying growth types to be clustered branching. See Appendix A for legends.

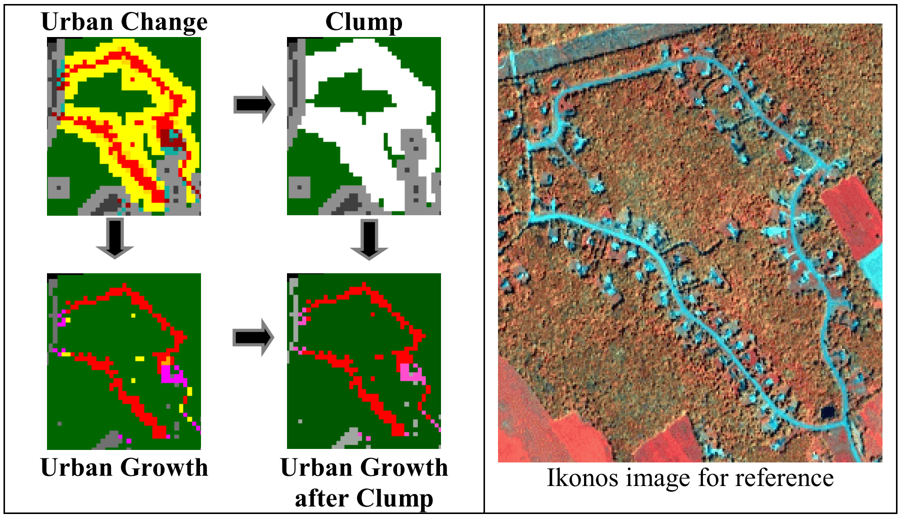


Figure 3. An example of the effect of the "clump" step. In the original urban growth map, the area of growth included a number of linear branching pixels as well as some isolated pixels. The clumping procedure changed all outlying growth types to be linear branching. See Appendix A for legends

RESULTS

The result of the model is an urban growth map consisting of no-change classes and urban growth classes (infill, expansion, isolated, linear branching, and clustered branching). Figures 4-8 show examples of each type of urban change and include a 1999 Ikonos image for reference. In all cases the Ikonos image was captured after all change in the urban growth map had occurred.

