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LAND DEVELOPMENT IN MASSACHUSETTS: ITS EFFECT ON THE ENVIRONMENT WITHIN ESSEX AND MIDDLESEX COUNTIES FROM 1990 TO 2007

By

PETER SEAN TARDIE

Bachelor of Science, Salem State College, 1999
Master of Science, University of New Hampshire, 2005

DISSERTATION

Submitted to the University of New Hampshire
in Partial Fulfillment of
the Requirements for the Degree of

Doctor of Philosophy

In

Natural Resources and Environmental Studies

May, 2010

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This dissertation has been examined and approved.

B. Rock

Dissertation Director,
Barrett N. Rock, Ph.D.
Professor of Forestry/Botany/Remote
Sensing, Complex Systems Research Center
(CSRC) & Department of Natural Resources
and the Environment

Thomas D. Lee, Ph.D.
Associate Professor of Forest Ecology,
Department of Natural Resources and the
Environment

John M. Halstead, Ph.D.
Professor of Environmental and Resource
Economics and Chair, Department of
Natural Resources and the Environment

John Hayes

John T. Hayes, Ph.D.
Associate Professor of Geography,
Salem State College, Salem, Massachusetts

Annette L Schloss

Annette L. Schloss, Ph.D.
Research Scientist, Complex Systems
Research Center (CSRC)

Feb. 3, 2010
Date

DEDICATION

For Mumsy and Dadio…

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ABSTRACT

LAND DEVELOPMENT IN MASSACHUSETTS: ITS EFFECT ON THE ENVIRONMENT WITHIN ESSEX AND MIDDLESEX COUNTIES FROM 1990 TO 2007

BY

PETER SEAN TARDIE
UNIVERSITY OF NEW HAMPSHIRE, MAY 2010

Since the 1970's urban centers in and surrounding Essex and Middlesex Counties in Massachusetts have expanded and proliferated into adjacent communities. This expansion has led to the conversion of land for housing, businesses, schools, recreation, and parks, placing significant strain on existing land cover, land use, and available natural resources. Mounting growth pressures and a reduction of undeveloped land have raised serious concerns as cropland and forest fragmentation, wetland destruction, protected open-space infringement, pollution, and systematic losses of rural conditions have become obvious. To monitor development, the post-classification change detection method was applied to Landsat Thematic Mapper (TM) satellite data and GIS was used to detect, quantify, and document the extent of development and its effect on the environment and to assess and quantify the demographic changes that occurred within the counties from 1990 to 2007.

Classification of the 1990 image resulted in 217 clusters and 214 clusters for the 2007 image. The overall accuracy achieved for the 1990 image classification was 87.3% with a KHAT value of 0.848, and the overall accuracy for the 2007 classification was 86.27% with a KHAT value of 0.840. From 1990 to 2007 land cover change occurred primarily along major transportation corridors. The post-classification change detection results indicate that Essex and Middlesex County combined gained 23,435.66 "new" acres of land development from 1990 to 2007 through a loss and change in acreage from the Bareland, Forest, Grassland, Water, and Wetland land cover class categories. Results indicate that there was an approximate 0.56% overall (net) increase of newly developed land areas within the 1990 and 2007 image classifications from 415.46 acres or 0.64 square miles. In addition, there was a substantial decrease (-40.0%) within the grassland category. Land development was responsible for a portion of the decrease of grasslands (-13.63%), which occurred mostly within Middlesex County.

Results also indicate that "new" land development occurred within several Commonwealth of Massachusetts designated environmentally-sensitive areas: 722 acres in areas of critical environmental concern, 670 acres in priority habitats of rare species, 1,092 acres in living waters core habitats and critical supporting watersheds, 1,318 acres in protected and recreational open spaces, and within 0-1000 feet of 600 certified vernal pools. In addition, several rare or imperiled species inhabiting these areas may have been adversely affected by land development through habitat loss, change, or fragmentation, and/or passage corridor disruptions. A GIS comparison of the "new" land development acreages and census demographic statistics within Essex and Middlesex County cities and towns during this period indicate that communities with more families with children exhibited more land development, and communities with higher median household income exhibited less land development. Land change detection over the 17-year period indicated encroachment of development in areas of environmental concern, but level of development varied by socio-demographic factors.

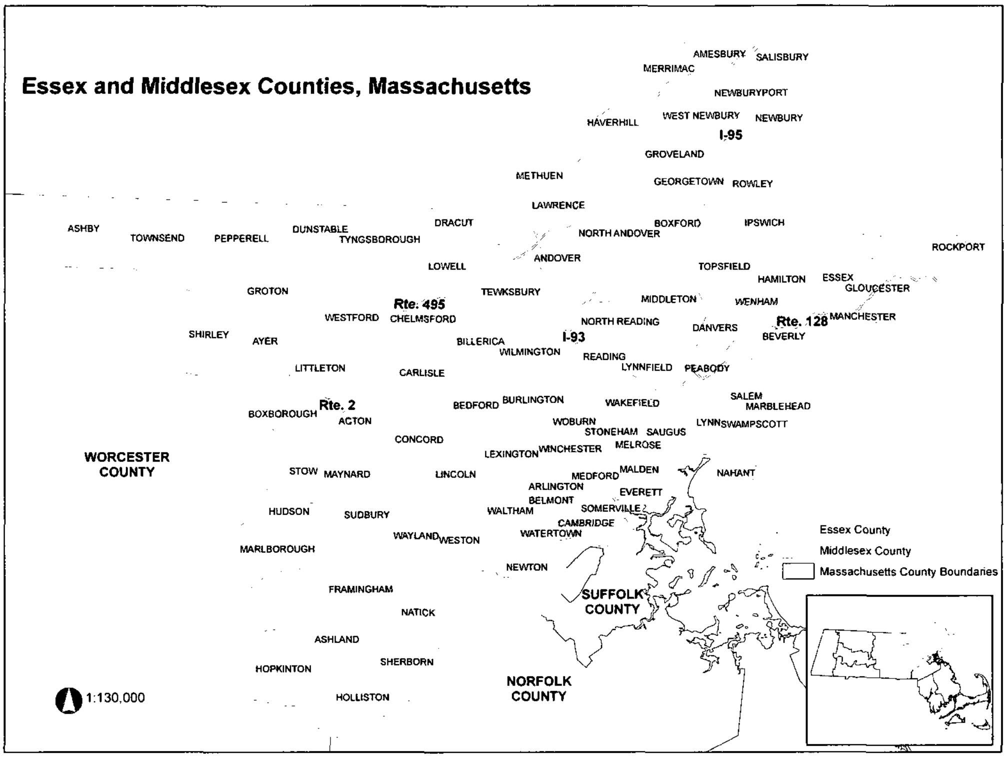
This study also illustrated that the combined use of remotely sensed data, Geographic Information Systems (GIS) technology, and demographic data are effective for use as a diagnostic tool and/or base to be built upon to explore associations, indicators, or drivers which may influence land cover change and its effects on existing environmental conditions in areas exhibiting change. In addition, this study provided awareness to ancillary research where scientific guidelines were derived for the protection of specific wildlife habitats and resident species. Lastly, this study presented several land cover modeling and web deployed data dissemination tools for the dissertation results as well as provided a conceptual framework for the successful adoption and implementation of these tools for organizations engaged in natural resource planning and management.

CHAPTER I. INTRODUCTION

Since the 1970's, population and development of land in both Essex and Middlesex Counties in Massachusetts have increased, and as neighboring urban centers expand, both have proliferated into adjacent communities (Figure 1). This expansion has led to the conversion of land for housing, businesses, schools, recreation, and parks, placing significant strain on remaining undeveloped land cover and land use as well as available natural resources. In addition, mounting growth pressures and a reduction of undeveloped land have raised serious concerns as cropland and forest fragmentation, wetland destruction, protected open-space infringement, air and water pollution, and systematic losses of rural conditions have accelerated. Essex and Middlesex Counties are unique places with historical significance and they contain many rare and endangered plant and animal species and a wealth of natural resources. Without focused land cover and land use change research and community-wide environmental education, the continued loss or degradation of land may be accepted as "just" the price of progress.

Key questions addressed within this dissertation research are: (1) how much land development occurred within Essex and Middlesex Counties from 1990 to 2007 and, what were the types and extent of this land development? (2) What were the effects from this land development on the environment, specifically to forests, grasslands, wetlands, barelands, and water? This dissertation research set out to: (1) detect, document, and quantify the recent types and extent of land development within Essex and Middlesex Counties from 1990 to 2007, and (2) assess how this land development has affected the environment. "Affect" was measured by quantifying (through data generation) the losses

Figure 1. The study area of Essex and Middlesex Counties, Massachusetts.



and gains (in acreage) of broad-based land cover types such as forests, wetlands, grasslands, barelands, and water. In addition, this dissertation research evaluated land development at the ecosystem-level by providing insight into and presenting how land cover and land use change relates to the habitat change of core habitats and key rare or imperiled species, by incorporating a wealth of existing data from the Commonwealth of Massachusetts State organizations, such as the Department of Fish and Game's Mass Wildlife and Natural Heritage and Endangered Species Program, Department of Environmental Protection, and Department of Conservation and Recreation. Data sources for the "effect" analysis consisted of Areas of Critical Environmental Concern, Priority Habitats of Rare Species, Certified Vernal Pool Areas, Protected and Recreational Open Space Land, and Living Water Core Habitats and Critical Supporting Watersheds.

These existing data provide understanding into the critical nature and extent of natural resource and habitat fragmentation, disruption, and loss. In addition, these data assisted in identifying areas where commercial or residential land development and/or encroaching land development may have affected native plant species, reduced species richness of native flora, degraded the wildlife habitat of certain species, influenced resident wildlife community census levels overall, affected riparian corridors, available water resources and water quality (e.g., areas which may contribute to eutrophication, over-use, groundwater discharge, disrupted or low stream-flow and storm water run-off, impacting overall water quality, etc.).

This dissertation research also determines where the extent of land cover change has been the greatest, for instance, in urban centers, suburban areas, or rural areas, and presented areas of land cover and land use change which have had the greatest negative impact on environmental conditions. In addition, this dissertation research provides insight into the types of environmental factors (biodiversity, invasive species, water quality, etc.) which may be the most sensitive to land cover and land use change, and discusses some of the socio-demographic factors which may drive it. Currently, there is little or no recorded land cover change research of this nature recorded in the literature for Essex and Middlesex County Massachusetts. Hence, this research provides both novel and useful literature on several aspects of research as it identifies and documents specific areas within these two counties where the environment was affected by development.

The land cover change analyses within this dissertation research were conducted using Landsat 5 Thematic Mapper (TM) 28.5 meter remotely sensed data (see Appendix A) and geographic information systems technology. These technologies were effective to monitor natural resources within the counties because they provided a means to detect and quantify change over time. In addition, the post-classification change detection method performed using the satellite imagery, not only quantifies how much land cover has changed due to development, but, also, converted (as categorized within the land cover classification scheme) from one category or type to another (i.e., from forest to grassland, developed, or bareland between 1990 and 2007 in each county). Through the use of these technologies this dissertation research documents, quantifies (through data generation), and promotes an awareness of the nature and extent of land development occurring within these two counties and its effects on the environment to state and local municipal leaders and county residents, through report and future websites, and sets the stage for the future development of an educational program.

This dissertation is presented within twelve chapters. Chapters 1 through 7 provide an introduction to the study area, a literature review on existing methods to assess land cover change, a historical perspective of the land cover change within the landscape of Essex and Middlesex Counties, the rationale of the study, and the objectives, conceptual framework, hypotheses, materials and methods used, and overall land cover change results. Chapters 8 through 11 utilize the results presented in Chapter 7 and additional methods to focus on four specialized topic areas. Chapter 8 investigates the demographic factors which may have influenced land cover change within the counties from 1990 to 2007, Chapter 9, (1) investigates the effects of land development on "protected" or "environmentally-sensitive" areas and (2) presents scientifically-derived guidelines to assist in the protection of "affected" rare or imperiled species, and Chapters 10 and 11, provide an awareness to and options for the development, adoption, successful implementation, and proliferation of the methodology, technological tools, and data findings to the research community, natural resource land managers, and/or the general public, and Chapter 12 provides an overall discussion of the study. This dissertation provides literature for the research community on the application, methodology, and the procedures to conduct temporal land cover analyses by combining the capabilities of existing geospatial technologies with a wide array of data sources.

CHAPTER II. LITERATURE REVIEW

This chapter is divided into three sub-sections. This literature review focuses on the existing technology and methodologies to conduct land cover change detection analyses. The first reviews land cover change detection and the post-classification technique, the second reviews the accuracy assessment technique used for image classification and post-classification change detection and ground reference data collection methods, and the third, reviews geographic information systems technology. Additional literature reviews for the specific topic areas investigated are provided in Chapters 8 through 11 in the appropriate sub-sections.

Land Cover Change Detection

Landscape change is a naturally occurring phenomenon which has been compounded by rising population and urbanization (Duncan et al., 1999; Pathirana, 1999). The changes in our environment have become a critical concern for all of us (Hallum, 1993), as increased land development, traffic, air and water pollution, and loss of green-space leave many communities ill-equipped to handle the impacts of rapid growth (Epstein et al., 2002). The need for improved land management practices and ways to monitor them have become evident (Brothers and Fish, 1978). Changes to the environment can provide insight into how land is or has been managed, and the use of established change detection research methodologies can serve to monitor these changes and evaluate management practices (Brothers and Fish, 1978; Im et al., 2008).

Change detection identifies the differences in the state of an object or phenomenon by observing it at different times and its methodology can provide the capability to (1) detect occurrences of land cover change, (2) identify the types or nature of change, and (3) quantify its spatial extent (Brothers and Fish, 1978; Singh, 1989; Macleod and Congalton, 1998). Change detection also can provide valuable insight into environmental and socio-economic conditions resulting from local, national, or international regulatory and/or land use policy changes over time (Lunetta and Elvidge, 1998; Bontemps et al., 2008).

Traditionally, aerial photography had been utilized to detect changes in land cover in many areas (Richter, 1969; Weismiller et al., 1977; Adeniyi, 1980; Lo and Wu, 1984; Lo and Shipman, 1990). However, identifying land cover change through the use of aerial photography can be difficult because it requires a large data collection effort, time, manual interpretation, which can be subjective, and sophisticated mathematical computation to determine the distribution of the land cover type of specific interest (Weismiller et al., 1977; Lo and Shipman, 1990). In addition, aerial photography cannot readily reveal the processes of land cover change without an extensive investigation or validation of the specific land cover classes of change within the field (Lo and Shipman, 1990).

Since 1972, the Landsat remote sensing satellite program has provided a more efficient and cost-effective method for monitoring land cover from space (Fung and LeDrew 1988; Lunetta and Elvidge, 1998; Singh, 1989). Landsat has been utilized as an exclusive source of multi-spectral data for many studies because of its advantages (i.e., multi-spectral bands, large coverage area, and repetitive acquisition) over more traditional data capture methods like aerial photography (Gordon, 1980; Martin, 1989; DeFries and Cheung-Wai Chan, 2000; Teillet et al., 2001). To detect changes in land cover, a comparison of two or more satellite images acquired at different times, can be used to evaluate the temporal or spectral reflectance differences that have occurred between them (Masry et al., 1975; Yuan and Elvidge, 1998). With its routine data acquisition (every 16 days), and seamless integration with advancing technologies such as geographic information systems (GIS), Landsat satellite data have made environmental monitoring applications such as change detection ubiquitous (Wickware and Howarth, 1981; Singh, 1989; Jensen, 1996; Macleod and Congalton, 1998; Rynzar and Wagner, 2001; Thome, 2001, Yuan et al., 2005; Wulder et al., 2008).

Post-Classification Change Detection

An increasingly popular application of remote sensing is change detection. In many change detection studies the post-classification method was found to be the most suitable and successful for detecting land cover change (Weismiller et al., 1977; Wickware and Howarth, 1981). This technique requires that two images from different dates be independently classified and then compared (Jensen, 1981; Jensen and Toll, 1982; Singh, 1989; Jensen, 1996; Yuan and Elvidge, 1998). Foody (2001) indicated that accurate classifications are imperative in order to perform a change detection analysis because it will ensure the development of precise change detection results.

Once the image classifications with the highest overall accuracy are selected they are then combined to form a "new" change image classification to produce matrix logic. Advanced GIS processing and analyses can then be used to enhance the post-classification technique to conduct further land cover change exploration through selection and thematic presentation of "from-to" land cover class changes. The post-classification technique can be iterative and usually requires refinement to produce accurate and informative change detection results.

Accuracy Assessment

Since 1972, the Landsat satellite sensor systems (MSS & TM/ETM+) have made remotely sensed data readily available and have offered an efficient means of collecting information about the environment (Fung and LeDrew 1988; Singh, 1989; Congalton, 1991; Macleod, 1994; Lunetta and Elvidge, 1998; Teillet et al., 2001; Thome, 2001; Wulder et al., 2008). Recent advances in remote sensing technologies and the increasing availability of high spatial and spectral resolution earth observation satellite data provide great potential for acquiring detailed spatial information to identify and monitor environmental problems within specific areas at desirable spatio-temporal scales (Miller and Small, 2003; Thapa and Murayama, 2009).

In environments disturbed by anthropogenic processes, transitions in building materials, density, size and shape, vegetation, and intensive socio-economic activities often transform the landscape towards heterogeneity (Thapa and Murayama, 2009). This heterogeneity often can confuse the image analyst in the discrimination of land cover types because of the high spatial and spectral diversity of surface materials (Macleod, 1994; Maktav et al., 2005). Congalton (2001) indicates that accuracy assessment or validation should be a key component of any project using spatial data.

Accuracy assessment is not only used to determine the accuracy of the information derived from remotely sensed data, but also to help image analysts increase and/or compare their interpretative skills to that of others (Macleod, 1994). Prior to 1990, the idea of assessing the classification accuracy of remotely sensed data was treated as an afterthought rather than an integral part of any project (Congalton, 1991). Many factors such as reference data spatial and spectral resolution, radiometry, rectification, variations in vegetation phenology and physiology, and urban development cycles, which can influence the accuracy of an image classification derived from remotely sensed data, must be investigated (Rock et al., 1986; Khorram et al., 1999).

As more advanced digital satellite remote sensing techniques become available, digital image classification becomes more complex (Aronoff, 1985; Congalton, 1988; Congalton, 1991; Fenstermaker, 1991). Despite these advances, computer-assisted image classification is still unable to produce land cover maps and statistics with high accuracy (Lo and Choi, 2004); therefore, it has become common practice to assess the reliability of the results (Aronoff, 1985; Congalton, 1988; Congalton, 1991; Fenstermaker, 1991). Because image classification or change-detection analysis maps are often used to assist the development of land planning and management practices, assessment of their accuracy is imperative (Congalton, 1988; Fenstermaker, 1991; Stehman, 1992; Powell et al., 2004; Wulder et al., 2006). Errors contained in the classified images can and will adversely affect the accuracy and validity of the resulting products, such as maps and reports (Pathirana, 1999; Dev Behera et al., 2000). To adequately assess the accuracy of a remotely sensed classification, Congalton (1991) expresses that accurate ground and reference data must be collected.

Ground Reference Data Collection Methods

Traditionally, classification accuracy obtained from remote sensing satellite data has been evaluated using reference data obtained through photo-interpretation, aerial reconnaissance, or ground-based field verification (Congalton, 1991; Dev Behera et al., 2000). Several studies have utilized a variety of methods to collect ground reference data for ground control, image classification training, accuracy assessment, and other GIS applications (Rock et al., 1986; Puterski et al., 1990; Ardo and Pilesjo, 1992; Lass and Callihan, 1993; Rigney, 1995; Liu and Brantigan, 1995; Latifovic and Olthof, 2004; Tardie and Congalton, 2002; Tardie et al., 2003; Tardie, 2005; Gorokhovich and Voustianiouk, 2006; Hais et al., 2009). In addition, a commonly accepted practice for assessing image classifications derived from coarse resolution satellite data involves the use of medium resolution satellite imagery as the reference for the comparison (DeFries et al., 1998; Mucher et al., 2000; Latifovic and Olthof, 2004). Although no reference data set may be completely accurate, it is important that it has high accuracy or else it will not provide a fair assessment (Congalton, 1991).

Global Positioning Systems (GPS) have become an important tool to acquire ground information with high accuracy for image classification training and accuracy assessment purposes (Farrell et al., 2003; Gorokhovich and Voustianiouk, 2006; Trimble Navigation Ltd., 2009). GPSs not only provide the capability to capture sub-meter accurate location data, but can be used to record valuable descriptive attributes for any given area of interest (Trimble Navigation Ltd, 2009). However, GPS acquisition of positional information can be sensitive to procedural variations, environmental factors (e.g., multi-path disturbance from tree canopy), and receiver quality (Dev Behera et al., 2000). Nevertheless, GPSs provide a lower cost alternative, require less time and labor, and produce higher output than traditional field surveying methods (Puterski et al., 1990; Bolstad and Smith, 1992).

In recent years, other established technologies such as digital still cameras, digital video cameras, and airborne inertial measurement units (IMU) have been integrated with GPS technology to acquire ground reference information or ground truth in a new way for a wide-range of GIS mapping applications, ground control for image rectification, image classification training, and thematic accuracy assessment (Trimble Navigation Ltd, 2009). Ochi and Takagi (1996) used GPS and hand-held camera to collect ground truth to geo-reference satellite imagery, assist in image classification, and develop a geodatabase for secondary education purposes. Kliman et al. (1996) used a color video camera to stamp time and GPS coordinate location to video to assess the accuracy of land cover maps derived from Advanced Very High Resolution Radiometer (AVHRR) imagery in Arizona. In 2000, the United States Geological Survey used aerial videography to develop ground reference data to assess the accuracy of land cover maps for the state of Colorado's Biodiversity GAP Analysis Project. Skaloud and Vallet (2002) used a hand-held GPS with an inertial measurement unit (IMU) onboard a helicopter to assess the mapping accuracy of sporadic and erratic occurrences of avalanches and landslides in Switzerland. Wang et al. (2003) used a digital camera and GPS to link mangrove sites in Tanzania Coast to individual pixels from remote sensing imagery.

Teachers and students in Androscoggin County, Maine used digital cameras and GPS as part of a partnership with the Global Learning and Observations to Benefit the Environment (GLOBE) program to ensure quality control and conduct an accuracy assessment for a land cover change analysis (University of New Hampshire, 2005; The GLOBE Program, 2009). Bannari et al. (2006) used a hand-held digital camera and GPS to field verify an image classification of crop residue locations within Saskatchewan, Canada using IKONOS imagery. Lazar and Ellenwood (2006) used GPS and an IMU to assess the accuracy of automated aerial triangulation for the ortho-rectification of acquired aerial imagery. Yamazaki and Matsouka (2006) used geo-referenced digital photos to map and perform a damage assessment from the impacts of an earthquake in Central Java. Wen et al. (2007) utilized digital cameras and GPS to collect field data for ground truthing to assess the mapping accuracy of several watersheds in Southern Guam. Rafieyan et al. (2009) used a portable digital camera and GPS to collect field reference data to update land cover maps for forest range management within central Iran. Zomer and Ustin (2009) designed a protocol using digital cameras to acquire ground truth verification for hyperspectral remotely sensed data.

Hand-held personal digital assistants (PDA) with onboard GPS capabilities, highly-portable GPS units, and ultra-portable digital cameras have facilitated the collection of location and position-based information. PDAs also have provided an efficient means to capture, share, and clearly document environmental information for an array of geographic information systems (GIS) analyses (Thapa and Murayama, 2009). Since 2006, Trimble Navigation Limited has published numerous white papers to introduce the methodology for time-syncing or stamping time, GPS coordinates, and metadata to digital images from GPS-compatible hand-held cameras for integration for analyses within geographic information systems. Several applications have been presented by Trimble (2009), and they range from the tracking of critical infrastructure and graffiti to potential environmental impacts on proposed development sites. Several studies present the usefulness of digital cameras with GPS time and coordinate positioning stamps for the purpose of compiling a digital ground reference data inventory (Trimble, 2009). However, few of these studies provide insight into the integration of this technology for established quantitative accuracy assessment techniques.

The Accuracy Assessment Technique

Because image classification or change-detection analysis maps are often used to assist the development of land planning and management practices, assessment of their accuracy is imperative (Congalton, 1988; Fenstermaker, 1991; Stehman, 1992). Errors contained in the classified images can and will adversely affect the accuracy and validity of the resulting products such as maps and reports (Pathirana, 1999). To adequately assess the accuracy of a remotely sensed classification, Congalton (1991) expresses that accurate ground and reference data must be collected. However, adequately assessing the accuracy of a remotely sensed classification can be expensive in both time and money (Skidmore and Turner, 1992; Congalton, 1988). Nevertheless, elements crucial to effective accuracy assessment such as sampling design, distribution intent of the map information, classification scheme, reference data collection methods, and statistical analysis techniques must be carefully considered or the assessment will produce meaningless results (Congalton, 1991; Congalton and Green, 1999).

In addition, there are several steps that interpreters should take to investigate the accuracy or errors often contained within the spatial data, including (1) visual inspection, (2) non-site specific analysis, (3) difference image creation, (4) error budgeting, and (5) quantitative accuracy assessment (Congalton and Green, 1999; Congalton, 2001). Congalton (2001) expresses that the majority of these steps are helpful in assessing the accuracy of the spatial data, but quantitative accuracy assessment provides the most powerful mechanism for its descriptive and analytical evaluation.

Components of the Error Matrix

Quantitative accuracy assessment in the form of an error or confusion matrix is efficient in its representation of map accuracy (Congalton and Green, 1999). Table 1 provides an example of the error matrix that is a square array of numbers organized in rows and columns that express the number of sample units (i.e., pixels, clusters of pixels, or polygons) assigned to a particular category relative to the actual category as indicated by the reference data (Congalton et al., 1983; Congalton, 2001). The columns represent the reference data and the rows indicate the classification generated from the remotely sensed data (Congalton, 2001).

The reference data samples summarized within the error matrix are used to estimate the overall classification accuracy of the map or individual map classes as measured against the actual land cover class on the ground (Story and Congalton, 1986; Skidmore and Turner, 1992; Stehman, 1992; Pathirana, 1999; Congalton, 2001). To calculate the overall accuracy of an image classification from the error matrix requires summing the major diagonal and dividing its total by the row or column total. In addition, the image classification producer's accuracy (omission error) and user's accuracy (commission error) can also be derived from the error matrix (Story and

Congalton, 1986). Complete agreement between the reference data and classification data occurs when all the off-diagonal counts are zero (SAS Institute, Inc., 2005).

Error Matrix Analysis

The error matrix can be used as a starting point for a series of descriptive and analytical statistics (Congalton, 1991; Congalton and Green, 1999). The Kappa analysis (Cohen, 1960) is a discrete multivariate technique that has become a standard component in most accuracy assessments (Congalton, 2001). The Kappa coefficient statistic or KHAT, calculated for each error matrix, can measure the actual agreement between the reference data versus the chance agreement between the classified data as well as whether one error matrix is significantly different than another (Congalton et al., 1983; Congalton and Green, 1999). Its ranges of values can fall within three groupings: values greater than 0.80 indicate a strong agreement; values between 0.40 and 0.80 a moderate agreement; and a value below 0.40 represents poor agreement (Congalton and Green, 1999). These values can allow the image analyst to determine whether the classification agreement is significantly greater than zero, or in other words, better than a classification where labels are assigned randomly (Congalton and Green, 1999; Congalton, 2001).

The Z statistic significance test also can be employed to determine if the image classification is significantly better than a random result (Congalton and Green, 1999). This test also can be utilized to evaluate individual image analysts, classification techniques or algorithms, or even two dates of imagery (Congalton and Green, 1999). For example, a Z statistic greater than 1.96 (at the 95% confidence level) can suggest that the results of the image classification are in fact significant; i.e., that it is better than one generated randomly (Congalton and Green, 1999). Both Congalton (1991) and Congalton and Green (1999) have reviewed all above mentioned as well as other error matrix analysis techniques extensively.

Table 1. An example of an error matrix.

SINGLE DATE IMAGE CLASSIFICATION

		REFERENCE DATA						
		D	B	F	G	W	WT	Row Total
CLASSIFIED DATA	D	**19**	0	0	0	0	0	19
	B	1	**17**	0	0	0	0	18
	F	0	2	**20**	2	0	10	34
	G	0	1	0	**18**	0	3	22
	W	0	0	0	0	**15**	2	17
	WT	0	0	0	0	5	**5**	10
	Col. Total	20	20	20	20	20	20	**94**

PRODUCER'S ACCURACY			USER'S ACCURACY		
DEVELOPED (D)	= 19/20	95.0%	DEVELOPED (D)	= 19/19	100.0%
BARELAND (B)	= 17/20	85.0%	BARELAND (B)	= 17/18	94.4%
FOREST (F)	= 20/20	100.0%	FOREST (F)	= 20/34	58.8%
GRASSLAND (G)	= 18/20	90.0%	GRASSLAND (G)	= 18/22	81.8%
WATER (W)	= 15/20	75.0%	WATER (W)	= 15/17	88.2%
WETLAND (WT)	= 05/20	25.0%	WETLAND (WT)	= 05/10	50.0%

OVERALL ACCURACY

=94/120 **78.3%**

KAPPA ANALYSIS RESULTS

KHAT	Variance	Z Statistic
0.724	0.0020245	16.107372

The Use of Geographic Information Systems (GIS)

Geographic Information Systems (GIS) can be quite valuable when used to explore land cover changes. GIS technology provides many researchers with the capability to store, search, analyze, manipulate, display, and distribute large amounts of descriptive geo-referenced and relational data using a wide array of selection criteria to model and further understand the environment (Congalton and Green, 1992). Since the early 1970s, GIS technology has been recognized for its usefulness in a variety of applications from historical land data analysis and environmental modeling to the instruction of geography and geospatial relationships to elementary to college age students (Elwood, 2006; O'Kelly, 2007; Marsh et al., 2008).

In this dissertation research, a GIS approach was developed, and it was not only used as a visualization tool to explore the results derived from the satellite data but also to quantitatively examine areas within each county where land development has impacted the environment. In addition, the GIS served to analyze, develop, and store a multitude of satellite and land-based data, historical records, and descriptive ground reference data, and will lay the groundwork for a host of future ecosystem-level research (e.g., monitoring land development, natural resource fragmentation, disruption, and loss, wildlife community population dynamics and census, and habitat assessment etc.).

CHAPTER III. LAND COVER CHANGE WITHIN MASSACHUSETTS: A HISTORICAL PERSPECTIVE

Introduction

There has been land development in Essex and Middlesex Counties in Massachusetts since the time of European settlement in the early 1600's. By the 19th century, eastern Massachusetts had been largely deforested as a result of the development of an agrarian landscape and endless quest for fuel, building materials of wood, and burning to clear land (Foster and Motzkin, 1998; Fuller et al., 1998). The nature of historical land development over the past 400 years, such as the placement of towns and cities, location of industry, and transportation corridors, is extensive and has undoubtedly influenced the present-day landscape.

Today, as land development continues, mounting growth pressures and a reduction of undeveloped land raise serious concerns, especially because cropland and forest fragmentation, wetland destruction, protected open-space infringement, pollution, and systematic losses of rural conditions have become common. By understanding the historical patterns of settlement in the two counties, we can better predict how land development may continue and perhaps take pro-active steps to ensure sound development practices.

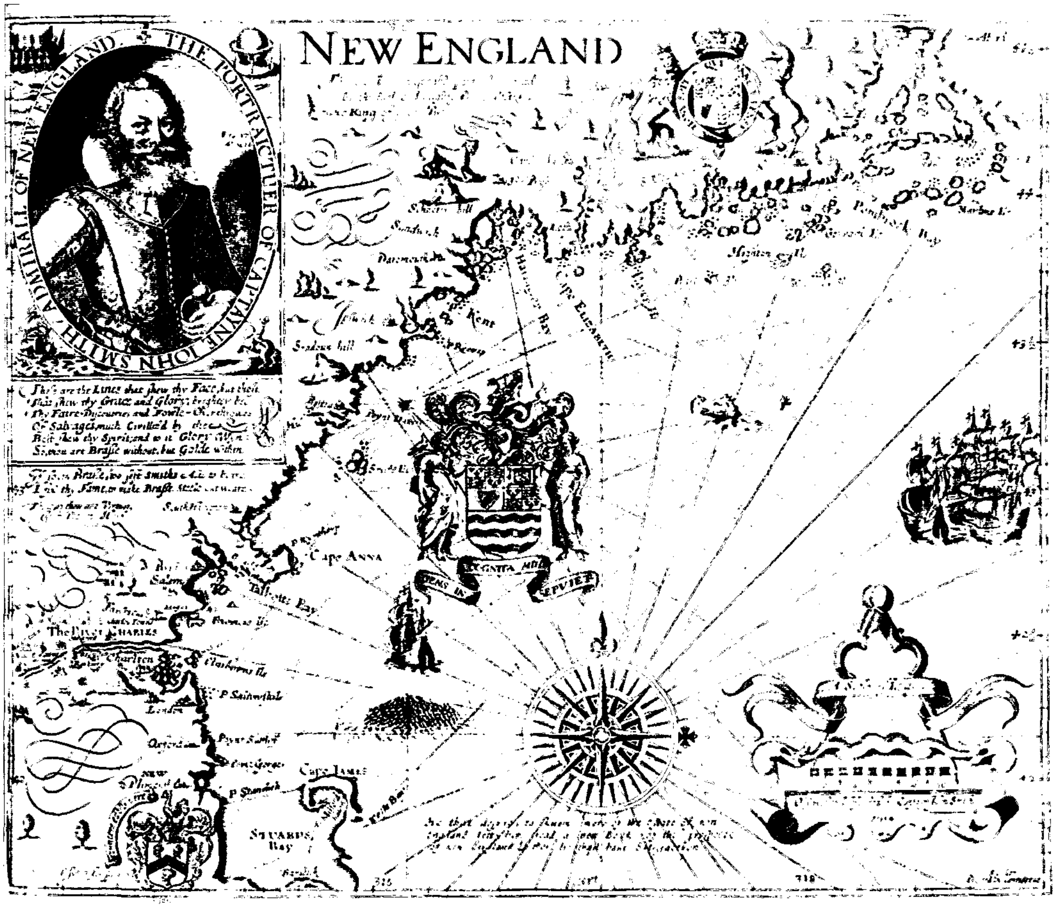
A brief review of the literature found several conceptual frameworks to assist in understanding the progression of land development. In particular, Lee (1979) suggests that there are six possible explanations or factors which can contribute or influence scattered and dispersed land development. These include (1) the physical characteristics of land, (2) site accessibility, (3) personal characteristics of landowners, (4) availability of public services, (5) developer initiative, and, (6) regulatory measures. This literature review will focus through the lenses of these six concepts.

The Colonial Period: 1600-1800

To understand how the six concepts as described by Lee (1979) influenced the development of colonial settlements, we need to explore the history of the region. Long before the arrival of English settlers in New England, native people had previously developed the landscape with well-defined trail systems through forests and grasslands within close proximity to water bodies to hunt for fish and game (Wood, 1919). In the early 1600s, to escape religious persecution, the first English settlers, the Puritans, began to put their mark on the landscape in New England and established small villages along the coast of Massachusetts (Figure 2) (Austin, 1876: Davis, 1900; Wood, 1919).

As the Puritans arrived in Massachusetts, they brought entrepreneurs, clergy, lawyers, and academics, but, the majority were God-fearing farmers from Lincolnshire and other eastern counties in England (Austin, 1876). By 1643, settlement of Massachusetts along the eastern coastline was occurring rapidly in what would become Essex County (Austin, 1876). Although the settlers faced challenging environmental conditions from harsh winters to rocky soils that were difficult to cultivate (Hayward, 1846), they endured and gradually ventured into and occupied the (western) wilderness including the future Middlesex County (Coburn, 1922).

Figure 2. Map of New England based on the 1613-1614 Virginia voyage by Captain John Smith (Smith, 1624).



As the first settlers arrived in New England, they found themselves in heated debates on who had the right and title to use the land. Sidney Perley's 1912 classic work, *The Indian Land Titles of Essex County, Massachusetts,* typifies this debate as he described, "the moral right to take by force the land of the aborigines is still an open question" (pp.1). In the mid 1600s, the transfer of land in Massachusetts from the native people to the English settlers was made legal through deed estoppels or releases (Figure 3) (Mirick, 1832; Shattuck, 1835; Davis, 1900; Perley, 1912; Coburn, 1922), and these lands were apportioned to settlers with restrictions upon their manner of habitation (Figure 4) (Carpenter, 1854; Austin, 1876; Benton, 1911).

Figure 3. Example of a deed estoppel (the Deed of Haverhill, Massachusetts in Essex County), with the markings of colonists, John Ward, Robert Clements, Tristram Coffin, Heugh Sherratt, William White, and Thomas Dauice, (left bottom) and of the native people, Passaquo and Saggahew (bottom right) April, 1671 (Perley, 1912).

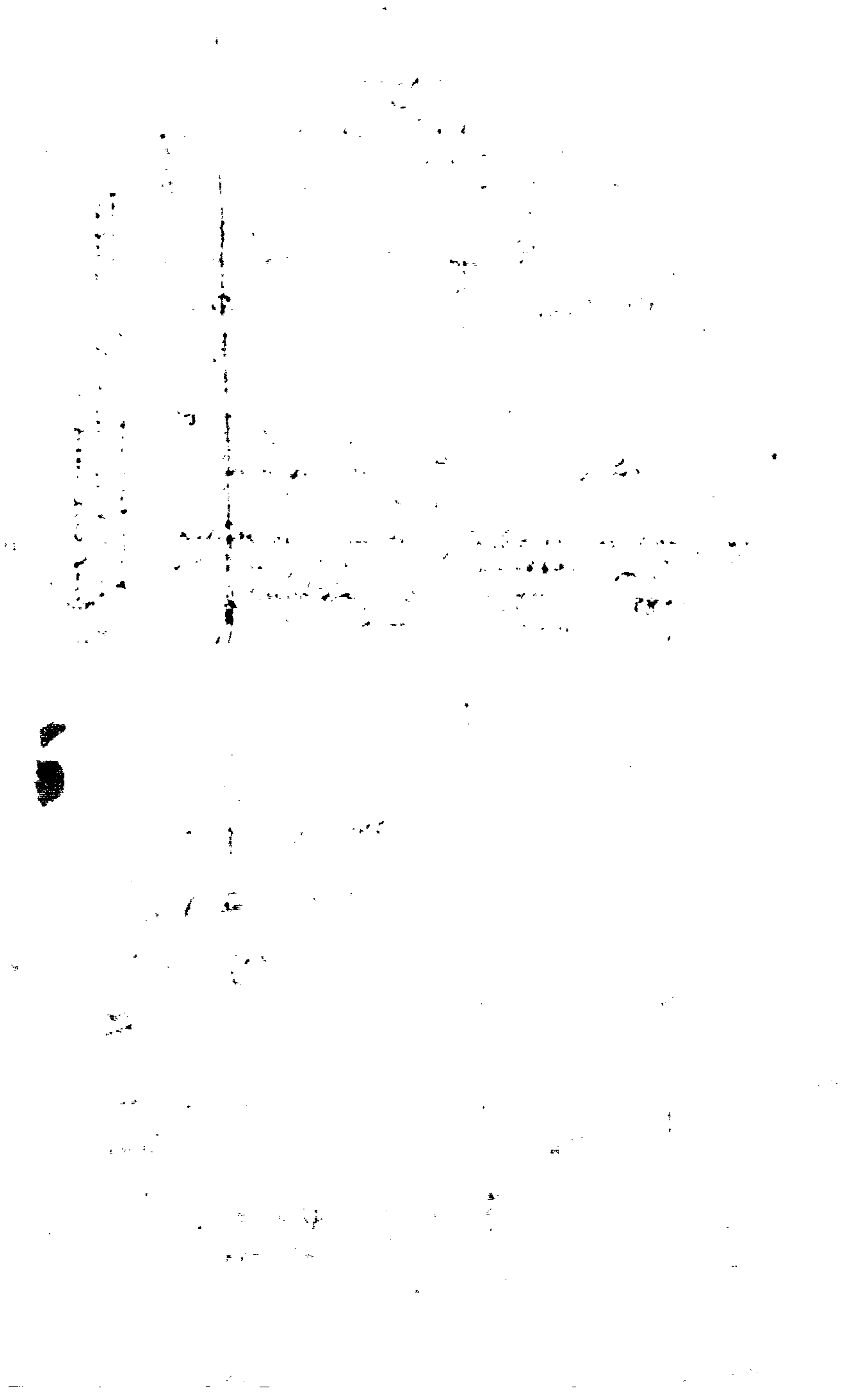
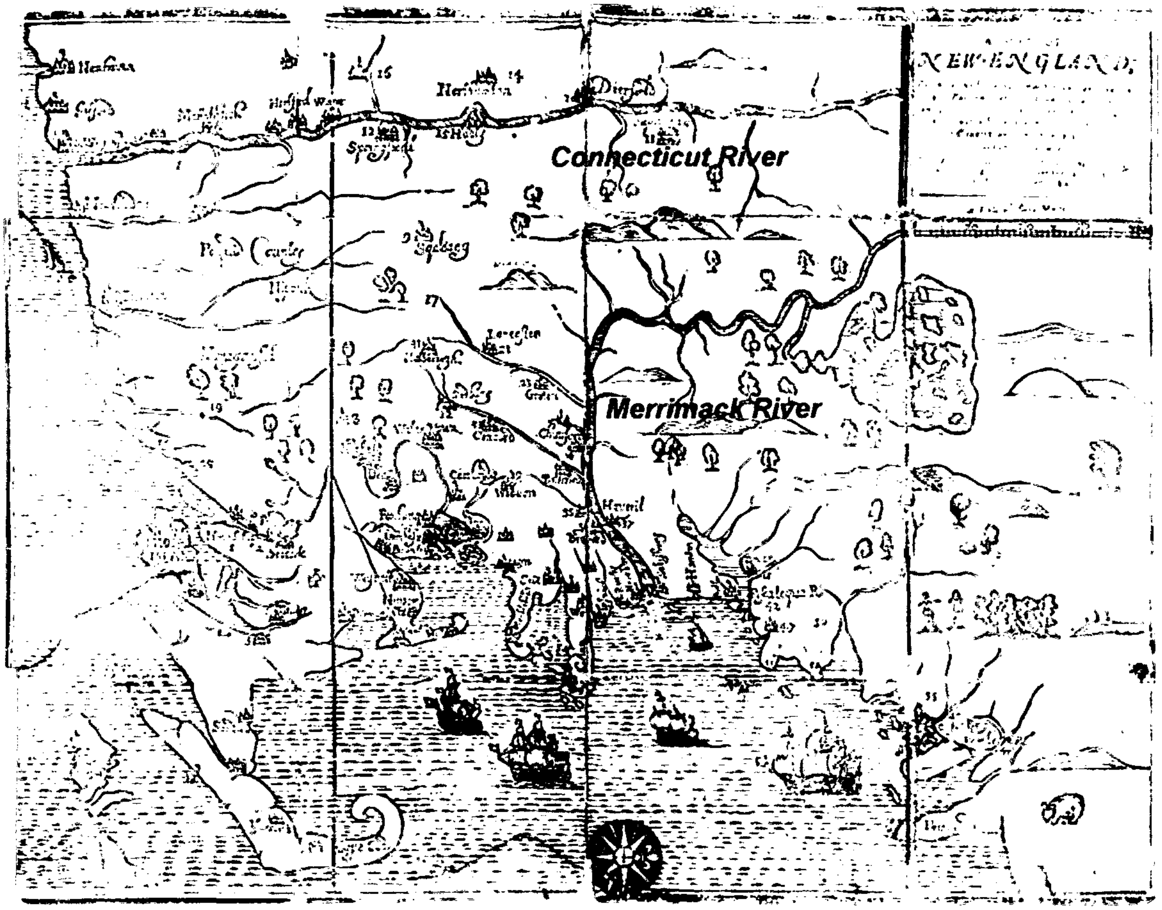


Figure 4. Map of New England which illustrates the extent of settlement at that time along coastal and river banks, printed from wood cut by John Foster (1648-1681) (Hubbard, 1677).



To maintain judicial order in the region prior to the development of the Commonwealth of Massachusetts, existing lands within settlements were assembled by King James in England in 1643, and subdivided into four counties: Essex Shire, Middlesex, Suffolk, and Old Norfolk (Davis, 1900; Flagg, 1907; Arrington, 1922). Essex Shire (County) consisted of the settlements of Salem, Lynn, Enon (Wenham), Ipswich, Rowley, Newbury, Gloucester, and Chochicawick (Andover), while Middlesex County contained Charlestown, Cambridge (New-town), Watertown, Sudbury, Concord, Woburn, Medford, and Linn Village (Reading) (Davis, 1900). As these counties developed further, courts were established to assist in legal and civil matters, prove wills and probate, and direct the transfer of land parcels for the development of homesteads and farms (Hurd, 1888).

The British government viewed the Massachusetts colonies as an important resource for extractive industrial purposes, and the settlers were encouraged to further explore and exploit their new environment to acquire raw materials, or to manufacture goods such as flour, wheat, lumber, corn, fish, and potash for trade (Day, 1907). To avoid dependence upon Baltic countries for the supply of wood, the British government encouraged the export of forest products from Massachusetts to be shipped to the West Indies for developing casks for transporting sugar products and wood products (e.g., boards and shingles) (Day, 1907).

The seemingly unlimited supply of timber resources in the area would later help establish large emporiums for lumber and firewood, and fuel the development of ship building and distilling centers in eastern Massachusetts, in the cities of Newburyport, Gloucester and Marblehead (Adams, 1892; Morison, 1921). Lumber was not the only valued commodity. Iron, for a variety of blacksmithing purposes, also was valuable, and it was found, at first, in abundance on the western bank of the Saugus River (Hayward, 1846). In 1643, in response to this discovery, a foundry was erected for the Saugus Iron Works to develop the resource further (Hayward, 1846; Arrington, 1922). Iron workers were given free reign to cut area timber for charcoal, to make roadways, and construct dams and ponds. By 1648, however, when iron was discovered in larger quantities farther west, the foundry and its occupied area were abandoned (Arrington, 1922).

According to Arrington (1922), farming was the chief industry for the early inhabitants. In 1643, nearly 15,000 acres of land was cultivated for grain, 1000 acres for orchards and gardens, and land for grazing was also needed for the 12,000 head of cattle and 3,000 sheep within Massachusetts (Austin, 1876). Beginning in 1623, fishing, whaling, and foreign trade opportunities developed, and they were pursued by many, including the Dorchester Company, who settled in Cape Ann (Gloucester and Marblehead in Essex County) (Palfrey, 1859; Winthrop, 1869; Austin, 1876; Roads, 1881; Day, 1907). However, when the company failed and was dissolved in 1626, most of its inhabitants moved to a more fruitful neck of land at Numkeag, now known as Salem (Austin, 1876).

As time passed, settlers grew intolerant of the authority of the British crown (Davis, 1900). By the 1640s, emigration of the English to Massachusetts had ended and contact with England became less important (Adams, 1892). To sustain or maintain their livelihood, finding food sources became essential for the colonists (Day, 1907). For example, like many early settlements in Essex Shire (County), Ipswich had been established in 1633 along river corridors because the soil was not only favorable for cultivating fruit, vegetables, rye and grain, but the waterways were pure, potable and abundant with fish (Bradford, 1835). As land exploration continued, English settlers encountered a large variety of game and wild-fowl (e.g., turkeys, deer, cranes, grouse, partridges, swans, wild geese, pigeon, ducks, doves, and quail) and often settled in areas where these food sources were abundant (Mirick, 1832; Forbush, 1912). Settlers frequently ventured further west into Massachusetts (e.g., Middlesex areas), and discovered fertile soils and grasslands along river corridors; gradually, they migrated inland from the shoreline to experiment with crops (Wood, 1919).

As settlers became more independent, they established villages where churches, blacksmiths and cobblers' shops, saw mills, grist mills, cotton and woolen mills, tanneries, and country stores were built (Wood, 1919). The existing trails and pathways, established by the native people, were gradually adopted by the settlers as their roadways (Wood, 1919). These roadways often were refined to reach homesteads of individual colonists without regard to directness between settlements, and they often meandered through abandoned paths, farm lanes, between thickets of barberry, alder-berry, rose-bush, fern and bramble—along with grand old elms seemingly leading nowhere (Adams, 1892; Hurd, 1888). Muddy trail areas often were converted into bridle paths via the felling of trees and hoisting of rocks; and primitive roads followed after these bridle paths (Hurd, 1888). Adams (1892) indicated that in order to connect settlements from Newbury and Hingham (Plymouth County), which were the northern and southern limits of the Massachusetts Bay Colony, one of the first primitive roads, "The Great Coast Road", was constructed in 1639. However, the preferred method of travel to Boston, Plymouth, and Cape Ann remained by water in a "dug-out" (hollowed-out pine log canoe) (Adams, 1892; Hurd, 1888; Wood, 1919).

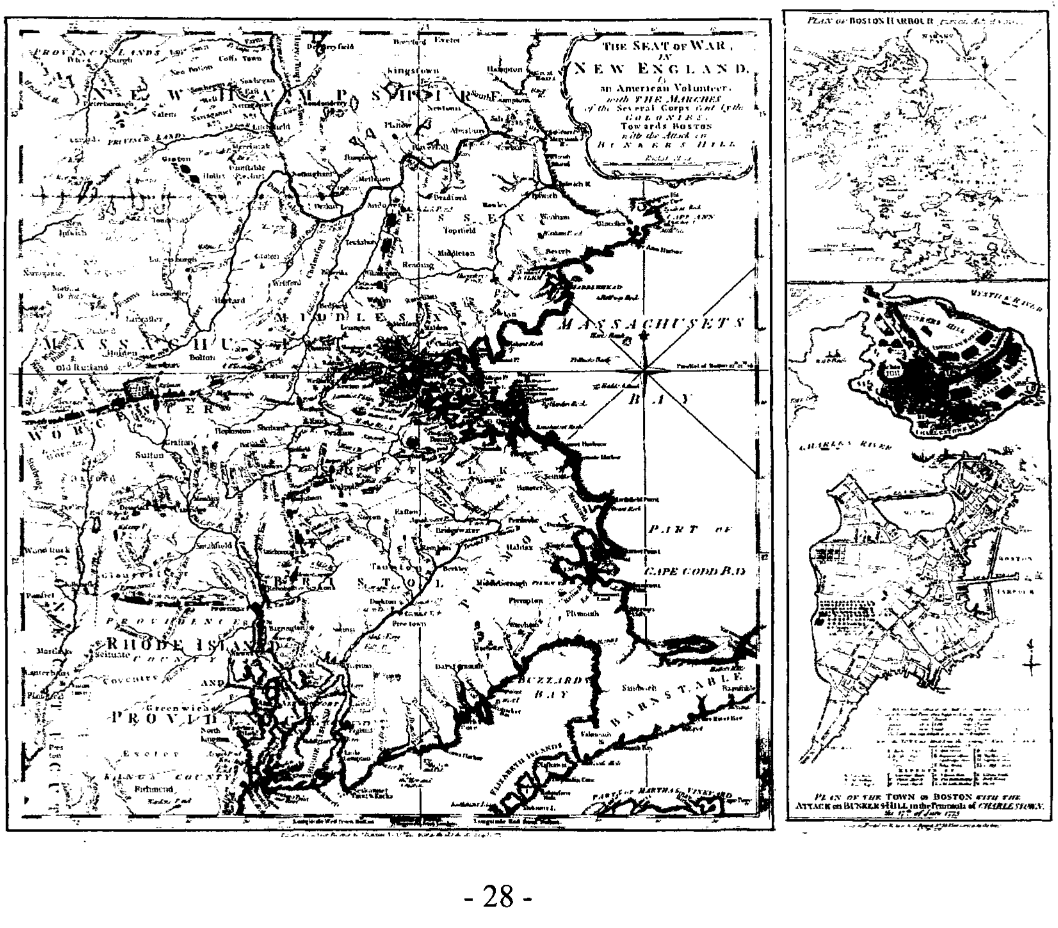
As quoted in Frederic J. Wood's 1919 classic work, *The Turnpikes of New England and Evolution of the Same Through England, Virginia, and Maryland*, "when the Indian trail gets widened, graded, and bridged to a good road, there is a benefactor, there is a missionary, a pacificator, a wealth bringer, a maker of markets, a vent for industry" (pp. 1). However, during the colonial period and even into the early 1800's, the use of many New England country roads was comparatively light because there was limited internal commerce (Day, 1907) and infrequent pleasure travel. Travelers journeyed on horseback, and roadways were kept in poor condition (Adams, 1892). For an alternative, the development of canals was contemplated, but the landscape configuration was considered unfavorable, and construction methods to build these canals had not yet advanced (Hurd, 1888; Dunbar, 1915; Wood, 1919). Furthermore, the restrictive nature of British inter-colonial trade policies made the transport of cargo out of settlements difficult and expensive, which discouraged settlers from developing these transportation networks further (Wood, 1919). Infrequent travel caused interstate trade and commerce to remain small and business remained localized around town country stores where farmers traded or disposed of their farm surplus for other items like sugar, molasses, tea, coffee, metals, hardware, cloth, books, glass, and earthenware (Adams, 1892).

Manufacturing also was restricted by England in fear that it would compete with their existing enterprises, and was limited to small establishments or within farmhouses where the hand-card, spinning wheel, hand and foot loom, or churners were commonly used (Bagnall, 1893). In Massachusetts, most colonists devoted their time to farming, lumbering, securing forest products, ship-building, flour-milling, and domestic or small-shop mill industries (Metre et al., 1915). By the end of the 1700's, nine tenths of the people in Massachusetts were engaged in agricultural pursuits and only one eighth were employed in manufacturing, trade or other occupations (Day, 1907; Metre et al., 1915).

A review of the colonial history, then, suggests that initial development in the 1600's within Massachusetts was largely confined to the eastern seaboard (i.e., in Essex

Shire or Essex County), where colonists balanced farming with trade and connection with England. As British subjects, colonists lived on land chartered by the king, abided by the rules of England, and worked according to the trade objectives of the English companies/developers. Land development was bounded by proximity to the sea and accessibility to meet the commercial objectives of the developers. Personal characteristics of settlers (such as strong religious ties) and the paucity of public services, such as transportation and roads, may have both isolated and bounded settlements together. Finally, regulatory restrictions on inter-colonial trade also may have discouraged expansions into new (more western) territories.

Figure 5. The seat of war in New England drawn by an American volunteer, illustrating the marches of the several corps sent by the Colonies towards Boston, with the attack on Bunkers-Hill, based from a 1775 plan, printed in 1778 (Library of Congress, 2009).



The Industrial Period: 1800-1900

By severing ties with England after the War of Independence (Figure 5), the citizens of the Commonwealth of Massachusetts looked to themselves for subsistence. In the late 1700s and early 1800s, people in Massachusetts learned that the earlier ways of settlement led to the duplication of labor in many communities, and that conserving such wasted resources in their midst could play an important role for their future stability and wealth (Wood, 1919). In this period, townships like Andover, Haverhill, North Andover, and Methuen (in Essex County) had many scattered settlements in agricultural districts and villages with light manufacturing capabilities within three miles of each other (Hayward, 1846).

To reduce duplicity and establish connections among rural areas, efforts were made to develop effective transportation and communication systems with the improvement of the highways and turnpikes (Raper, 1912). However, transportation capabilities remained limited, as roads were badly constructed; wagon conveyance was slow, uncomfortable, and expensive; the postal service was irregular and often hazardous; and many waterways were underutilized (Hadley, 1903). The period of the 1800's gave rise to many significant improvements in transportation methods which would play an important role in shaping the landscape in the counties (Raper, 1912).

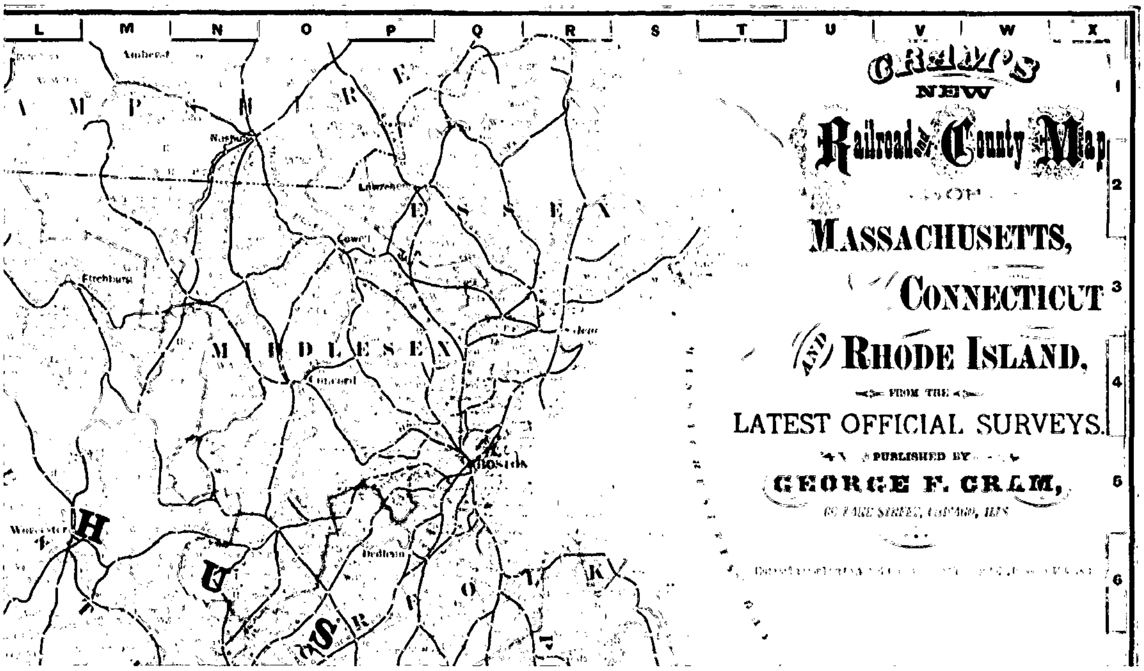
With the passing of the *Massachusetts Act of Incorporation for Manufacturing* in 1789, land, which had been previously settled along river corridors where water resources for power and drainage were favorable, was sought after and acquired for the development of mills (Hayward, 1846). At this time, many residents shifted their focus from farming to more lucrative opportunities, such as manufacturing in cities such as

Lowell, Dracut, Somerville, Medford, Waltham, Lawrence, Haverhill, and Beverly, and commercial fishing and trade in Newburyport, Salem, and Marblehead (Carter and Brooks, 1830; Mellen, 1839; Wadsworth, 1880; Morison, 1921). By the 1800s, a majority of residents would leave the world of agricultural toil behind (Foster and Motzkin, 1998).

Because James Watt's steam engine for power generation had not yet been approved for practical application, at first, most mills, like those in Lawrence, were built near rivers with suitable falls and with water velocities suitable to provide ample power for their operation (Lardner, 1801; Bagnall, 1893; Wood, 1919). In addition, industrial entrepreneurs and pioneers went to great lengths to construct dams and build canals to divert water for mechanical power sources (Wadsworth, 1880; Hayward, 1846). These mills would grow to be some of largest in the world and would produce textiles including cotton flannels, linen yarns, wool, and other products such as paper, lumber, leather, shoes and boots, and wooden furniture (Wadsworth, 1880). However, with the large amount of products being produced, existing canals and roadways soon became inadequate to distribute the freight (Bagnall, 1893). Furthermore, existing small-town centers that were close in proximity to the mills did not provide large enough retail outlets or markets (Wood, 1919). Therefore, the development of an effective transportation system was vital to sustain the growth, development, and distribution of products of the manufacturing industry in Massachusetts (Raper, 1912; Brown and Tager, 2000).

In 1826, Massachusetts authorized the first railroad charter (Dunbar, 1915), and the first freight to be moved on a railway was from a quarry in Quincy that provided the cornerstone for the Bunker Hill Monument in Boston (The New International Encyclopaedia, 1930; Hurd, 1888). From 1829 to 1830, Massachusetts chartered three railroads, the Boston and Lowell, Boston and Providence, and the Boston and Worcester (Dunbar, 1915). From 1833 to 1835, the Boston and Lowell Railroad extended its line through Wilmington, Andover, and Haverhill (Hurd, 1888), and from the 1850s to 1880s, the rail system rapidly developed across Massachusetts (Figure 6) (Dunbar, 1915). As can be seen in Figure 6, (the black lines with red print above), these railroads brought cotton, wool, iron, coal, livestock, wheat, flour, and corn from all corners of the state to newly developing towns and mill cities, as well as carried finished manufactured goods west and south (Figure 6) (Dunbar, 1915; Brown and Tager, 2000).

Figure 6. George Cram's 1879 Railroad and County Survey Map of Massachusetts, Connecticut, and Rhode Island (Cram, 1879).



The railroads also carried large numbers of factory workers into newly emerging urban centers where labor was needed (Dunbar, 1915) and soldiers for the civil war effort. The large migration of existing populations from rural areas, coupled with the immigration of foreigners in pursuit of economic betterment, led to exponential population increases in many factory towns. To accommodate the large number of workers, housing was built, and thus, the industrialization and urbanization of Massachusetts had begun (Brown and Tager, 2000).

Figure 7. The mills in full operation along the Merrimack River in Lowell, Massachusetts, photographed in 1910 (Malone, 2005).

The industrial period saw the growth of mill and port cities, with their large urban populations, situated along main seaports, waterways and transportation routes (Figure 7). Physical characteristics of the land (its location, proximity to water power, etc.) and its site accessibility to transportation corridors largely dictated which areas would be developed and become the population hubs of Massachusetts. The rise of the railways, arguably a type of public service passed by regulatory policies, allowed for the transportation of both humans and cargo across a larger expanse of land, and into various Massachusetts communities. Personal characteristics of the 'land owners' also evolved from the colonial period: citizens in the industrial era were more willing to leave their homes and families in pursuit of work and new social opportunities in large cities. While the colonial period limited expansion and migration across townships, the industrial age gave rise to new urban centers sprinkled across Massachusetts, both in Essex and Middlesex counties.

The Modern Period: 1900 to the Present

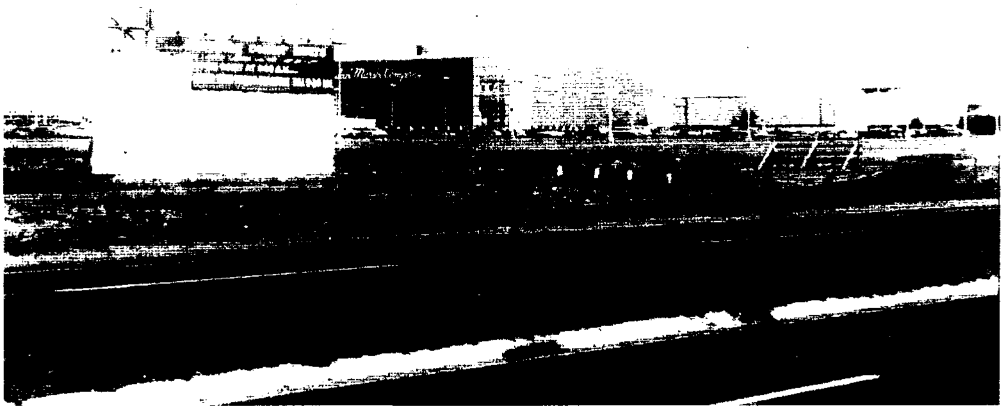
By the late nineteenth century, however, the decline of factory towns in Massachusetts began (Brown and Tager, 2000). Southern states provided a closer proximity to less expensive raw materials, such as coal and cotton, lower shipping costs, and cheaper non-union labor (The New International Encyclopaedia, 1930). The two World Wars halted this decline, but populations and property values within the urban centers continued to fall, taxes increased, socio-economic problems arose, and the middle class continued to move into the suburbs (Brown and Tager, 2000; Brown et al., 2005). In the early 1900's, in efforts to promote area trade, the state of Massachusetts engaged in the development of local highways and electric railways (Figure 8) (The New International Encyclopaedia, 1930).

Beginning in the 1930s, the development of interstate highway systems in Massachusetts, such as I-93, I-95, and Routes 1, 2, 3, and 128, began to play an important role in transforming the region's industry from manufacturing to science and high technology (Figure 8) (Earls, 2002; Mohl, 2003). The rise of these business sectors is attributable to the human capital made available from having some of the world's best academic institutions in the area. Potential business opportunities attracted real estate entrepreneurs to the region, and they built some of the largest industrial business parks, shopping malls, and residential subdivisions in the nation (Figure 9) (Earls, 2002).

Figure 8. Construction of Route 128 a westerly view towards Woburn, Massachusetts photography taken in the fall of 1950 (Tsipis and Kruh, 2003).

From the 1960s to the 1980s, largely on the strength of the Whirlwind computer project at the Massachusetts Institute of Technology (MIT) in Cambridge (in Middlesex County), many micro-computer companies and defense contracting agencies developed and flourished in cities within close proximity to rapid transportation corridors, namely Routes 128 and 3, such as Burlington, Bedford, Waltham, and Lexington in Middlesex County (Earls, 2002). As people came to work in the region, they began to develop and purchase homes within close proximity to their employment (Green, 2001). In addition, beginning in the 1970's, there was a "rural population turnaround" or out-migration from urban centers. This "rural sprawl", or "suburban sprawl", indicated a pattern of development decreasingly linked by proximity to urban centers and their socio-economic troubles, and was increasingly driven by access to open space and recreational opportunities (Brown et al., 2005).

Figure 9. Industrial Parks were not the only land development pioneering innovation. Shopping centers like the "Northshore", (constructed in 1958), in Peabody, Massachusetts (Essex County), brought and combined high volume department stores and smaller boutiques which were convenient and in automobile-friendly locations for access to suburban dwellers, photograph taken in the early 1960's (Tsipis and Kruh, 2003).



The modern period was marked by the decrease of manufacturing opportunities and the increase of science and technology jobs that require a higher level of education.

The readily available highway systems and personal automobiles allowed mobility without the reliance of public services or transportation. Businesses and residential developments required available land that are accessible by roads and have the modern amenities of electricity and telecommunication capabilities.

Conclusion

Settlement and the use of land within Essex and Middlesex County Massachusetts have been extensive since the mid 1600s. The land and its natural resources have provided people with the capability to enjoy religious freedom and to acquire knowledge and wealth, through the growth of extractive industries, agriculture, fishing and commercial trade, manufacturing, and, more recently, through science and technology enterprises. While there is no literature that directly compares the differences in the historical patterns of land development between Essex and Middlesex in Massachusetts, the literature review provided insight into the location of settlements, characteristics of the areas residents, rise of urban and suburban areas, as well as the deforestation effects which has occurred since the arrival of the Europeans. There is substantial literature that suggests that historical land development within many townships in the counties, in pursuit of agricultural and manufacturing activities, was largely similar from the industrial era forward.

Nevertheless, a deeper review of the literature suggests that several geographic differences may actually exist between the counties. For example, soil conditions were said to be more suitable for agriculture in Middlesex County, while soils in Essex County were not as easily cultivated due to their rocky nature. On the other hand, Essex County may have had an advantage over Middlesex County in other ways. Maps of the region illustrate that Essex County's eastern portion borders the Atlantic Ocean, and its southern portion is within close proximity to Boston. This geographic circumstance has influenced the historical pattern of land development because the colonists who settled along the coast later developed the settlements of Cape Ann such as Salem, Marblehead, and north, in Newbury. Due to proximity of these settlements to the ocean and its access to a wealth of resources such as the commercial fishing, trade, ship building, and supply industries, these areas gradually grew to become wealthy seaport hubs.

Essex County also contains greater interior riverfront access on the Merrimack River, to provide more towns like Lawrence, North Andover, Haverhill, Amesbury, and Merrimac with the capability draw power for the development of manufacturing enterprise. In addition, because of its access, this transportation corridor provided easier access to a wealth of resources available from port towns like Newburyport. As a result, communities with riverfront access like Lowell (in Middlesex County), Lawrence, and Haverhill, (in Essex County) were able to become quickly established and successful during the industrial age.

The literature also indicates that in the colonial period, land development mostly occurred in small settlements, along fertile riverbanks for agriculture, or within close proximity to water for additional food sources, trade, transportation, and to remain in communication with England. In the industrial period land development, particularly the development of mills and housing for mills workers was concentrated and restricted to rivers to utilize water to generate power. By the nineteenth and twentieth centuries, with the rapid improvement and innovations in transportation and technology in

Massachusetts, such as the railroads, public utilities transfer systems, steam-powered or combustion engines, the automobile, and the interstate highway systems, growth and the development of the transistor, semiconductor, and various computer industries, land development around water resources became unnecessary.

Furthermore, an investigation of the land cover change which has occurred in these areas has shown that in the period of 1990 to 2007, land development has occurred in the form of large box stores (e.g., Walmart, Home Depot, and Lowes Building Supplies), as well as residential apartment, assisted living complexes, and large warehouse and manufacturing structures along transportation corridors and in subdivisions within residential areas (outside of urban centers) within Essex and Middlesex County, Massachusetts (Figure 22 on page 80 and Figure 39 on page 154 provide an example of the location and nature of development which has occurred). With the continuation of suburban or rural sprawl, especially along the automobile transportation corridors (i.e., highways), and the continual growth of the health, science and technology sectors of businesses, it is likely that towns and cities that are close to these businesses will continue to develop. Therefore, towns with readily available land for development, which are close to these business hubs and meet the personal preferences and requirements of its residents, will have seen a dramatic increase in developed land in the recent years.

CHAPTER IV. RATIONALE AND OBJECTIVES

Across New England, environmental and land management issues make sound ecological information and conservation thinking a major imperative (Foster, 2002). New England supports a large and affluent population, and as it continues to urbanize, it is faced with potential widespread development and environmental degradation (Foster, 2002). Essex and Middlesex Counties are unique places filled with many rare and endangered plant and animal species and a wealth of natural resources like the Great Marsh, in the north-shore of Essex County, which is the largest contiguous salt marsh in New England (Massachusetts Audubon Society, 2003).

Settled in the early 1600's, these counties quickly grew to become the manufacturing and agricultural hubs of New England (Hurd, 1888). As transportation corridors developed and evolved extensively since the mid 1950's, population and land conversion for development increased (Wilson et al., 2002). As a result of its history and economic growth, Massachusetts faces many conflicting proposals for its land conservation and stewardship, and there is a great need for the type of broad ecological insights afforded by historical-geographical research (Foster, 2002).

According to the Mass Audubon Society, from 1985 to 1999, Massachusetts lost 40 acres per day as a result of residential development. From 2000 to 2002, residential lot sizes in some Massachusetts counties increased 47.0%, and in others, lot sizes have doubled (Massachusetts Audubon Society, 2003). As documented in Schneider and Pontius, Jr. (2001), forest loss from residential development has contributed to eutrophication, ground water loss, and loss of wildlife habitat. While progress has been made in land protection, habitats of many rare species, such riparian areas surrounding aquatic species habitats, have little or no permanent protection; fragmentation continues to threaten these areas (Mass Audubon Society, 2003). Massachusetts's undeveloped and recreational land generates more than $6 billion annually in non-market ecosystem services and 85.0% of this value is provided by forest, wetlands, lakes, and rivers left in their natural state (Mass Audubon Society, 2003). The loss of these "free" services would increase the taxpayer burden for water treatment, climate regulation, flood control, as well as reduce property values and tourism revenues (Mass Audubon Society, 2003).

There is wide variety of literature (Table 2) focusing on the anthropogenic disturbance and the impacts of land-use change on biodiversity, forest ecology, salt marshes, wildlife habitats, wildlife population dynamics, in addition to hyperspectral remote sensing investigations of foliar (canopy) nitrogen, forest health, and forest species composition in Massachusetts (Martin et al., 1998; Bellemare et al., 2002; Cogbill et al., 2002; Gerhardt and Foster, 2002; Hall et al., 2002; Parshall and Foster, 2002; Foster et al., 2002a; Foster et al., 2002b; Foster et al., 2002c; Bromberg and Bertness, 2005; MacDonald et al., 2007; Martin et al., 2008). However, few researchers have employed the direct use of satellite remote sensing to detect land development or land cover change and the impact it has had on the environment in Massachusetts.

Table 2. Literature references specific to Massachusetts and New England.

Research Focus	Location	Reference
Forest land cover classification	Harvard Forest, Massachusetts (Central)	Martin et at. 1998
Anthropogenic disturbance	Rich Mesic Forests (RMF), Massachusetts (Western)	Bellemare et al. 2002
Historical reconstruction of forests	New England	Cogbill et al. 2002
Physiogaphical/historical effects on forests	Petersham, Massachusetts (Central New England)	Gerhardt and Foster, 2002
Forest composition and structure change	Massachusetts (Commonwealth)	Hall et al. 2002
Fire disturbance within forest	Massachusetts (north, central, coastal)/New England	Parshall and Foster, 2002
Wildlife dynamics in areas of landscape change	Massachusetts (Commonwealth)	Foster et al. 2002a
Historical reconstruction of forests	New Salem, Massachusetts (North-central Massachusetts)	Foster et al. 2002b
Vegetation patterns	Martha's Vineyard, Massachusetts	Foster et al. 2002c
Salt marsh reconstruction	New England	Bromberg and Bertness, 2005
Effect of protected lands on surrounding environment	Massachusetts (Central-Quabbin) and other locations	MacDonald et al. 2007
Remote sensing of foliar nitrogen	Harvard Forest, Massachusetts (Central) and other locations	Martin et at. 2008

Several land cover change research methodologies have been developed using aerial photography and satellite remote sensing technology. These established methodologies can provide insight into how land is, or has been managed, and also can serve to monitor the types and extent of change (Brothers and Fish, 1978; Im et al., 2008). Extensive literature on change detection, an application of remote sensing, has been recorded, and its applications exist across a wide research spectrum within the world, ranging from the refinement, automation, and hybridization of techniques to conduct change detection analyses to more practical applications, such as the detection of urban sprawl to mapping coastal zone erosion (Richter, 1969; Weismiller et al., 1977; Adeniyi, 1980; Lo and Wu, 1984; Lo and Shipman, 1990; Brothers and Fish, 1978; Wickware and Howarth, 1981; Singh, 1989; Lunetta and Elvidge, 1998; Macleod and Congalton, 1998; Rynzar and Wagner, 2001; Thome, 2001; Yuan et al., 2005; Bontemps et al., 2008; Wulder et al., 2008). In regards to an assessment of recent land development in Massachusetts and the overall impact it has on this environment, there is still much work to be done.

In the mid 1990s, Vogelmann (1995) used 80-meter pixel spatial resolution Landsat Multispectral Scanner (MSS) satellite data of 1973 and 1988, and GIS to map forest fragmentation against population in 157 towns, within southern New Hampshire and northern Massachusetts. Schneider and Pontius, Jr. (2001) conducted a GIS-based land cover change analysis within parts of 21 towns within the Ipswich River Watershed, using temporal land-use maps from 1971, 1985, and 1991, to model deforestation and examine the relationship between residential development and increased nitrogen run-off.

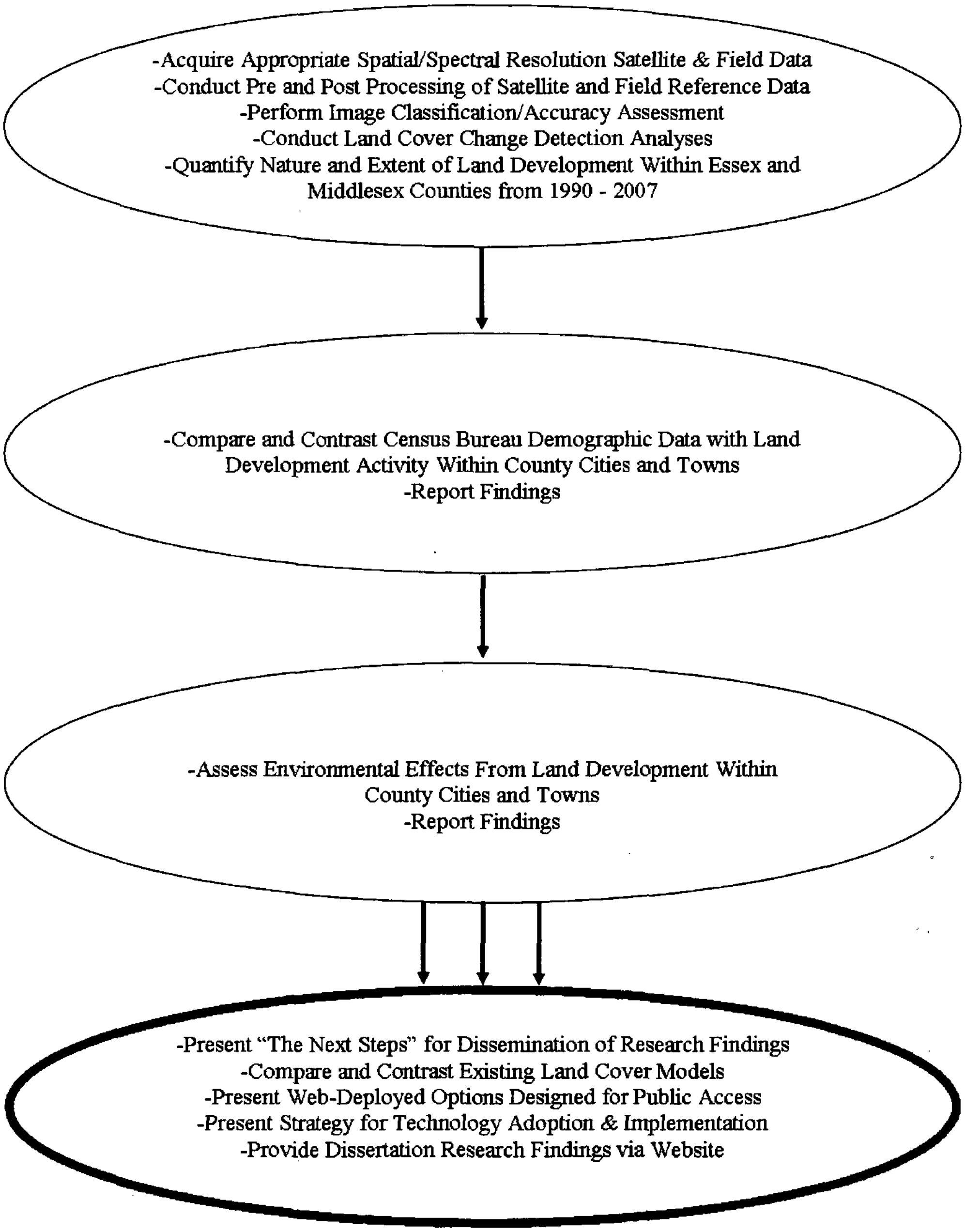
Pontius, Jr. and Schneider (2001) evaluated a land cover change model (relative operating characteristic (ROC) approach), using the data results derived from their deforestation analysis in Massachusetts. Holden et al. (2003) discussed the types of data (e.g., paper land use maps and census roadway data) used within the 2001 Schneider and Pontius, Jr. analysis. Tardie (2005) and Tardie and Congalton (2002) focused on Essex County and utilized a 1990 Landsat Thematic Mapper (TM) and a 2001 Enhanced Thematic Mapper (ETM) scenes to compare three change detection methods to detect land development. This research documented a 26.0% increase of new development from land cover change that took place from 1990 to 2001.

However, Tardie (2005) did not include additional portions of Massachusetts, nor looked at land development since 2001. Moreover, Tardie (2005) did not look at how historical population dynamics may have influenced land change or how land development affected existing environmental conditions or wildlife and their respective habitats. Currently, there is little or no recorded land cover change research of this nature in the literature for Essex and Middlesex County Massachusetts. This study builds upon the previous study performed by Tardie (2005), and provides both novel approaches and useful literature on several aspects. The goal of this study is to provide a basis from which additional research may be developed.

Conceptual Framework

There are several studies that have developed and utilized a variety of conceptual frameworks which outline the numerous factors and/or drivers of change and the implications of land use/land cover changes for society (e.g., human health, economic development), and the environment (e.g., wildlife habitat, climate change)(Turner et al., 1995; Lambin et al., 1999; Smucker et al., 2007). The conceptual framework for this study will comprise three foci: 1) to detect, quantify, and document the nature and extent of land development and land cover change within Essex and Middlesex Counties in Massachusetts from 1990 to 2007, 2) compare and contrast the demographic and/or historical population dynamics within areas of land cover change, and 3) to assess the effects from land development on the environment (e.g., on specific areas of environmental concern, wildlife habitat areas and associated wildlife species)(Figure 10). In addition, this study will present several existing land cover models that could employ the findings from this research for future land cover change investigations and assessments, present various web-deployed data dissemination options to facilitate environmental awareness through public access, and provide a strategy for the successful adoption and implementation of these technological options.

Figure 10. Conceptual Framework.



Objectives

The primary objectives of this research are: (1) to quantify and document the recent nature and extent of land development within Essex and Middlesex Counties, Massachusetts, from 1990 to 2007, (2) to assess how this land development has affected the environment of the area, as well as the demographics, and (3) to substantiate these effects and/or impacts using Census data, and a variety of Commonwealth of Massachusetts environmental data (as outlined in the following Materials and Methods section).

The specific objectives of this study are:

(1) To perform the post-classification land cover change detection method to detect, quantify and document the recent types and extent of land development within Essex and Middlesex Counties from 1990 to 2007; This finding will be used as a base or impetus for monitoring future land development,

(2) To use more recent (1990 and 2007) and accurate Landsat Thematic Mapper (TM) satellite imagery -- rather than coarse-scale historic land-use maps -- with a higher pixel spatial resolution (28.5 meters vs. 80-meters), and higher spectral resolution (7-bands vs. 4-bands), to more accurately detect and quantify "new" land development,

(3) To evaluate the nature and extent of land cover change by developing GIS data from the satellite imagery, which will quantify the losses and gains of six independent land cover classes of development, forests, wetlands, grasslands, barelands, and water and report the "from-to" land cover changes of these six land cover classes that have occurred (i.e., from forest to development, from grassland to development, etc.),

(4) To evaluate the effects from land development at the ecosystem-level by (a) combining the change detection results with environmental datasets from three Commonwealth of Massachusetts state organizations (i.e., the Department of Fish and Game's Mass Wildlife and Natural Heritage and Endangered Species Program, Department of Environmental Protection, and Department of Conservation and Recreation), (b) identifying, to the extent possible, the specific species inhabiting the impacted areas, and (c) reviewing recent literature on how land cover and land use change relates to the habitat change of certain plant and

wildlife species biodiversity and census. Specifically, this study intends to assess how land development has fragmented, reduced, disrupted, or encroached upon areas of critical environmental concern, wildlife habitats, and designated open and recreational spaces,

(5) To compare and contrast the changes in population dynamics within these areas of land cover change,

(6) To publish peer-reviewed literature for the research community on the application, methodology, and procedures to be used to conduct temporal land cover analyses by combining the capabilities of existing geospatial technologies with a wide array of data sources,

(7) To publish literature on future steps to assist county-level land cover change modeling efforts and online mapping and visualization of land cover change data, and,

(8) To provide all satellite imagery and GIS derived data layers and results from this dissertation to be published as a template to a website (to be developed), with the goal to assist municipalities, state organizations, and residents in advancing sound and sustainable land-use practices, as well as provide educational outreach resources within the counties.

CHAPTER V. HYPOTHESES

This dissertation research aims to quantify and document the recent nature and extent of land development within Essex and Middlesex Counties Massachusetts from 1990 to 2007, and assess how this land development has effected the environment by quantifying the loss (in acreage) of forests, wetlands, grasslands, and water bodies and comparing those losses to environmental data acquired from the Commonwealth of Massachusetts (as outlined in the following Materials and Methods section). In doing so, this will allow several hypotheses to be considered and addressed.

This dissertation research aims to indicate, that:

> ***H1. Land development has increased within the region comprising the counties of Essex and Middlesex in Massachusetts from 1990 to 2007; and this will be countered by marked decreases in the land cover classes (forest, grassland, bare-land, wetland, and water) as specified within the image classification scheme.***

According to the United States Bureau of the Census (2008), there was a general increase in population coupled with the "dot-com" boom (from 1995 to 2000), in northeastern Massachusetts. I hypothesize that land development will have increased both for residential and commercial use. I further hypothesize that Middlesex County will exhibit more land development than Essex because of its accessibility to the SR-128 technology corridor and proximity to Boston.

Data source: Land development data derived from Landsat Thematic Mapper (TM) 1990 & 2007 Path/Row: 12/30 & 12/31 satellite imagery.

H2. Newly developed land areas in both counties will be built upon existing grasslands rather than forests.

In 2008, the Massachusetts Farm Bureau's Census of Agriculture's County Profile indicated that there was a 40.0% combined loss of agricultural farms in Essex and Middlesex Counties, (from 1,219 in 1997 to 979 in 2002), leaving their associated cleared agricultural fields and/or grass lands as "ready-made" for land development for residential and business development.

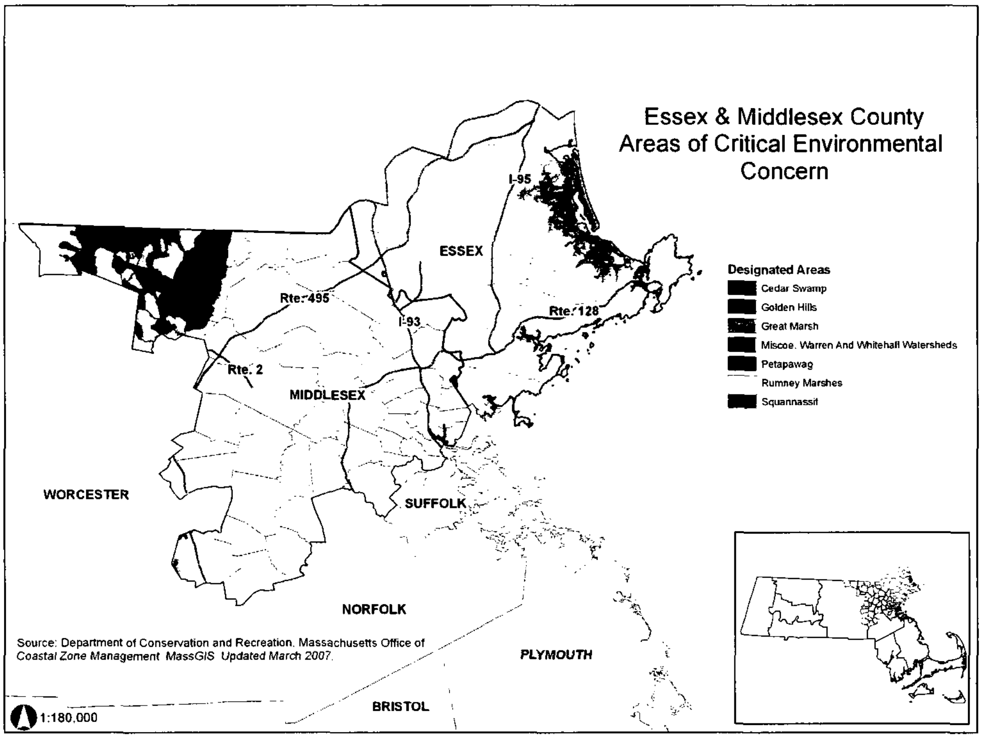
Data source: Landsat Thematic Mapper (TM) 1990 & 2007 Path/Row: 12/30 & 12/31 satellite imagery.