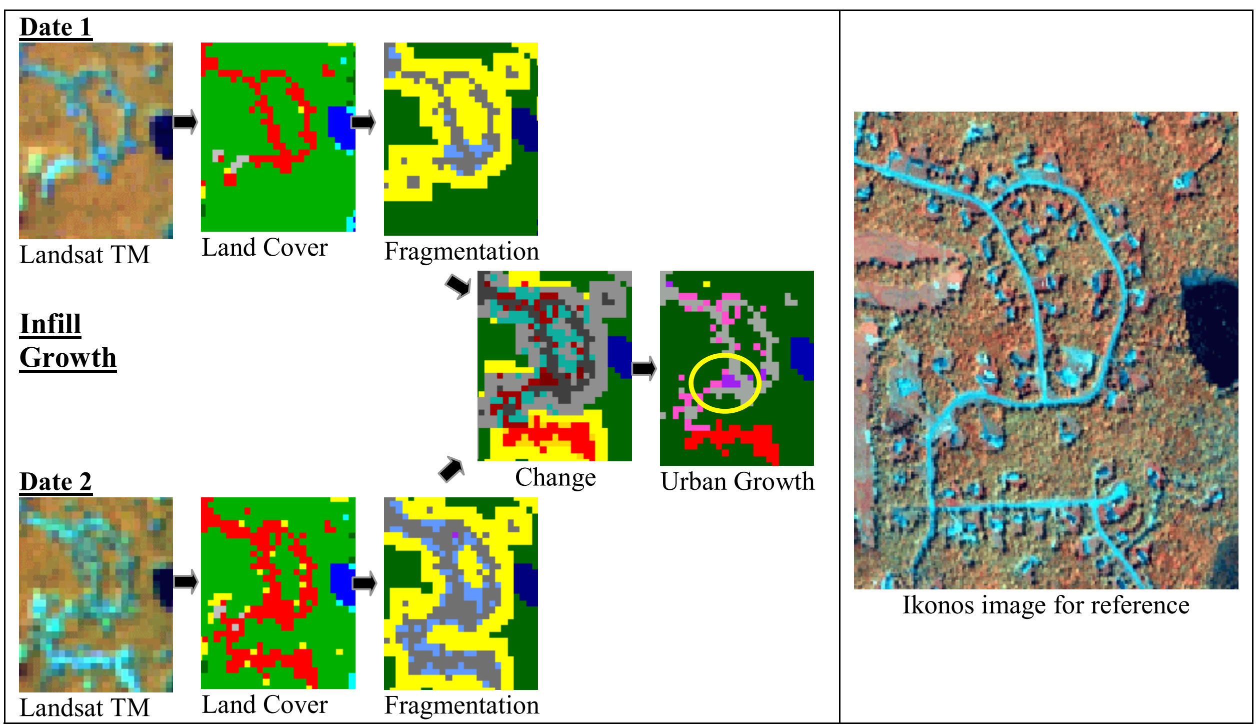


Figure 4. An example of infill growth (purple). In this case, several houses were added in the corner of an existing residential development. See Appendix A for legends.

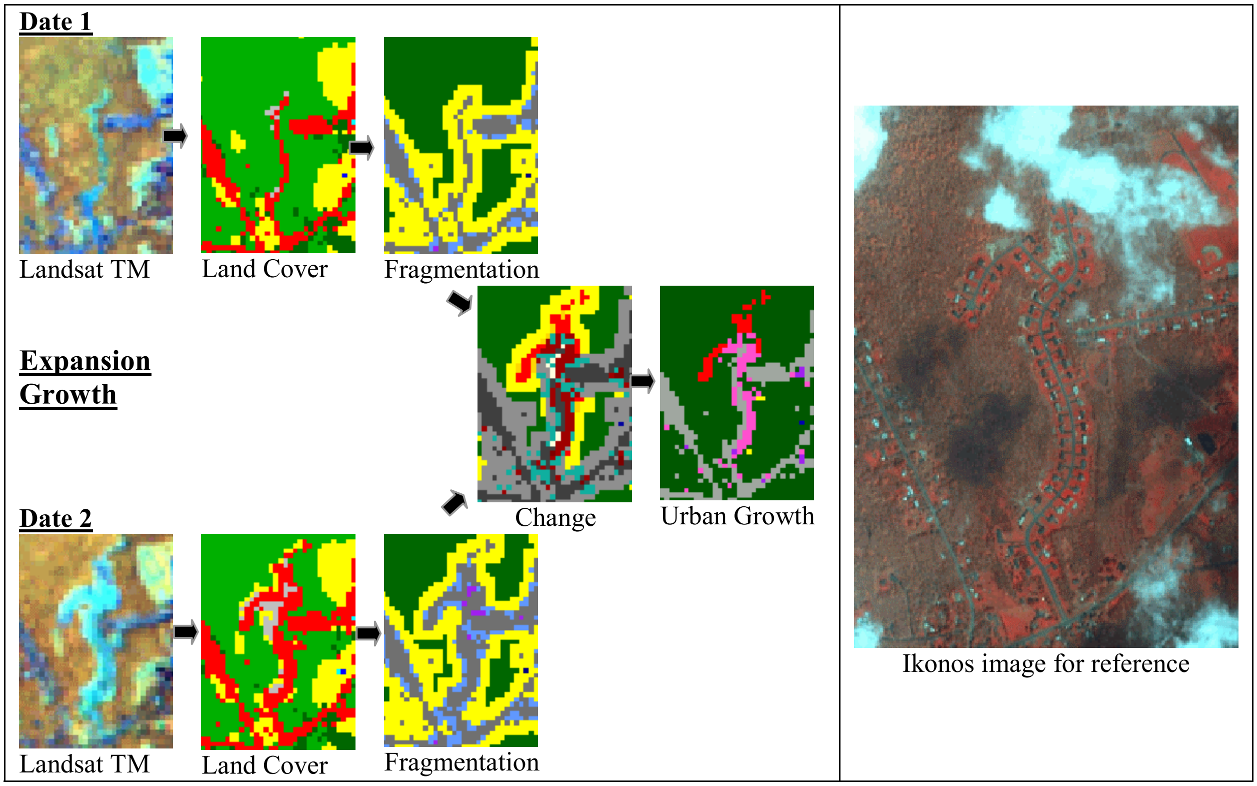


Figure 5. An example of expansion growth (magenta). In this case, a road had been built, then houses and driveways were constructed along the road. See Appendix A for legends.