H3. Newly developed land areas will affect areas of critical environmental concern.

Areas of critical environmental concern are places in Massachusetts that receive special recognition because of the quality, uniqueness and significance of their natural and cultural resources (Figure 11) (Commonwealth of Massachusetts, Dept. of Conservation and Recreation, 2008). These areas are identified and nominated at the community level and are reviewed and designated by the state's Secretary of Environmental Affairs. ACEC designation creates a framework for local and regional stewardship of these critical resource areas and ecosystems (Commonwealth of Massachusetts, Dept. of Conservation and Recreation, 2008). Land development in both counties will disrupt, fragment, and remove forest, grassland, wetlands, and water, thus, impacting areas of critical environmental concern.

Data source: (1) Land development data derived from Landsat Thematic Mapper (TM) 1990 & 2007 Path/Row: 12/30 & 12/31 satellite imagery, (2) Commonwealth of Massachusetts, Department of Conservation and Recreation Areas of Critical Environmental Concern - 1:25,000 - Updated March 2007.

Figure 11. Areas of Critical Environmental Concern.



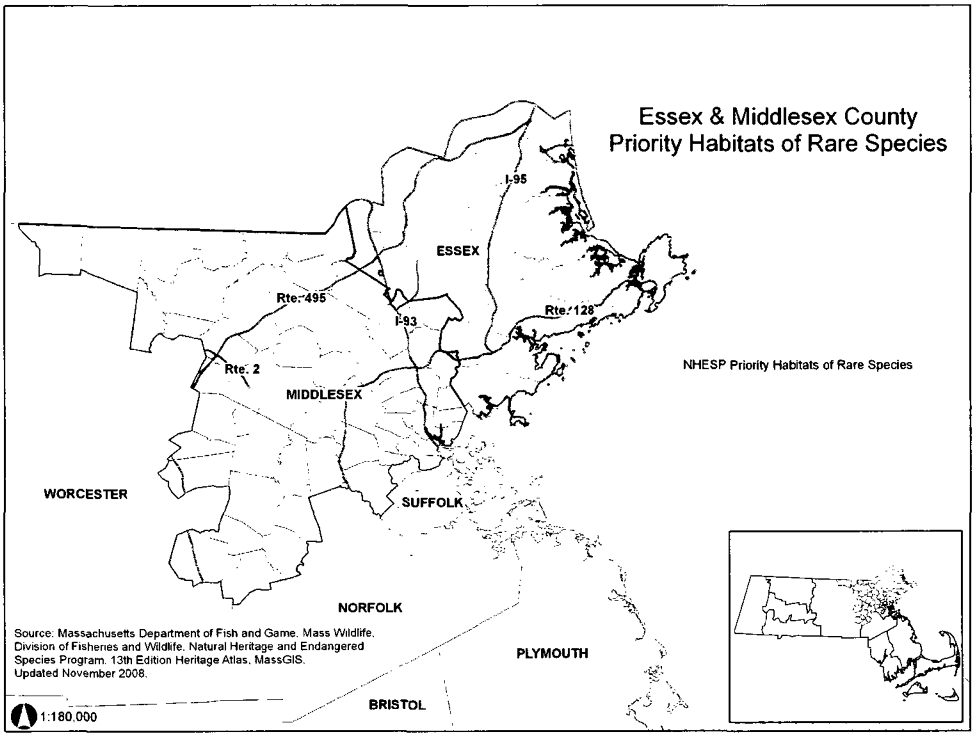
Source: Department of Conservation and Recreation. Massachusetts Office of *Coastal Zone Management MassGIS Updated March 2007.*

H4. Newly developed land areas will affect or encroach upon the priority habitats of rare species.

Priority habitats represent the geographical extent of habitats for all state-listed rare species, both plants and animals, and are codified under the Massachusetts Endangered Species Act (MESA) (Figure 12) (Commonwealth of Massachusetts, Mass Wildlife, 2008). Habitat alteration within priority habitats may result in a displacement of a state-listed species, and is subject to regulatory review by the Natural Heritage & Endangered Species Program (Mass Wildlife, 2008). Land development in both counties will disrupt or fragment the natural habitats of a variety of plant and animal species.

Data source: (1) Land development data derived from Landsat Thematic Mapper (TM) 1990 & 2007 Path/Row: 12/30 & 12/31 satellite imagery, (2) Commonwealth of Massachusetts, Department of Fish and Game, Mass Wildlife, Natural Heritage & Endangered Species Program, Priority Habitats of Rare Species – 1:25,000 - Updated September 2008.

Figure 12. Priority Habitats of Rare Species.



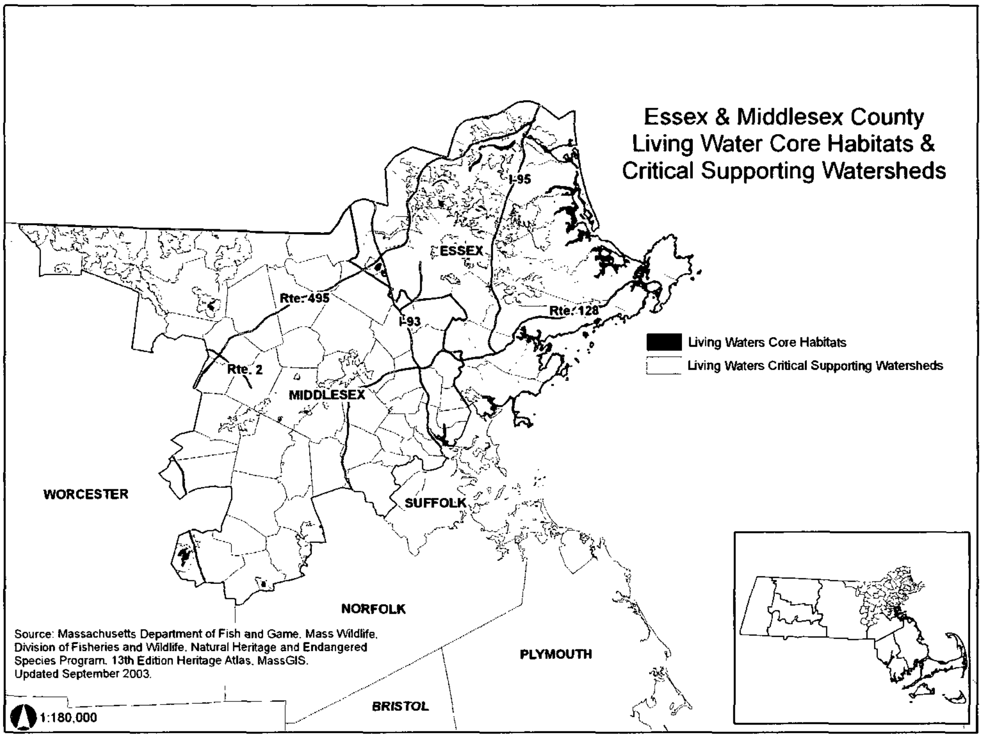
Source: Massachusetts Department of Fish and Game. Mass Wildlife. Division of Fisheries and Wildlife. Natural Heritage and Endangered Species Program. 13th Edition Heritage Atlas. MassGIS. Updated November 2008.

H5. Newly developed land areas will affect or encroach upon living waters core habitats and critical supporting watersheds.

Living Waters Core Habitats represent lakes, ponds, rivers, and streams that are important for the promotion of freshwater biodiversity in Massachusetts (Figure 13) (Mass Wildlife, 2008). The Critical Supporting Watersheds are the most immediate hydrologic contributors to Living Waters Core Habitats, and these watershed areas have the highest potential to sustain or degrade biodiversity (Mass Wildlife, 2008). However, these areas are often altered by land development and its impact is frequently overlooked.

Data source: (1) Land development data derived from Landsat Thematic Mapper (TM) 1990 & 2007 Path/Row: 12/30 & 12/31 satellite imagery, (2) Commonwealth of Massachusetts, Department of Fish and Game, Mass Wildlife, Natural Heritage & Endangered Species Program, Living Waters Core Habitats - 1:25,000 - Updated Nov. 2003, Living Waters Critical Supporting Watersheds - 1:25,000 - Updated Nov. 2003.

Figure 13. Living Water Core Habitats & Critical Supporting Watersheds.



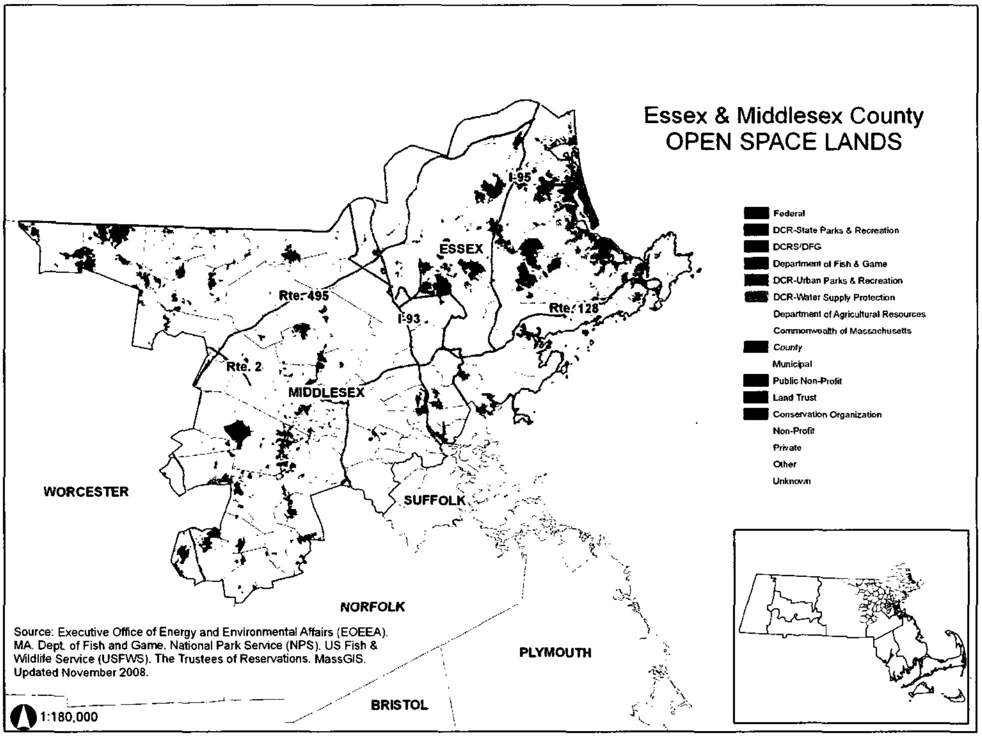
Source: Massachusetts Department of Fish and Game. Mass Wildlife, Division of Fisheries and Wildlife. Natural Heritage and Endangered Species Program. 13th Edition Heritage Atlas. MassGIS. Updated September 2003.

H6. Newly developed land areas will affect or encroach upon state designated open and recreational space.

Protected and recreational open space areas are conservation lands and outdoor recreation facilities in Massachusetts (Figure 14) (Mass Wildlife, 2008). Not all of these land areas are protected the same way or in perpetuity. Open and recreational space areas such as farms, former farm areas, forests, and designated reservations, provide unique plants and animals, wildlife habitats and corridors, critical habitats (i.e., wetlands), natural watersheds, aesthetic and scenic value, and promote a variety of activities, from walking and hiking, to cross-country skiing, hunting, fishing, and nature study. In addition, open space bolsters property values, increases tourism, and reduces the need to spend on new and costly infrastructure projects (Schwartz, 2007). These lands also protect the health and safety of our communities by preserving natural environments and ecosystems, which in turn, improves water quality, reduces air, noise and sound pollution, and creates more livable communities (Schwartz, 2007). These areas are often disrupted and fragmented by encroaching land development at their boundaries, in order to promote their conservation within the counties, it is important to determine the areas where land development has had an impact.

Data source: (1) Land development data derived from Landsat Thematic Mapper (TM) 1990 & 2007 Path/Row: 12/30 & 12/31 satellite imagery, (2) Commonwealth of Massachusetts, Department of Conservation and Recreation, Protected and Recreational Open Space - 1:25,000 - Updated Nov. 2008.

Figure 14. Protected and Recreational Open Space Lands.



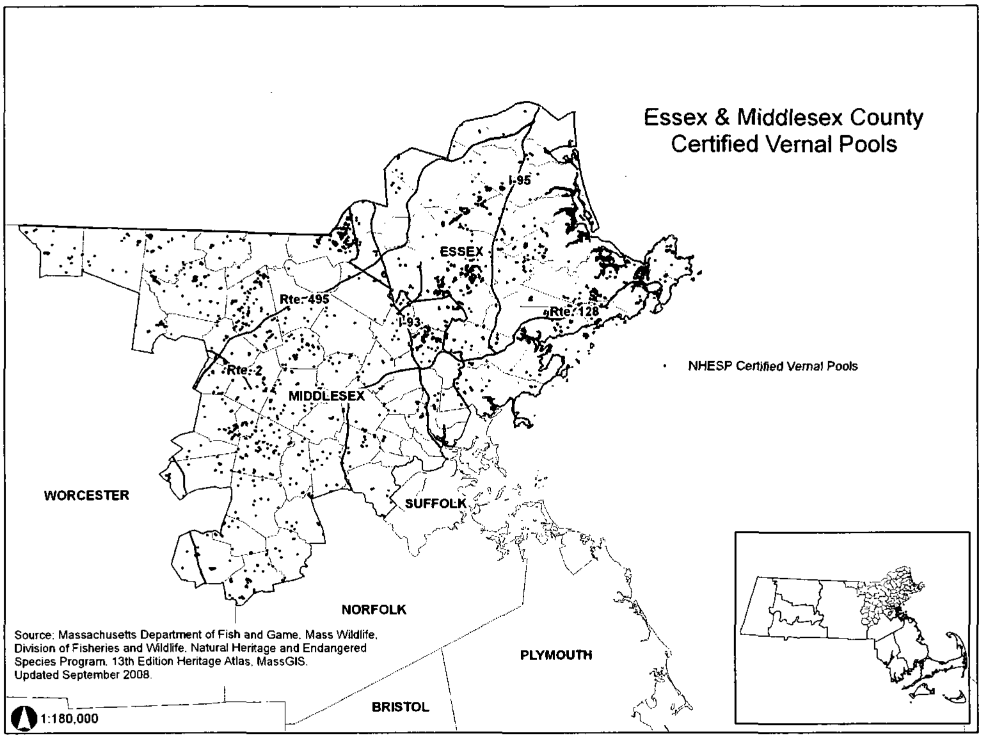
Source: Executive Office of Energy and Environmental Affairs (EOEEA). MA. Dept. of Fish and Game. National Park Service (NPS). US Fish & Wildlife Service (USFWS). The Trustees of Reservations. MassGIS. Updated November 2008.

H7. Newly developed land areas will impact vernal pools.

Vernal pools are unique and vulnerable kinds of wetlands and are usually ephemeral pools that fill with snow-melt and spring-runoff, and are sometime dry during the summer (Figure 15) (University of Maine, 2008). Vernal pools are a vital breeding habitat for certain amphibians and invertebrates (e.g., wood frogs, blue spotted salamanders, and fairy shrimp), and resting areas for a variety of other species (e.g., spring peepers, gray tree frogs, and birds) (University of Maine, 2008). These important wetlands are some of the most vulnerable because they are small, isolated, and often dry and therefore unrecognizable; which makes them easily destroyed (University of Maine, 2008). Land development in both counties will disrupt, fragment or encroach upon areas where vernal pools commonly exist, such as in forest, grasslands, and wetland areas. Removal or altering of vernal pools within a wetland mosaic would not only impact the habitat for local plants and animals, but, may promote the isolation of wildlife populations, and make these populations more vulnerable to changes in their surroundings (University of Maine, 2008).

Data source: (1) Land development data derived from Landsat Thematic Mapper (TM) 1990 & 2007 Path/Row: 12/30 & 12/31 satellite imagery, (2) Commonwealth of Massachusetts, Department of Fish and Game, Mass Wildlife, Natural Heritage & Endangered Species Program, Certified Vernal Pools - 1:25,000 - Updated Sept. 2008, Potential Vernal Pools - 1:25,000 - Updated Sept. 2000.

Figure 15. Certified Vernal Pool Areas.



Source: Massachusetts Department of Fish and Game, Mass Wildlife, Division of Fisheries and Wildlife, Natural Heritage and Endangered Species Program. 13th Edition Heritage Atlas. MassGIS. Updated September 2008.

H8. Areas with the largest change in land development will be associated with the largest growth in population and income.

Newly developed land in the two counties is expected to result from growth in residential units. Therefore, population, including families with children, will increase within areas of newly developed land. The nature of the job growth along the Route 128 corridor in Middlesex County is also expected to result in households with higher median income compared to those in Essex County.

Data source: (1) Land development data derived from Landsat Thematic Mapper (TM) 1990 & 2007 Path/Row: 12/30 & 12/31 satellite imagery, (2) United States Bureau of the Census, 1990 & 2000 Gazetteer STF1a, STF3a Data Files. Massachusetts State and Essex and Middlesex County Quick Facts 2006 estimates.

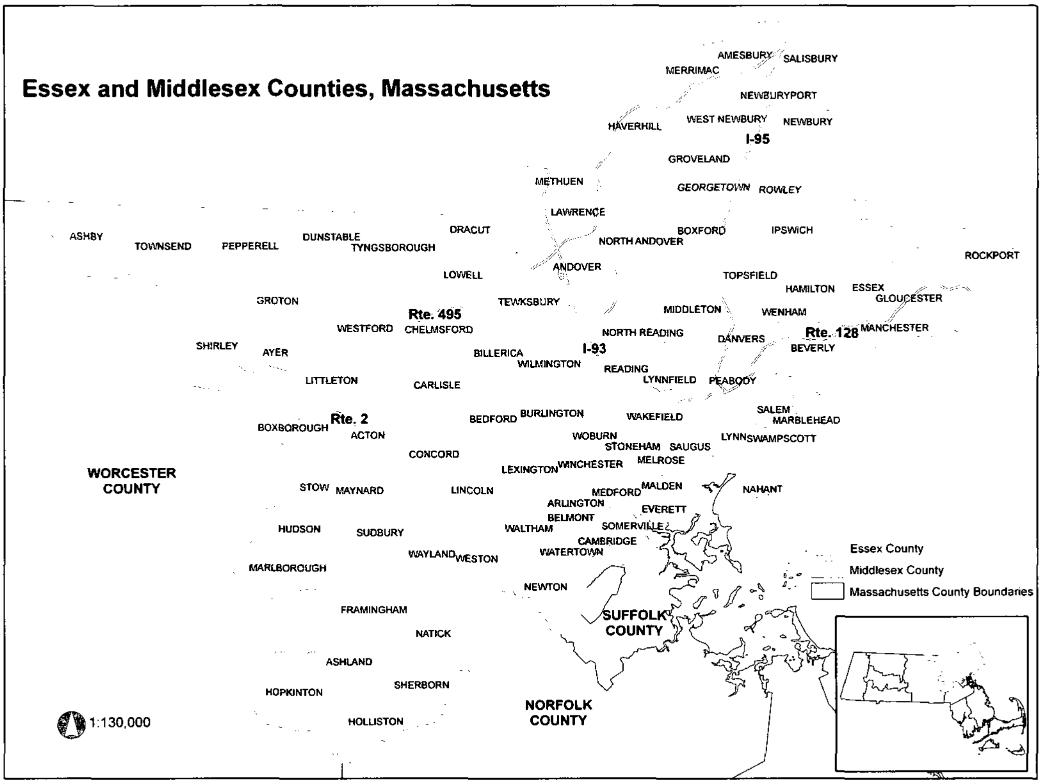
CHAPTER VI. MATERIALS AND METHODS

The following methods section is divided into a description of the study area, hardware and software, satellite image data, reference data, image processing, and change-detection. Additional materials and methods for specific topic areas investigated are presented in the following chapters in the appropriate sub-sections.

Study Area

The study area consists of Essex and Middlesex Counties, which are located in the northeast and north-central portions of the Commonwealth of Massachusetts and border New Hampshire to their north, and Suffolk County to their southeast and southwest, respectively (Figure 16). Essex County comprises a land area of approximately 501 square miles (320,640 acres), and contains thirty-four municipalities most of which are bucolic in character. Essex County also has seven major highways passing through it, (routes: US-1, I-95, I-93, Rte. 1, Rte. 2, SR-128, I-495), contains three predominant urban centers: Lawrence, Lynn, and Peabody, and has a population of approximately 750,000. Middlesex County has four major highways passing through it, (routes: SR-2, I-93, SR-128, I-495), and contains five predominant urban centers: Cambridge, Burlington, Somerville, Waltham, and Lowell. Middlesex County comprises a land area of approximately 847 square miles (541,818 acres), contains fifty-four municipalities most of which are suburban in character, and a population of approximately 1,400,000.

Figure 16. The study area of Essex and Middlesex Counties, Massachusetts.



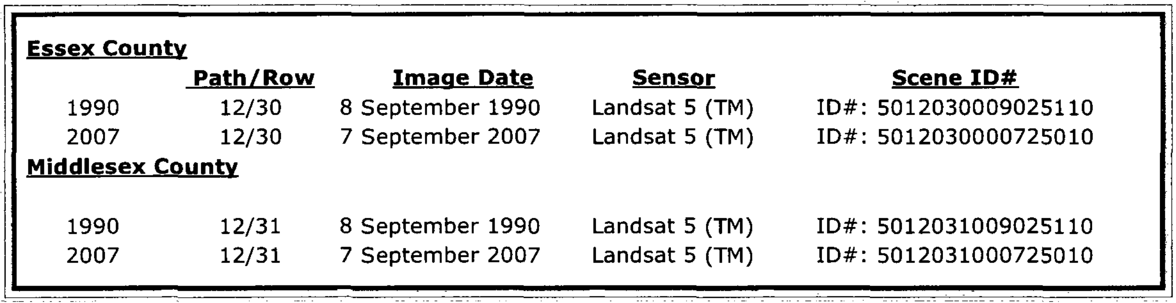
Hardware and Software

To conduct the change detection analyses (i.e., satellite data processing, change detection analyses, and map production), use of two raster and vector relational data-based software platforms were required: ESRI ArcGIS 9.2 and Erdas IMAGINE 9.2. For field data collection and positional/locational accuracy assessment (with respect to the spatial resolution of the satellite image data), use of a sub-meter global positioning system (GPS) was required. In addition, a hand-held single-lens reflex (SLR) digital camera (Canon EOS 30D), was used to assist the image classification training and accuracy assessment and document specific areas exhibiting land cover change within the counties.

Satellite Image Data

To ensure the accurate detection of land cover change, and reduce the effects of seasonal phenological differences of vegetation, four near-anniversary Landsat Thematic Mapper (TM) 5 28.5 meter resolution images were used. In addition, the image acquisition dates selected provided ideal image conditions (e.g., coverage area, appropriate spectral bands, spatial resolution, little or no cloud cover and/or sensor error artifacts) required for these temporal analyses. Table 3 provides a summary of the data used within this project. A detailed description of the Landsat satellite platform used can be found in Appendix A.

Table 3. Landsat Thematic Mapper (TM) Data used.



Essex County	**Path/Row**	**Image Date**	**Sensor**	**Scene ID#**
1990	12/30	8 September 1990	Landsat 5 (TM)	ID#: 5012030009025110
2007	12/30	7 September 2007	Landsat 5 (TM)	ID#: 5012030000725010
Middlesex County				
1990	12/31	8 September 1990	Landsat 5 (TM)	ID#: 5012031009025110
2007	12/31	7 September 2007	Landsat 5 (TM)	ID#: 5012031000725010

Reference Data

Reference data (vector/raster) of Essex and Middlesex Counties for image classification and accuracy assessment were obtained from a variety of sources: (1) Commonwealth of Massachusetts Office of Geographic Information Systems (MassGIS); (2) Commonwealth of Massachusetts ecosystem data (to be discussed in Chapter 9), (3) United States Bureau of the Census (to be discussed in Chapter 8), (4) Department of Natural Resources Conservation Resource Mapping Land Information Systems

Laboratory at the University of Massachusetts (Amherst campus); (5) Global Positioning System (GPS) field assessments, (6) aerial photography and imagery interpretations, and, (7) existing holdings from Masters research (Tardie, 2005).

These data consisted of 0.5-meter resolution 1:5,000 scale black and white digital ortho-images produced in 1995, 0.5-meter resolution 1:5,000 scale color digital ortho-images produced in 2001, 0.3 and 0.15-meter resolution 1:5,000 scale color digital ortho-images produced in 2008, 1:12,000 scale color infrared (CIR) analog ortho-photographs produced in 1991, and scanned 1:24,000 scale USGS topographic quadrangles produced from 1982 to 1987. In addition, 1:5,000 scale GIS vector shape-files produced from 1971 to 1999 comprising local, state, county, and township political boundaries also were acquired and used for image masking and community landmark identification.

Reference data used exclusively for the accuracy assessment of the 1990 and 2007 imagery were acquired through aerial photography/imagery interpretations and periodic GPS field surveys. These data were consolidated and transformed into six GIS vector (point) shape-files each containing fifty land cover class-specific reference data samples. Descriptive attributes embedded within these shape-files (i.e., identification, land cover type, field position, etc.) were standardized using alphanumeric coding and condensed to form one conglomerate shape-file which housed all reference data samples (600 in total).

GIS reference data also was acquired from MassGIS from several Commonwealth of Massachusetts organizations to asses the effect of land development on existing environmental conditions. In addition, to compare and contrast population dynamics within areas of land cover change within the counties, tabular reference data was acquired and compiled from several sources within the United Bureau of the Census. Both the environmental and demographic data sources will be discussed in greater detail in the following chapters. All digital reference data (raster/vector), utilized for comparison with the Landsat TM image classifications were projected into Massachusetts State Plane Coordinate System, North American Datum (NAD83) meters, and used in the ESRI ArcGIS version 9.2 Geographic Information System and Erdas IMAGINE version 9.2 image processing platforms.

Image Classification Scheme

Image classification of each satellite image was required in order to perform the post-classification change detection technique. In addition, the development of a classification scheme was essential in order to organize and characterize the spatial information contained within the imagery into logical map categories for the change detection analyses (Congalton and Green, 1999). The National Ocean Service's C-CAP Coastal Land-Cover Classification System served as the primary reference guide to assist in its development and it consisted of seven distinct class categories (Figure 17): (1) Developed, (2) Bareland, (3) Forest, (4) Grassland, (5) Water, (6) Wetland, and (7) Unclassified. C-CAP was used because it provides national standards, practices, and procedures for land cover classification and habitat change monitoring in coastal and adjacent upland areas as well as for change detection analyses and data dissemination.

Image Processing

Image processing was divided into six major steps: (1) image rectification and masking, (2) image normalization, (3) data exploration, (4) image classification, (5) classification accuracy assessment, and, (6) post-classification change detection. All image processing was performed using Erdas IMAGINE version 9.2 software (ERDAS, 2009).

Figure 17. Image classification scheme for 1990 and 2007 Landsat Thematic Mapper (TM) Imagery.

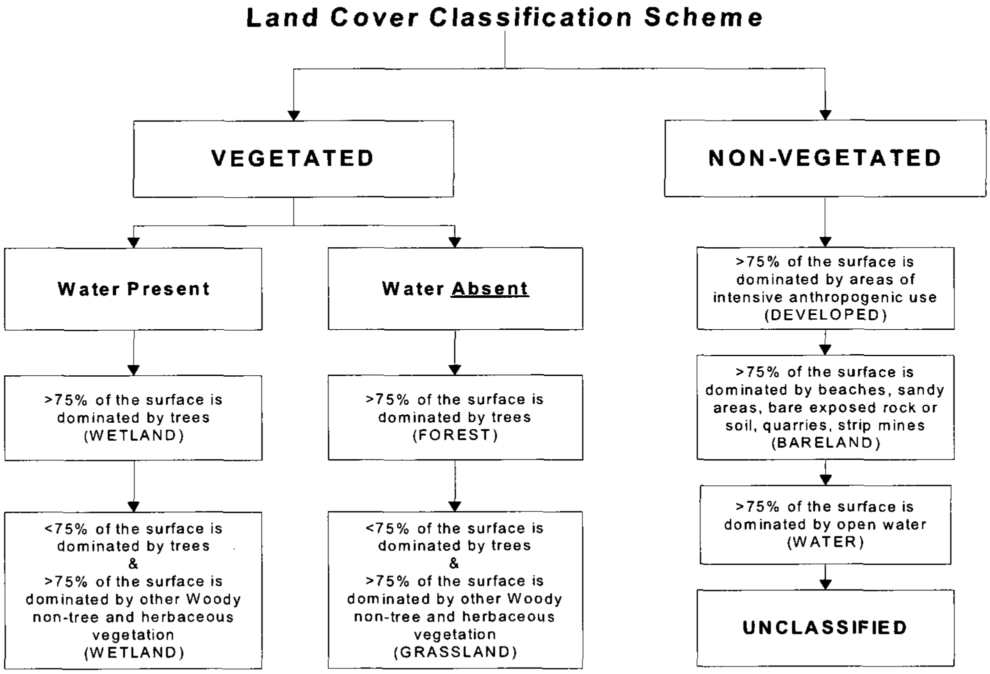


Image Rectification and Masking

To prepare two or more satellite images for an accurate change detection comparison, it is imperative to geometrically rectify the imagery (Townshend et al., 1992; Macleod and Congalton, 1998; Kwarteng and Chavez, 1998). Any quantitative use of remote sensing satellite data requires that the geometric distortion present within the imagery be corrected or rectified to a desired map projection (Ford and Zanelli, 1985). To lessen impact of mis-registration on the change detection results, geometric registration was performed on a pixel-by-pixel basis. Lunetta and Elvidge (1998) indicate that if any mis-registration greater than one pixel occurs, erroneous land cover change results will result. However, achieving perfect co-registration of multi-temporal images is impossible because of residual error most often found in many rectification models (Labovitz and Marvin, 1986; Verbyla and Boles; 2000). The accuracy of image registration is usually conveyed in terms of root-mean-square (RMS) error and for Landsat TM imagery, the acceptable RMS error is 0.5 pixels (Townshend et al., 1992; Yuan and Elvidge, 1998; Lunetta and Elvidge, 1998).

To determine if the 1990 and 2007 imagery were co-registered to the appropriate coordinate system each of the four scenes were overlaid within an image viewer and evaluated. The four Landsat Thematic Mapper (TM) scenes comprising Essex and Middlesex Counties were then geo-referenced using ground control points (GCPs) established by a sub-meter accurate global positioning system (GPS), and from additional ground reference coordinates from a geo-referenced Landsat 7 ETM+ image mosaic of Path/Row: 12/30 and 12/31, from 8/29/01 (scene ID# 7012030000124150 and ID# 7012031000124150). The 1990 and 2007 images were then projected into the Massachusetts State Plane Horizontal Coordinate System, North American Datum (NAD83), meters. Each scene was then mosaicked according to year (date of acquisition) within Erdas IMAGINE 9.2, and subset using area of interest (AOI) polygons constructed from the Commonwealth of Massachusetts Essex and Middlesex county legal boundary delineations. Additional AOI polygons were constructed to remove minute areas of cloud/cloud shadow and to exclude offshore island from the imagery prior to performing the change detection analyses.

Image Normalization

Image normalization during the pre-processing stage can improve the results of change detection analyses (Yuan and Elvidge, 1998). Imagery obtained by the same sensor at different times does not usually exhibit the same radiometric characteristics because of variations caused by solar illumination conditions, atmospheric scattering and absorption, and changes in atmospheric conditions such as the presence of clouds (Mas, 1999). Radiometric correction can eliminate or reduce the differences introduced from sensor instrument artifacts, atmospheric path degradation and/or changing atmospheric conditions (Chavez and MacKinnon, 1994; Kwarteng and Chavez, 1998; Vogelmann et al., 2001).

Song et al. (2001) and Dobson et al. (1995) express that imagery should be radiometrically normalized before any change detection analysis, to allow only the differences of pixel brightness values between multi-date images to remain as the actual changes in surface conditions. One of the most widely used techniques used for atmospheric radiometric correction prior to multi-spectral image classification and change detection is dark-object subtraction (DOS) (Pax-Lenney et al., 2001; Song et al., 2001). This approach assumes the existence of a horizontally homogeneous atmospheric condition and the presence of dark objects with zero or small surface reflectance values throughout any given Landsat TM scene (Pax-Lenney et al., 2001; Song et al., 2001).

The data collected in the visible wavelengths (e.g., TM bands 1 to 3) often exhibit a higher minimum digital number (DN) value because of the increased atmospheric scattering taking place within these wavelengths (Jensen, 1996). This minimum DN value is often attributed to the effects of the atmosphere and can be subtracted from all of the pixels to shift the image histogram to the left so that zero values appear within the data, thus minimizing the effects of atmospheric scattering (Chavez, 1989; Jensen, 1996; Pax-Lenney et al., 2001; Song et al., 2001). As cited in Song et al. (2001), Gordon (1978) determined that deep water bodies were acceptable for use as the (dark) object to derive atmospheric optical information for radiometric normalization (i.e., histogram adjustment).

An assessment of the pixel reflectance values for clear and deep water bodies in the counties was performed within the 1990 and 2007 images to determine if the atmospheric conditions did in fact affect the imagery. The spectral bands within each image were then extracted individually and evaluated. A spatial model was then constructed to normalize the reflectance values within the affected spectral band histograms of the 1990 and 2007 images. The spectral bands were then re-assembled into their appropriate origin and all histograms (adjusted and unadjusted) were reviewed to confirm the reliability of the corrections prior to performing the selected change detection analyses.

Data Exploration

Prior to image classification, a variety of false color composites were generated for each of the normalized images by loading the spectral bands in the imagery as follows: (R,G,B - 4, 3, 2 (TM Band 4 (NIR), TM Band 3 (Red), TM Band 2 (Green)) and R,G,B - 5, 4, 2 (TM Band 5 (MIR), TM Band 4 (NIR), TM Band 2 (Green)). These composites were used qualitatively to enhance the visual discrimination of land cover class types using the specific responsiveness characteristics of each spectral band. In addition, spectral pattern analyses and bi-spectral plots were developed and spectral/spatial enhancement filters (e.g., texture and smoothing filters, principal component analysis (PCA), and tasseled cap transformations) were incorporated to qualitatively distinguish land cover types and to assist with image classification.

Image Classification

The 1990 and 2007 images were classified independently using the unsupervised ISODATA (Iterative Self-Organizing Data Analysis Technique) algorithm (ERDAS, 2004), to produce an output layer and signature to identify the spectrally unique clusters contained within the imagery. The pixels represented by these clusters were layered upon the rectified and normalized imagery for labeling. Clusters that could not be readily classified were subjected to an iterative "cluster-busting" algorithm technique for further ISODATA processing to identify additional clusters (Jensen et al., 1993).

This procedure was iterated to achieve the desired level of classification for each image. Upon completion, the final clusters were recompiled, mosaicked, and recoded into the appropriate categories of the classification scheme and smoothed using a 3x3 majority filter to remove or reduce speckling. These Essex and Middlesex County classification maps were now prepared for accuracy assessment and for use in the post-classification change detection analysis.

Classification Accuracy Assessment

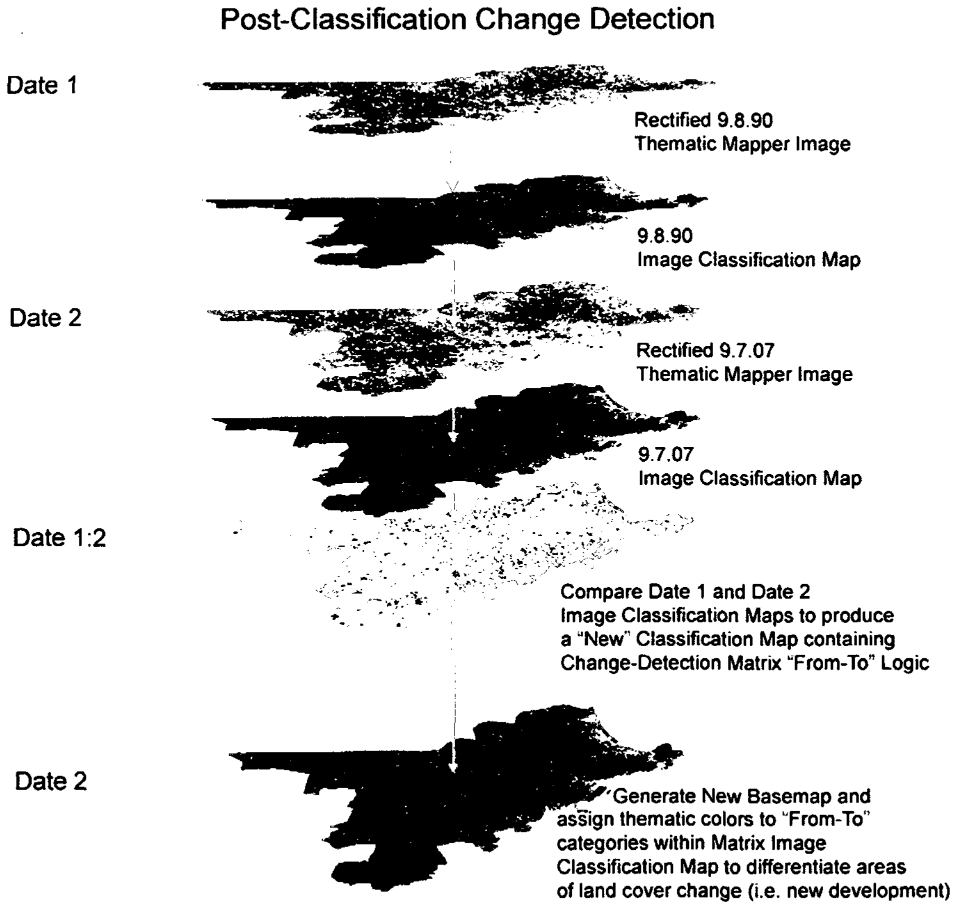
An independent and quantitative accuracy assessment was performed within the Erdas IMAGINE Accuracy Assessment module on the resulting 1990 and 2007 image classifications (independently) using the reference data and individual 6-class single date error matrices (Congalton, 1988). First, ground coordinate locations from the reference data were imported into the table array. Second, the coded class values from the reference data (cross-referenced with GIS) were then entered in the reference table column field within the array.

In consideration of GPS positional errors often introduced during the field data acquisition process (i.e., from GPS unit limitations, satellite constellation configuration, atmospheric or ground surface disturbances, or forest canopy obstructions), 3x3, 6x6, and 9x9 window majority sizes (using a variety of clear majority thresholds), were tested in order to determine class value. The results for each of the selected window sizes and thresholds were similar. Therefore, the 6x6 window majority size using a 36 out of 36 clear majority threshold rule was selected and used for the assessment. Accuracy assessment measures (error matrix, class accuracy totals, and Kappa statistics), were generated for the 1990 and 2007 image classifications, and a Visual Basic program, KAPPA (Congalton, 2004), was used to test and confirm the accuracy assessment statistics.

Change Detection

The Post-Classification change detection method was used to perform the land cover change detection analyses as it can provide the capability to quantify the nature and extent of land cover change by combining multi-temporal image classifications. In the post-classification technique (Figure 18), the 1990 and 2007 images were classified independently following the procedures outlined in the image processing classification section and then compared. Post accuracy assessment, the two different dates were combined into a matrix to produce a "new" change image classification containing "from-to" matrix logic (based on the image classification scheme). The pixel areas within the matrix change image classification were then color-coded to differentiate the developed from non-developed land cover classes and filtered using a 3x3 majority to remove speckling.

Figure 18. Procedural Steps of the Post-Classification Change Detection Method.



The matrix change image classification was then compared within an ArcGIS workspace with the reference data. A GIS analysis was conducted using structured query language (SQL) tools to refine the change image classification and "select-out" the areas where the land cover changed to "new" development (i.e., From Forest to Land Development, From Grassland to Development, etc.). These areas were then assigned a distinctive thematic color value to differentiate the "from-to" or type and nature of land cover change which took place, and the corresponding pixel count information for each land cover class was then converted into ground area measurement units (acres) to quantify its extent.

These data were now prepared for comparison with the Commonwealth of Massachusetts environmental reference data to investigate if land development occurred within or adjacent to delineated plant and wildlife species habitat areas and other areas environmental concern. In addition, these data also were now prepared for comparison to the United States Bureau of the Census demographic reference data to investigate population change in communities exhibiting land development.

CHAPTER VII. RESULTS

The following section reports the results from image rectification, image normalization, the 1990 and 2007 image classifications, the accuracy assessment of the 1990 and 2007 image classifications, the post-classification change detection. Additional results from the demographic and environmental comparison analyses will be presented in the following chapters.

Image Rectification

The 1990 (Path/Row: 12/30 and 12/31) and the 2007 (Path/Row: 12/30 and 12/31) images were geo-referenced using ground control points (GCPs) established by a sub-meter accurate global positioning system (GPS), and from ground reference coordinates from the geo-referenced Landsat 7 ETM+ image mosaic of Path/Row: 12/30 and 12/31, from 8/29/01 (scene ID# 7012030000124150 and ID# 7012031000124150). Initially, the 2001 imagery were to be used in the land cover change detection analyses. However, the scope of the study evolved and 2007 imagery became available. Of the imagery acquired for this study, the 2001 image mosaic did not exhibit ground coordinate registration errors and were deemed appropriate for use for rectification of the 1990 and 2007 imagery.

The 1990 12/30 image exhibited a south-easterly ground coordinate position shift of 1,018.5 meters from the 2001 image mosaic. The 1990 12/31 image exhibited a north-easterly ground coordinate position shift of 563.4 meters from the 2001 image mosaic. In addition, because of this ground coordinate position shift, constructing a mosaic of the

1990 12/30 and 12/31 scenes was not feasible, as the boundary of these scenes bisected the study area within Middlesex County. However, the 2007 imagery did not exhibit a ground coordinate position shift at the 12/30 and 12/31 boundary, and was mosaicked to produce one scene comprising the research area. However, the resulting image mosaic exhibited a north-easterly ground coordinate position shift of 876.9 meters from the 2001 imagery.

A geometric correction was performed in three iterations using a first order polynomial transformation and nearest neighbor re-sampling algorithm to register the 1990 and 2007 images to the 2001 image mosaic: 1) the 2007 image mosaic was registered to the 2001 image mosaic using 110 ground control points (GCPs), 2) the 1990 12/30 image was registered to the 2001 image mosaic using 78 GCPs, and, 3) the 1990 12/31 image was registered to the 2001 image mosaic using 26 GCPs. Geometric registration of the 2007 image to the 2001 image resulted in an overall root-mean-square (RMS) error of 14.0 meters, the 1990 12/30 image resulted in an overall root-mean-square (RMS) error of 13.8 meters, and 1990 12/31 image resulted in an overall root-mean-square (RMS) error of 12.4 meters, which were well within the documented acceptable limits (Townshend et al., 1992; Yuan and Elvidge, 1998; Lunetta and Elvidge, 1998). Both image data sets were then re-projected into Massachusetts State Plane Coordinate System (NAD83) meters and subset to extract the research area using combined Essex and Middlesex County political boundary GIS shape-files.

Image Normalization

Prior to performing the selected change detection analyses, the values of selected pixels within clear and deep-water bodies (Gordon, 1978), within the 1990 and 2007 images, were compared to determine if atmospheric (haze) conditions affected the imagery. Several differences were discovered for several pixels within deep and clear water bodies within the counties. Using the pixels' associated ground coordinates, a comparison of the reflectance values for each pixel was made. In addition, the individual histograms of each spectral band contained within the imagery were then compared.