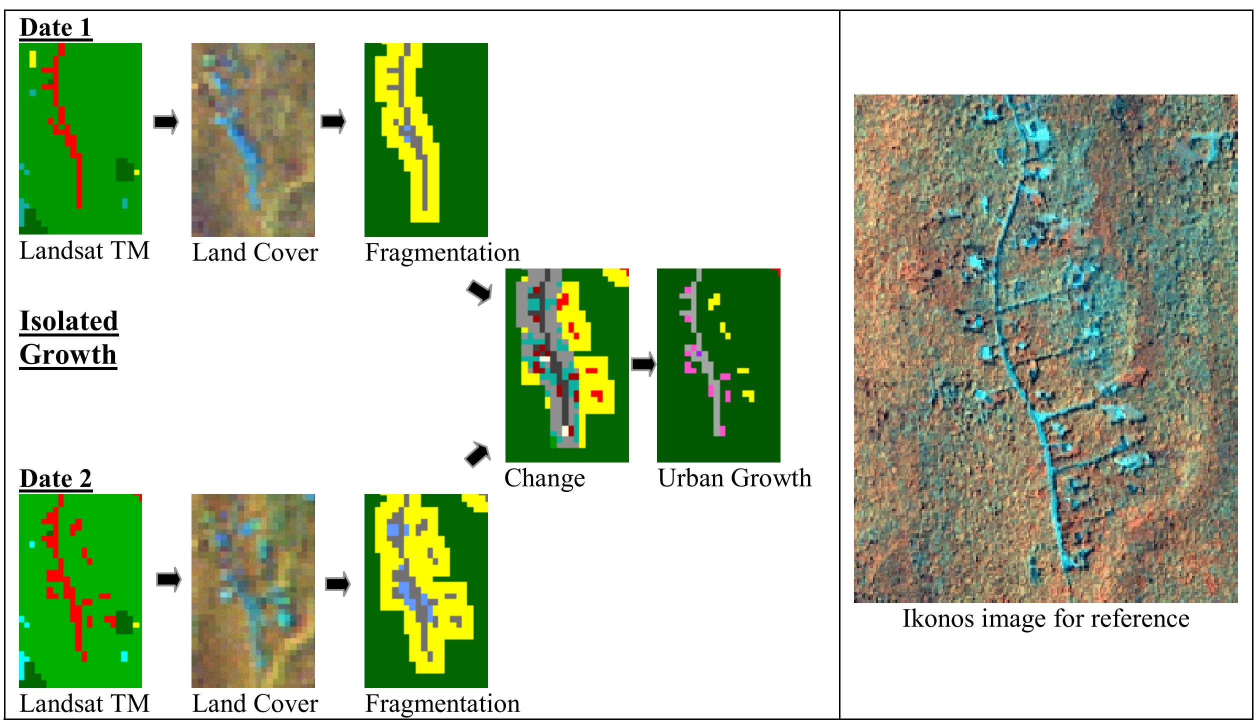


Figure 6. An example of isolated growth (yellow). Here, a road had been previously built, then houses were added some distance from the road and some distance from each other, resulting in the distinction of isolated growth. See Appendix A for legends.