Table 4 displays the values within each of the histograms (affected and unaffected) for the 1990 and 2007 images. A noticeable upward shift in the pixel values from 1990 to 2007 was present within some of the spectral bands of the imagery (primarily the visible bands 1-3), likely a result of effects of atmospheric conditions at the time of satellite acquisition (i.e., differences in band-passes, variations in the radiometric response of the sensors, differences in the distribution of cloud and cloud shadow, variations in solar irradiance and solar angles, or variations in atmospheric scattering and absorption) (Jensen, 1996). In addition, the National Oceanic and Atmospheric Administration (NOAA) recorded differences in the temperature and precipitation values (in several climate monitoring stations county-wide) for each image acquisition date (Appendix B).

In order to normalize the data from each scene so that valid comparisons could be made, the image spectral bands (Landsat TM bands 5, 6, and 7) were removed and (Landsat TM bands 1, 2, 3, and 4) were extracted individually from each image data set following the procedure as outlined in the preceding methods section. The high minimum values were then subtracted using a spatial model with the appropriate bias values to adjust and shift the affected histograms in each image to the left to within one positive brightness value of a zero reflectance value.

Table 4. The original and adjusted histograms of the spectral bands for the 1990 and 2007 Path/Row: 12/30 and 12/31 Landsat Thematic Mapper imagery.

	ORIGINAL DATA					ADJUSTED DATA			
9/08/90 Path/Row: 12/30									
Band	**Min**	**Max**	**Mean**	**Std. Dev.**	**Adjustment**	**Min**	**Max**	**Mean**	**Std. Dev.**
TM Band 1 (Blue)	50	255	61.549	6.397	**-49**	1	206	12.549	6.397
TM Band 2 (Green)	13	209	21.885	4.953	**-12**	1	197	9.885	4.953
TM Band 3 (Red)	8	255	18.097	7.336	**-7**	1	248	11.097	7.336
TM Band 4 (NIR)	2	255	54.997	38.264	**-12**	1	254	53.997	38.264
9/08/90 Path/Row: 12/31									
Band	**Min**	**Max**	**Mean**	**Std. Dev.**	**Adjustment**	**Min**	**Max**	**Mean**	**Std. Dev.**
Band 1 (Blue)	42	255	64.214	21.049	**-41**	1	214	23.214	21.049
Band 2 (Green)	12	249	24.113	11.793	**-11**	1	238	8.158	11.267
Band 3 (Red)	8	255	18.674	14.397	**-7**	1	248	7.263	12.688
Band 4 (NIR)	1	255	49.782	36.898	**-0**	1	255	49.782	36.898
9/07/07 Path/Row: 12/30									
Band	**Min**	**Max**	**Mean**	**Std. Dev.**	**Adjustment**	**Min**	**Max**	**Mean**	**Std. Dev.**
Band 1 (Blue)	61	255	89.608	41.157	**-60**	1	195	29.608	41.457
Band 2 (Green)	20	255	36.521	28.083	**-19**	1	236	17.521	28.083
Band 3 (Red)	15	255	33.516	34.124	**-14**	1	241	19.516	34.124
Band 4 (NIR)	1	255	57.535	41.952	**-0**	1	255	57.535	41.952
9/07/07 Path/Row: 12/31									
Band	**Min**	**Max**	**Mean**	**Std. Dev.**	**Adjustment**	**Min**	**Max**	**Mean**	**Std. Dev.**
Band 1 (Blue)	59	255	71.903	8.01	**-58**	1	197	13.903	8.01
Band 2 (Green)	18	156	26.903	5.154	**-17**	1	139	9.903	5.154
Band 3 (Red)	15	195	22.7	7.493	**-14**	1	181	8.7	7.493
Band 4 (NIR)	8	249	48.22	34.547	**-7**	1	242	41.22	34.547

Image Classification

The land cover classification scheme derived referencing NOAA's C-CAP Coastal Land-Cover Classification System resulted in the development of seven distinct class categories: (1) Developed, (2) Bareland, (3) Forest, (4) Grassland, (5) Water, (6) Wetland, and (7) Unclassified. Post data exploration, the 1990 and 2001 images were then classified independently with the iterative "cluster-busting" (Jensen, 1996), classification technique using Erdas IMAGINE's ISODATA algorithm with 200 clusters initially.

The pixels represented by these clusters were then layered upon the imagery for labeling. The clusters which could not be labeled were then further subjected to the "cluster-busting" algorithm technique and extracted to separate images using 10 to 50 class clustering increments. The resulting images were then recompiled and recoded to produce 217 clusters for the 1990 image (Figure 19) and 214 clusters for the 2007 image (Figure 20). The final clusters within each image data set were then labeled (recoded) and collapsed into the appropriate categories of the classification scheme and were filtered using the 3x3 majority (to reduce or remove speckling) to produce Essex and Middlesex County land cover maps. The final image classifications were then compared to the reference data for accuracy assessment prior to performing the post-classification change-detection analysis.

Figure 19. Land Cover Classification Map of Essex and Middlesex Counties September 8th, 1990.

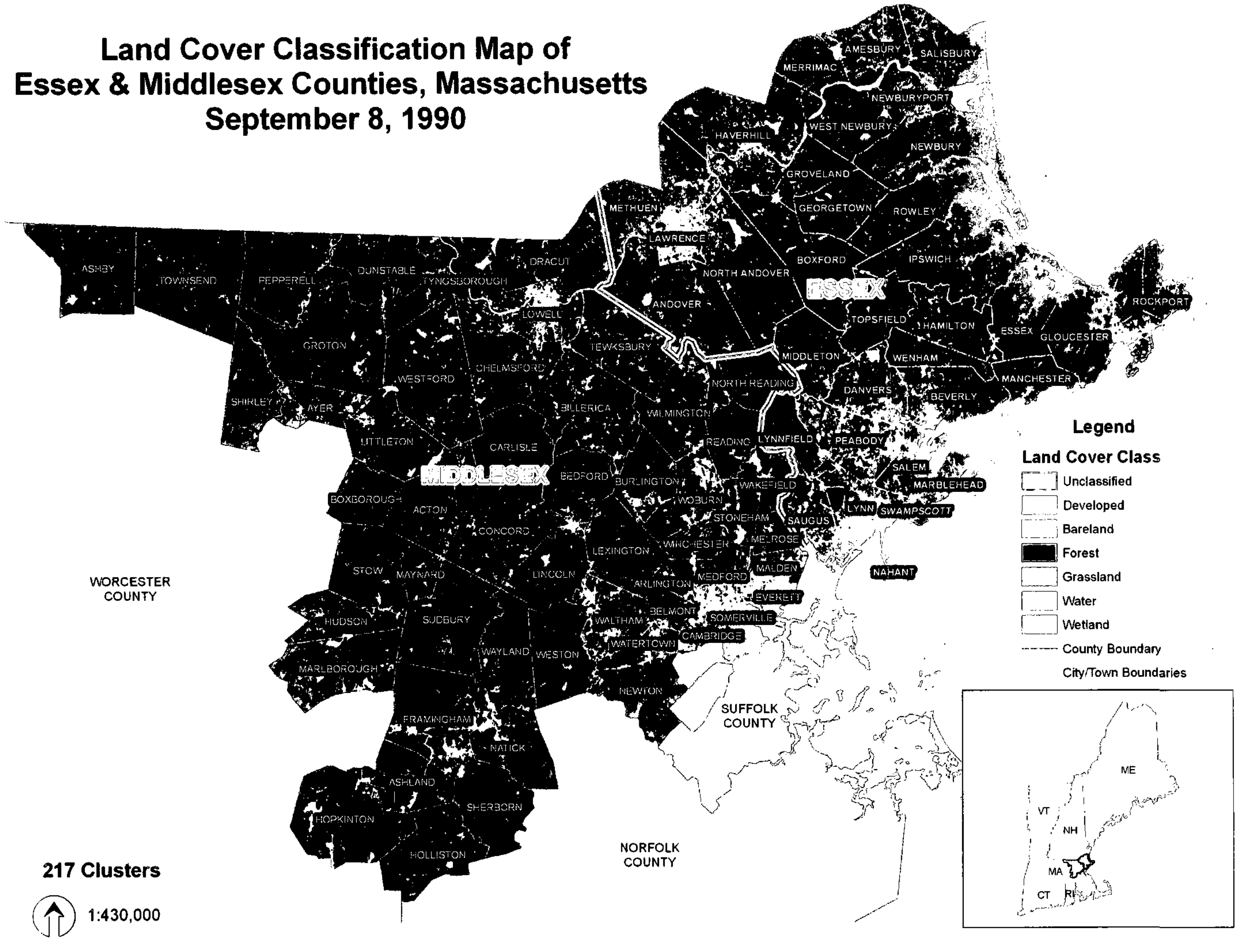
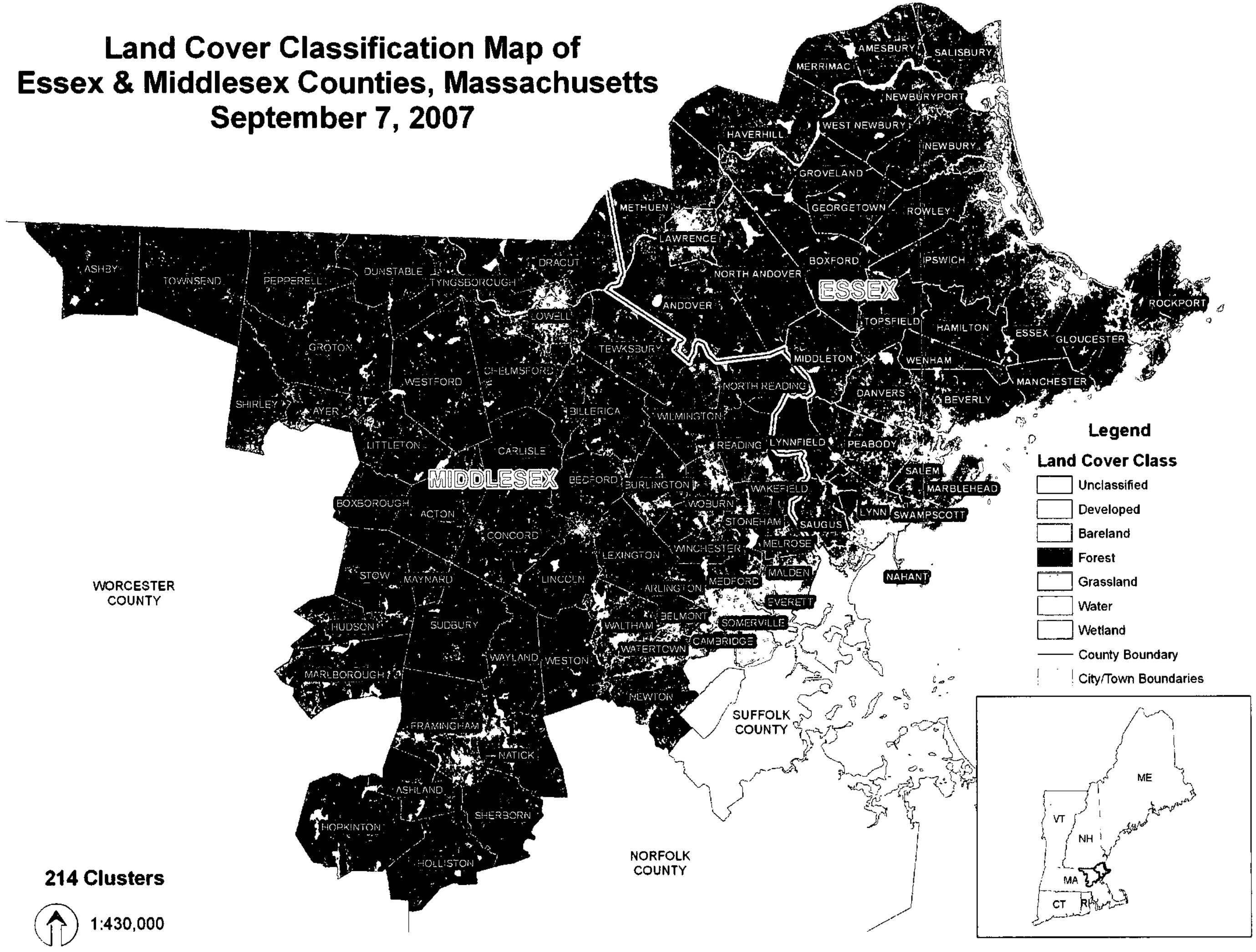


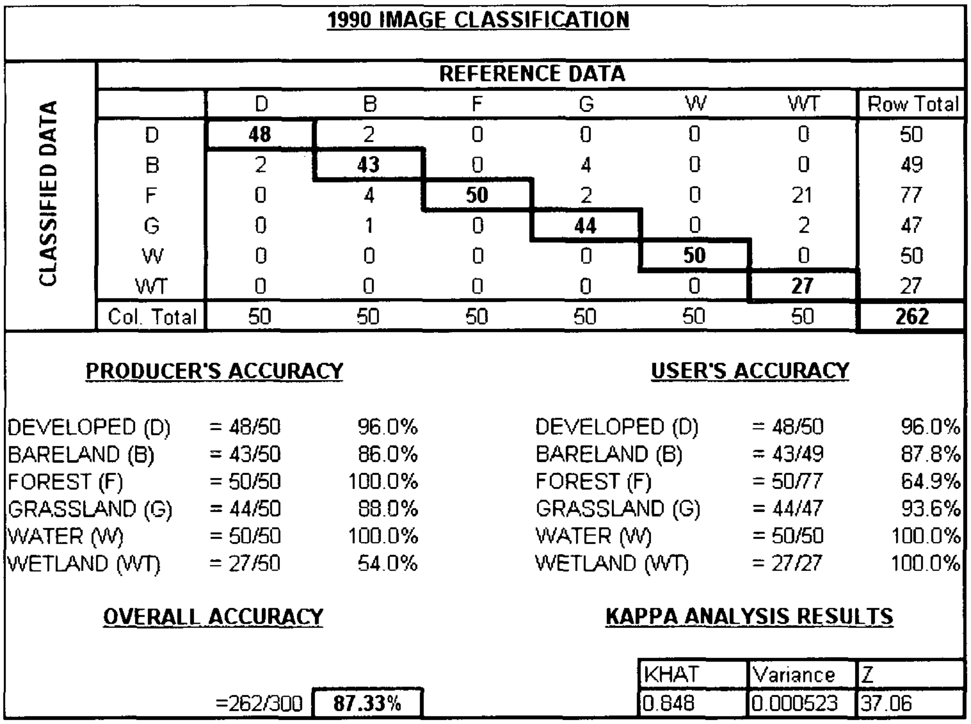
Figure 20. Land Cover Classification Map of Essex and Middlesex Counties September 7th, 2007.



Accuracy Assessment

Prior to performing the post-classification change detection, the 1990 and 2007 image classifications were evaluated for accuracy using the 600 reference data samples contained within the consolidated GPS and photo/image interpretation GIS point shapefile. Table 5 and 6 display the assessment results from the error matrices derived for each image classification. The overall accuracy achieved for the 1990 classification was 87.3% with a KHAT value of 0.848, and the overall accuracy for the 2007 classification was 86.27% with a KHAT value of 0.84.

Table 5. Accuracy assessment of the 1990 image classification.



1990 IMAGE CLASSIFICATION

		REFERENCE DATA						
		D	B	F	G	W	WT	Row Total
CLASSIFIED DATA	D	**48**	2	0	0	0	0	50
	B	2	**43**	0	4	0	0	49
	F	0	4	**50**	2	0	21	77
	G	0	1	0	**44**	0	2	47
	W	0	0	0	0	**50**	0	50
	WT	0	0	0	0	0	**27**	27
	Col. Total	50	50	50	50	50	50	**262**

PRODUCER'S ACCURACY

DEVELOPED (D)	= 48/50	96.0%
BARELAND (B)	= 43/50	86.0%
FOREST (F)	= 50/50	100.0%
GRASSLAND (G)	= 44/50	88.0%
WATER (W)	= 50/50	100.0%
WETLAND (WT)	= 27/50	54.0%

USER'S ACCURACY

DEVELOPED (D)	= 48/50	96.0%
BARELAND (B)	= 43/49	87.8%
FOREST (F)	= 50/77	64.9%
GRASSLAND (G)	= 44/47	93.6%
WATER (W)	= 50/50	100.0%
WETLAND (WT)	= 27/27	100.0%

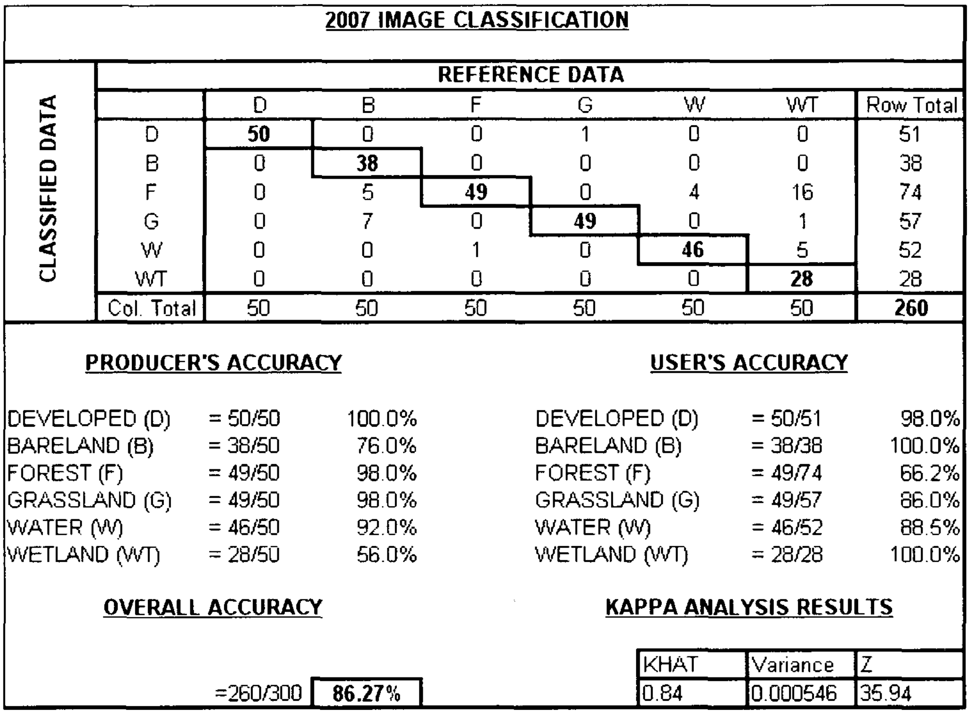
OVERALL ACCURACY

=262/300 **87.33%**

KAPPA ANALYSIS RESULTS

KHAT	Variance	Z
0.848	0.000523	37.06

Table 6. Accuracy assessment of the 2007 image classification.



2007 IMAGE CLASSIFICATION

CLASSIFIED DATA	REFERENCE DATA						
	D	B	F	G	W	WT	Row Total
D	**50**	0	0	1	0	0	51
B	0	**38**	0	0	0	0	38
F	0	5	**49**	0	4	16	74
G	0	7	0	**49**	0	1	57
W	0	0	1	0	**46**	5	52
WT	0	0	0	0	0	**28**	28
Col. Total	50	50	50	50	50	50	**260**

PRODUCER'S ACCURACY

DEVELOPED (D)	= 50/50	100.0%
BARELAND (B)	= 38/50	76.0%
FOREST (F)	= 49/50	98.0%
GRASSLAND (G)	= 49/50	98.0%
WATER (W)	= 46/50	92.0%
WETLAND (WT)	= 28/50	56.0%

USER'S ACCURACY

DEVELOPED (D)	= 50/51	98.0%
BARELAND (B)	= 38/38	100.0%
FOREST (F)	= 49/74	66.2%
GRASSLAND (G)	= 49/57	86.0%
WATER (W)	= 46/52	88.5%
WETLAND (WT)	= 28/28	100.0%

OVERALL ACCURACY

=260/300 **86.27%**

KAPPA ANALYSIS RESULTS

KHAT	Variance	Z
0.84	0.000546	35.94

Change Detection - Post Classification

The post classification change detection was accomplished using the 1990 and 2007 image classifications. The overall results from the post classification change detection analyses performed indicate that land cover change took place within Essex and Middlesex County between 1990 and 2007. Specific results from the post-classification change detection method are presented in the following section.

Prior to performing this technique, the image classifications were refined (recoded) to reflect the six land cover class categories (Developed, Bareland, Forest, Grassland, Water, and Wetland), contained within the classification scheme (excluding the unclassified category). The image classifications were then compared within Erdas IMAGINE and combined using the GIS MATRIX technique. This procedure produced a grayscale matrix change image classification (raster) with an associated database attribute table (.dbf) depicting the land cover class changes that occurred between the 1990 and 2007 image classifications using thirty-six "from-to" land cover class identifier categories with corresponding classified pixel counts.

This study's primary focus was to detect, quantify, and document areas within Essex and Middlesex County that land cover changed to development. Therefore, the appropriate "from-to" class identifier categories and/or pixel regions within the matrix change image classification (i.e., From Bareland to Developed, From Forest to Developed, From Grassland to Developed, etc.), were highlighted and "selected-out" using structured query language (SQL) and then GIS-layered onto a multi-date visual composite image and explored.

Initially, the resulting "from-to" class change identifier categories within the matrix change image classification were assigned a distinct thematic color value (red pixels) in order to illustrate only the "newly" developed areas that appeared within the county. Additional thematic colors were then assigned and used to differentiate the nature of land cover change that had occurred. The next step was to quantify the loss from the existing land cover class types to newly developed land areas. Therefore, the pixel count values were "selected-out" from each of the "from-to" development land cover class categories within the matrix change image classification database attribute table. The pixels from within each selection were then converted to the actual ground surface area by multiplying the pixel count by 0.168 acres (the area value in acres of one 28.5-meter Landsat TM pixel) and compared to the 1990 image classification pixel counts.

Figure 21 illustrates the results from the post-classification analysis technique and Figure 22 provides a larger scale subset (1:60,000) of those results within the towns surrounding Lawrence (Essex County). Table 7 provides the statistics of the land cover changes for the two counties and Tables 8 and 9 present the statistics for Essex and Middlesex Counties individually. As can be seen in Table 7, the region gained 23,435.66 "new" acres of land development from 1990 to 2007 through a combined loss and change in acreage from the Bareland, Forest, Grassland, Water, and Wetland land cover class categories. This indicates that there was an approximate 0.56% overall (net) increase in developed land areas within the 1990 and 2007 image classifications from 415.46 acres or 0.64 square miles. All thirty-six "from-to" land cover change class categories are listed within Appendix C.

Figure 21. Land Cover Change Classification Map of Essex and Middlesex Counties, Massachusetts from 1990 to 2007.

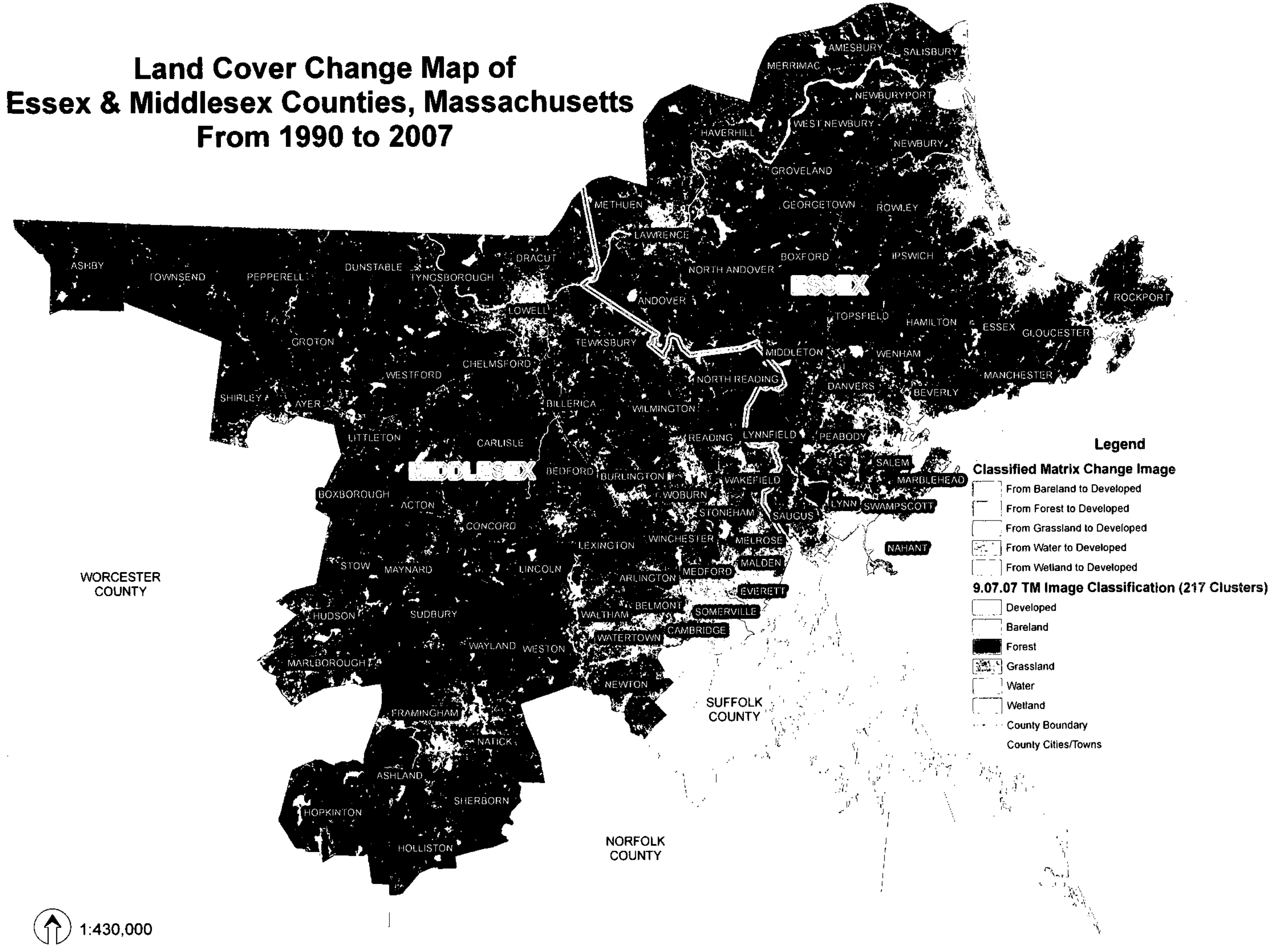


Figure 22. Subset of Land Cover Change Classification Map of Essex and Middlesex Counties.

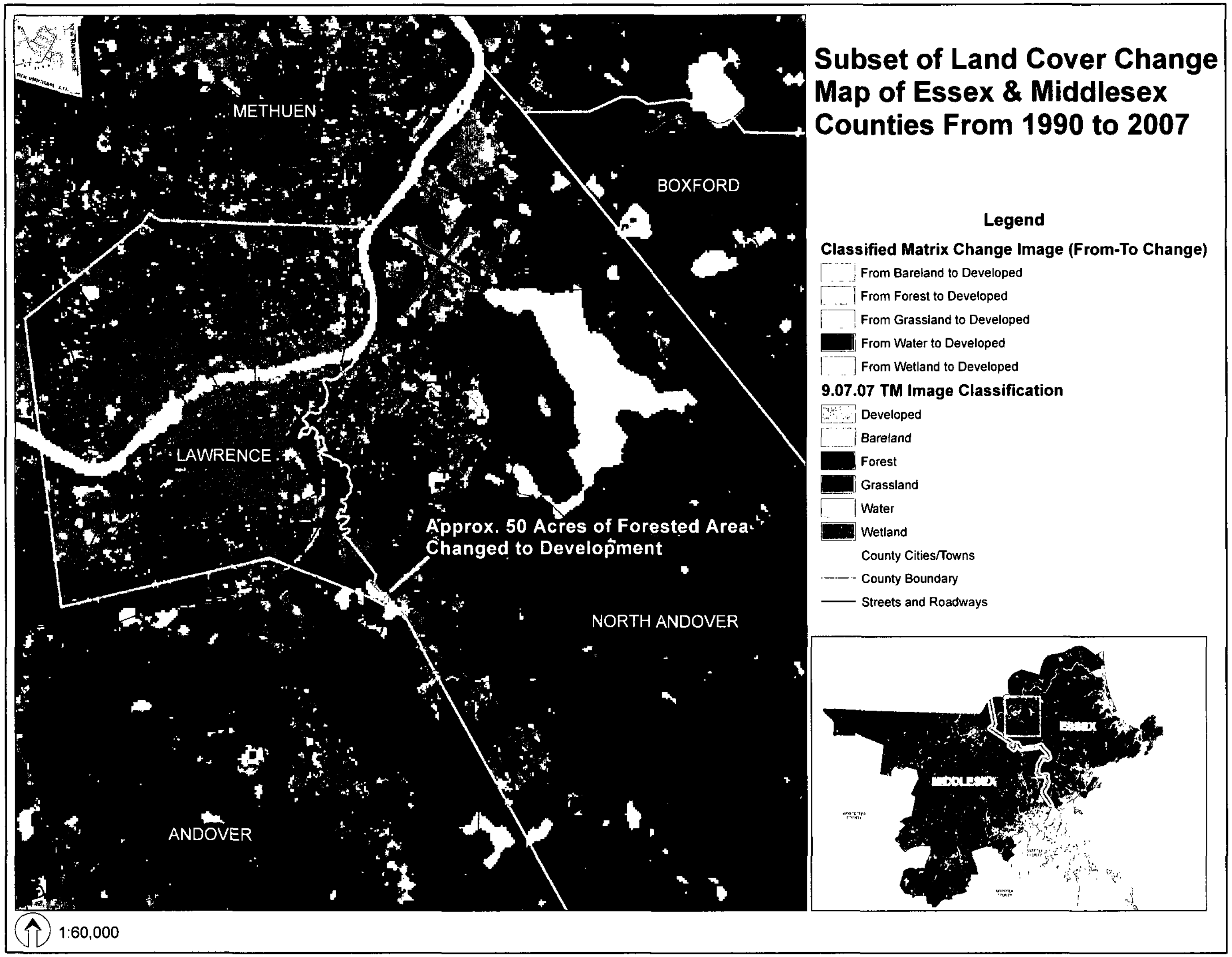


Table 7. Land cover class change results for Essex and Middlesex Counties (combined).

LAND COVER CLASS CHANGE FOR ESSEX AND MIDDLESEX COUNTIES (COMBINED)

Land Cover Class	1990 Pixels	1990 (Acres)	2007 Pixels	2007 (Acres)	Land Change (Acres)	%Change
DEVELOPED	443,951	74,583.77	446,424	74,999.23	415.46	0.56
BARELAND	78,537	13,194.22	92,757	15,583.18	2,388.96	18.11
FOREST	3,338,248	560,825.66	3,426,619	575,671.99	14,846.33	2.65
GRASSLAND	340,472	57,199.30	202,911	34,089.05	23,110.25	-40.40
WATER	136,777	22,978.54	170,443	28,634.42	5,655.89	24.61
WETLAND	4,701	789.77	3,478	584.30	-205.46	-26.02

LAND COVER CLASS CHANGE FROM DEVELOPED

Land Cover Class	1990 Pixels	1990 Class (Acres)	Change-Matrix Pixels	Class Change (Difference in Acres)	2007 Remaining Original Class (Acres)	%Change
From DEVELOPED to BARELAND	443,951	74,583.77	25,083	4,213.94	70,369.82	-5.65
From DEVELOPED to FOREST	443,951	74,583.77	91,230	15,326.64	59,257.13	-20.55
From DEVELOPED to GRASSLAND	443,951	74,583.77	14,849	2,494.63	72,089.14	-3.34
From DEVELOPED to WATER	443,951	74,583.77	5,110	858.48	73,725.29	-1.15
From DEVELOPED to WETLAND	443,951	74,583.77	178	29.90	74,553.86	-0.04
			TOTAL:	22,923.60		

LAND COVER CLASS CHANGE TO DEVELOPED

Land Cover Class	1990 Pixels	1990 Class (Acres)	Change-Matrix Pixels	Class Change (Difference in Acres)	2007 Remaining Original Class (Acres)	%Change
FROM BARELAND to DEVELOPED	78,537	13,194.22	12,726	2,137.97	11,056.25	-16.20
FROM FOREST to DEVELOPED	3,338,248	560,825.66	77,277	12,982.54	547,843.13	-2.31
FROM GRASSLAND to DEVELOPED	340,472	57,199.30	46,394	7,794.19	49,405.10	-13.63
FROM WATER to DEVELOPED	136,777	22,978.54	2,858	480.14	22,498.38	-2.09
FROM WETLAND to DEVELOPED	4,701	789.77	243	40.82	748.94	-5.17
			TOTAL:	23,435.66		

1 Landsat Thematic Mapper Pixel = 0.168 Acres

Table 8. Land cover class change results for Essex County.

LAND COVER CLASS CHANGE FOR ESSEX COUNTY

Land Cover Class	1990 Pixels	1990 (Acres)	2007 Pixels	2007 (Acres)	Land Change (Acres)	%Change
DEVELOPED	213,514	35,870.35	171,090	28,743.12	-7,127.23	-19.87
BARELAND	39,574	6,648.43	44,309	7,443.91	795.48	11.96
FOREST	1,096,832	184,267.78	1,225,660	205,910.88	21,643.10	11.75
GRASSLAND	224,187	37,663.42	112,206	18,850.61	-18,812.81	-49.95
WATER	58,951	9,903.77	83,780	14,075.04	4,171.27	42.12
WETLAND	4,148	696.86	2,745	461.16	-235.70	-33.82

LAND COVER CLASS CHANGE FROM DEVELOPED

Land Cover Class	1990 Pixels	1990 Class (Acres)	Change-Matrix Pixels	Class Change (Difference in Acres)	2007 Remaining Original Class (Acres)	%Change
From DEVELOPED to BARELAND	213,514	35,870.35	12,460	2,093.28	33,777.07	-5.84
From DEVELOPED to FOREST	213,514	35,870.35	57,513	9,662.18	26,208.17	-26.94
From DEVELOPED to GRASSLAND	213,514	35,870.35	9,832	1,651.78	34,218.58	-4.60
From DEVELOPED to WATER	213,514	35,870.35	3,242	544.66	35,325.70	-1.52
From DEVELOPED to WETLAND	213,514	35,870.35	105	17.64	35,852.71	-0.05
			TOTAL:	**13,969.54**		

LAND COVER CLASS CHANGE TO DEVELOPED

Land Cover Class	1990 Pixels	1990 Class (Acres)	Change-Matrix Pixels	Class Change (Difference in Acres)	2007 Remaining Original Class (Acres)	%Change
FROM BARELAND to DEVELOPED	39,574	6,648.43	4,298	722.06	5,926.37	-10.86
FROM FOREST to DEVELOPED	1,096,832	184,267.78	16,358	2,748.14	181,519.63	-1.49
FROM GRASSLAND to DEVELOPED	224,187	37,663.42	18,902	3,175.54	34,487.88	-8.43
FROM WATER to DEVELOPED	58,951	9,903.77	947	159.10	9,744.67	-1.61
FROM WETLAND to DEVELOPED	4,148	696.86	102	17.14	679.73	-2.46
			TOTAL:	**6,821.98**		

1 Landsat Thematic Mapper Pixel = 0.168 Acres

Table 9. Land cover class change results for Middlesex County.

LAND COVER CLASS CHANGE FOR MIDDLESEX COUNTY

Land Cover Class	1990 Pixels	1990 (Acres)	2007 Pixels	2007 (Acres)	Land Change (Acres)	%Change
DEVELOPED	229,685	38,587.08	275,048	46,208.06	7,620.98	19.75
BARELAND	38,748	6,509.66	48,403	8,131.70	1,622.04	24.92
FOREST	2,241,850	376,630.80	2,200,240	369,640.32	-6,990.48	-1.86
GRASSLAND	115,629	19,425.67	90,646	15,228.53	-4,197.14	-21.61
WATER	77,734	13,059.31	86,380	14,511.84	1,452.53	11.12
WETLAND	508	85.34	733	123.14	37.80	44.29

LAND COVER CLASS CHANGE FROM DEVELOPED

Land Cover Class	1990 Pixels	1990 Class (Acres)	Change-Matrix Pixels	Class Change (Difference in Acres)	2007 Remaining Original Class (Acres)	%Change
From DEVELOPED to BARELAND	229,685	38,587.08	12,620	2,120.16	36,466.92	-5.49
From DEVELOPED to FOREST	229,685	38,587.08	33,732	5,666.98	32,920.10	-14.69
From DEVELOPED to GRASSLAND	229,685	38,587.08	5,014	842.35	37,744.73	-2.18
From DEVELOPED to WATER	229,685	38,587.08	1,860	312.48	38,274.60	-0.81
From DEVELOPED to WETLAND	229,685	38,587.08	73	12.26	38,574.82	-0.03
			TOTAL:	8,954.23		

LAND COVER CLASS CHANGE TO DEVELOPED

Land Cover Class	1990 Pixels	1990 Class (Acres)	Change-Matrix Pixels	Class Change (Difference in Acres)	2007 Remaining Original Class (Acres)	%Change
FROM BARELAND to DEVELOPED	38,748	6,509.66	8,425	1,415.40	5,094.26	-21.74
FROM FOREST to DEVELOPED	2,241,850	376,630.80	60,935	10,237.08	366,393.72	-2.72
FROM GRASSLAND to DEVELOPED	115,629	19,425.67	27,471	4,615.13	14,810.54	-23.76
FROM WATER to DEVELOPED	77,734	13,059.31	1,892	317.86	12,741.46	-2.43
FROM WETLAND to DEVELOPED	508	85.34	141	23.69	61.66	-27.76
			TOTAL:	16,609.15		

1 Landsat Thematic Mapper pixel = 28.5 meters or 0.168 acres.

CHAPTER VIII. AN ASSESSMENT OF LAND DEVELOPMENT AND DEMOGRAPHIC CHANGE WITHIN ESSEX AND MIDDLESEX COUNTIES MASSACHUSETTS FROM 1990 TO 2007

Abstract

Land use and land cover changes can result from the interaction between humans and the biophysical environment (Etter et al., 2008), and these changes have accelerated in Essex and Middlesex Counties from 1990 and 2007. The development of land can decrease the amount of forest area, farmland, woodlots, wetlands, and open space and also break up what is left into small pieces that disrupt ecosystems and fragment habitats (Wilson et al., 2002; Madon, 2008). In addition, the loss of open space can negatively impact many potential public goods, such as aesthetics, recreation, and biodiversity values as well as other associated ecosystem services, for example flood control and water purification (Geoghegan, 2002). Land development also can have many economic and social effects and can result in deterioration of urban communities and the quality of life in suburbia, reduce of local commerce by attracting consumers to larger, regional malls and restaurants, give rise to longer commutes, increase traffic congestion, and reduce the way people socially interact through low-density development (Wilson et al., 2002).

This study applies the use of remotely sensed data and geographic information systems (GIS), with ancillary data to compare and contrast the population dynamics within areas of land cover change. Specifically, this study uses Landsat Thematic Mapper (TM) satellite imagery, the post-classification change detection technique, and

geographic information systems (GIS) technology to: 1) quantify the extent of land development which has occurred within Essex and Middlesex Counties from 1990 to 2007 and 2) compare the results from the post-classification technique with demographic data from the United States Bureau of the Census to investigate if areas with the largest change in land development were associated with the largest growth in population and household income.

Results from the comparison of the post-classification technique and GIS analyses indicate that many county communities with larger increases in families with children exhibited moderate to high increases of land development, and communities with higher increases in median household income exhibited low to moderate land development. Land change detection over the 17-year period concluded that the level of land development within Essex and Middlesex Counties varied by sociodemographic factors. In addition, this study illustrates that the combined use of remotely sensed data, geographic information systems (GIS) technology, and demographic data are effective for use as a diagnostic tool and/or base (which could be built upon) to explore the indicators or drivers which may influence land cover change in areas exhibiting change. Moreover, this study provides an example of the methodology to assist land managers or stewards in promoting and enhancing existing or in preparing future resource management strategies or initiatives for available natural resources within Essex and Middlesex Counties or other areas.

Introduction

From 1982 to 1992, approximately 6.2 million acres of agricultural land and 5.1 million acres of forested land were converted to urban and other developed uses in the United States (Vesterby et al., 1997; Geoghegan, 2002). In recent years, Essex and Middlesex Counties in Massachusetts, like many areas in the United States, have encountered substantial residential development and urban sprawl. The perspective on urban sprawl adopted here follows from Gottman and Harper's classic 1967 work, *Metropolis on the Move: Geographers Look at Urban Sprawl.* They describe that "sprawling evokes a pattern of movement and of use of space" (1967, p.4). They also suggest that a certain freedom of movement occurs in a broad context or frame, and that the "common man's use of the term 'urban sprawl' generally has the connotation of being berating or bemoaning," and that "it does not befit cities in such a fashion; and it is not likable" (1967, p. 4).

We all know what urban sprawl is, where it comes from, and what its effects are (Gottman and Harper, 1967). But, most are well aware, as Gottman and Harper state, "modern city dwellers have higher incomes and purchasing power, more economic security, more leisure, better medical care, better distributed food supplies, and other services, even better education" (1967, pp. 5). In addition, despite the well-known terrible sprawling urban areas "with inadequate transportation facilities, polluted air and questionable water quality, ugly or monotonous suburban developments, numerous blighted sectors, much poverty and crime, and congestion and lower standards of servicing" the urban way of life is "preferred by most people" (1967, pp. 5).

Demographic, economic, and social changes can determine the change in the use of land (Gottman and Harper, 1967), and New England has undergone major periods of landscape transformation since its settlement (Vogelmann, 1995). The Massachusetts economic boom of the late 1970's and early 1980's set the stage for urban sprawl, as many "high-tech" research firms and defense contracting agencies developed and diffused out of Boston (Harrison and Kluver, 1989). In 1988, more than 440,000 new jobs were created and the value of residential construction grew four times faster than the nation as a whole (Harrison and Kluver, 1989). As people came to work in these counties they began to purchase homes in close proximity to their employment (Green, 2001). This influx of new residents began to transform the existing landscape by increasing the amount and rate of residential land development activity and acquisition of available housing.

The effects of population growth since the 1970s also have transformed the region's landscape through a decrease in agricultural activity (Vogelmann, 1995); farmland conversion for residential development and commercial expansion have led to the reduction of agriculture-based institutions. According to the Massachusetts Farm Bureau's Census of Agriculture's County Profile in 2008, there was a 40.0% loss of these institutions in Essex and Middlesex Counties, (from 1,219 in 1997 to 979 in 2002), leaving their associated cleared agricultural fields and/or grass lands as "ready-made" for land development for residential and business development.

In the mid to late 1990's, the "dot-com" industry came to New England, and as these new businesses expanded into many rural communities of Massachusetts, so too did the population; and this expansion and subsequent change in the landscape can be used as an indicator of new land development (Sudhira et al., 2004). Beginning in 1972, the Landsat remote sensing satellite program has provided a more efficient and cost-effective method for monitoring land cover from space (Fung and LeDrew 1988; Singh et al., 1989; Lunetta and Elvidge, 1998). An application of remote sensing, specifically change detection, can provide valuable insight into environmental and socio-economic conditions resulting from local, national, or international regulatory and/or land use policy changes over time (Lunetta and Elvidge, 1998; Bontemps et al., 2008). Several studies (Table 10) have investigated land cover change with demographic data by combining one or more of the following methods: aerial photography, remotely sensed data, geographic information systems (GIS) technology, and census statistics (Evans and Moran, 2002; Hunter et al., 2003; Sudhira et al., 2004; Conway and Lathrop, 2005; Huston, 2005; Grove et al., 2006; Otswald and Chen, 2006; Wagner and Gobster, 2007). In addition, several of these studies focused within Massachusetts or in the surrounding New England states (Vogelmann, 1995; Hall et al., 2002; Huffaker and Pontius, 2002; Motzkin et al., 2002; Palmer, 2004; MacDonald et al., 2006). However, the majority used an array of demographic data types and land cover change detection methods to model or recreate historical forested landscapes, to assess forest composition or investigate forest disturbance, and estimate harvesting predictions. In addition, these studies also employed census data for delineating legal boundaries of areas of focus throughout specific research areas of interest.

Table 10. Studies which investigated land cover change with census statistics.

Research Focus	Location	Reference
Forest fragmentation	Southern New Hampshire & Southeastern Massachusetts	Vogelmann, 1995
Spatial integration of factors relating to land cover change	Brazil, Thailand, Indiana	Evans and Moran, 2002
Historical forest composition, structure, distribution	Massachusetts	Hall et al. 2002
Historical land cover reconstruction	Ipswich Watershed, Massachusetts	Huffaker and Pontius, 2002
Environmental/historical determinants of modern species	Cape Cod, Massachusetts	Motzkin et al. 2002
Population and land-use change	California Mojave	Hunter et al. 2003
Predicting scenic perception in changing landscape	Dennis, Massachusetts	Palmer, 2004
Modelling urban sprawl with GIS	Mangalore, India	Sudhira et al. 2004
Modelling ecological consequences of land-use policies	New Jersey, USA	Conway and Lathrop, 2005
Land-use change and biodiversity	Varied sites in rural parts of USA	Huston, 2005
Social and vegetation structure of urban neighborhoods	Baltimore, MD	Grove et al. 2006
Forest harvesting and land use conversion	Massachusetts	MacDonald et al. 2006
Land-use change-climate variations and policies	Loess Plateau, China	Otswald and Chen, 2006
Interpreting landscape change (biophysical and social)	Central Iowa	Wagner and Gobster, 2007

The primary objective of this study is to combine the use of remotely sensed data, change detection methodology, and a geographic information system (GIS), to detect, quantify, and document the extent of new land development within the focus area of Essex and Middlesex County Massachusetts since 1990 to 2007. The specific objectives of this study are to; 1) compare and contrast the changes in population dynamics using demographic data within areas exhibiting land cover change and 2) investigate if areas with the largest change in land development were associated with the largest growth in population and income. In addition, the intent of this study is to provide an example of methodology to assist resource managers or land stewards in predicting land cover changes and the potential impacts from those changes, and promote, enhance, or prepare future land management strategies or initiatives for available natural resources within Essex and Middlesex Counties or other areas.

Literature Review

This section is divided into two sections. The first reviews the effects from land cover change and the second reviews the demographic changes within Essex and Middlesex Counties from 1990 to 2007. A literature review of the land cover change detection, post-classification, image classification accuracy assessment, and ground reference data collection methods, as well as geographic information systems technology used can be found in Chapter 2 Literature Review in the appropriate sub-sections.

Land Cover Change Effects

In Essex and Middlesex Counties there were once many farms. Gottman and Harper (1967) found agriculture's extensive use of land cannot successfully compete with variable real estate market prices within areas where intensive land uses and values continue to rise, and land development and/or urban sprawl could be a result of peoples escape from farming homesteads, and that it results from a "demographic expansion and an economic expansion, both good, and progressive trends" (1967, pp. 18). Land which is used for agriculture can become increasingly difficult to justify as increasing public demand, smaller parcel sizes, and a sluggish supply response can combine to force rural land real estate prices to record levels (Levia, 1998). Although the Commonwealth of Massachusetts has taken steps to preserve agricultural and horticultural, forest, and recreational lands in general, with the enactment of Chapters 61, 61A, and 61B, of Massachusetts General Laws, high real estate values have continued to downplay its overall intent (Levia, 1998; Commonwealth of Massachusetts, General Laws, 2009).

As both population and land development continue to increase within these counties, several problems may indeed arise for its residents. Long-term effects of development on the environment are often not addressed. If left unmonitored, development can lead to inefficient and destructive land uses, traffic pattern disruptions, and tremendous burdens on schools (King and Harris, 1989). In addition, the scenic quality, agricultural and forest resources, and rural character of these communities can remain at risk for degradation and ecologically sensitive areas can be infringed upon

(King and Harris, 1989). Neiman and Fernandez (2000) indicate that a sense of "rampant intrusion" also can develop among existing residents through the disappearance, destruction, or reshaping of familiar local landmarks to make way for new development.

In general, people do want land use to be rational, efficient, and equitable, and do not want any degradation of its quality to occur (Jacobs, 1999). Strategic planning has therefore become essential. Many land planners have begun to design strategies aimed at reducing "land-eating" development and/or promote responsible growth and natural resource conservation. Although these strategies or plans are innovative, they are not always foolproof, and the preservation of the environment and a healthy tax base are often at odds (Campbell, 1996). As Talen states "suburban sprawl is a fact of American life that many planners, urban designers, and politicians would like to change...if policymakers are to abate growth, they must find ways to convince suburban residents that there are benefits to a more urban, compact style of living" (2001, pp.199).

Demographic Change within Essex and Middlesex Counties

According to census statistics documented by the United States Bureau of the Census, Essex and Middlesex Counties have experienced moderate population expansion and commercial development activity during the period of 1990 to 2007. In 1990, the United States Census Bureau estimated that 670,080 persons dwelled within 271,977 households within Essex County, indicating a density of 2.46 persons per household with 1,337 people per square mile (U.S. Census Bureau, 2009). In 2000, the population increased by 53,339 to reach 723,419 persons within 287,144 households, increasing the density to 2.52 persons per household and 1,444 persons per square mile (U.S. Census

Bureau, 2009). In 2007, the population increased by 9,682 people to reach 735,101 persons within 297,444 households per square mile, increasing the density to approximately 2.55 persons per household and 1,463 persons per square mile (U.S. Census Bureau, 2009). On average, the resident population increased 9.4% within Essex County from 1990 to 2007.

From 1993 to 2006, Essex County's number of construction establishments (primarily engaged in the construction of buildings and other structures, heavy construction, additions, alterations, reconstruction, installation, and maintenance and repairs), increased 48.7%, from 1,391 to 2,069 (U.S. Census Bureau, 2009). Essex County's privately-owned residential building permits increased 38.5%, from 961 buildings consisting of 1,210 units in 1990 to 1,331 buildings with 1,937 units in 2000 (U.S. Census Bureau, 2009). From 2000 to 2007, Essex County's building permit count decreased 16.0% to 1,118 buildings and 2,193 units (U.S. Census Bureau, 2009). On average, privately-owned residential building permits increased 16.34% from 1990 to 2007 (U.S. Census Bureau, 2009). Essex County's number of business establishments also increased. In 1993, the Census Bureau estimated that there were 16,276 establishments and in 2006 establishments increased 14.0%, to reach 18,549 (U.S. Census Bureau, 2009).

Middlesex County also experienced similar percentage increases in population, construction, and new business establishments. In 1990, the Census Bureau population estimates indicated that 1,398,468 persons dwelled within 519,527 households, representing a density of 2.69 persons per household with 1,651 people per square mile. In 2000, the population increased by 66,928 to reach 1,465,396 persons within 561,220 households, decreasing the density to 2.61 persons per household and 1,730 people per square mile. In 2007, census population estimates indicated an increase of 8,020 people to reach 1,473,416 persons within 593,209 households per square mile, decreasing the density to 2.48 persons per household with 1,739 people per square mile. On average, the resident population increased 5.4% within Middlesex County from 1990 to 2007.

In addition to population, Middlesex County's total number of construction establishments increased 32.8%, from 3,382 in 1993 to 4,494 in 2006, and its privately-owned residential building permits increased 33.1% from 1,840 buildings consisting of 2,314 units in 1990 to 2,449 buildings with 3,617 units in 2000. From 2000 to 2006, Middlesex County's new building permit count decreased 14.0% to 2,105 buildings with 3,358 units. However, on average, privately-owned residential building permits increased 14.4% from 1990 to 2007 (U.S. Census Bureau, 2009). Middlesex County's number of business establishments also increased. In 1993, the Census Bureau estimated that there were 38,546 and in 2006, the number of establishments increased 11.41% to reach 42,945.

Additional Materials and Methods

A detailed description of the study area, hardware and software used, satellite image data, reference data, pre and post image processing steps, image classification, accuracy assessment, and post-classification change detection can be found within Chapter 6 in the Materials and Methods section.

Additional Reference Data

City and town-level demographic GIS data layers were developed from existing 1990 and 2000 decennial census statistics and estimates which were developed by the United States Bureau of the Census. Demographic data also was compiled from estimates of additional surveys conducted in 2005, 2006, 2007, and 2008. These data were compiled from the following sources: the American Fact Finder, 2008 Population Estimates, 1990 and 2000 Decennial Census, and 2005 and 2007 American Community Survey, as well as 1990 & 2000 Gazetteer STF1a, STF3a Data Files, Massachusetts State and Essex and Middlesex County Quick Facts 2006 estimates, and other federal/state/county/local sources. These data consisted of population, families with own children under 18 years of age, and median household income, as these data can be considered as causal factors which drive sprawl and the development of land (Sudhira et al., 2004). In addition, to perform the assessment, a political boundaries ArcGIS shape-file data layer (provided by MassGIS), was acquired for the eighty-eight cities and towns within Essex and Middlesex counties. Demographic data values were then compiled for each community within this shape-file within the GIS according to year. These GIS data were then used for comparison with the results generated from the post-classification change detection method, which quantified the extent of land development from 1990 to 2007.

Land Development and Demographic Data Comparison

Using the 1990 and 2007 image classifications, the post-classification method generated a "new" classified image containing thirty-six "from-to" land cover change categories (i.e., from forest to developed, from grassland to developed, etc.). To conduct a valid comparison of these results with the demographic data, it was necessary to "select-out" six of the thirty-six land cover change categories which changed to development from 1990 to 2007 (e.g., from forest to development, from grassland to development).

Once these categories were subset from the matrix image classification, they were combined (collapsed) into one separate land cover class defined as land development. The land development class pixels were then converted into a ground area value (acres) for each of the cities and townships political boundary polygons within the two counties. This was achieved by multiplying each "new" development pixel by 0.168 (the ground area value of one Landsat Thematic Mapper (TM) 28.5 meter pixel). Land development acreages were then stored within the political boundary shape-file attribute table for each community within the GIS and used to thematically display the distribution of land development within the counties.

For the demographic data, the decennial census years of 1990 and 2000 represented "complete" datasets which were acceptable for the comparison, for 2007, one-third of the demographic data was available. Percent change statistics were derived for each of the census data types (e.g., population, families with children, and median household income) and placed within a new column or field within the attribute table within the political boundary GIS shape-file. Both land development data and demographic data were then thematically categorized and ready for the comparison. Results from the demographic data percentage changes were displayed in map format for 1990, 2000, and in data available areas for 2007 estimates. An assessment of demographic percent change statistics within areas of land cover change was then made to investigate if areas with the largest change in land development were associated with the largest growth in population and income.

Results

The results from the comparison analyses of the post-classification change detection method results and the demographic GIS data will be presented in four sections: 1) the post-classification change detection, 2) population percent change and new land development, 3) families with own children under 18 percent change and new land development, and, 4) median household income percent and new land development. Specific results from the pre and post image processing steps, image classification, and accuracy assessment are located within Chapter 7 Results in the appropriate sub-sections.

Post-Classification Change Detection

The results from the post-classification technique indicate that land cover change occurred within Essex and Middlesex Counties from 1990 to 2007. In addition, a further investigation of the matrix image classification categories generated by the post-classification indicated that "new" land development occurred during this period. Specific land cover class change results derived from the post-classification change detection method applied to the Landsat Thematic Mapper (TM) imagery are presented in Chapter 7 Results in the Change Detection – Post Classification section.

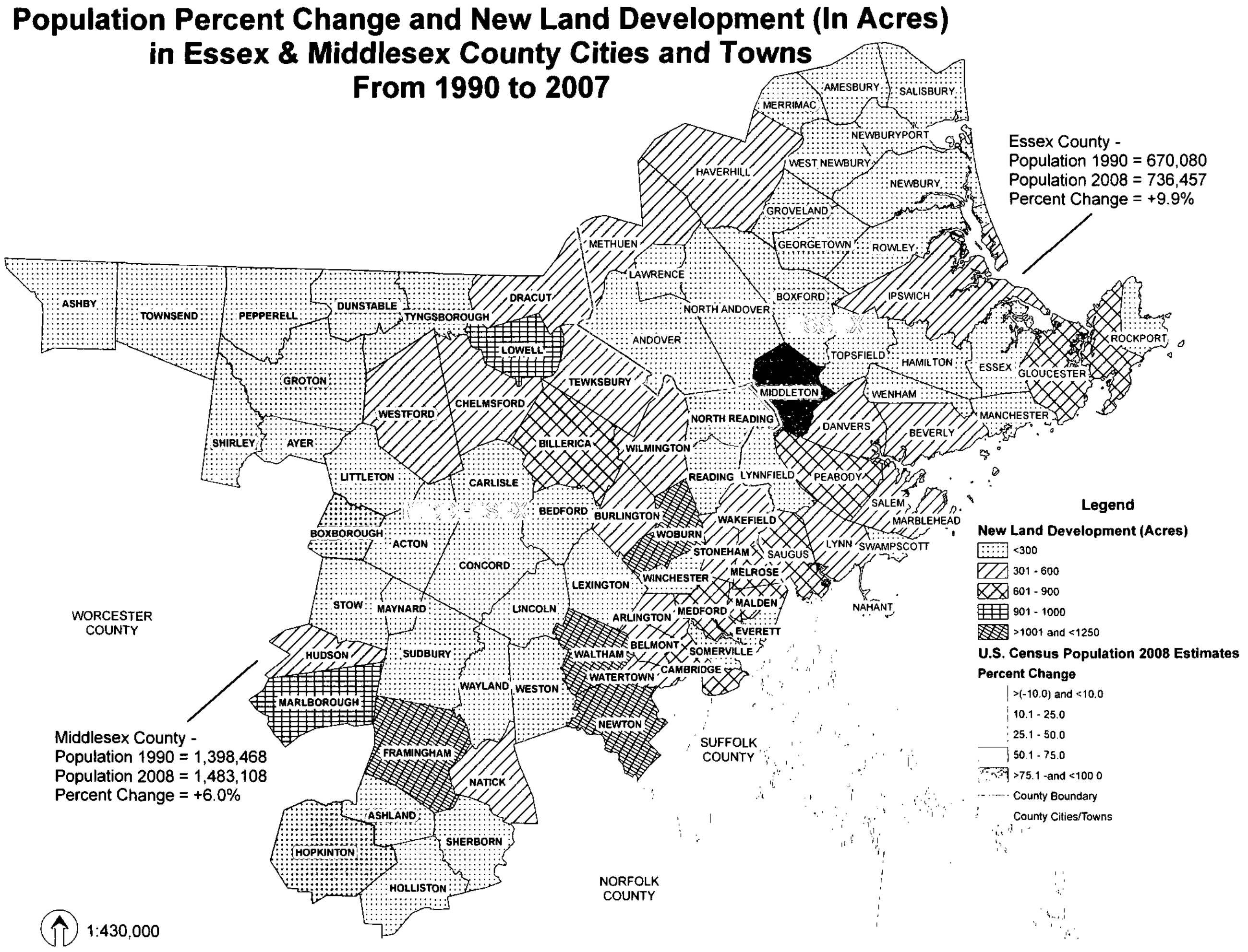
Population and New Land Development

From 1990 to 2007, the results of the post-classification technique indicated that land development within Essex and Middlesex Counties (combined) had increased by 23,436 acres attributed to the loss and gain of classified pixels within the other land cover class categories within the image classifications (e.g., Bareland, Forest, Grassland, Water, and Wetland). Essex County gained 6,821 acres from other land cover class changes to "newly" developed land areas while Middlesex County gained 16,609 acres. From 1990 to 2007, Essex County exhibited a 19.87 percent net decrease in developed land areas (7,127 acres) while Middlesex County exhibited a 19.75 net increase (7,621 acres). On average, there was a 0.56 percent overall (net) increase (415.46 acres) of "newly" developed land areas within these counties (combined) from 1990 to 2007.

Figure 23 illustrates the distribution of "new" land development in acres across the cities and towns within Essex and Middlesex Counties. Of the areas illustrated, the highest acreage increases of "new" land development from 1990 to 2007 occurred within the cities and towns of Newton, Waltham, Framingham, and Woburn, and Lowell, (Middlesex County) (displayed in a cross-hatch pattern), ranging from approx. 900 to 1,250 acres. One third of the communities within the study area, (e.g., Billerica, Gloucester, and Peabody) exhibited moderate increases, ranging from approximately 501 to 900 acres. The remaining one third of the communities (e.g., Ashby, Townsend, Pepperell, and Dunstable) exhibited low levels of land development, and in some communities, less than 300 acres of land development occurred.

According to the demographic data compiled from the United States Bureau of the Census, Essex County exhibited a 9.9 percent increase population, while Middlesex County exhibited a 6.0 percent increase from 1990 to 2008, indicating a combined 15.9 percent increase in population from 1990 to 2008, from 2,068,548 to 2,219,565 persons. As seen in Figure 23, the Town of Middleton (Essex County) (displayed in bright red) exhibited the highest percent increase in population during this period. Figure 23 also

Figure 23. Percent change of population and new land development (in acres) from 1990 to 2007.



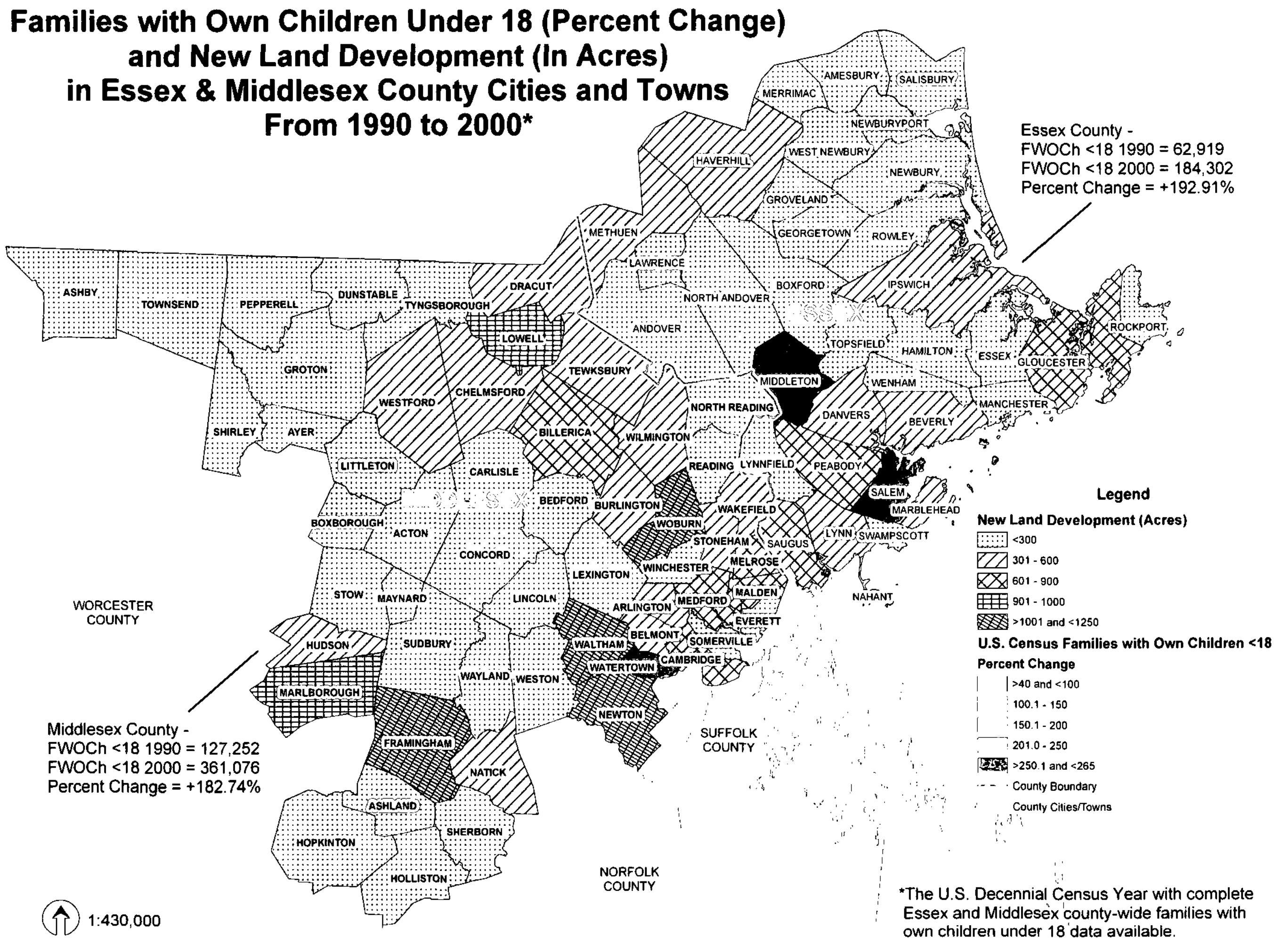
indicates that the towns of Boxford, Georgetown, Rowley, Groveland, Merrimac, in Essex County, and Hopkinton, Boxborough, Westford, Dunstable, Tyngsborough, Groton, Shirley, and Ashland, in Middlesex County (displayed in a lesser red) experienced moderate increases during this period. For one third of the cities and towns within the study area, less than 10 percent exhibited increases in population (displayed in white).

Families with Children and New Land Development

The 1990 and 2000 decennial census provided "complete" data for the eighty-eight cities and towns within the counties for families with own children under 18. For 2007, only a select number of cities and towns were estimated through a variety of surveys (as mentioned in the preceding Additional Methods section). Therefore, two comparison maps resulted, one that illustrated the distribution of data for 1990 and 2000, and the other, which illustrated the complete data for 1990 and 2007 estimates. Both the 1990 to 2000 and 1990 to 2007 data were compared to the results derived from the post-classification technique.

The results from the GIS comparison of families with own children under 18 with the distribution of new land development within Essex County indicate that there was an approximate 192.91 percent increase of families with own children under 18 from 1990 to 2007, while Middlesex County, exhibited an approximate 182.74 percent increase during this period (Figure 24). The Town of Middleton and City of Salem (both in Essex County), (displayed in bright red), exhibited large increases in families with own children under 18 from 1990 to 2000, ranging from approximately 250 to 265 percent.

Figure 24. Percent change of families with own children under 18 and new land development (in acres) from 1990 and 2000*.



*The U.S. Decennial Census Year with complete Essex and Middlesex county-wide families with own children under 18 data available.

Two-thirds of the communities within the study area (displayed in lighter red), exhibited moderate increases ranging from approximately 150 to 250 percent. While the towns of: Ashby, Peperell, Shirley, and Ayer, (displayed in a lighter red), exhibited low percentage increases. Merrimac (displayed in white) exhibited the smallest percentage increase during this period, ranging from approximately 40 to 100 percent. According to the available data within the 2007 estimates, the cities and towns of Lawrence, Lynn, Acton, and Westford, had the highest percentage increases in this category (Figure 25). Communities such as Gloucester, Haverhill, and North Andover, increased comparatively to the results observed within1990 demographic data.

Median Household Income and New Land Development

Similar to the datasets used within the preceding section, the 1990 and 2000 decennial census provided "complete" data for the eighty-eight cities and towns within the counties for median household income. For 2007, only a select number of cities and towns were estimated through a variety of surveys (mentioned in the preceding Additional Methods section). Therefore, two comparison maps resulted, one that illustrated the distribution of data for 1990 and 2000, and the other, which illustrated the complete data for 1990 and 2007 estimates. Like the data in the preceding section, both the 1990 to 2000 and 1990 to 2007 data were compared to the results derived from the post-classification technique.

According to the demographic data findings, Essex County exhibited a 36.3 percent increase in median household income from 1990 to 2000, while Middlesex County exhibited a 36.7 percent increase (Figure 26). Figure 26 also illustrates the cities and towns (e.g., Newbury, West Newbury, Georgetown, Wenham, Westford, Hopkinton,

Figure 25. Percent change of families with own children under 18 and new land development (in acres) from 1990 and 2007*.

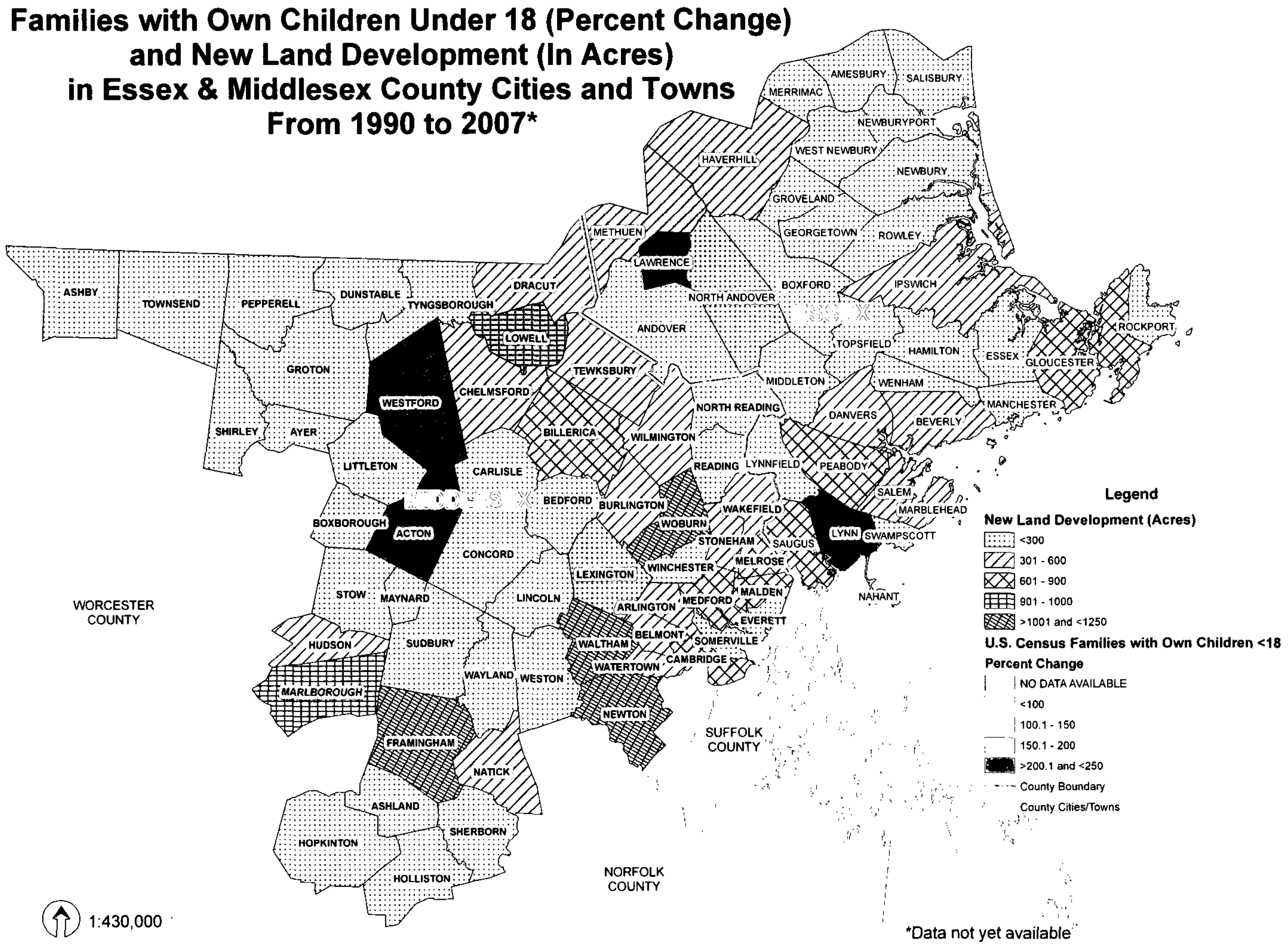
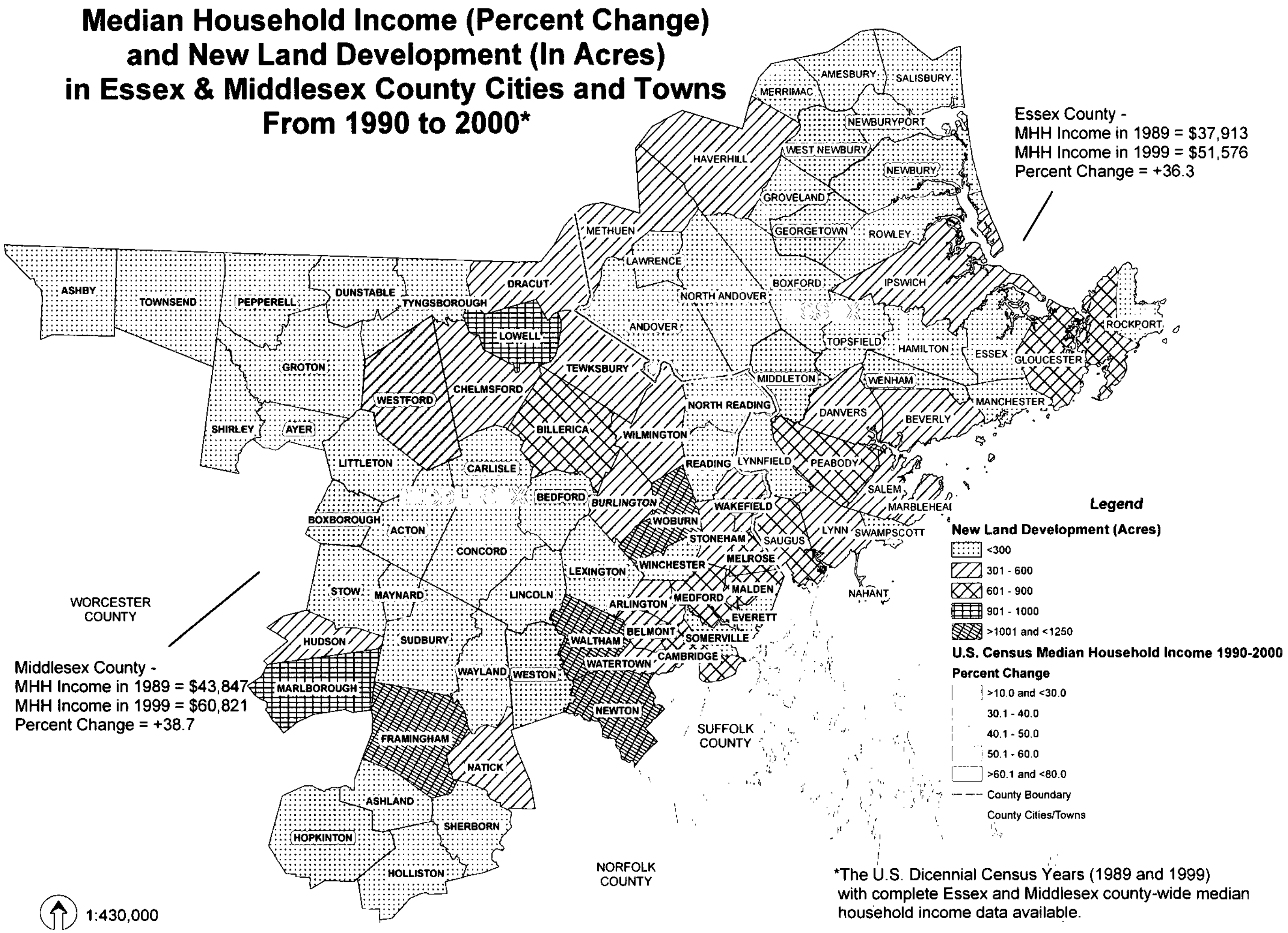


Figure 26. Percent change of median household income and new land development (in acres) from 1990 to 2000.



Median Household Income (Percent Change) and New Land Development (In Acres) in Essex & Middlesex County Cities and Towns From 1990 to 2000*

Essex County -
MHH Income in 1989 = $37,913
MHH Income in 1999 = $51,576
Percent Change = +36.3

Middlesex County -
MHH Income in 1989 = $43,847
MHH Income in 1999 = $60,821
Percent Change = +38.7

Legend

New Land Development (Acres)
- ░ <300
- ▨ 301 - 600
- ☒ 601 - 900
- ▦ 901 - 1000
- ▩ >1001 and <1250

U.S. Census Median Household Income 1990-2000

Percent Change
- >10.0 and <30.0
- 30.1 - 40.0
- 40.1 - 50.0
- 50.1 - 60.0
- >60.1 and <80.0
- County Boundary
- County Cities/Towns

1:430,000

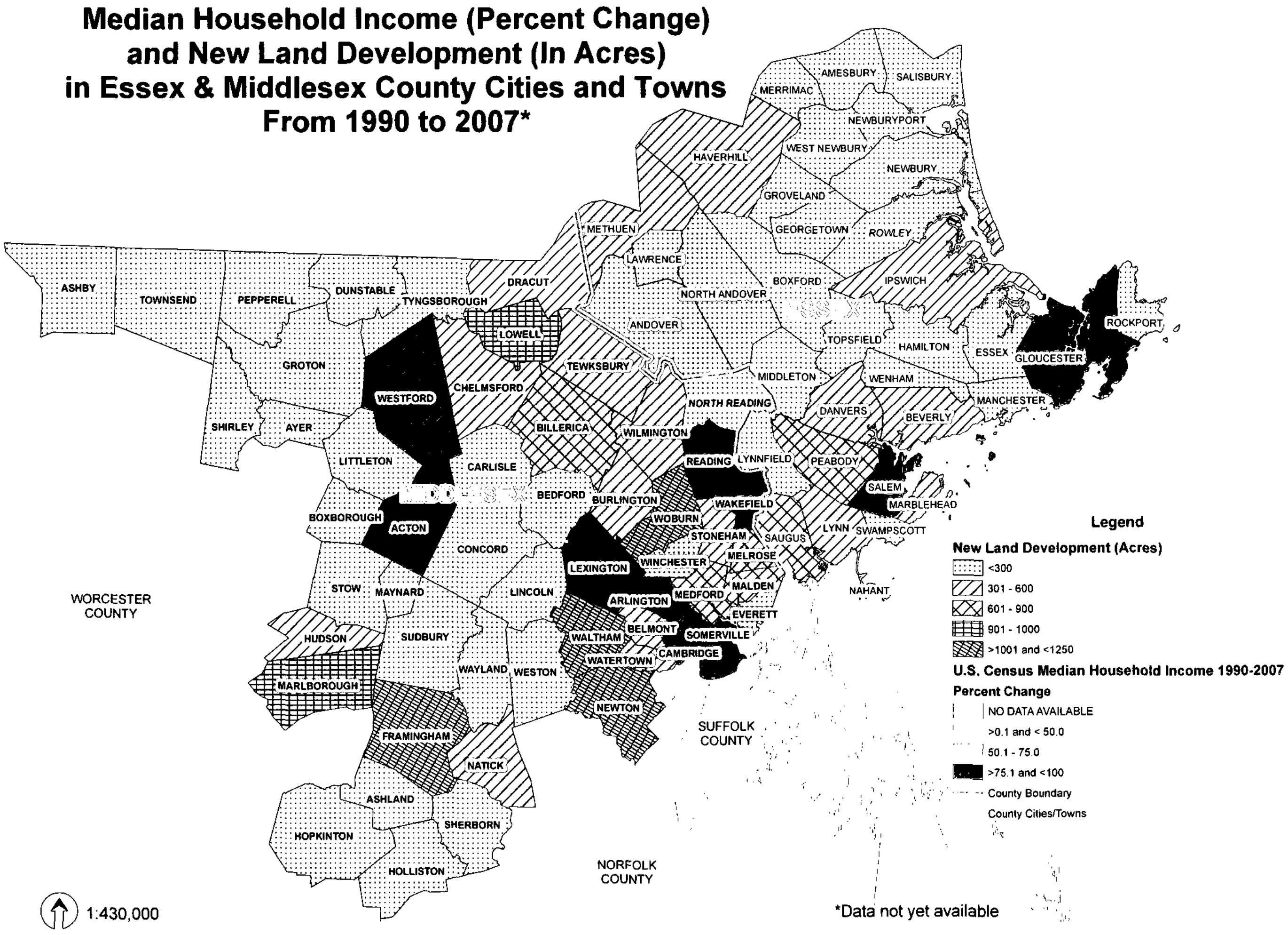
*The U.S. Dicennial Census Years (1989 and 1999) with complete Essex and Middlesex county-wide median household income data available.

and Weston) (displayed in bright red), where the highest increases in median household income occurred during this period. While two thirds of the communities within the study area exhibit moderate percent increases, (e.g., Rowley, Essex, Lawrence, Concord), the remaining communities reflect increases ranging from approximately 10 to 30 percent. The 2007 estimates (Figure 27) indicate that several communities (e.g., Gloucester, Reading, Westford, Acton, Salem, and Lexington), which had moderate to large increases during the period of 1990 to 2000, exhibited high increases during this period as well.

Discussion and Conclusions

This study provided the application and methodology to compare, contrast, and combine remotely sensed data and ancillary data from an array of survey sources within a geographic information system (GIS) to explore land cover and demographic change at the county, city, and town levels. Specifically, this study applied an application of Landsat Thematic Mapper (TM) 5 imagery, and the post-classification change detection methodology to detect, quantify, and document the nature and extent of land development and investigate and compare population change using three census data types (i.e., population, families with children, median household income) in areas of land cover change within Essex and Middlesex Counties from 1990 to 2007. This study illustrated that the combined use of remotely sensed data, geographic information systems (GIS) technology, and demographic data are effective for use as a diagnostic tool to explore the indicators or drivers which may influence land cover change in areas exhibiting change and its methodology will promote, assist, or enhance land managers, in existing or in

Figure 27. Percent change of median household income and new land development (in acres) from 1990 to 2007.



preparation for the future management practices of available natural resources within Essex and Middlesex Counties or other areas.

Assessing land cover change through the use of remotely sensed data can often be challenging and the results uncertain. Extensive processing of satellite imagery is required in order to produce accurate change detection results. In addition, although demographic data can be used as an indicator of land development, gaps or incomplete data coverage can adversely impact or even hinder the comparative assessment process. However, this study has shown that the integrated use of satellite remote sensing, geographic information systems (GIS) technology is suitable to quantify the extent of land development from 1990 to 2007 and that the demographic which was available was acceptable and appropriate to gather insight into sociodemographic factors may influence land development. In addition, this study provides a base or impetus for future land cover change and demographic research to occur.

The comparison of demographic data with the land development results from the post-classification technique indicated that communities with larger increases in families with children exhibited moderate to high increases of land development, while communities with higher increases in median household income exhibited low to moderate land development. Land cover change detection over the 17-year period indicated that land development occurred in many areas, but level of development varied by sociodemographic factors.

As observed from the comparison of the imagery during this period, many land areas within the counties were developed for residential (e.g., subdivisions, houses, and apartment complexes) and for commercial purposes (e.g., box-department stores). The communities of Middleton, Groveland, North Reading, Boxford, Georgetown, Dunstable, Tyngsborough, Shirley, among others, exhibited large percent increases in population and low levels of land development activity. These communities may be right on the cusp of where the "next" land development activity will occur. For the communities exhibiting larger increases of families with children, the nature of land development consisted of a variety of large campus-style and/or box-style commercial and residential establishments. An example of this is located within the City of Marlborough (Middlesex County), where a commercial site, a bio-fuels company was developed on approximately 50 acres of a previously forested area. To the southeast of this company's location a residential apartment complex also was developed on a previously forested area (approx. 20 acres).

The City of Marlborough also exhibited land development along or near the Massachusetts State Highway Route 290. Several large box stores (e.g., sporting goods and electronics), just southwest of the bio-fuels and residential apartment complex sites were built on approximately 20 acres of a previously forested area. In addition, bio-technology, insurance, medical-technology (or pharmaceutical), data warehousing and information technology management firms to the northeast of these sites, also have arrived and have expanded in Marlborough. Most of the associated structures, typically large office complexes or buildings were constructed on several 20 acre parcels, most of which were previously forested. In the Town of Middleton (Essex County), the majority of land development occurred near or adjacent to State Highway Route 114 and consisted of light industrial complexes as well as small multi-dwelling residential subdivisions.

Communities with higher increases in median household income exhibited low to moderate land development. The cities and towns of Newburyport, Newbury, West

Newbury, Westford, Wenham, Weston, and Sudbury provide examples of moderate to affluent “bed-room” communities and offer larger and more expensive homes, larger parcel sizes, greater expanses of recreational and open space, scenic and rural or bucolic character, “better” school systems, little or no industry, easily accessible agricultural field lands and other larger natural areas such as forests, grasslands, wetlands, lakes, ponds and streams, and other amenities. The vast majority of middle and upper income households live further from the city centers in separate sub-urban communities (Wheaton, 1977). The consequences of this spatial pattern have been quite serious for many American cities, as the outward mobility of those with means has left many city centers as segregated domains for the poor (Wheaton, 1977). Within city boundaries the poor can tax only themselves for necessary but deteriorating services, and mid to high level income residents, having escaped this tax burden, can enjoy a substantial "fiscal surplus" within the suburbs--providing an implicit and regressive redistribution of income (Wheaton, 1977).

Future research should investigate whether employment or occupational data may influence land cover change as well. The nature of occupation, business type, employment and/or shifts of employment may lead to the development of specific or purposed buildings and/or types of structures designed to support their associated activities. In addition, to determine when land development occurred historically or to predict or forecast future land development in specific areas, additional data such as successive or biannually-acquired satellite imagery as well as additional census data which describes the age of housing stock to separate or differentiate the construction ages of their development (from old to new) may prove beneficial.

As this study focused on the city of town polygon-level within the GIS, further investigation of economic census data including census tract or block information should be used to further understand the drivers (at a more specific location) of land development within this region. In addition, both the demographic data and results from these analyses should be integrated within other GIS-type modules (e.g., Census Bureau's Community 2020 software program or within the American Forests Smart Communities growth model), to further environmental impacts from existing land development and demographic data type changes on locations of plant and animal habitats, the locations of water bodies to foster protection, conservation, and stewardship and assist land use planning and management. Moreover, selection of the appropriate spatial resolution of the satellite imagery and level of image classification scheme also should be considered. Because higher spatial resolution satellite or aerial data as well as additional land cover class categories may be able to provide a more spatially and spectrally accurate depiction of the nature and extent of land cover changes that can occur within any given environment.

The next chapter will discuss the environmental effects from land development in Essex and Middlesex Counties from 1990 to 2007.

CHAPTER IX. REMOTE SENSING, GIS, AND SCIENTIFICALLY-BASED GUIDELINES AS METHODS TO UNDERSTAND AND CONSERVE BIOLOGICAL DIVERSITY IN NORTHEAST USA

Abstract

Since the 1970's urban centers in and surrounding Essex and Middlesex Counties in Massachusetts have expanded and proliferated into adjacent communities. Not only has this expansion placed significant strain on existing land cover, land use, and available natural resources, it continues to encroach upon, disrupt, and fragment many wildlife habitat areas. Research efforts are increasing in response to conserve biological diversity of species because of their sensitivities to environmental disturbances and the corresponding declines, range constrictions, and extinctions worldwide (Hermann et al., 2005). Researchers have found that trends in their disturbance are strongly linked to the fragmentation and modification of habitat by humans for agriculture, forestry, and urbanization (Blaustein et al., 1994; Skelly et al., 1999; Semlitsch, 2000; Young et al., 2001; Halverson et al., 2002; Hermann et al., 2005). To monitor land development and its effect on the environment within the counties, the post-classification change detection method was applied to Landsat Thematic Mapper (TM) satellite data and geographic information systems (GIS) technology was used to detect, quantify, and document the extent of development from 1990 to 2007.