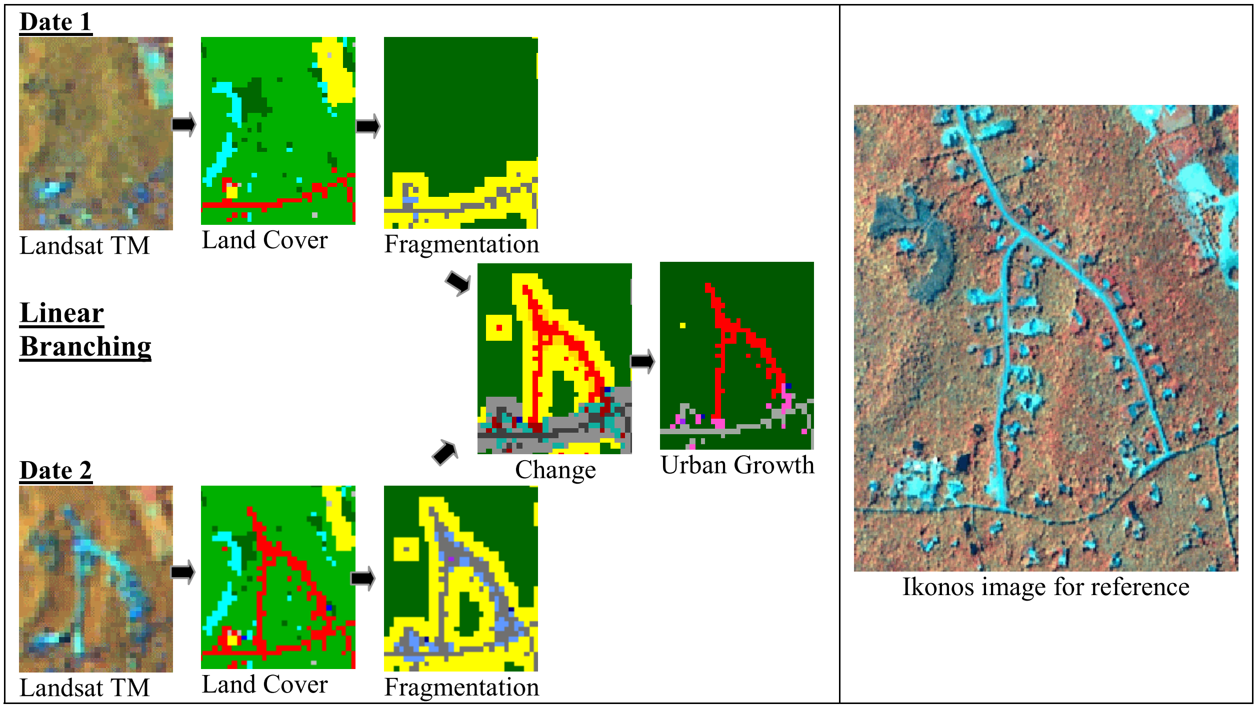


Figure 7. As example of linear branching (red). A new road and houses were built in a forested area. See Appendix A for legends.