Results from these analyses indicate that 23,436 acres of new land development occurred within these counties and within several of the Commonwealth of Massachusetts's delineated "environmentally-sensitive" areas. Approximately 722 acres

of new land development occurred within areas of critical environmental concern, 670 acres in priority habitats of rare species, 1,092 acres in living waters core habitats and critical supporting watersheds, 1,318 acres in protected and recreational open spaces, and within 0-1000 feet of 600 certified vernal pool areas. The primary goal of this study is to demonstrate the combined used of remotely sensed data and geographic information systems (GIS) with ancillary data from a variety of the Commonwealth of Massachusetts's environmental management agencies to assess land development and its effect environmental conditions. In addition, this study provides insight into specific wildlife habitat areas and selected threatened or endangered species which may have been affected by land development, and presents the findings of several studies which have derived scientific guidelines to assist natural resource managers and land planners in their protection.

Introduction

From 1985 to 1999, Massachusetts lost 40 acres per day as a result of land development (Mass Audubon Society, 2003). From 2000 to 2002, residential lot sizes in some Massachusetts counties increased 47.0%, and in others, lot sizes have doubled. In 2008, the Massachusetts Farm Bureau's Census of Agriculture's County Profile indicated that there was a 40.0% combined loss of agricultural farms in Essex and Middlesex Counties, (from 1,219 in 1997 to 979 in 2002), leaving their associated cleared agricultural fields and/or grass lands as "ready-made" for land development both residential and commercial. Schneider and Pontius, Jr. (2001) found that forest loss from land development can contribute to eutrophication, ground water loss, and loss of wildlife habitat. While progress has been made in land protection, habitats of many rare species, such as riparian areas surrounding aquatic species habitats, have little or no permanent protection; fragmentation continues to threaten these areas (Mass Audubon Society, 2003).

Environmental and land management issues across New England make sound ecological information and conservation thinking a major imperative (Foster, 2002). New England supports a large and affluent population, and as it continues to urbanize, it is faced with potential widespread development and environmental degradation (Foster, 2002). Essex and Middlesex Counties are unique places filled with many rare and endangered plant and animal species and a wealth of natural resources like the Great Marsh, in the northshore of Essex County, which is the largest contiguous salt marsh in New England (Mass Audubon Society, 2003). Settled in the early 1600's, these counties quickly grew to become the manufacturing and agricultural hubs of New England (Hurd, 1888). As transportation corridors developed and evolved extensively since the mid 1950's, population and land conversion for development increased (Wilson et al., 2002).

As a result of its history and economic growth, Massachusetts faces many conflicting proposals for its land conservation and stewardship, and there is a great need for the type of broad ecological insights afforded by historical-geographical research (Foster, 2002) and scientifically-based guidelines. Scientifically-based guidelines are critical to establish land-use thresholds to maintain species richness and individual species, and will provide regulators with biological framework for conservation management to better ensure the persistence of a variety of species in New England, and possibly other regions (Herrmann et al., 2005).

Beginning in 1972, the Landsat remote sensing satellite program has provided a more efficient and cost-effective method to conduct land cover monitoring from space (Fung and LeDrew 1988; Lunetta and Elvidge, 1998; Singh, 1989). Landsat has produced many applications; one, change detection has become an important process for historical monitoring and managing natural resources because it provides a means to quantify the extent and nature of the change within the environment. Coupled with remotely sensed data, Geographic Information Systems (GIS) technology enables researchers with a powerful capability to store, search, analyze, manipulate, display, and distribute large amounts of descriptive geo-referenced and relational data (Congalton and Green, 1992). In addition, GISs can be used to develop a wide array of selection criteria to generate and convey information about a specific area of interest as well as model and further understand the environment (Congalton and Green, 1992).

The primary goal of this study is to demonstrate the combined used of remotely sensed data and geographic information systems (GIS) with ancillary data from a variety of agencies to assess land development and its effect on environmental conditions. The specific objectives of this research are to: 1) apply the use of Landsat Thematic Mapper (TM) remotely sensed data, 2) perform the post-classification change detection method, and 3) use GIS to detect, quantify, and document the extent of development and to evaluate its effects at the ecosystem-level by (a) combining the change detection results with environmental datasets from three Commonwealth of Massachusetts state organizations (i.e., the Department of Fish and Game's Mass Wildlife and Natural Heritage and Endangered Species Program, Department of Environmental Protection, and Department of Conservation and Recreation), (b) identifying, to the extent possible, the specific species inhabiting the impacted areas, and (c) reviewing recent literature on how land cover and land use change relates to the habitat change of certain plant and wildlife species biodiversity. Specifically, this study intends to assess how land development has fragmented, disrupted, or encroached upon areas of critical environmental concern, wildlife habitats, designated open and recreational spaces.

In addition, the intent of this study is also to promote an awareness to several studies which have generated scientifically-based guidelines for environmental protection mechanisms such as: (a) minimum width of vegetated buffers for stream, lake, and wetland ecosystems, (b) percent of impervious surface in watersheds, (c) minimum size (area) of forest habitat for rare or imperiled terrestrial vertebrates, and (d) dimensions for vegetated corridors designed to allow terrestrial vertebrate migration between protected areas. Moreover, this study will provide a base or impetus for future monitoring of land development in Massachusetts, and literature resources for the future development of conservation, stewardship, and management policies for the flora, fauna, and natural resources within these counties.

Literature Review

This section is divided into five sections. The first reviews land development and its effects on the environment, the second reviews the minimum width of vegetated buffers for stream, lake, and wetland ecosystems, the third reviews the percent of impervious surface in watersheds, the fourth reviews the minimum size (area) requirements of forest habitat for rare or imperiled terrestrial vertebrates, and the fifth reviews the dimensions for vegetated corridors designed to allow terrestrial vertebrate migration between protected areas.

A literature review of land cover change detection, the post-classification technique, image classification accuracy assessment, ground reference data collection methods, and geographic information systems technology can be found in Chapter 2 Literature Review in the appropriate sub-sections.

Land Development and Its Effects on the Environment

The interaction between humans and the biophysical environment results in land use and land cover changes (Etter et al., 2008), and these changes have accelerated between 1990 and 2007 in Essex and Middlesex Counties. The development of land can not only decrease the amount of forest area, farmland, woodlots, wetlands, and open space but also break up what is left into small pieces that disrupt ecosystems and fragment habitats (Wilson et al., 2002; Madon, 2008). Land development also can alter critical wildlife corridors and can influence the presence, distribution, and demographic characteristics of wildlife and amphibian populations in different ways including altering their spatial use, dispersal, and movement patterns (Gaughan and Destefano, 2005; Hamer and McDonell, 2008). In addition, land development also can substantially impact wetlands, and in recent years, infringement upon wetlands has increased and has raised public concerns. Wetlands not only support a unique habitat for a great variety of hydrophytic plants, fish, wildlife and insects, and provide tourist destinations, but, perform a wide range of stabilizing functions, including water quality protection through particulate and nutrient cycling and retention, minimize flooding, erosion, control stream flow, and recharge groundwater (Toyra et al., 2001; Schmidt et al., 2003; Nielsen et al., 2008).

According to Nielsen et al. 2008, wetlands can be created, modified, and destroyed by a variety of natural processes, but, the direct or indirect impacts of human disturbance is the main cause of wetland change or loss within the United States. In many coastal areas, housing complexes, marinas, docks, tide gates, culverts and dikes can often threaten wetlands through bisection, affecting tides, causing ocean inlets to close, changes in water quality and water level, sedimentation, and can negatively affect wetland biota and benthic organisms (Madon, 2008). In addition, wetlands can be severely impacted by the increased nutrient run-off from encroaching agricultural, urban, and residential areas (Siciliano et al., 2008), and according to Liu et al. 2008, in areas of rapid development and/or economic growth, increased nitrogen in human waste run-off from residential development, was found to be the second largest source of nutrient load in water bodies next to agricultural chemical fertilizers.

Wetlands are not the only ecosystem which can be affected by development. Development also can have ecologically significant and lasting effects on forest ecosystems as well (Heckmann et al., 2008), by producing some of the greatest local extinction rates and frequent elimination of a large majority of native species (McKinney, 2002). Urbanization often can increase the number of non-native plant species, decrease the richness of native flora, under-represent significant habitat elements (e.g., large diameter trees, canopy gaps, coarse woody debris), limit the range of seral or ecological succession stages, and can threaten the biological uniqueness of these ecosystems (Medley et al., 1995; Howard and Lee, 2002; McKinney, 2002; Litvaitis, 2003;

Heckmann et al., 2008). Urban planners strive to retain many of the natural elements of these systems for aesthetics, recreation, biological diversity, insect control, flood control, and pollination (Heckmann et al., 2008). However, the dynamic nature of these communities makes it difficult to achieve the social, ecological, and economic objectives which commonly drive their retention; and these ecosystems are particularly vulnerable to loss of ecological integrity because of their intrinsic complexity, structure, and function (Heckmann et al., 2008).

Minimum width of vegetated buffers in stream, lake, and wetland ecosystems

An estimated 53% of original wetlands in the United States have been lost to human development during the past 200 years, likely resulting in the irreversible loss of habitat for a wide variety of plants and animals (Semlitsch, 1998). Wetland areas in the United States have been converted to residential property and agricultural fields, which has led to several wetland conservation statutes being enacted during the past decade (Dahl, 1990; Gibbs 1993; Mitsch and Gosselink 1993; Burke and Gibbons, 1995). To be successful in protecting these areas, conservation effort will require legislation that mandates large and sometimes economically disadvantageous buffer zones around wetland areas (Burke and Gibbons, 1995).

Riparian zones occur as transitional areas between aquatic and upland terrestrial habitats, and they can be described generally as long linear strips of vegetation adjacent to rivers, lakes, reservoirs, and other inland aquatic systems (Fischer and Fischenich, 2000). Riparian zones have been widely recognized as functionally unique and dynamic ecosystems capable of protecting water quality (Fischer and Fischenich, 2000). There is considerable confusion in the literature regarding wetlands and riparian zones, specifically the distinction between vegetated buffer strips and corridors (Fischer and Fischenich, 2000). Vegetated buffer strips (e.g., riparian buffer strips or wildlife movement corridors) are a linear band of permanent vegetation adjacent to an aquatic ecosystems intended to maintain or improve water quality through the trapping and removing various non-point source pollutants (i.e., herbicides, pesticides, nutrients from fertilizer, and sediment from upland soils) from overland and shallow surface flow (Fischer and Fischenich, 2000; Davis et al., 2007; Mankin et al., 2007; Mayer et al., 2007). In addition, these buffer strips may provide habitat and movement corridors to support the life-cycle needs of a variety of plants and animals species (Fischer and Fischenich, 2000). Riparian corridors or wildlife corridors can be strips of vegetation that connects two or more larger patches of vegetation (i.e., habitat) to facilitate movement or dispersal of organisms; and this is critical for reconnecting fragmented habitat islands (Fischer and Fischenich, 2000).

The research community recommends the retention of buffers for controlling erosion, sedimentation, moderating stream temperature and light, the input of fine and large organic debris, for maintaining invertebrate communities, fish communities, near-shore vegetation, and bird communities and mammals (Lee et al., 2004). Lee et al. (2004) indicates that it also is important to understand that the diversity of biota in riparian areas as it reflects a spatially and temporally heterogeneous environment created by varied processes. These processes include fluvial disturbances (flooding, erosion, sedimentation, geomorphic channel processes), non-fluvial disturbances (fire, insects, wind), variable light environment, variable soils, variable topography, and other upland disturbances (Lee et al., 2004). A major objective is to translate the spatial extent of riparian processes and patterns into management practice, particularly buffer widths (Lee et al., 2004).

There have been several studies which have provided guidelines and recommendations for the widths of vegetated buffer zones and corridors for a variety of purposes. Young et al. (1980) indicates that a ≥25m wide buffer strip was effective in reducing 92 percent of the suspended sediment from feed-lot runoff. Moring (1982) determined that a ≥30m wide buffer was needed to ensure that increased sediment from intense logging along stream banks did not disrupt the development of salmon and alevin eggs in adjacent areas. Lynch et al. (1985) indicates that a ≥30m buffer between logging activity, wetlands, and streams removed an average of 75 to 80 percent of suspended sediment in storm-water, reduced nutrients to acceptable levels, and maintained water temperatures near their normal mean.

Dillaha et al. (1989) indicated that a ≥9m wide buffer strip was effective in removing 84 percent of suspended solids, 79 percent of phosphorus, and 73 percent of nitrogen from agricultural run-off. Madison et al. (1992) indicated that a ≥5m wide buffer strip removed 90 percent of nitrates and phosphates from tillage areas. Lowrance (1992) indicates that a ≥7m wide buffer strip was successful in reducing nitrate concentrations due to microbial denitrification and plant uptake. Ghaffarzadeh et al. (1992) indicated that a ≥9m wide buffer strip removed 85 percent of sediment on 7 and 12 percent slopes. Castelle et al. (1994) indicated that a buffer of ≥15m was found to be necessary to protect wetlands and streams under most conditions. Burke and Gibbons (1995) determined that a ≥275m upland buffer was necessary to protect 100 percent of the freshwater turtles inhabiting wetlands in their sites and a ≥73 m buffer would protect

95 percent of the populations. Woodard and Rock (1995) indicated that a ≥15m hardwood buffer was effective for reducing phosphorus concentrations adjacent to single family homes.

Semlitsch (1998) indicated that large terrestrial areas adjacent to wetlands are often used by adult-pond breeding salamanders and newly metamorphosed juveniles throughout the majority of the year. The author also indicated that exclusion of these terrestrial areas from protection would most likely reduce recruitment of juveniles into the breeding adult population, reduce adult survival, and reduce the potential for the population to exist. The paper further indicated that a ≥164m vegetated buffer was needed protect 95% of a salamander population, but this may underestimate the requirement needed to protect other taxa of salamanders or anurans. In addition, it is critical for land managers to realized that any application of the ≥164m buffer zone protects only that specific population as long as it remains viable; hence, a successful management plan must also protect additional terrestrial habitats for corridors of movement of salamanders from source ponds to new sites and for re-colonization or rescue of extinct populations at old sites (Semlitsch, 1998). In addition, because of the complexity of the variation of the terrestrial habitats used by salamanders and other amphibians and semi-aquatic species, (e.g., climate and habitat, particular ponds with different topographical, vegetation, and wetland sizes), buffer zones cannot be realistically and statically determined (Semlitsch, 1998).

Herrmann et al. (2005) indicated that forested habitat in vegetation buffers is critical to many pond-breeding amphibians because it creates diverse habitats, provides shade, moderates temperature, retains moisture and contributes to organic matter. Their recent study investigated the effects of landscape characteristics on amphibian distribution in a forest-dominated landscape. They determined that ponds surrounded by >60% forest within a 1000m radius may be necessary to support species rich amphibian assemblages, and those surrounded by <40% forest within a 1000m radius generally contained depauperate larval amphibian assemblages in southern New Hampshire. Mankin et al. (2007) indicated that a ≥8m grass-shrub buffer as effective for the removal of sediment, phosphorus, and nitrogen from simulated run-off from agricultural fields. Clearly, the size recommendations and effectiveness of buffer zones required to maintain the integrity of many flora and fauna populations and to preserve water quality within the literature are numerous. Buffer zones vary by wetland type, upland characteristics, geographic region, and resident species (Burke and Tibbons, 1995). For riparian zones and the protection of the water quality in streams, lakes, and wetland ecosystems, one size does not fit all.

Percent of impervious surfaces in watersheds

Urbanization of rural lands is an important problem in the world as urban areas exert an enormous amount of stress on natural resources and the environment (Amirsalari and Li, 2007). Watershed urbanization has been known to harm aquatic ecosystems (Booth et al., 2002). About 90% of the rain that falls on natural vegetated landscapes infiltrates the soil, while the remaining rainfall runs off into streams. In particular, where man-made surfaces have been created, less rain is able to infiltrate the soil and runoff increases (Reilly et al., 2004). By definition, urban pavements, such as rooftops, road, sidewalks, parking lots, driveways, and other manmade concrete surfaces are among impervious surface contributors (Zhou and Wang, 2007).

For many years, impervious surfaces have been recognized as an indicator of the intensity of the urban environment (Hart, 1976; Brabec et al., 2002), and the effects of watershed urbanization on streams are well-documented and they include extensive changes in basin hydrologic regime, channel morphology, and water quality (May et al., 1997). In addition, to best evaluate the environmental impact of impervious surface, it is important to know the current trends, and satellite remote sensing has been long proven to be one of the best tools to serve this purpose (Ridd, 1995; Amirsalari and Li, 2007). Impervious surfaces generate pollution and are major contributors to changes in watershed hydrology which may drive many of the physical changes affecting many streams (May et al., 1997).

With the advent of urban sprawl, impervious surfaces have become a key issue in growth management and watershed planning due to their impact on habitat health (Zhou and Wang, 2007). Impervious surface areas also can be used to explain and predict ecosystem health in relationship to watershed development (Zhou and Wang, 2007). Urbanization can increase impervious cover and the corresponding loss of natural vegetation through land clearing, soil compaction, riparian corridor encroachment, and modifications to the surface water drainage network (May et al., 1997). In addition, as cited in Brabec et al. (2002), Leopold (1968) and Carter (1961) indicate that increased amounts of impervious surfaces can decrease the amount of forested lands, wetlands, and other forms of open space that absorb and clean storm-water before it enters into the natural system. This change in balance can significantly degrade streams and watershed systems because of the additional quantity of sediment and pollutant load added (Morisawa and LaFlure, 1979; Arnold et al., 1982; Bannerman et al., 1993; Arnold and

Gibbons, 1996; Brabec et al., 2002). Researchers indicate that urban runoff is the leading source of pollution in estuaries, lakes, and rivers (Arnold and Gibbons, 1996; Booth and Jackson, 1997; Zhou and Wang, 2007). Nevertheless, many factors can contribute to the quality of a stream and how it is affected by impervious surfaces, and these include factors such as stream hydrology and other function including climate, geology, soils, land use, and vegetation (Morisawa and LaFlure, 1979).

According to Brabec et al. (2002), the most important numerical quantification of the impact of imperviousness on stream quality from a planning perspective is the threshold level at which water quality impacts occur. Watershed urbanization is most often quantified in terms of the proportion of basin area covered by impervious surfaces (Schueler, 1994; Arnold and Gibbons, 1996; May et al., 1997). In addition, the percent of a watershed that is covered by an impervious surface is a good indicator for the amount of land development and its effects of the hydrology in urban watershed (Schueler, 1994). As cited in Booth et al. (2002), Klein (1979) published the first study which reported a rapid decline in biotic diversity where watershed imperviousness exceeded 10 percent. Arnold and Gibbons (1996) defined an average range of imperviousness based on Schueler (1995), with a lower threshold at 10 percent at which watershed degradation first occurs, to 30 percent where degradation becomes extremely severe as to become almost unavoidable. As cited in Zhou and Wang (2007), Schueler (2003) predicts that most water-quality indicators for streams decline when the watershed impervious surface area exceeds 10 percent. Brabec et al. (2002) indicated a ranking of stream health can be roughly characterized as protected (less than 10% impervious surface), impacted (10%-30% impervious surface), and degraded (over 30% impervious surface). Booth et al. (2002) indicated that the most commonly chosen thresholds – a maximum of 10 percent of effective impervious area (EIA) and a minimum 65 percent of forest cover - mark an observed transition in downstream channels from minimally to severely degraded stream conditions. However, both Booth and Jackson (1997) and Booth et al. (2002) indicated that upland land use is critical in determining overall stream function, degradation, and rehabilitation potential. Even with the best efforts toward mitigation, downstream aquatic system damage is inevitable without limiting the extent of watershed development itself (Booth et al., 2002).

Forest habitat size (area) requirements for rare or imperiled terrestrial vertebrates

Many forested landscapes have been replaced by agriculture, suburban and urban development (Baldwin et al., 2004). Habitat destruction is the leading cause of species endangerment as it appropriates primary habitats, fragments the remaining portions, and leaves forest in pieces that are often too small to support viable populations (Harris and Pimm, 2008). Fragmentation of forests can affect the population of vertebrates by reducing the habitat abundance and increasing predation rates (Baldwin et al., 2004). In addition, global warming is threatening the survival of many species as they may not adapt or migrate to upland areas fast enough (Harris and Pimm, 2008).

Understanding the home range and habitat use pattern of certain threatened and endangered species are fundamental to guiding appropriate land management and conservation approaches (Innes et al., 2008). The effects of habitat fragmentation have been investigated among a variety of vertebrate taxa, including birds, mammals, and amphibians. According to Arbuthnot (2008), the threatened New England cottontail rabbit *(Sylvilagus transitionalis)*, prefers an early-successional forest habitat area of approximately 25 acres, and its mortality rate doubles on patches smaller than 6 acres compared to 12 acres. Arbuthnot (2008) also indicates that habitat patches in Massachusetts, Maine, New Hampshire, New York, and western Connecticut where New England cottontails have been observed are less than 7.5 acres in size and support no more than 3-4 cottontails; and these patches are too small and fragmented to support sustainable cottontail populations (Litvaitis et al., 2006). Milam and Melvin (2001) indicated that the Spotted Turtle (*Clemmys guttata*), requires a habitat home range area of 3.5 hectares, home range length of 313 meters, and a maximum travel distance of 265 meters. As cited in Innes et al. (2008), Grgurovic and Sievert (2005) determined that the threatened Blanding's Turtles (*Emydoidea blandingii)* in New England preferred home range size between .56-63.0 hectares. Thus, forest habitat requirements vary by species type (Baldwin et al., 2004). In addition, there are many factors that may contribute to variations in home range estimates for a variety of species. Mainly due to methodological differences in the specific studies, these factors include age, size, sex, population density, and year-to-year fluctuations in climatic conditions (Innes et al., 2008).

Dimensions for vegetated corridors to allow terrestrial vertebrate migration between protected areas

As cited in Burbrink et al. (1998), Beier and Lowe (1992) indicates that faunal dispersal corridor is a linear habitat that connects two or more large areas of habitat or core areas. Corridors usually connect habitat fragments that were contiguous before urban, industrial, or agricultural development (Burbrink et al., 1998). Mammals, birds, and plants use stream corridors as habitats connectors, travel corridors and refugia, but the relative importance of these corridor functions for most taxa is not known (Spackman and Hughes, 1995). Wildlife habitat and movement corridors in riparian zones are important for species conservation and depend on several factors, including the type of stream and the taxonomy of concern (Spackman and Hughes, 1995; Fischer and Fischenisch, 2000). Animals that use corridors to move between habitats can be considered either passage species (i.e., medium to large mammals and birds) or corridor dwellers (amphibians and reptiles) (Burbrink et al., 1998). The widths and lengths recommended for ecologic concerns are much larger than those recommended for water quality concerns (Fischer and Fishencisch, 2000). In addition, the width, length, type of habitat, human activities, and location affect its utility (Burbrink et al., 1998).

Fixed-width buffers are often based on a single parameter or function, and are easier to enforce and administer by regulatory agencies (Castelle et al., 1994; Fischer et al., 2000). However, these buffer types fail to provide for many ecological functions (Castelle et al., 1994; Fischer et al., 2000). On the other hand, variable width buffer strips are generally based on a variety of functions and usually account for site-specific conditions (i.e., vegetation, topography, and hydrology) and fish and wildlife considerations. These continuous buffers are more effective at moderating stream temperatures, reducing gaps in protection from non-point source pollution, and providing movement corridors for wildlife (Fischer and Fishencisch, 2000; Fischer et al., 2000).

There have been several studies which provide recommendations on dimensions for vegetated corridors to allow terrestrial vertebrate migration between protected areas. Spackman and Hughes (1995) determined that a ≥150m riparian buffer width was necessary to include 90 percent of the bird species along mid-order streams in Vermont. Mitchell (1996) indicated that greater than ≥100m buffer corridor provides sufficient breeding habitat for area-sensitive forest birds and nesting sites for red-shouldered hawks in New Hampshire. Vander Haegen and deGraaf (1996) recommend that ≥150m wide buffer strips were needed to reduce edge-related nest predation of birds, especially in landscapes where buffer strips are important components of the existing mature forest. Burbrink et al. (1998) recommend a vegetated corridor width to support reptiles and amphibians. As mentioned earlier, Semlitsch (1998) indicates that ≥164m wide buffer strip will maintain viable populations, communities, and migratory habits of ambystomatid salamanders. According to Fischer et al. (2000), at a minimum, buffer strips of ≥15m or wider should be promoted for providing a range of multiple objectives, including water quality, and widths of ≥100m are needed to ensure values related to wildlife habitat and use as migration corridors. A detailed listing of other previous research which established scientifically-derived buffers for a variety of species in a variety of habitats can be found in Appendix D.

Conclusion

Understanding land cover change and it associated effects on the environment as well as scientifically-based guidelines are critical for the conservation, preservation, and management of ecosystems. Accurate and frequently updated maps of environmentally sensitive areas are vital for their protection, but, obtaining ground information through traditional methods like surveys can be logistically difficult, costly, and spatially non-specific (Toyra et al., 2001). Therefore, satellite remote sensing has become an important tool as it can provide a lower cost alternative than traditional survey methods, as providing a spatial component not available otherwise by providing ground information in a temporal context (Toyra et al., 2001). In addition, coupled with remotely sensed data, Geographic Information Systems (GIS) technology can offer researchers the capability to store, search, analyze, manipulate, display, and distribute large amounts of descriptive geo-referenced and relational data using a wide array of selection criteria to model and further understand the environment (Congalton and Green, 1992).

Additional Materials and Methods

A detailed description of the study area, hardware and software used, satellite image data, reference data, pre and post image processing steps, image classification, accuracy assessment, and post-classification change detection methods is located within Chapter 6 in the Materials and Methods section. This section will present additional materials and methods in two sections 1) environmental reference data, and 2) environmental GIS analyses.

Environmental Reference Data

For many years, the Commonwealth of Massachusetts has been active in managing its environment. To further understand, protect, and promote its value to the general public, the Commonwealth has developed a variety of large scale geospatial data sets in many conservation and recreational regulatory management realms. However, a recent an extensive survey of numerous environmental regulatory agency websites within the Commonwealth revealed an absence of the use of remotely sensed data in their data development activity. One goal of this study is to promote an awareness, through the application of land cover change detection and the combined use of existing geospatial datasets with remotely sensed data, to further understand existing land development and its effects on designated environmentally sensitive areas, assist the Commonwealth and its residents in dissolving egocentric views of the environment, and facilitate the development proactive land management strategies and/or endeavors.

To evaluate the fragmentation, disruption, or encroachment of these designated areas of critical environmental concern, wildlife habitats, designated open and recreational spaces, and foster efforts toward their continued protection, data from the organizations which have developed, established, and are managing these "sensitive" areas were required. Therefore, after an extensive search, several datasets focusing on these areas were found and acquired from the holdings of the Commonwealth's Geographic and Environmental Information (MassGIS) repository. These data were acquired in ESRI ArcGIS shape-file format and used for comparison with the land development results generated from the post-classification analyses of the Landsat Thematic Mapper (TM) satellite data. The following Commonwealth of Massachusetts organizations and relevant data sets were used in this study:

Secretary of Environmental Affairs Department of Conservation and Recreation DATA - Areas of Critical Environmental Concern - 1:25,000 - Updated March 2007

Areas of critical environmental concern are places in Massachusetts that receive special recognition because of the quality, uniqueness and significance of their natural and cultural resources (Comm. of Mass, Dept. of Conservation and Recreation, 2008). These areas are identified and nominated at the community level and are reviewed and designated by the state's Secretary of Environmental Affairs. ACEC designation creates a framework for local and regional stewardship of these critical resource areas and ecosystems (Commonwealth of Massachusetts, Dept. of Conservation and Recreation, 2008).

Department of Fish and Game, Mass Wildlife, Natural Heritage & Endangered Species Program

DATA - Priority Habitats of Rare Species – 1:25,000 - Updated September 2008

Priority habitats represent the geographical extent of habitats for all state-listed rare species, both plants and animals, and are codified under the Massachusetts Endangered Species Act (MESA) (Mass Wildlife, 2008). Habitat alteration within priority habitats may result in a displacement of a state-listed species, and is subject to regulatory review by the Natural Heritage & Endangered Species Program (Mass Wildlife, 2008).

DATA - Living Waters Core Habitats and Critical Supporting Watersheds - 1:25,000 - Updated Nov. 2003

Living Waters Core Habitats represent lakes, ponds, rivers, and streams that are important for the promotion of freshwater biodiversity in Massachusetts (Mass Wildlife, 2008). The Critical Supporting Watersheds are the most immediate hydrologic contributors to Living Waters Core Habitats, and these watershed areas have the highest potential to sustain or degrade biodiversity (Mass Wildlife, 2008). However, these areas are often altered by land development and its impact is frequently overlooked.

DATA - Certified Vernal Pools - 1:25,000 - Updated Sept. 2008

Vernal pools are unique and vulnerable kinds of wetlands and are usually ephemeral pools that fill with snow-melt and spring-runoff, and are sometime dry during the summer (University of Maine, 2008). Vernal pools are a vital breeding habitat for certain amphibians and invertebrates (e.g., wood frogs, blue spotted salamanders, and fairy shrimp), and resting areas for a variety of other species (e.g., spring peepers, gray tree frogs, and birds) (University of Maine, 2008). These important wetlands are some of the most vulnerable because they are small, isolated, and often dry and therefore unrecognizable; which makes them easily destroyed (University of Maine, 2008). Land development in both counties will disrupt, fragment or encroach upon areas where vernal pools commonly exist, such as in forest, grasslands, and wetland areas. Removal or altering of vernal pools within a wetland mosaic would not only impact the habitat for local plants and animals, but, may promote the isolation of wildlife populations, and make these populations more vulnerable to changes in their surroundings (University of Maine, 2008). This data layer contains points for all vernal pools that have been certified by the Natural Heritage & Endangered Species Program (NHESP) according to the Guidelines for Certification of Vernal Pool Habitat (Mass Wildlife, 2008; MassGIS, 2008).

Massachusetts Department of Conservation and Recreation
DATA - Protected and Recreational Open Space - 1:25,000 - Updated Nov. 2008

Protected and recreational open space areas are conservation lands and outdoor recreation facilities in Massachusetts (Mass Wildlife, 2008). Not all of these land areas are protected the same way or in perpetuity. Open and recreational space areas such as farms, former farm areas, forests, and designated reservations, provide unique plants and animals, wildlife habitats and corridors, critical habitats (i.e., wetlands), natural watersheds, aesthetic and scenic value, and promote a variety of activities, from walking and hiking, to cross-country skiing, hunting, fishing, and nature study. In addition, open space bolsters property values, increases tourism, and reduces the need to spend on new and costly infrastructure projects (Schwartz, 2007). These lands also protect the health and safety of our communities by preserving natural environments and ecosystems, which in turn, improves water quality, reduces air, noise and sound pollution, and creates more livable communities (Schwartz, 2007). These areas are often disrupted and fragmented by encroaching land development at their boundaries, in order to promote their conservation within the counties, it is important to determine the areas where land development has had an impact.

Environmental GIS Analyses

To quantify the extent of land development within the delineated "environmentally-sensitive" areas within Essex and Middlesex counties from 1990 to 2007, results derived from the post-classification change detection of Landsat Thematic Mapper (TM) satellite data method were imported into the GIS for comparison. First, the results from the post-classification technique and the newly developed areas within the satellite imagery (which occurred from 1990 to 2007), were imported into the GIS GRID format and then converted into an ESRI shape-file. The "from-to" land cover change classes derived from the post-classification change matrix image (from forest to developed, etc), within the shape-file were then merged to form a separate and new class ("newly-developed-land") and shape-file, and were now ready for comparison to the point and area delineations contained within data sets from the Commonwealth of Massachusetts. All pixel areas within these shape-files were converted into polygons within the GIS and acreages were calculated and compared to existing acreages of each land cover class within the 1990 and 2007 image classifications to ensure that data remained intact during the conversion process.

The Commonwealth of Massachusetts data of: Areas of Critical Environmental Concern (ACEC), Priority Habitats of Rare Species (PHRS), Living Waters Core Habitats and Critical Supporting Watersheds (LWCSW), Protected and Recreational Open Space Lands (PROSL), and Certified Vernal Pool Areas (CVPA), were imported into the GIS and used individually to determine the extent of land development within the delineated areas and derived from the post-classification method. First, each coverage area supplied by the Commonwealth was subset to the legal delineation of both the Essex and Middlesex county boundary. Second, to determine the extent of land development that occurred within the polygon regions comprising the ACEC, PHRS, and PROSL, the shape-file containing areas of new land development also was subset to the boundaries of the Commonwealth's individual environmental data coverages. Acreages were then calculated for each subset of the delineated areas and the land development within these areas (e.g., ACEC, PHRS, and PROSL), to determine the extent.

For the Certified Vernal Pool Areas (CVPA) point dataset, several buffer and proximity analyses were conducted. First, CVPA were queried through a locational analysis using the new land development shape-file to determine if any land development intersected any CVPA. Statistical buffer zones were then generated 25 and 50 foot range intervals from 0 to 1000 feet from newly developed land areas to determine the number of CVPA impacted. In addition, a structured query language (SQL) GIS selection was then used to compare the counties, and illustrate communities where new land development had occurred from 1990 to 2007 within the ACEC, PHRS, and PROSL datasets, and where land development occurred within 50 feet of CVPA locations. Rare or imperiled wildlife species data (as obtained from Mass Wildlife) which may inhabit areas delineated by the Commonwealth were added to the GIS data and presented (as stated in objective four). In addition, the matrix change image classification was further explored to investigate other more specific land cover class changes resulting in early-successional areas (e.g., from grasslands and to forests), or to illustrate fragmented forest areas, (e.g., from forest to development), and identify specific wildlife species likely affected.

Results

The results from the comparison analyses of the post-classification change detection method results and the Commonwealth of Massachusetts environmental GIS data will be presented in six sections 1) post-classification change detection, 2) areas of critical environmental concern, 3) priority habitats of rare species, 4) living waters core habitats and critical supporting watersheds, 5) protected and recreational open space lands, and 6) certified vernal pool areas.

Post-Classification Change Detection

The results from the post-classification technique indicate the land cover change occurred within Essex and Middlesex Counties from 1990 to 2007. In addition, a further investigation of the matrix image classification categories generated by the post-classification indicated that "new" land development occurred during this period. Specific results derived from the post-classification change detection method applied to the Landsat Thematic Mapper (TM) imagery are presented in Chapter 7 Results in the Change Detection, Post Classification section.

Areas of Critical Environmental Concern

As derived from the Commonwealth's 1:25,000 scale GIS data, Essex and Middlesex County have approximately 80,800 acres designated as areas of critical environmental concern. Of those areas, the GIS analyses results indicate that approximately 722.15 acres within these regions have changed or have been lost to new land development. Figure 28 illustrates the areas where new land development occurred within these areas (red pixel regions), and the total acreage of land cover change to development within each county. As can be seen from Figure 28 new land development acreage within areas of critical environmental concern is higher within Essex County as compared to Middlesex. As Essex County's new land development acreage within these areas is approximately 560.25 acres and Middlesex County's is approximately 161.90 acres. Figure 29 is a large scale subset (1:55,000) of Figure 28 and it provides an example of land development which occurred within the Petapawag area within the designated ACEC. As can be seen from Figure 29, in Groton (Middlesex County), approximately 100 acres of previously forested areas were converted for the development of parking areas (with paved asphalt surfaces), buildings associated with two major supermarket and drugstore chains (lower left and lower right), and for a multi-community regional high-school (upper right). Table 11 illustrates the "from-to" development land cover changes (in acres) within the ACEC which resulted from the post-classification method. Of the sixteen communities where the Commonwealth's designated areas of critical environmental concern exist, fourteen (displayed in orange polygons within Figure 28), exhibited new land development from 1990 to 2007.

Figure 28. New developed land in Areas of Critical Environmental Concern.

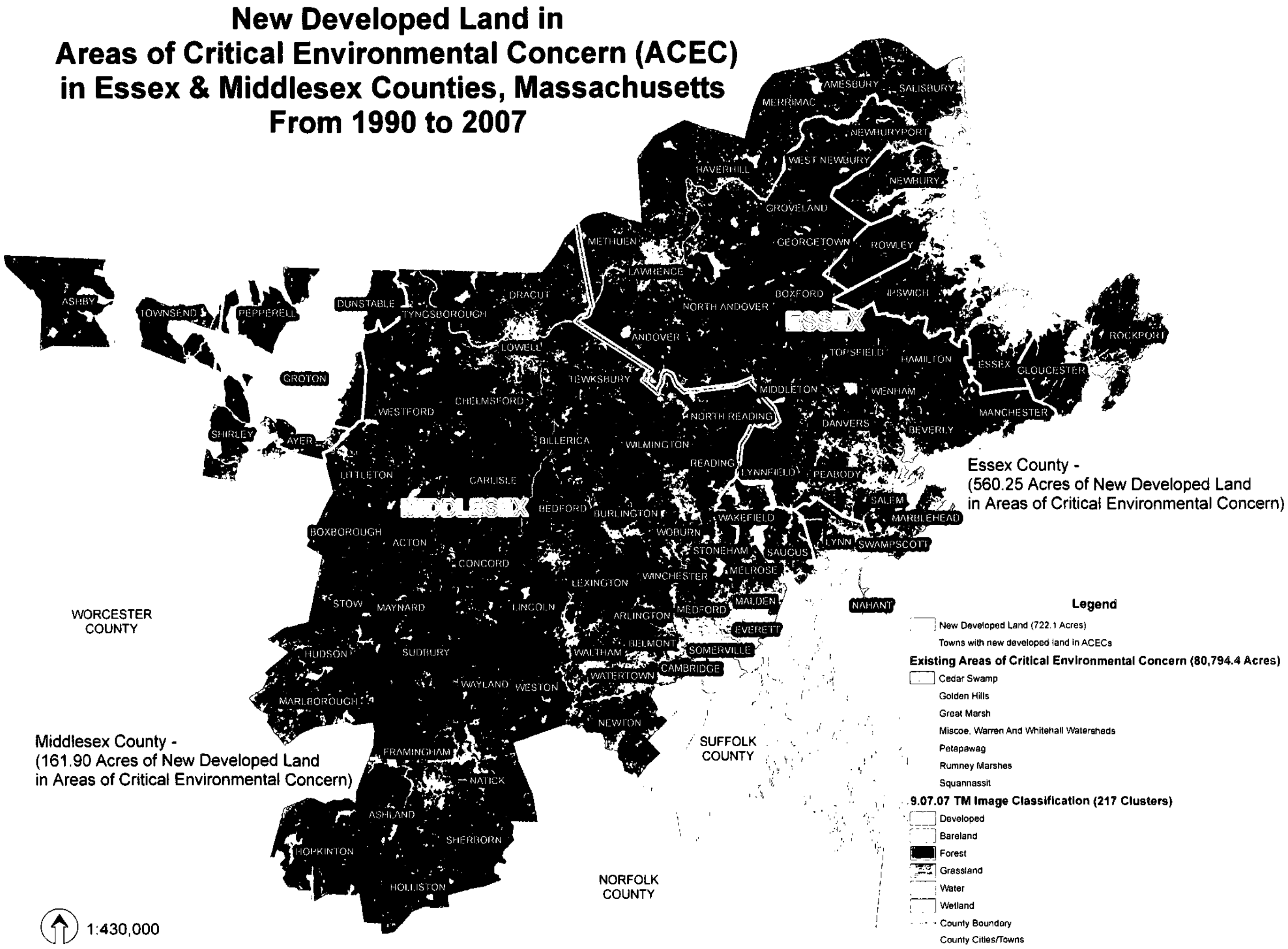


Figure 29. New developed land in Areas of Critical Environmental Concern (ACEC) (Subset).

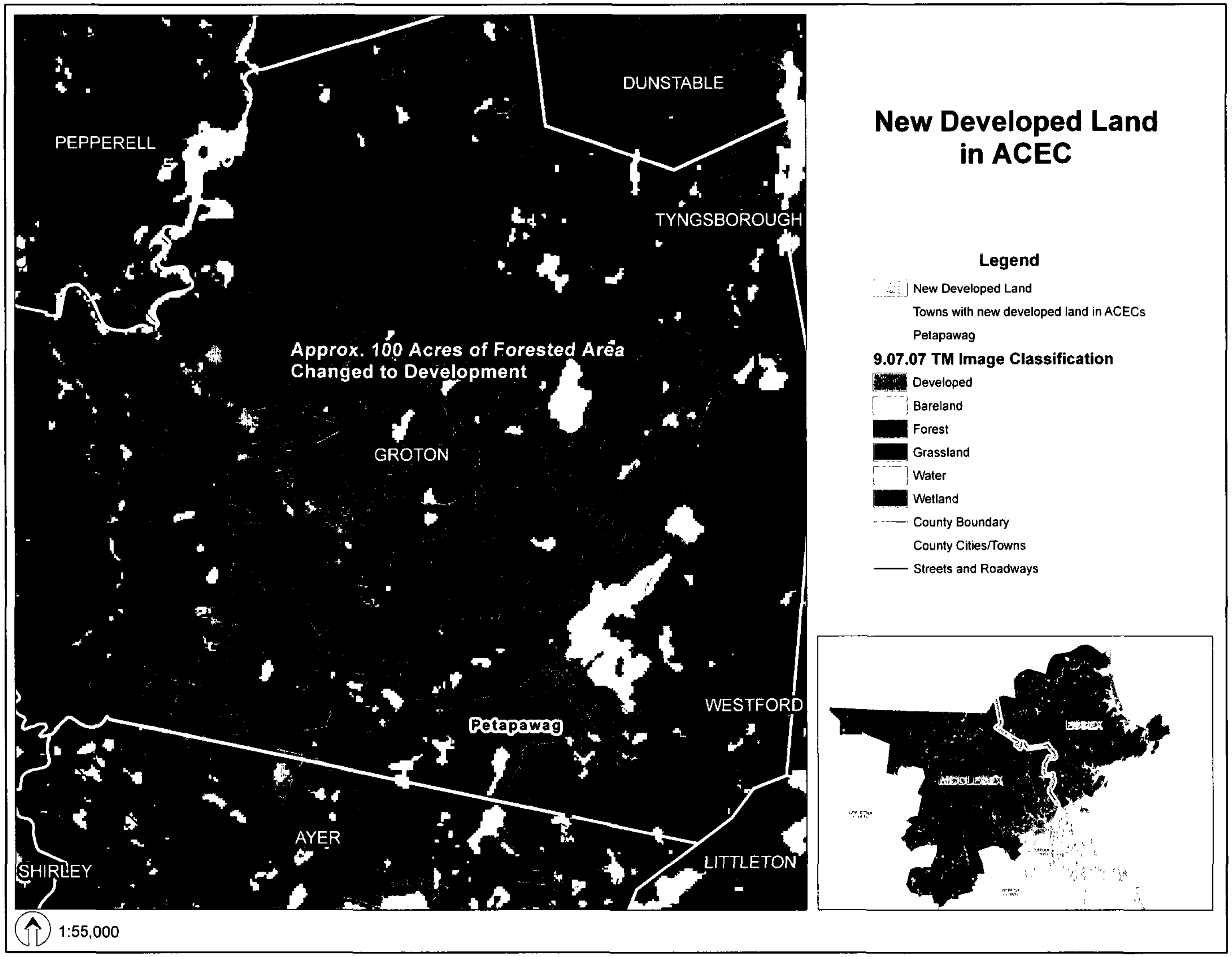


Table 11. From land cover class to developed in Areas of Critical Environmental Concern (ACEC).