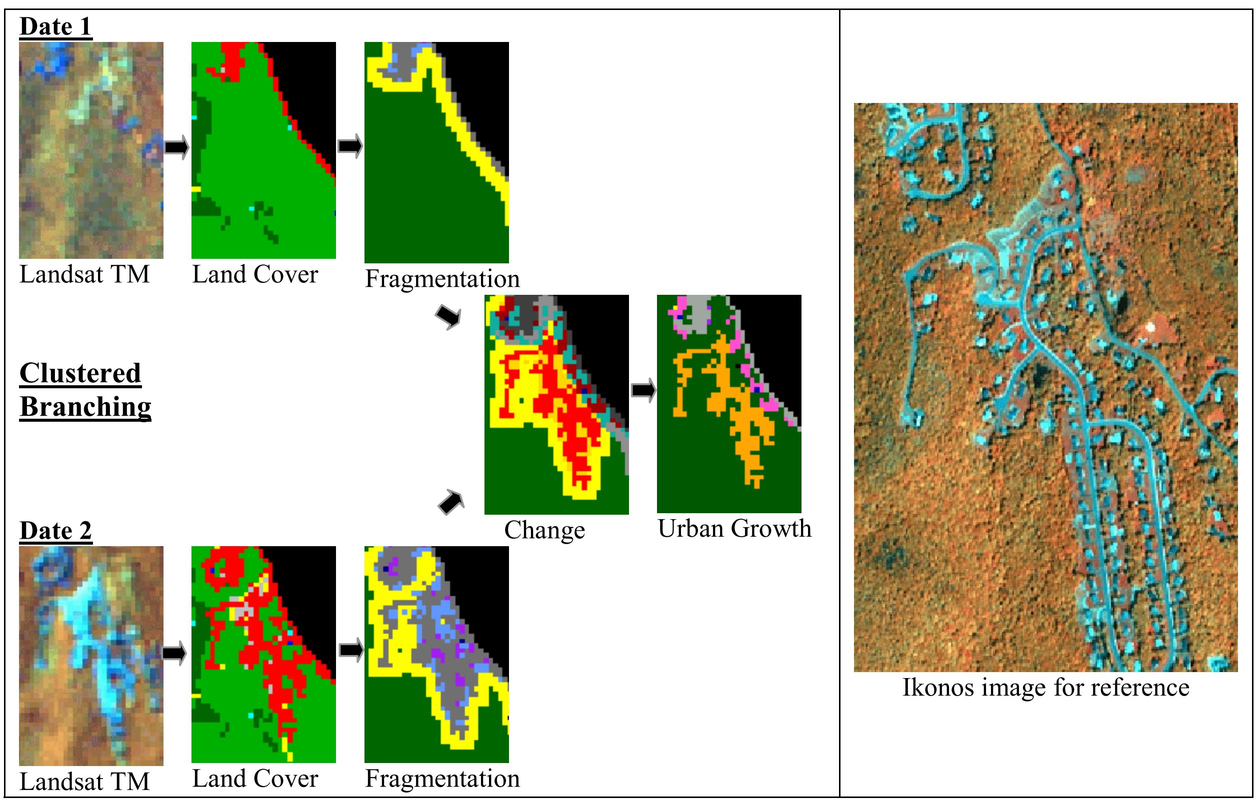


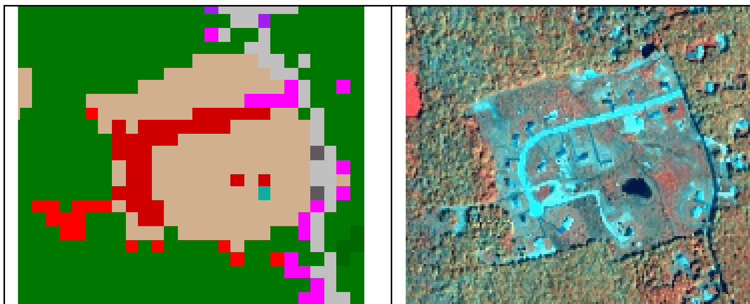
Figure 8. An example of clustered branching growth (orange). Here, a new neighborhood was constructed. See Appendix A for legends.

DISCUSSION AND CONCLUSIONS

Applications

The urban growth model was designed in ERDAS Imagine v8.4 using the Spatial Modeler. SML and EML scripting has been implemented so the model can easily be accessed and employed within the software interface. This allows the model to be implemented for many different applications. Several are highlighted below.

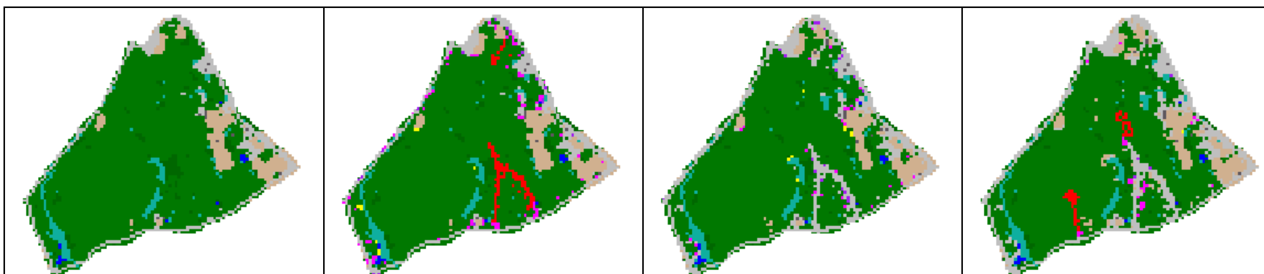
Natural Land Lost. One application of the urban growth model is to determine what kind of land is being lost to development (Figure 9). In New England, forest and farm land are both being developed. A quantification of the type of land lost in conjunction with a temporal factor is valuable information for assessing this issue.