Land Cover Class Change (From-To)	**Land Cover Change (Acres)**
From Bareland to Developed	190.87
From Forest to Developed	191.67
From Grassland to Developed	292.83
From Water to Developed	29.50
From Wetland to Developed	17.26
Total	**722.15 Acres**

Priority Habitat of Rare Species

Essex and Middlesex County have approximately 142,417 acres designated as priority habitat of rare species (as derived from the Commonwealth's 1:25,000 scale GIS data). Of those areas, the GIS analyses results indicate that approximately 669.56 acres within these regions have changed or have been lost to new land development. Figure 30 illustrates the areas where new land development occurred within these areas (red pixel regions), and the total acreage of change to development within each county.

As can be seen from Figure 30 new land development acreage within priority habitat of rare species is higher within Essex County as compared to Middlesex. As Essex County's new land development acreage within these areas is approximately 407.43 acres and Middlesex County's is approximately 262.13 acres. Figure 31 is a large scale subset (1:42,000) of Figure 30 and it provides an example of land development which occurred within the PHRS within the Town of Dracut (Middlesex County). As can be seen from Figure 31, in Dracut (Middlesex County), approximately 40 acres of previously forested areas were developed to expand the area of two existing gravel or stone yards. Table 12 illustrates the "from-to" development land cover changes (in acres) which resulted from the post-classification method. Of the eighty-eight communities

Figure 30. New developed land in Priority Habitats of Rare Species.

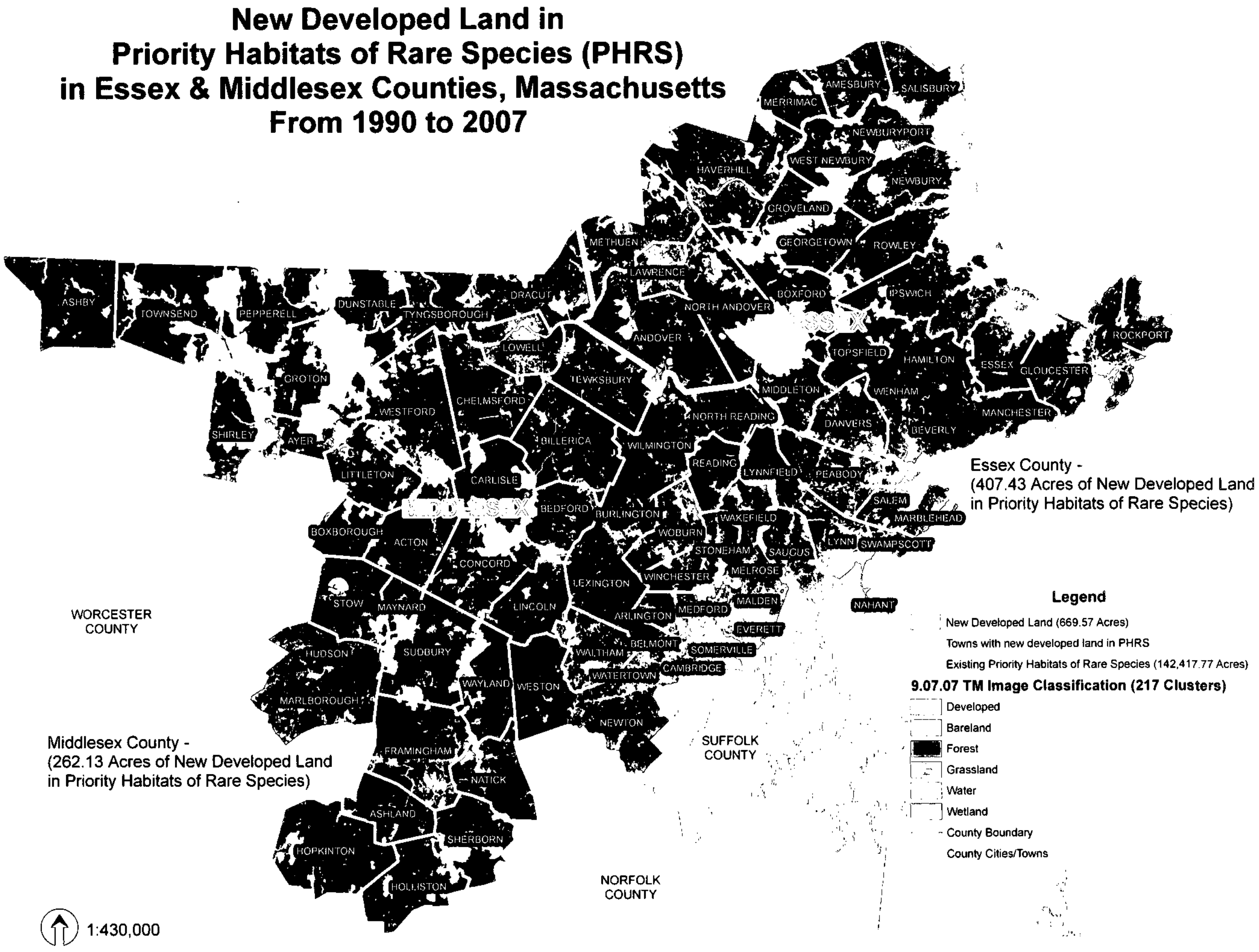
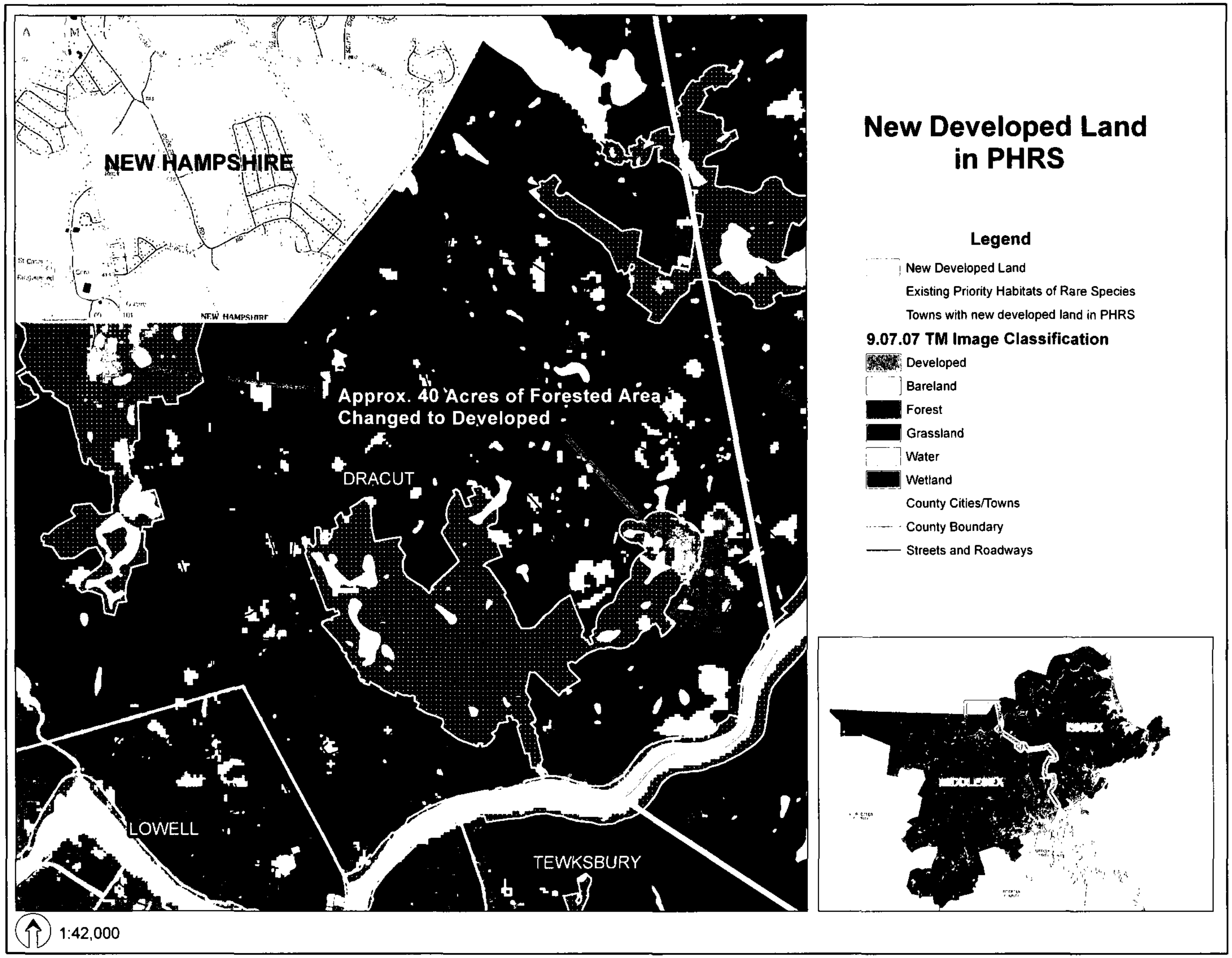


Figure 31. New developed land in Priority Habitats of Rare Species (Subset).



where the Commonwealth's designated areas of priority habitat of rare species exist, seventy-four (displayed in orange polygons), exhibited new land development from 1990 to 2007.

Table 12. From land cover class to developed in Priority Habitats of Rare Species (PHRS).

Land Cover Class Change (From-To)	Land Cover Change (Acres)
From Bareland to Developed	192.48
From Forest to Developed	188.66
From Grassland to Developed	212.35
From Water to Developed	60.41
From Wetland to Developed	15.65
Total	**669.56 Acres**

Living Waters Core Habitats and Critical Supporting Watersheds

Essex and Middlesex County have approximately 112,757 acres designated as living waters core habitats and critical supporting watersheds (as derived from the Commonwealth's 1:25,000 scale GIS data). Of those areas, the GIS analyses results indicate that approximately 1,091.65 acres within these regions have changed or have been lost to new land development. Figure 32 illustrates the areas where new land development occurred within these areas (red pixel regions), and the total acreage of change to development within each county.

As can be seen from Figure 32 new land development acreage within priority habitat of rare species is higher within Essex County as compared to Middlesex. As Essex County's new land development acreage within these areas is approximately 736.6 acres and Middlesex County's is approximately 355.05 acres. As Essex County's new land development acreage within these areas is approximately 407.43 acres and Middlesex County's is approximately 262.13 acres. Figure 33 is a large scale subset

Figure 32. New developed land in Living Waters Core Habitats and Critical Supporting Watersheds.

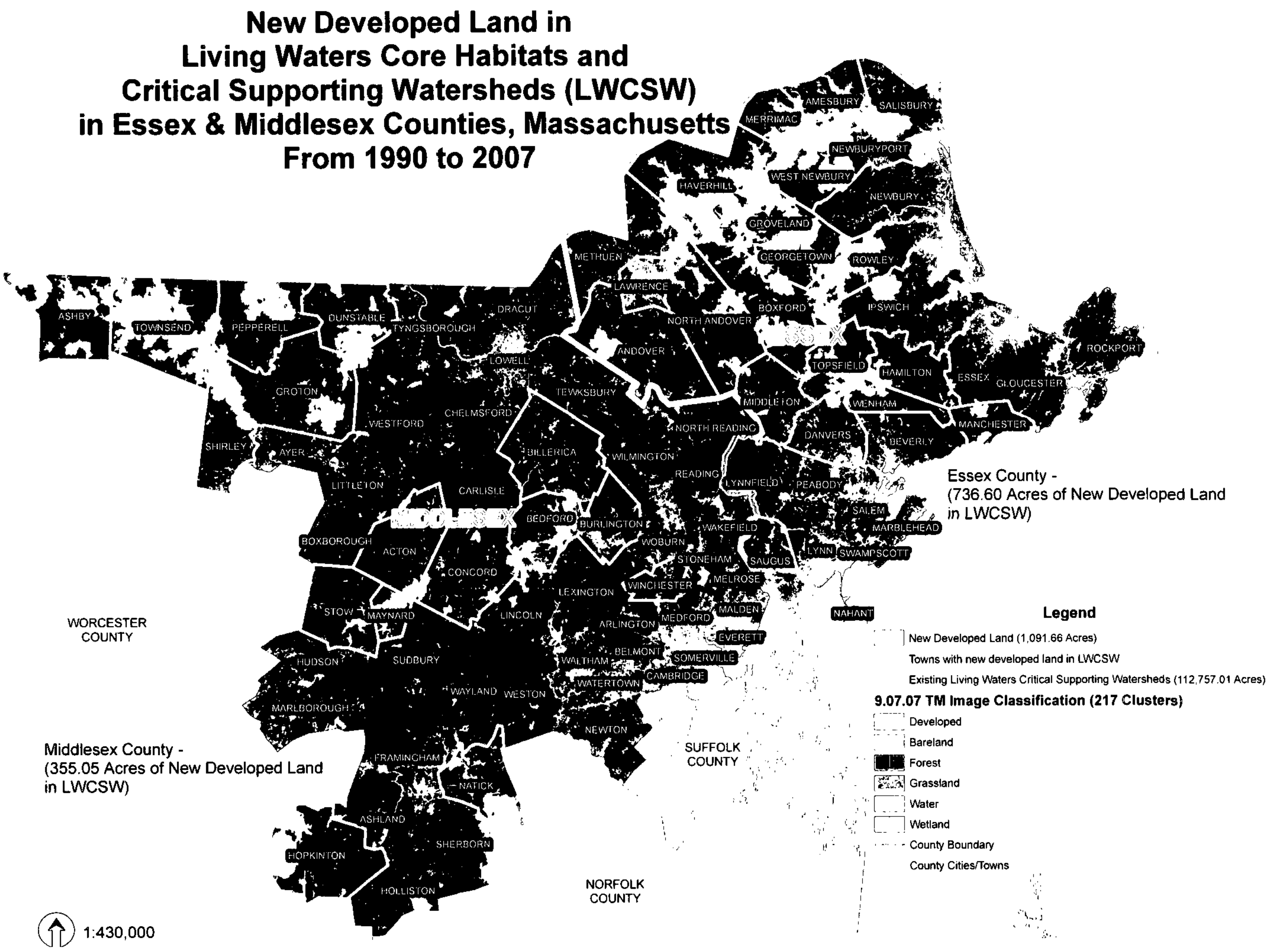
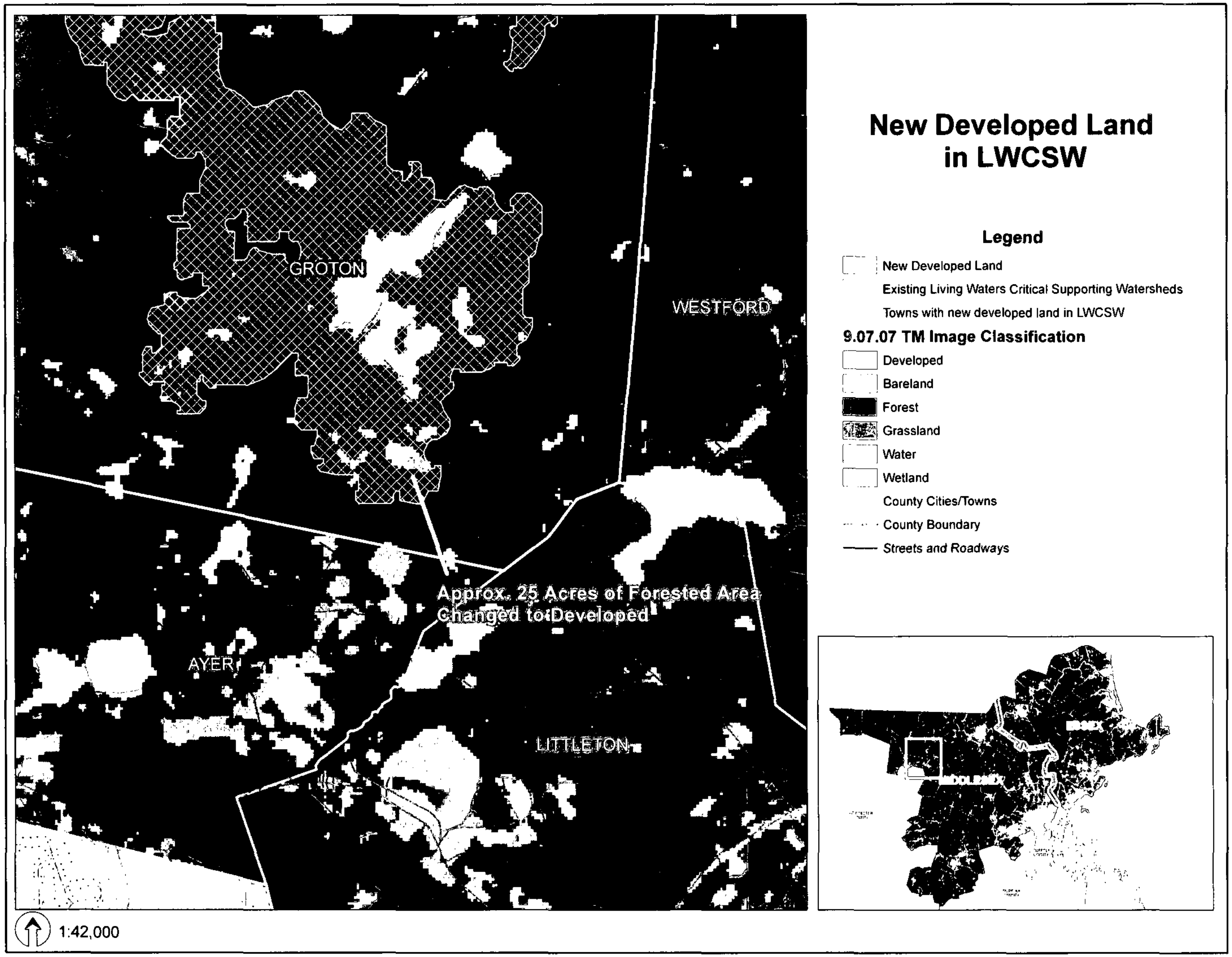


Figure 33. New developed land in Living Waters Core Habitats and Critical Supporting Watersheds (LWCSW) (Subset).



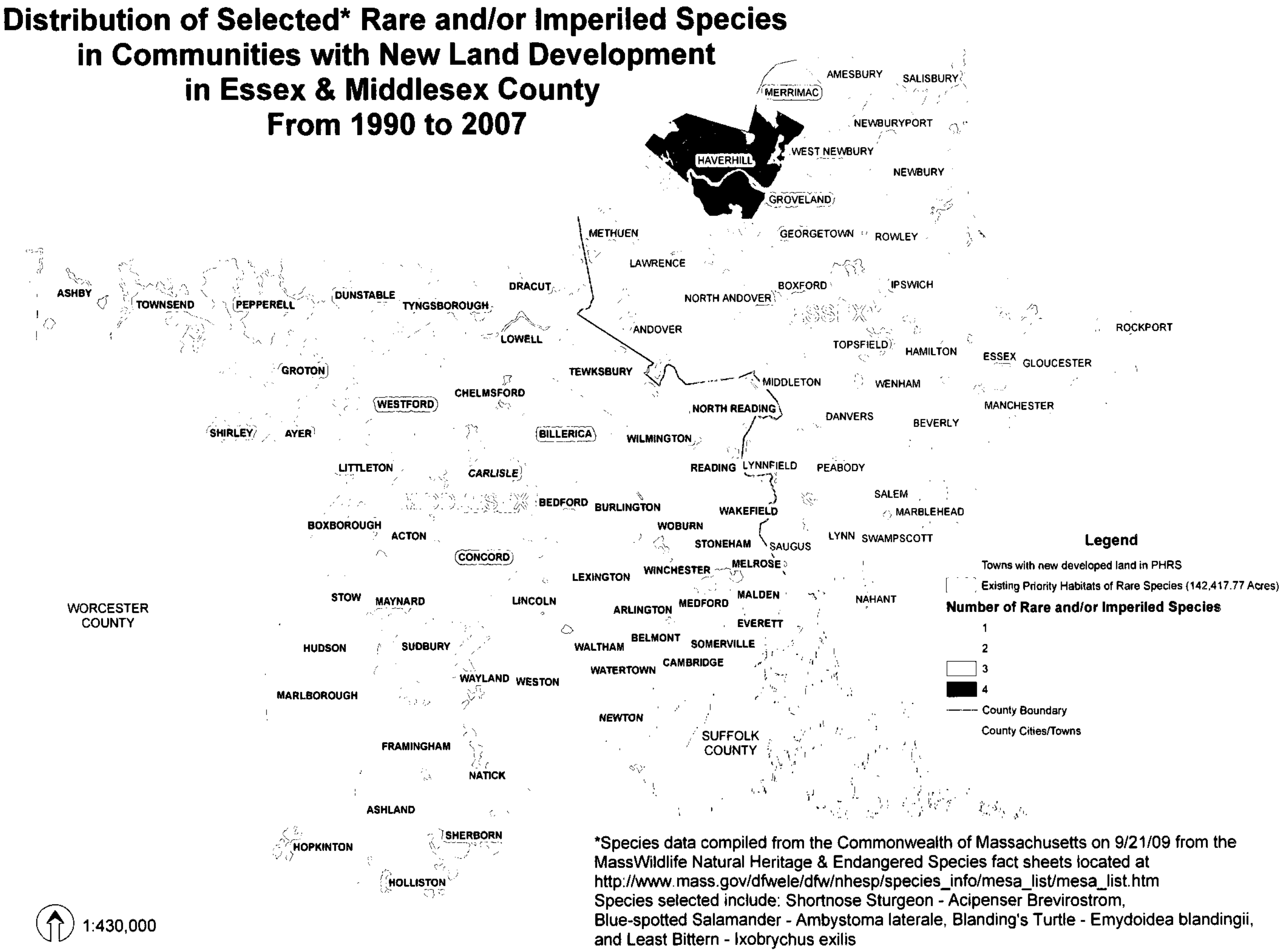
1:42,000) of Figure 32 and it provides an example of land development which occurred within a portion of LWCSW within the Town of Groton (Middlesex County). As can be seen from Figure 33, approximately 25 acres of forest was removed for the development of buildings associated with two major supermarket and drugstore chains. Table 13 illustrates the "from-to" development land cover changes (in acres) which resulted from the post-classification method. Of the thirty-seven communities where the Commonwealth's designated areas of living waters core habitats and critical supporting watersheds exist, all thirty-seven (displayed in orange polygons within Figure 32), exhibited new land development from 1990 to 2007.

Table 13. From land cover class to developed in Living Waters Core Habitats and Critical Supporting Watersheds (LWCSW).

Land Cover Class Change (From-To)	**Land Cover Change (Acres)**
From Bareland to Developed	130.06
From Forest to Developed	554.36
From Grassland to Developed	362.88
From Water to Developed	42.95
From Wetland to Developed	1.40
Total	**1,091.65 Acres**

Figure 34 displays the seventy-four communities where new land development occurred within the priority habitats of rare species and exhibits the distribution (as published by Mass Wildlife Natural Heritage and Endangered Species Program and in the Code of Massachusetts Regulations, August 2008), of selected rare and/or imperiled species which may have been affected (e.g., Shortnose Sturgeon (*Acipenser Brevirostrom)*, Blue-Spotted Salamander (*Ambystoma laterale)*, Blanding's Turtle (*Emydoidea Blandingii)*, Least Bittern (*Ixobrychus exilis*).

Figure 34. Distribution of selected* rare and/or imperiled species within communities exhibiting new land development from 1990 too 2007.



*Species data compiled from the Commonwealth of Massachusetts on 9/21/09 from the MassWildlife Natural Heritage & Endangered Species fact sheets located at http://www.mass.gov/dfwele/dfw/nhesp/species_info/mesa_list/mesa_list.htm
Species selected include: Shortnose Sturgeon - Acipenser Brevirostrom, Blue-spotted Salamander - Ambystoma laterale, Blanding's Turtle - Emydoidea blandingii, and Least Bittern - Ixobrychus exilis

In addition, other rare and/or imperiled other species which are not depicted within the map (e.g., American Bittern (*Botaurus lentiginosus*), Common Tern (*Sterna hirundo*), Grasshopper Sparrow (*Ammodramus savannarum*), Vesper Sparrow (*Pooecetes gramineus*), Peregrine Falcon (*Falco pergrinus*), Marblehead Salamander (*Ambystoma opacum*) Eastern Pondmussel (*Ligumia nasuta*), Wood Turtle (*Glyptemys insculpta*), Bridle Shiner (*Notropis bifrenatus*)), also may have been affected by land development and associated anthropogenic disturbances not only within the delineated regions of priority habitats of rare species but also within the living waters core habitats and critical supporting watershed areas.

Protected and Recreational Open Space Lands

Essex and Middlesex County have approximately 200,065 acres designated as protected and recreational open space lands (as derived from the Commonwealth's 1:25,000 scale GIS data). Of those areas, the GIS analyses results indicate that approximately 1,318.26 acres within these regions have changed or have been lost to new land development. Figure 35 illustrates the areas where new land development occurred within these areas (red pixel regions), and the total acreage of change to development within each county.

As can be seen from Figure 35 new land development acreage within protected and recreational open space lands is higher within Middlesex County as compared to Essex. As Middlesex County's new land development acreage within these areas is approximately 710.31 acres and Essex County's is approximately 607.95 acres. Figure 36 is a large scale subset (1:42,000) of Figure 35 and it provides an example of land development which occurred within a portion of PROSL within the Town of Ashland

Figure 35. New developed land in Protected and Recreational Open Space Land.

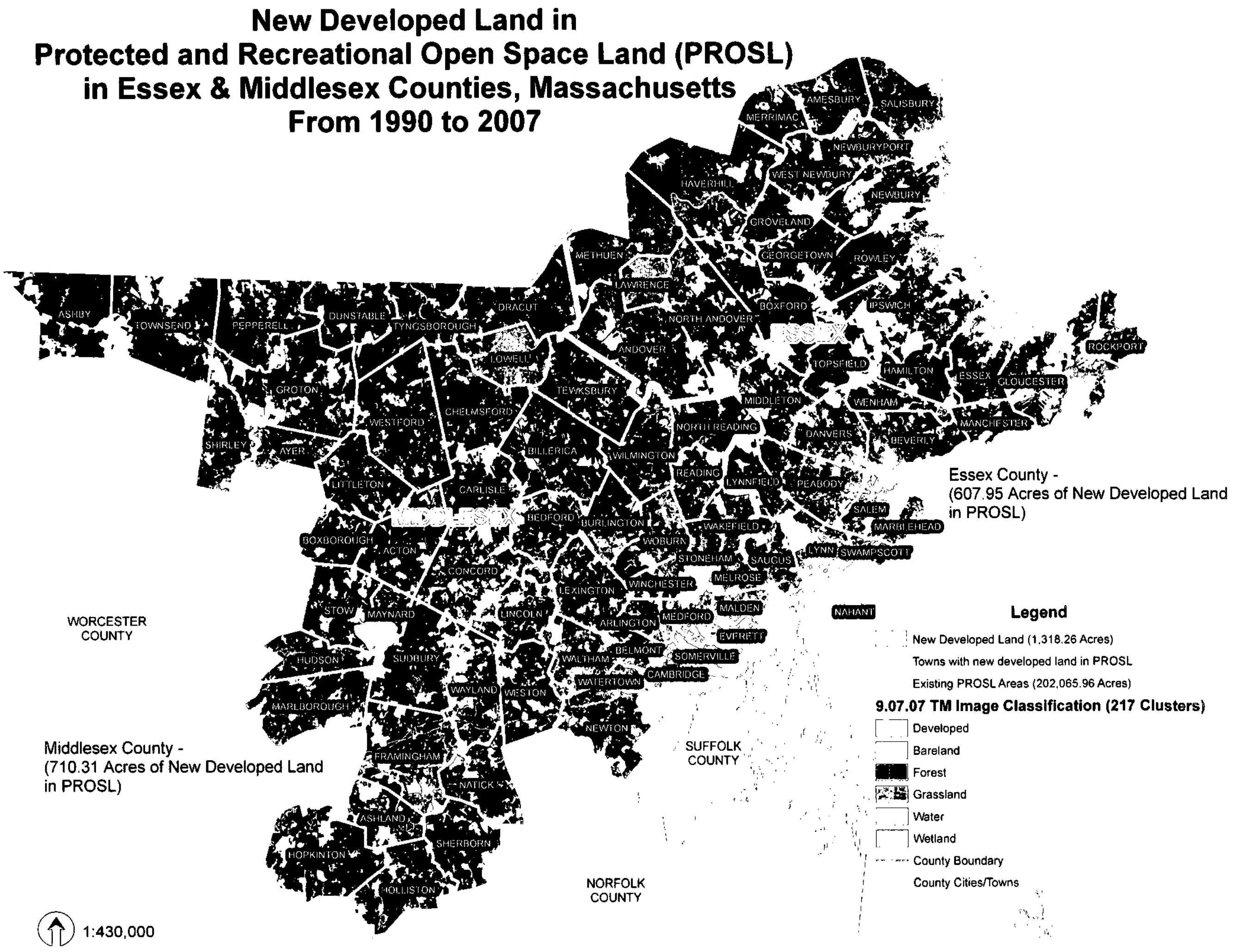
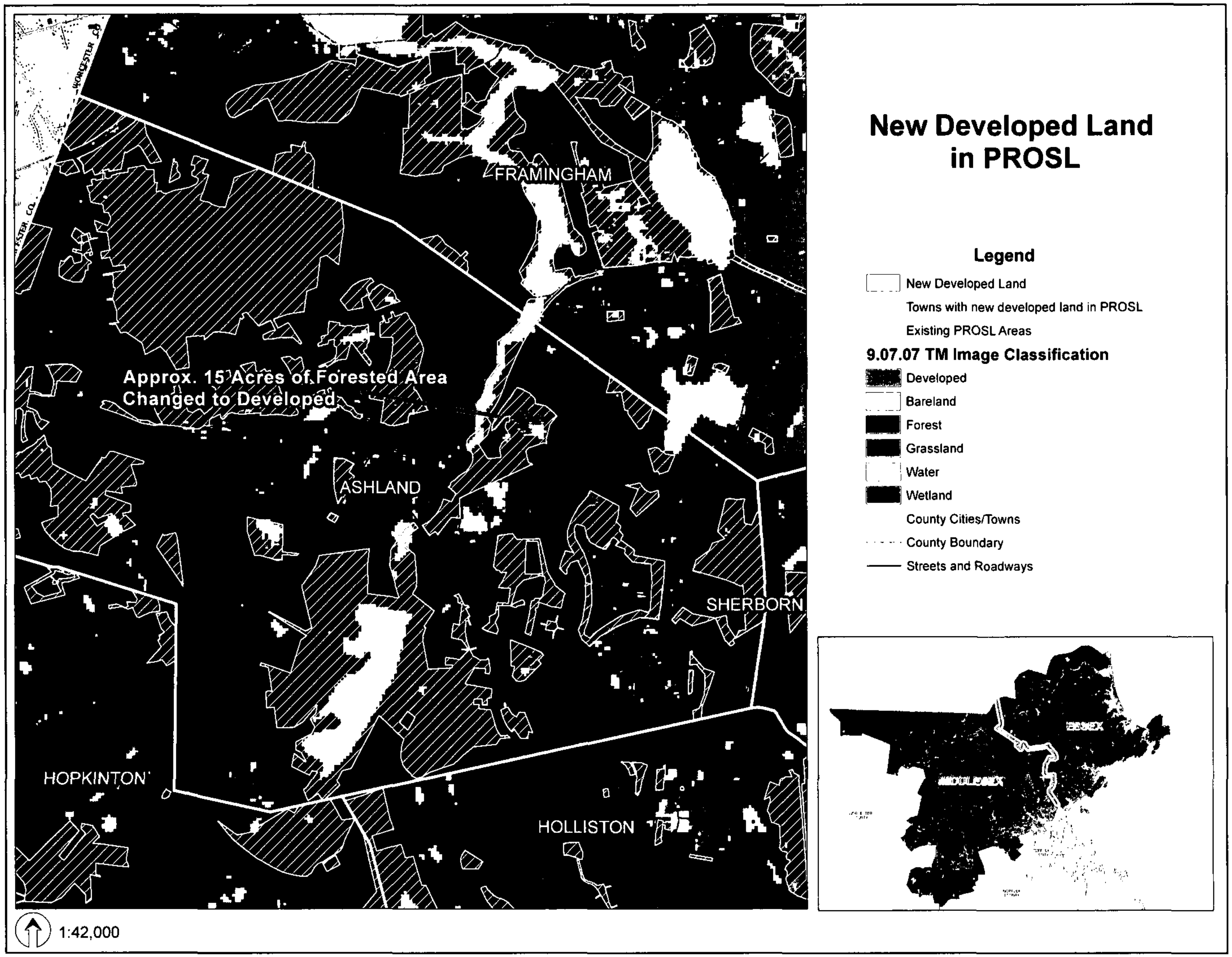


Figure 36. New developed land in Priority Habitats of Rare Species (PROSL) (Subset).



(Middlesex County). As can be seen from Figure 36, approximately 15 acres of forest was removed for the development of a school. Table 14 illustrates the "from-to" development land cover changes (in acres) which resulted from the post-classification method. Of the eighty-eight communities where Commonwealth's designated areas of protected and recreational open space lands exist, all eighty-eight (displayed in orange polygons within Figure 35), exhibited new land development from 1990 to 2007.

Table 14. From land cover class to developed in Protected and Recreational Open Space Land (PROSL).

Land Cover Class Change (From-To)	Land Cover Change (Acres)
From Bareland to Developed	292.83
From Forest to Developed	575.23
From Grassland to Developed	397.00
From Water to Developed	42.75
From Wetland to Developed	10.43
Total	**1,318.26 Acres**

Certified Vernal Pool Areas

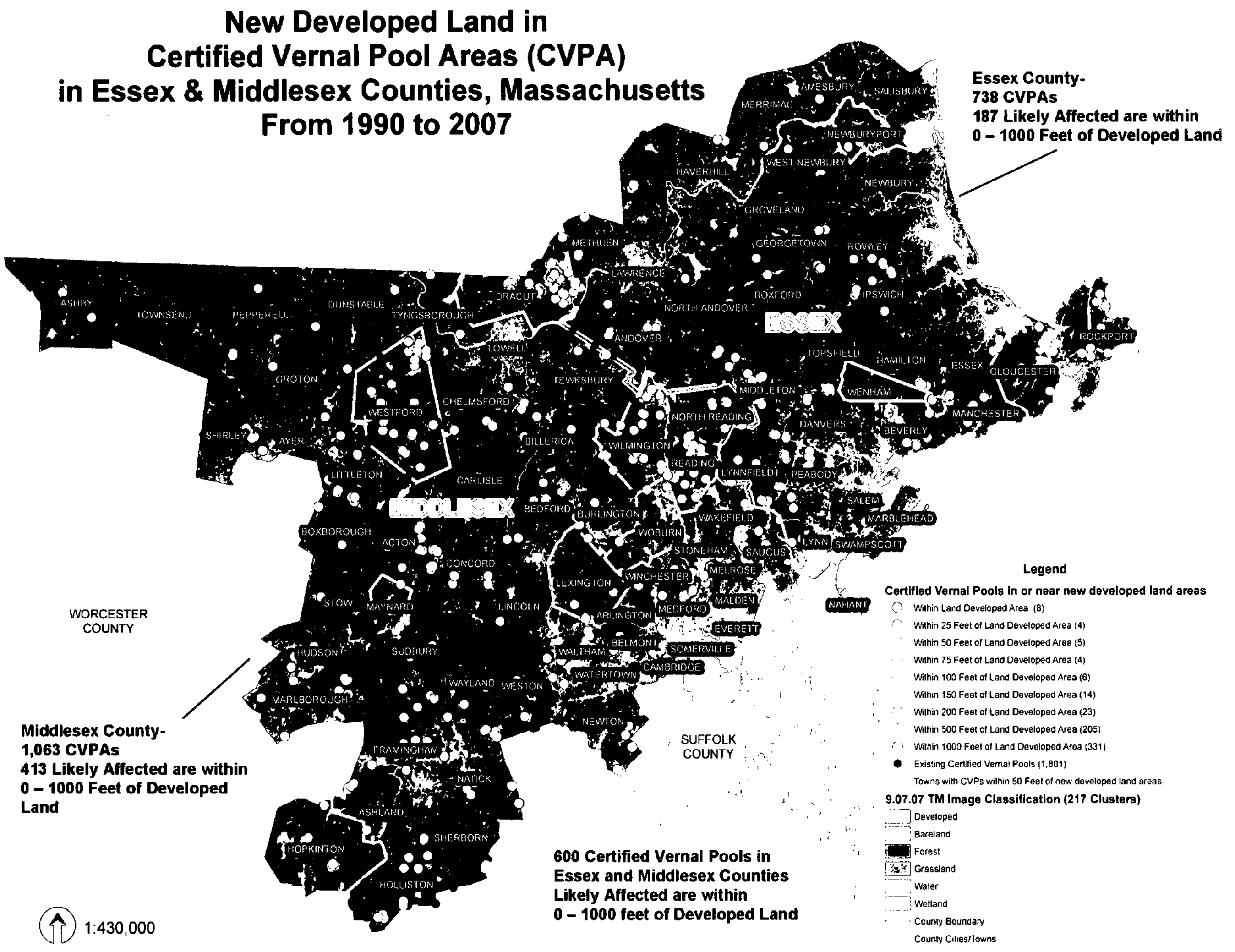
Essex and Middlesex County have approximately 1,801 designated and certified vernal pool areas (CVPA) (as derived from the Commonwealth's 1:25,000 scale GIS data). Of those areas, the GIS analyses results indicate that 600 CVPAs are likely to be affected by new land development which has occurred with 0 to 1000 feet of their location. Figure 37 illustrates the areas where new land development has occurred within the CVPAs (red pixel regions), and the number of CVPAs likely effected within each county.

As can be seen from Figure 37, Middlesex County has 413 CVPAs likely affected by new land development while Essex County has 187. Figure 38 is a large scale subset (1:42,000) of Figure 37 and it provides an example of a cluster of CVPAs within 1,000 feet of new land development (assorted manufacturing facilities) within the Town of Dracut (Middlesex County). Of the eighty-eight communities where Commonwealth's designated areas of CVPAs exist, thirteen (displayed in orange polygons within Figure 37), exhibited new land development within 50 feet of these areas from 1990 to 2007, and five communities had eight CVPAs within 0-5 feet of newly developed land.

Discussion and Conclusions

This study provided the methodology to compare results from a change detection technique using Geographic Information Systems (GIS) technology and ancillary environmental data sources to investigate the effects of land development within environmentally sensitive areas. Specifically, this study applied the use of remotely sensed data, Landsat Thematic Mapper (TM) imagery, and the post-classification change detection methodology to detect, quantify, and document the nature and extent of land development and its effects using environmental data sources from the Commonwealth of Massachusetts within Essex and Middlesex Counties from 1990 to 2007. Like the previous paper in Chapter VIII, assessing land cover change through the use of remotely sensed data can often be challenging and the results uncertain, and extensive processing of satellite imagery is required in order to produce accurate change detection results. This study has shown that the integrated use of satellite remote sensing and geographic information systems (GIS) technology is suitable for the detection and quantification of the nature and extent of land development from 1990 to 2007.

Figure 37. New developed land in or near Certified Vernal Pool Areas.



Legend

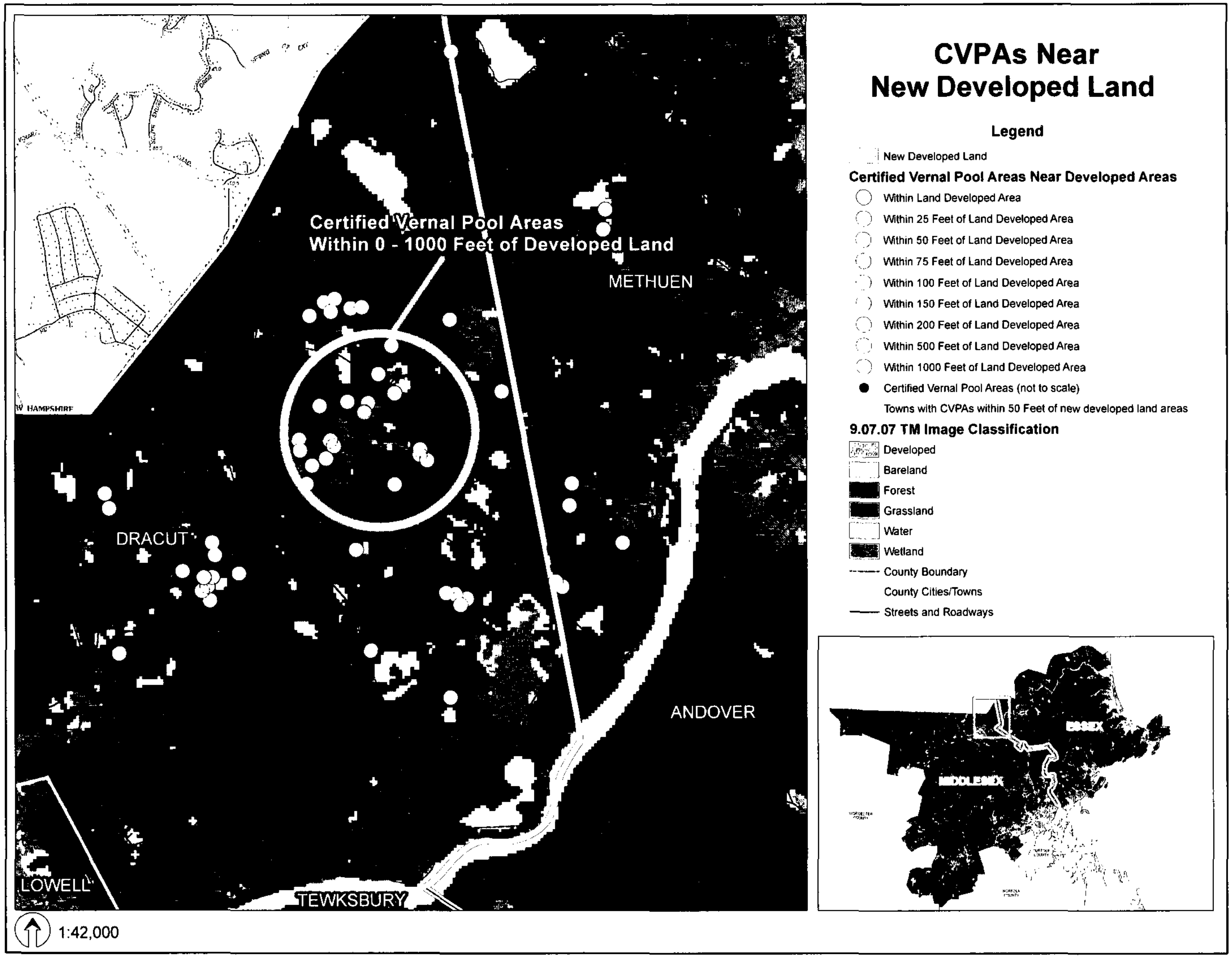
Certified Vernal Pools in or near new developed land areas

- ○ Within Land Developed Area (8)
- Within 25 Feet of Land Developed Area (4)
- Within 50 Feet of Land Developed Area (5)
- Within 75 Feet of Land Developed Area (4)
- Within 100 Feet of Land Developed Area (6)
- Within 150 Feet of Land Developed Area (14)
- Within 200 Feet of Land Developed Area (23)
- Within 500 Feet of Land Developed Area (205)
- Within 1000 Feet of Land Developed Area (331)
- ● Existing Certified Vernal Pools (1,801)
- Towns with CVPs within 50 Feet of new developed land areas

9.07.07 TM Image Classification (217 Clusters)

- ☐ Developed
- ☐ Bareland
- ■ Forest
- ▨ Grassland
- ☐ Water
- ☐ Wetland
- County Boundary
- County Cities/Towns

Figure 38. CVPAs near new developed land (Subset).