Urban Growth Map | Ikonos Image

Figure 9. An example of how the urban growth model can be used to visualize and quantify what type of land is being developed. Here, a residential neighborhood was built on a non-forested field (shown in the darker red on the urban growth map) with a small extension of the development occurring in a forested area (shown in the brighter red on the left side of the growth image). An Ikonos image is provided for reference.

Fragmentation of forest and/or open space. Urban development causes a decrease in the amount of forest area, farmland, and open space, and also breaks up what is left into small chunks that disrupt ecosystems and fragment habitats. Viewing the urban growth maps with land cover over time reveals the real consequence of development on the landscape. Figure 10 shows a predominantly forested patch that experienced linear branching residential development between 1985 and 1990 as well as between 1995 and 1999. It is clear that the compound result of the development on the forest patch is a decrease in forest area and an increase in fragmentation.



1985 Land Cover | 1985-1990 Land Cover and Urban Growth | 1990-1995 Land Cover and Urban Growth | 1995-1999 Land Cover and Urban Growth

Figure 10. An example of the effect of urban growth on a predominantly forested patch of land. See Appendix A for legends.

Landscape Dynamics. Viewing static urban growth maps over time as well as animations and other visualizations allows citizens and town officials to visualize the collective result of many site-level decisions on the landscape as a whole. It also allows users to predict what the effect of pending or proposed developments might be on the town landscape. Visualizing urban growth in the form of a map also allows residents and town officials to look across the boundaries of their towns to their neighbors. Ideally, this would encourage the preservation of important natural areas that cross boundaries, as well as large blocks of forest and other habitat types. The town of

Colchester, Connecticut has experienced residential development. Colchester is used here as an example in Figure 11 showing how the landscape of a town can change depending on how much and where development occurs over time. The accuracy has not been assessed.

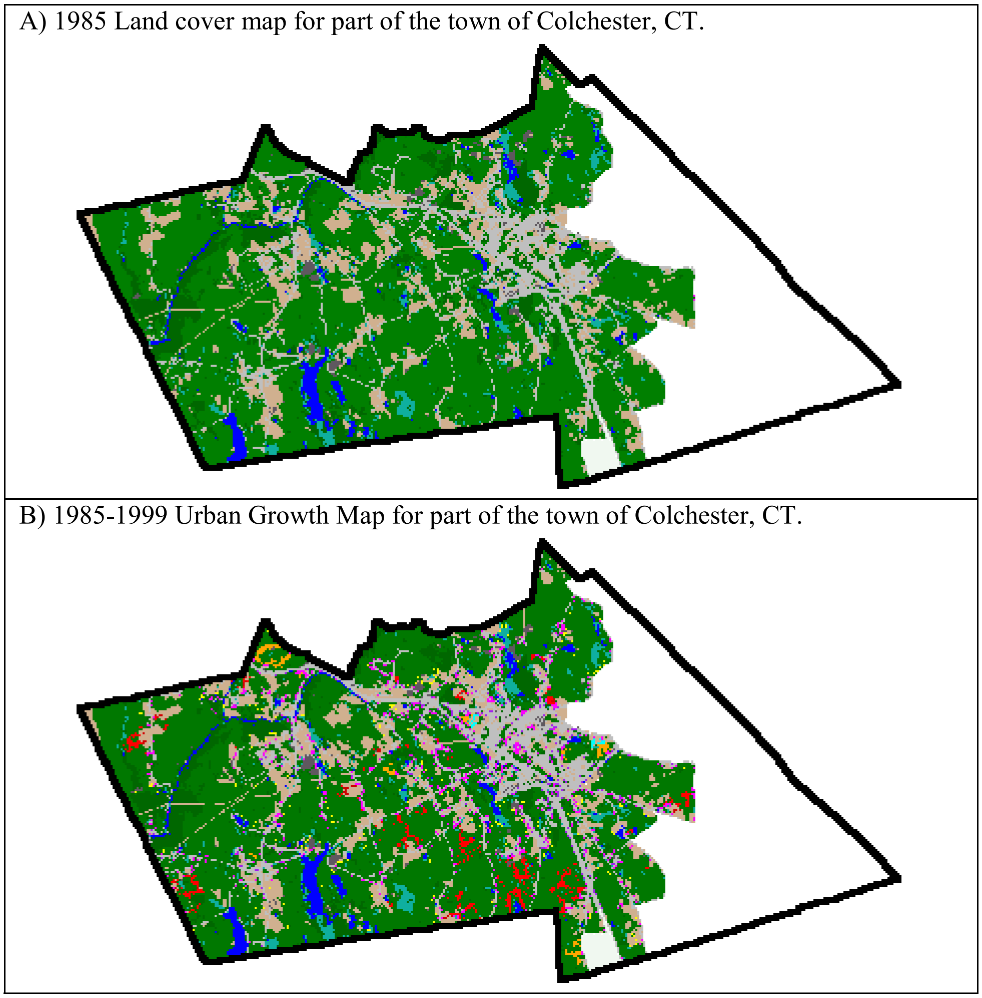


Figure 11. The 1985 land cover map for part of the town of Colchester, CT (A). Only part of the town was covered by the extended Salmon River watershed land cover maps, therefore, the urban growth model has only been applied part of the town. (B) shows the urban growth map from 1985-1999. The extent of growth indicates how the urban growth model can help officials and the public visualize how site-level developments have changed the landscape of their town.

Limitations

There are several limitations to the urban growth model. First, the results are only as good as the input land cover data. Some error inherently exists in most satellite-derived land cover maps. The use of two or more land cover maps could compound the error and result in an urban growth map with decreased accuracy. Also, 30-meter pixels do not always identify all roads on the landscape. Because the distinction between urban growth types is largely due to distance from existing urban areas, omission of urban areas can affect the output urban growth map. Finally, the date of image capture in conjunction with the date of development can influence the type of growth. For example, a linear development would be identified if a change were captured only when a road had been built. The next change map would likely show an expansion where houses were built. However, if houses had already been built along the road when the first image was captured, the change would likely be determined to be a linear or clustered branch.

Further work

There are many avenues of exploration for the urban growth model. Currently, only a 5x5 pixel window is available. We would like to develop the model further so that a user could choose the window size, such as 7x7 or 9x9. This is essential if other resolution data sets, such as Ikonos, are to be used. We would like to test the model on classifications derived from means other than per-pixel classifiers, such as photo-interpretation or image segmentation. We would like to experiment with the model in other areas of the country that experience growth different from what is commonly found in New England and adapt the model and the results to assess the loss of farmland to development. There are many more potential applications for the urban growth model that need to be further tested and explored.

ACKNOWLEDGEMENTS

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APPENDIX A

Land Cover Map Legend	
	Developed
	Non-woody Vegetation
	Deciduous Forest
	Coniferous Forest
	Water
	Wetland
	Barren

Non-urban Fragmentation Map Legend	
	Water
	Developed
	Interior
	Patch
	Transitional
	Perforated/Edge

Change Map Legend	
	Water – no change
	Developed – no change
	Interior – no change
	Fragmentation – no change
	Interior to Developed
	Interior to Perforated/edge
	Interior to Patch/Transitional
	Change within Fragmentation
	Perforated/edge to Developed
	Patch/transitional to Developed
	Change to Interior

Urban Growth Map Legend	
	Developed
	Water
	Non-developed (Deciduous)
	Non-developed (Coniferous)
	Non-developed (Non-woody Veg.)
	Non-developed (Wetland)
	Non-developed (Barren)
	In-Fill Growth
	Expansion Growth
	Isolated Growth
	Linear Branching Growth
	Clustered Branching Growth