An assessment of the results indicate that new land development occurred from 1990 to 2007 within Essex and Middlesex County within and adjacent to the Commonwealth of Massachusetts' delineated Areas of Critical Environmental Concern, Priority Habitats of Rare Species, Living Waters Core Habitats and Critical Supporting Watersheds, Protected and Recreational Open Space Lands, and Certified Vernal Pool Areas. Figure 39 illustrates two examples of the type of "land-eating" development which occurred within these areas. These "land-eaters" range in size and consist of residential and commercial structures in the form of campus-style businesses, warehouses, box-stores, subdivisions, apartments and condominium complexes. In addition, the results also indicated that Essex, rather than Middlesex County, had greater land development within the delineated areas of environmental concern. However, Middlesex County exhibited more land development in the protected and recreational open space areas.

Through several comparisons, numerous GIS datasets were generated and will undoubtedly serve to provide a basis for future research to be conducted within these areas. These data were not only valuable for the development of detailed maps depicting the location of the Commonwealth's designated areas of specific environmental concern within the counties but the locations of communities where land development within each of these specific areas occurred. Moreover, the GIS data from this study identified where habitat areas with specific rare of imperiled wildlife species may have been affected and provided a base or impetus for future monitoring of land development, land cover change, wildlife persistence, habitat encroachment, fragmentation, disruption, and destruction in Massachusetts, and literature resources to assist in providing an awareness to and future development of conservation, stewardship, and management policies and practices of the flora and fauna and natural resources within these counties.

Figure 39. Examples of "land-eating" development.

Land Cover Type Change

The results derived from the post-classification technique indicated that land development was not solely responsible for the land cover change occurring within Essex and Middlesex Counties from 1990 to 2007. Several land cover class changes occurred and these changes affected many areas of critical environmental concern which include the habitats of many rare or imperiled plants and animal species. Land development cannot not only alter the physical structure and characteristics of these areas (e.g., through the removal of vegetation, soils, and resident species, the disruption of food and water supplies, and restrict movement), but, anthropogenic processes within or adjacent to these areas (e.g., building construction, land clearing, eutrophication from fertilization and/or nutrient loading, point or non-pollution from impervious surfaces run-off including but not limited to sediment, water temperature, bacteria, detergents and petroleum products), also can have harmful and dramatic effects.

In addition to land development occurring within these areas (e.g., ACEC, PHRS, LWCSW, PROSL, CVPAs), land cover type changes (other than development) also can have a dramatic effect on the wildlife habitat environments as well. Land cover type change can contribute to a reduction of habitat size, fragmentation, and decreased suitability, corridor passage disruptions, and influence breeding habits, predation, and population levels of resident species. In turn, land development and other land cover changes can produce the combined dramatic effect of a "one-two" punch that can adversely alter the environment which can ultimately affect the persistence or success rate of a wide variety of plant and animal species.

One of the powerful capabilities of the post-classification method is that it can provide the means to selectively quantify the nature and extent of change of specific land cover class types (depending on the image classification scheme) within a given area and within a specific temporal period of interest. For this study, this method was used to compare land development through the loss of other land cover classes within the image classification scheme of the 1990 and 2007 scenes. But, the post-classification change detection method generated thirty other "from-to" classes of land cover change categories (i.e., from grassland to developed, from forest to grassland, from forest to developed). Therefore, researchers who may be interested in quantifying the extent of land cover change from forest to grasslands or grasslands to forests per se are able to do so with this technique. Moreover, this technique allows researchers with the capability to investigate other land cover type changes which may have occurred which will then provide a clearer picture of the nature of land cover change (and its associated effects) occurring within the landscape rather than those facilitated by development only.

To provide an example, the results from the post-classification technique indicated that forest experienced a net gain of approx. 2,000 acres within these counties.

This value was calculated in the same manner that land development was; a comparison of forest acreage to land development in 1990 as compared to the acreage value for the same land cover class presented in 2007. The results from this comparison analysis indicated the forest land cover class lost approx. 13,000 acres to land development. Conversely, during this period, areas which were once developed (as classified within the 1990 imagery) (approximately 15,000 acres), transformed back into forest in 2007, which then resulted in the net gain of 2,000 acres of "new" forested land cover. In this study, in addition to land development, the post-classification method determined that although vegetated or forested areas are continuing to be created within these counties, in other areas, they are being severely disturbed or fragmented by land development. Moreover, further research could then be conducted to determine if these "new" forested or other vegetated areas such as grasslands or wetlands which were created from previous "non-vegetated or forested" areas are viable or can provide suitable habitat to support wildlife species populations. Therefore, the post-classification technique allows researchers with a very powerful tool to highlight specific areas experiencing specific land cover type change.

An example can be seen in Rowley, Massachusetts (Essex County), where approx. 117 acres of forest was lost to commercial and residential development resulting in a fragmentation of this ecosystem (Figure 40). Given that this forested area is adjacent to a wetland, this fragmented area has undoubtedly had an effect on the habitat of certain plant and wildlife species residing in it through a removal of vegetation, canopy protection, and interrupted a movement corridor to the adjacent water/food sources (at left within imagery). Figure 41 provides an additional example of a fragmented forested

Figure 40. Example of forest fragmentation in Rowley, Massachusetts from 1990 to 2007.

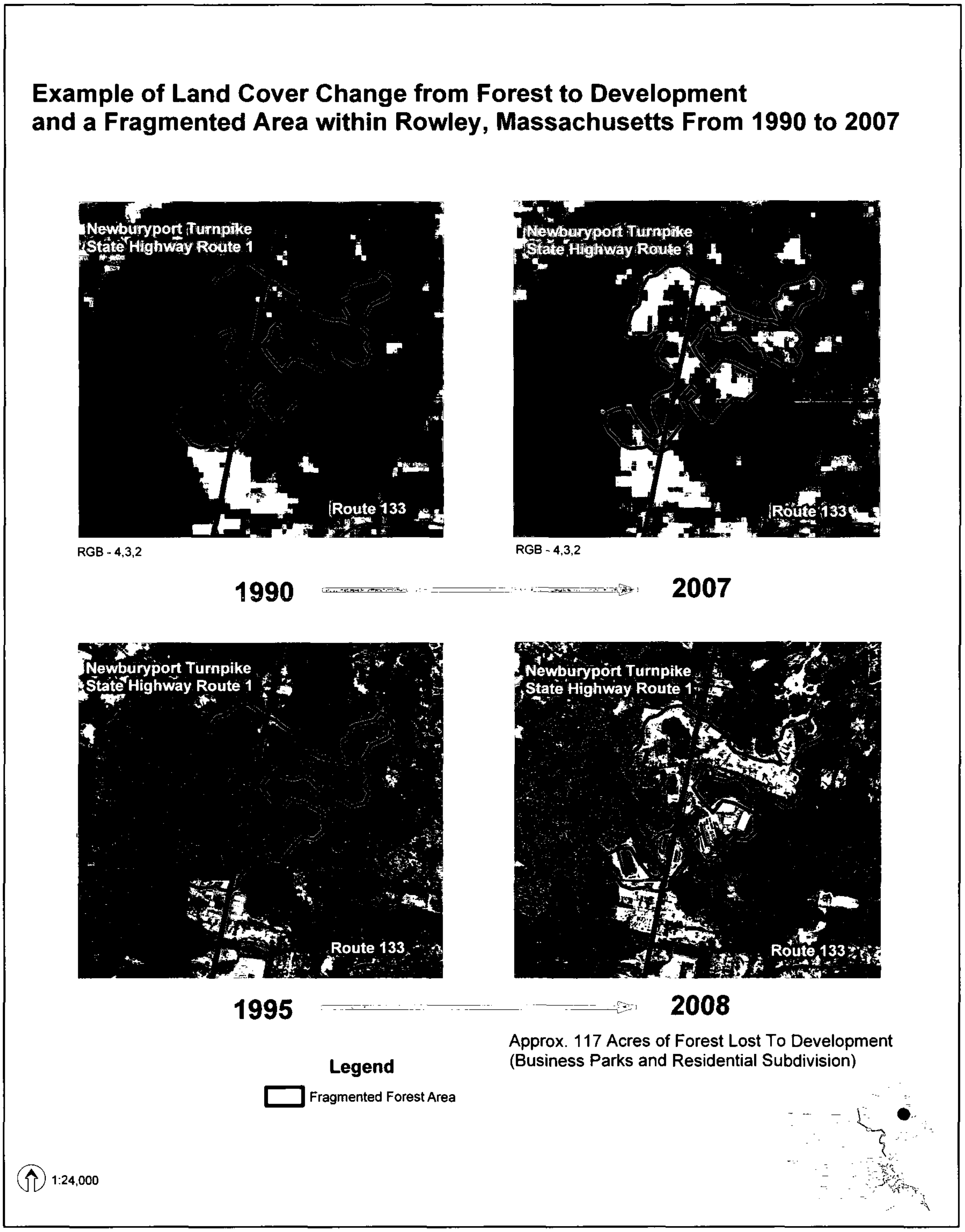
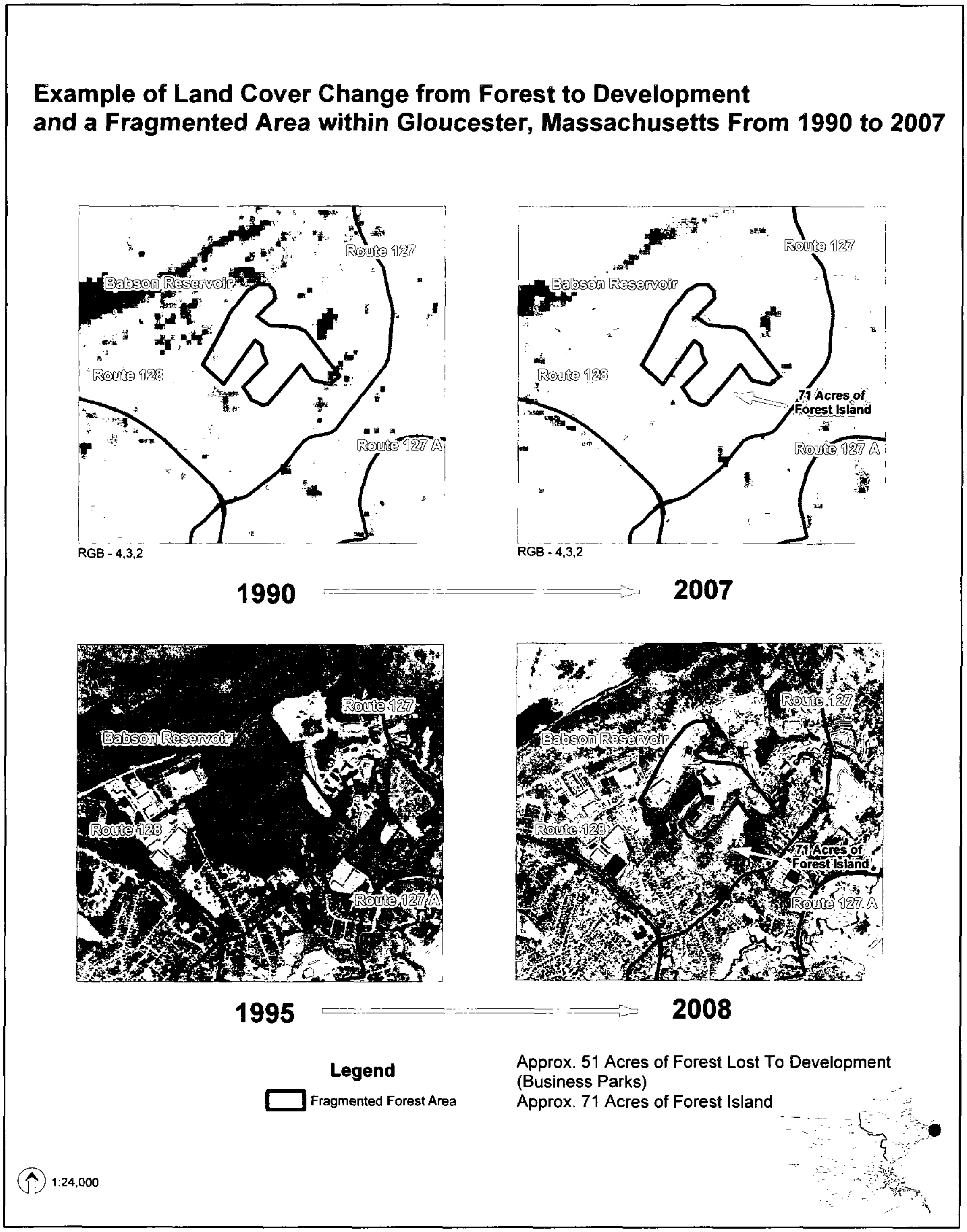


Figure 41. Additional example of forest fragmentation (as a result of "From Forest To Development" land cover change) in Gloucester, Massachusetts from 1990 to 2007.



Example of Land Cover Change from Forest to Development and a Fragmented Area within Gloucester, Massachusetts From 1990 to 2007

Approx. 51 Acres of Forest Lost To Development (Business Parks)
Approx. 71 Acres of Forest Island

area which is located within Gloucester, (Essex County). In Figure 41, a forested area had been previously disturbed by three roadways as well as residential development. In addition, Figure 41 illustrates the recent development of a business park which has further bisected this forested area leaving approx. 71 acres of forested land as an island, therefore, likely limiting access for species to access to the adjacent water supply.

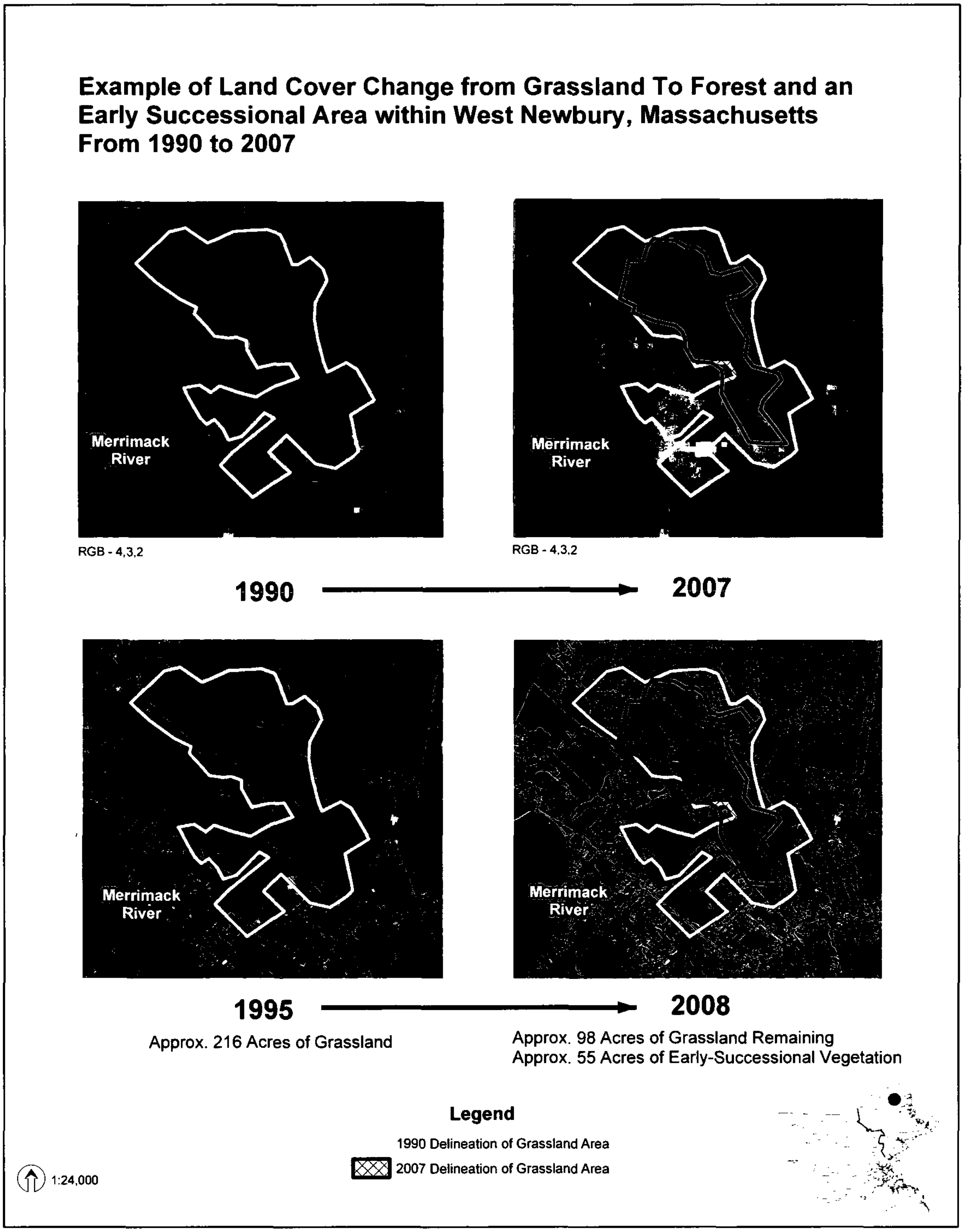
Fragmentation can have a dramatic effect on a variety of habitats and the persistence of many species dwelling in those habitats. Gibbs (1998) found that amphibian populations may be especially prone to local extinction resulting from human-caused transformation and fragmentation of their habitat particularly because of the spatially and temporally dynamic nature of their populations. Riiters et al. (2002) found that forest fragmentation also increases the energy cost/benefit ratio of movement because movement patterns become more contorted. Some species can adapt to edge or interior habitats created by natural disturbance regimes; but when forest spatial pattern changes, the fitness of forest dependent organisms to the environment decreases, and competitive advantages among populations change (Riiters et al., 2002).

Another notable land cover type change that occurred within the counties, which should be mentioned, was in grasslands. Since the advent of the industrial mills in Massachusetts, there has been a rapid decline of farms and farming establishments. In this study, the change detection results indicated that from 1990 to 2007, 40% of the grasslands within these counties changed to a different land cover type. Using the post-classification method to compare the "from-to" changes of three land cover classes (development, forest, and bareland) against the grassland land cover class within the post-classification matrix, results indicate that 13.6% or 7,794.19 acres of grasslands changed to development, 53.4% or 30,580.03 acres changed to forest, and 6.0% or 3,448 acres to bareland. Conversely, there was change amongst the land cover classes to grassland as well; development lost 2,494 acres to grassland, forest 15,770 acres, and bareland, 2,051 acres. Therefore, overall, 43,503 acres of grasslands changed to form the other land cover class categories, while 20,581 acres changed from the other land cover class categories to grassland, resulting in an approximate net change of 22,921 acres "new" grassland areas developed within the counties.

In many areas of grassland change, the once productive and well-maintained agricultural lands which have been abandoned, and not yet consumed for land development have, in some cases, begun to be replaced or colonized by pioneer species of vines, shrubs, and trees (Askins, 2001; Thompson and DeGraaf, 2001). This land cover type change from grassland to forest can be commonly referred to as an early-successional habitat where plants colonize treeless areas often through the result of river action, glaciation, or abandonment of cleared land (Askins, 2001). Figure 42 provides an example of an early-successional area in West Newbury (Essex County). As can be seen in Figure 42, approximately 55 acres of pioneer species have begun to develop around the edge of this once productive farm land area.

This transition can provide many unique habitat opportunities for a wide range plant and wildlife species such as the Ruffed Grouse (*Bonasa umbellus*), American Woodcock (*Scolopax minor),* Upland Sand-piper (*Bartramia longicauda*), Short-eared Owl (*Asio flammeus*), Golden Winged Warbler (*Vermivora chrysoptera*), and the New England Cottontail (*Sylvilagus transitionalis).* However, the transitional early-successional habitat land cover type change can negatively impact grassland dependent

Figure 42. Example of grassland to forest change in West Newbury, Massachusetts from 1990 to 2007.



species and have dramatic consequences on wildlife species such as the Bobolink (*Dolichonyx oryzivo*rus), Meadowlark (*Sturnella magna*), American Bittern (*Botaurus lentiginosus*), and Northern Harrier (*Circus cyaneus*) as many of these species do not favor "new" burgeoning forested areas over their previous grassland habitats. Therefore, using the previous examples above, it is easy to illustrate how remotely sensed data, GIS, and the post-classification technique's results can be used to develop a clear picture on the dynamics or effects of land cover change within the environment as well as provide the capability to draw informed conclusions to the health of a variety of plant/wildlife species within a given area of interest within a given temporal period. Therefore, given the land cover change aspects that this study did not cover, it would be beneficial for future research to be conducted to further investigate the results from the post-classification method in this region to further assess how specific land cover type changes may have compounded the effects from encroaching land development on plant and wildlife habitats and on resident species in environmentally sensitive and or areas currently classified or defined as insignificant or "non-sensitive".

In addition, as this study focused on the effects from land development on the habitats of rare or imperiled species, further research of these effects should be conducted upon the existing natural community designations, as the results from these findings may determine if other species are risk and may require additional protection. In addition, to lessen the impacts of land development within many "environmentally-sensitive" areas, communities should use these findings presented in this study as a basis to seek out and promote environmental awareness education on the effects of unmonitored land development within ecosystems and promote smart development practices to reduce its impact on natural, threatened or endangered plant and animal species. Therefore, further investigation of the post-classification method's results can then provide greater insight into the nature of other land cover changes which occur and provide a larger picture of how this region and others are experiencing the combined effects from land cover change.

CHAPTER X. LAND COVER CHANGE DETECTION RESEARCH RESULTS: WHAT'S NEXT?

Introduction

This dissertation research sought to demonstrate an application of remotely sensed data and geographic information systems (GIS) technology to detect, quantify, and document the nature and extent of land development within Essex and Middlesex Counties in Massachusetts from 1990 to 2007. In addition, this research also assessed the environmental effects from land development at the ecosystem-level including wildlife habitat fragmentation, disruption, and loss and investigated if socio-economic factors or indicators varied within areas of land cover change. To communicate the findings of this research to a wide audience for the purpose of assisting municipal leaders, county land managers, and the general public, in dissolving their egocentric views on the environment, to promote conservation, protection, and stewardship efforts, and assist in the development of sound and sustainable management practices and strategies, it is necessary to explore and provide a mechanism by which these findings could be viewed, distributed, disseminated, built or improved upon, and/or used a basis for future research endeavors.

Therefore, this paper will set out to provide an awareness of the tools that land planners use or can use to explore land cover changes within the environment, provide examples of specific land planning models and their associated requirements, benefits and challenges, and cost, and provide examples of "smart-growth" organizations which are becoming increasingly important to provide a more well-informed and participatory land planning practices.

Literature Review

Land use patterns provide a story of human activity and environmental evolution, and future settlement patterns are of interest to many (Zhou and Kockelman, 2008). Urban land use change will be one of the biggest environmental challenges of the 21st century (Fragkis and Seto, 2007). A major element of environmental change is the modification of natural land-cover due to human land uses, which are altering the landscape at unprecedented rates and magnitudes (Schneider and Pontius, 2001). In addition, the expansion land-use change, its transformation and envelopment of the surrounding landscape also will impact the environment at multiple spatial and temporal scales, through changing regional energy budgets, loss of wildlife habitat and biodiversity, and demand for natural resources (Fragkis and Seto, 2007).

Urban planners have always sought tools to enhance their analytical problem solving and decision-making capabilities (Mandelbaum, 1996). Beginning in the late 1950's, many urban planners began to develop computerized models, planning information systems, and decision support systems to improve performance (Wegener, 1995; Nedovic-Budic, 2000; Iacono et al., 2008). In the 1960's, the "Model of Metropolis", developed by Ira Lowry, was considered to be the first operational simulation model for urban land use planning (Lowry, 1964; Iacono et al., 2008). Since then, the advancement of computer processing power has revolutionized the way land use planning procedures are performed (Rinner, 2001).

The advent of computer simulated modeling has allowed many planners to visualize, manage, and disseminate vast amounts of geographic data effectively and efficiently (Oh and Jeong, 2002). During the last decade, extensive development of urban models occurred, and growth modeling has become very important and appropriate in areas experiencing, or anticipating, rapid urbanization, the associated problems of traffic congestion, inadequate public infrastructure, and the loss of agricultural and open land (Klostermann, 1998). Urban growth models have been evolved to accommodate high-resolution data and can focus on the behavior and transformations of many urban objects (Hatna and Benenson, 2007). In addition, growth models can quantify land-use change because they can integrate the measurement of changes in land-cover and associated to its drivers (Lambin et al., 1999; Petrov et al., 2009).

As cited in Schneider and Pontius (2001), Lambin (1997) indicates that models can assist scientists in generating hypotheses and, in some cases, answer three main questions such as: (1) What biophysical and socio-economic variables explain land cover changes? (2) Where are the locations affected by the changes? (3) At what rate do land-cover changes advance? Models then can be effective in explaining and/or predicting land-use and land cover processes in many areas (Schneider and Pontius, 2001), as they use rules of land availability and suitability for development (Zhou and Kockelman, 2006). Several of these data intensive models exist today and they can fall into four broad categories including land-use, transportation, economic, and environmental impact (U.S. EPA, 2000). Three such land-use models will be discussed in the following sections.

The State of Maryland's Office of Planning Growth Simulation Model (GSM), developed in 1992, is built on a public domain framework to project population growth and new development effects on land-use, land cover, nutrient pollution loads, and small streams under alternative land management strategies. To estimate the demand for residential and commercial development, the GSM requires that numerous data be inputted to perform the growth analyses. Data included population, household, employment projections, land-use, soils, watershed boundaries, streams, buffer zones, environmentally sensitive areas, zoning, land preservation boundaries, and sewer service boundaries. Once these data have been inputted into the model, the demand for land is then distributed to developable land, based on the current capacity or requirements of existing or alternative zoning, development regulations, resource conservation mechanisms, and other added information related to development patterns and trends. Land use change within the model is then estimated to accommodate for projected growth (U.S. EPA, 2000; The State of Maryland, 2009).

The GSM can be designed to focus on several urban land-use types, including residential, commercial, mixed-use, and industrial, as well as non-urban land use types such as agricultural, forest, wetlands, water, preservation, and parkland. This model can address effects upon on these land-use types from changes in community actions, such as the development of transportation infrastructure, local zoning changes, city/county master plan visions, changing fiscal policies, and environmental regulatory constraints (U.S. EPA, 2000; The State of Maryland, 2009). Specifically, this model also can assess the effects from land-use pattern changes on a variety of community characteristics, as well as travel demand, availability of open-space, environmental quality, land-use, stream buffering, and nutrient pollutant loads. The results from this model can then be customized to work on a variety of different scales and can be further designed to extrapolate land-use changes for larger geographic areas. Moreover, the model can provide its output into GIS format to derive land-based statistics and associated land-use projections graphics (U.S. EPA, 2000; The State of Maryland, 2009).

The INDEX model, developed by Criterion Planners, Inc. in 1994 (U.S. EPA, 2000; Criterion Planners, Inc. 2009) can be used to measure the characteristics and performance of land-use plans and urban designs with indicators derived from community goals and policies. Like GSM, INDEX also can model several urban land-use categories such as residential, commercial, mixed-use, and industrial and can address land-use changes in agricultural, forest, wetlands, water, preservation, and parkland. In addition, INDEX can visualize effects on land-use patterns from changes in local zoning, city and county master plans, and can address the effects of changing land-use patterns on community characteristics, such as available open-space and environmental quality (U.S. EPA, 2000; Criterion Planners, Inc. 2009). Outputs from INDEX can illustrate jobs-to-housing ratios, residential densities, employment changes, mixed land-use types, as well as calculate greenhouse gas emissions, impervious surface areas, and other transportation-related issues (U.S. EPA, 2000; Criterion Planners, Inc. 2009). Like the GSM, the INDEX model requires a variety of data for input to perform the analyses such as: population, housing, and employment projections, GIS data of parcel delineations, street centerlines, land-use types, computer-aided design (CAD) data of sidewalks, building footprints, and other significant environmental features. In addition, this model is built primarily upon GIS-hub framework, and all associated output can be produced with the aid of Environmental Sciences Research Institute (ESRI) ArcGIS software suite (ESRI, 2009).

Another urban growth model, METROSIM, was developed by Alex Anas Associates, Inc. in the mid 1990's (Anas and Arnott, 1994). METROSIM uses an economic approach to forecast the effect of transportation on land use at the metropolitan level. METROSIM can be used to evaluate transportation and travel changes, land-use controls, employment and income growth scenarios (U.S. EPA, 2000; Oryani and Harris, 1996). Like GSM and INDEX, METROSIM can address several categories of land-use, such as residential, commercial, mixed-use, industrial, and others, as well as non-urban land-use categories including agricultural, forest, wetlands, water, preservation, and parkland. The model also addresses the effects of land-use pattern changes from a variety of community actions (e.g., transportation infrastructure, local zoning, city/county master plans, and local fiscal policy changes). The METROSIM model is particularly helpful in assisting communities in assessing travel demand, open-space, environmental, school quality, crime, and other quality of life conditions. In addition, METROSIM provides an interface to work directly with a GIS and also can provide numerous outputs in GIS format. Like the previous models discussed, METROSIM requires population, housing, and employment projections from the U.S. Census Bureau (U.S. EPA, 2000; Oryani and Harris, 1996).

Excluding the GSM, urban growth models like INDEX and METROSIM can cost between $10K to $75K to acquire, and may require additional software maintenance, training, and customization fees ranging from $15K to $25K per year (U.S. EPA, 2000). Furthermore, obtaining data for these models will require an additional purchase of remotely sensed data (for land cover classification or change detection mapping), which can cost \$450 to \$6,000 per scene, as well as aerial imagery at comparable costs. In addition, software licensure, such as ESRI's GIS software or Erdas IMAGINE, may be required to support the model platform to perform image classification processing. These licenses and additional software modular interfaces can cost from \$2,000 to over \$10K. In addition, the development of land-use, zoning, and other planning data in digital format may require additional technical or GIS staff.

Some commonalities found among the models discussed, is that they require population, housing, and employment projections from the U.S. Census Bureau to function. Unfortunately, the use of census projection data may lead to the assumption that populations tend to remain in the same place, and that it will increase at a constant rate. In addition, another assumption is that population in areas of transportation corridors will lead to the land development (Swenson and Dock, 2009). According to Stoto (1983), census population projections are extrapolations of current trends and assumptions about the future. They can be used to illustrate and compare the results of various policies, or to warn policy makers about the consequences of current trends. However, others indicate that projections are often made and evaluated in a limited historical context; errors are frequent because the world changes in new and unexpected ways, and can never exactly foretell the future (Pittenger, 1978). In addition, economic conditions change and employment levels fluctuate, thus the projections are often based upon imperfect information (The State of Ohio, 2008).

Although urban growth models may use inaccurate census projections, and can be expensive to acquire while requiring additional staff and data resources to implement, they are useful. According to Klosterman (1998), the "what-if" scenarios generated by models do not attempt to predict future conditions exactly, but rather are meant to serve as policy-oriented planning tools that can be used to determine what would happen if certain policy choices are made and the assumptions concerning the future prove to be correct. In addition, the visualization of alternative land use policy scenarios provides planners and the general public with concrete expressions of the likely results (Klostermann, 1998). In recent years, modeling has become increasingly accessible through the evolution of GIS technology and the Internet (Ribeiro, 2002; Stevens and Dragicevic, 2007; Yang et al., 2007). Many of the web-based modeling tools have provided urban planners, as well as the general public, with greater opportunities for structured cooperation. This has promoted the development of sustainable solutions, and cost effective access to baseline data needed for effective planning (Peng, 2001; Dragicevic and Balram, 2004). In addition, because urban growth models are successful in promoting interactive participation, they can facilitate the development of land use policies that are seemingly more authentic and authoritative, regardless of the soundness (or unsoundness) of the underlying data within the model (Carver et al., 2001; Rinner, 2001; Peng, 2001).

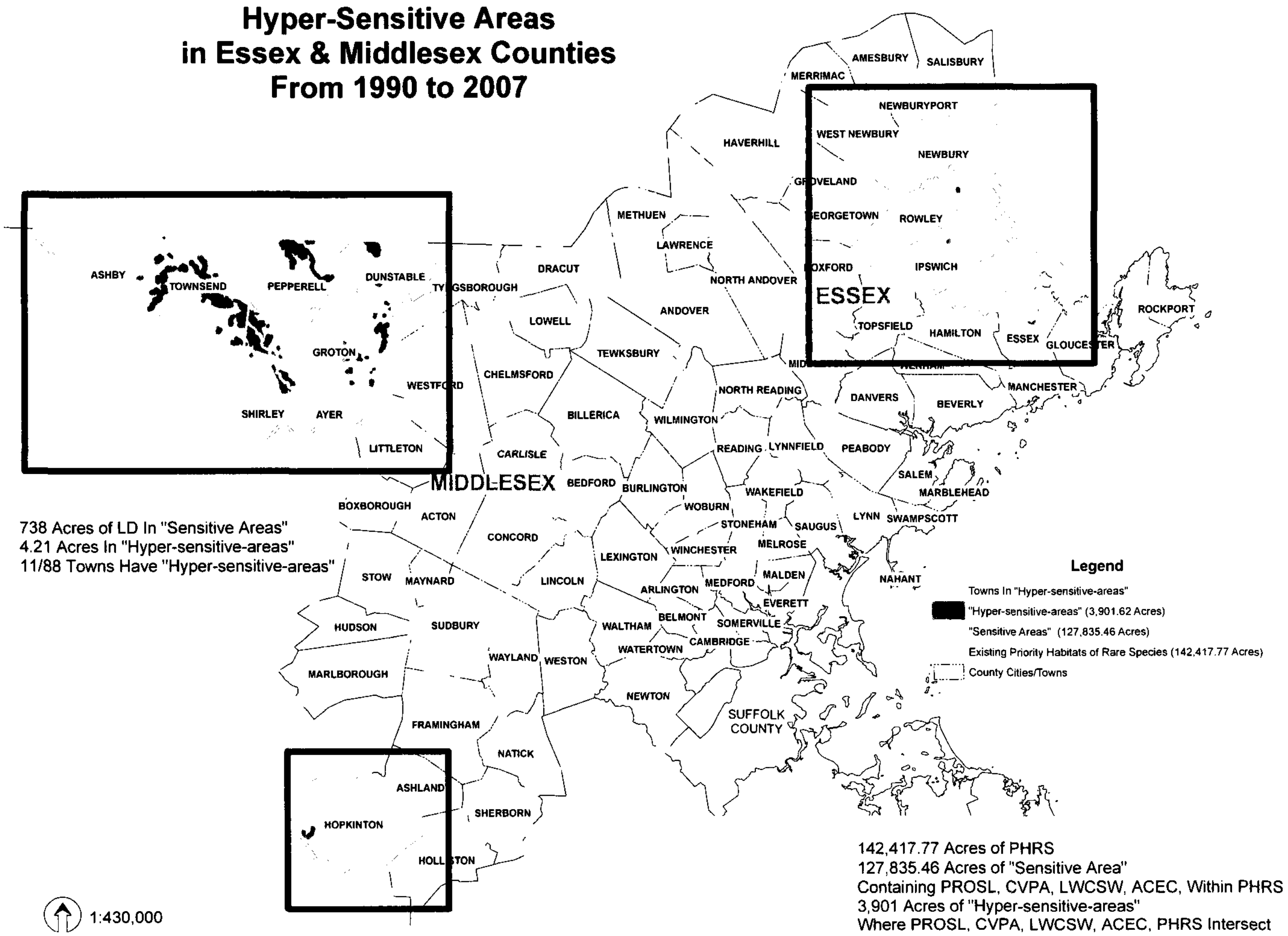
The Next Steps for Dissertation Research Findings

Unlike the models discussed in the previous section, this dissertation research is slightly different. The intent of this research was to provide a retrospective analysis of the landscape within Essex and Middlesex Counties rather than a prospective or predictive approach as provided by many urban growth models. Many urban growth models require data sources from zoning, current and future land-use plans, and census projections on population, housing, and employment as the base for forecasting the future. In essence, the results generated from this research can serve as additional input data into a growth model in the future. This may be done by identifying existing factors that are associated with land protection or land development.

To evaluate the effects of land development on ecosystems and their respective inhabitants, this study compared the remotely sensed data results with GIS data provided by the Commonwealth of Massachusetts. Furthermore, this research investigated if the population change since 1990 promoted land development within these two counties using existing census data. These findings assisted in identifying areas of land development which have been affected by changes in human demographics, and how these changes have impacted native plant species, reduced species richness of native flora, degraded the wildlife habitat of specific rare or imperiled species, influenced resident wildlife community census levels overall, impacted riparian corridors, and affected available water resources and water quality (i.e., eutrophication, over-use, groundwater discharge, disrupted stream-flow and storm water run-off, impacting overall water quality, etc.).

In addition, further use of remotely sensed data as well as GIS processing of dissertation results, may provide a platform to: 1) introduce ancillary data-layers to identify "hyper-sensitive" areas and refine previously delineated "protected" or "environmentally-sensitive" areas (Figure 43), 2) identify areas where land development could "threaten" larger or more diverse populations of existing species, 3) identify areas/conditions susceptible to promote invasive species, 4) introduce wildlife "footprint"

Figure 43. Hyper-Sensitive Areas in Essex and Middlesex Counties.



data to enhance monitoring of rare or imperiled species and determine appropriate areas and levels of habitat suitability for specific species, 5) gain additional knowledge at the ecosystem-level which may facilitate the development of more comprehensive protection and conservation measures or foster stewardship opportunities, 6) develop "citizen-scientist" outreach monitoring programs and a wide variety student research opportunities, 7) conduct annual/bi-annual "threat-assessments", and 8) monitoring the progression and movement of land development and its effects over time. Having such a wealth of "baseline" information will undoubtedly prove useful in providing additional as well as highly valuable input to generate more comprehensive urban growth models.

Even though this dissertation focused on "modeling" the landscape retrospectively, there were several assumptions and/or hypotheses which were made: (1) the topographic conditions are level (i.e., landscape change can result from slope differences), (2) land development occurred within the period of 1990 to 2007, (3) there were decreases in forest, bareland, grassland, wetland, and water, (4) land development is having an adverse effect on the existing environment, (5) existing grasslands, rather than forests, have been developed upon, (6) newly developed land areas have effected areas of critical environmental concern, (7) newly developed land areas have effected or encroached upon the priority of habitats of rare or imperiled species, (8) newly developed land areas have affected or encroached upon living waters core habitats and critical supporting watersheds, (9) newly developed land areas have effected or encroached upon state designated open and recreational space, (10) newly developed land areas have impacted vernal pools, (11) growth in development is equivalent to growth in population and the economy, and, (12) placement of industry affects land development in certain communities. With the exception of assumption 1, the use of two temporal periods of remotely sensed data, the GIS data provided by the Commonwealth of Massachusetts, and the census information assisted in determining that these assumptions were correct. In addition, not unlike the predictive models, there are several costs associated with this project. While these costs are absorbed by the University during the pursuit of my doctoral degree, they may be cost-prohibitive for most municipalities to conduct research of this nature in this current economic climate. The reason is that in order to perform the land cover change analyses, municipalities would have to purchase Landsat satellite imagery ($450 per scene), at least two expensive software platforms such as Erdas IMAGINE and ESRI ArcGIS ($50K plus training and license maintenance), field equipment such as a Global Positioning System (GPS) ($5K-$15K to be used for image processing training and field accuracy assessment), and state GIS data ($100-$200). In addition, to develop the data for the analyses, additional technical staff would be required and project costs could range from $50K to $150K.

Nevertheless, there is an upside. In recent years, there has been extensive development of a wealth of data resources provided by several state GIS data clearinghouses and open-source (free to the public) Internet-based GIS mapping technologies. The clearinghouses can provide recent aerial imagery and environmentally-based data relating to habitat locations, rivers, wetlands, ponds, lakes, streams, and other natural features. The open-source Internet-GIS mapping technologies can provide a venue for public visualization of the data. In addition, in response the overwhelming success of Google, Inc.'s, *Google Earth* online GIS mapping tool, the

United States Geological Survey has begun a yearly program to capture .15m or 6 inch (high resolution) digital aerial imagery for the coterminous United States.

Advancements in geographic information systems (GIS) and other visualization technologies also have allowed for the development of numerous planning decision support tools (Nedovic-Budic et al., 2006). These tools have facilitated the process of urban and suburban planning to draw from multiple technologies for data management, analysis, problem solving, design, decision-making, visualization of hypothetical situations, and communication activities (Hopkins, 1999; Nedovic-Budic et al., 2006). The development and use of these tools are crucial for land use monitoring, code enforcement, permit tracking, and provide a means to foster articulation and negotiation among stakeholders, consensus building and dispute resolution (Innes, 1996; Klosterman, 1998; Hopkins, 1999; Klosterman, 2001; Nedovic-Budic et al., 2006).

Land cover classification maps derived from remotely sensed data can used to further explore sustainable development practices or environmentally-based "what-if" scenarios or possibilities through integration with numerous multiple media and GIS-based toolkits (Smart Communities Network, 2009). The toolkits, three of which to be presented here, are specifically designed to support and foster sound, sustainable, and participatory planning processes, and are readily available to the public, and the Environmental Systems Research Institute's (ESRI) GIS software suite has provided the platform for development for many planning support systems (ESRI, 2009).

CITYgreen, a GIS-based software extension developed by American Forests, can use land cover image classification maps with ESRI's ArcGIS software suite to conduct complex analyses of ecosystem services, and calculate the cost benefits for services provided by trees and other green space within a given area of interest (American Forests, 2009). It also can generate land-based models for storm-water runoff, air pollution removal, carbon storage and sequestration, land cover type, and alternate scenarios. Moreover, CITYgreen can analyze the ecological and economic benefits of the tree canopy and other green space for urban and allow suburban planners and natural resources professionals, to test landscape ordinances, evaluate site plans, and model development scenarios that capture the benefits of trees (American Forests, 2009).

The Department of Housing and Urban Development offers a desktop geographic information system, Community 2020, that utilizes a variety of U.S. Census Bureau demographic, economic, and HUD program data to enable communities to visualize where HUD resources are going and how these resources relates to community conditions (HUD, 2009). In addition, Community 2020 fosters participation in the Consolidated Planning process, can integrate a variety of data sources and provide detailed descriptions on upcoming projects, projects that are underway, funding sources, building characteristics, performance indicators, and neighborhood locations (HUD, 2009). Placeways, Inc. offers an array of realistic and interactive GIS-based toolkits such as Community Viz, Scenario 360, Sitebuilder 3D, and LandFrag (Placeways, 2009). These tools allow urban and suburban planners to visualize, analyze, and communicate the potential environmental and social impacts of planning scenarios, conduct build-out analyses, evaluate temporal changes, determine land and water use and associated costs (Placeways, 2009). They also measure the impact of new roads, buildings and other development on the natural landscape (Placeways, 2009).

Therefore, it is my intention, upon completion of my degree, to further develop the methodology used within this research. The goal will be to streamline and substantially reduce the cost of performing the land cover change detection analyses for municipalities and/or the general public within these counties by developing more intuitive and user-friendly tools using open-source Internet-GIS mapping solutions, with a variety of data freely available to the public. The dissertation research findings have been published in website format using Google, Inc. free web service at (http://sites.google.com/site/sites/) to meet the above mentioned purpose.

Conclusion

It is true, predictive models are large data intensive systems which often use unrealistic assumptions and hold critical elements influencing growth constant. However, they are worth developing as planning tools, because the "what-if" scenarios provided can forecast what would happen if certain policy choices are made and the assumptions concerning the future prove to be correct. In addition, models can provide greater opportunities for structured cooperation, cost effective access to baseline data, and assist in the development of sound and sustainable land use practices.

Retrospective models are not unlike the predictive models as they can be large data intensive systems and can cost a great deal to use. However, they are worth developing as planning tools, because retrospective models can assess the results of the policy choices made in the past, and provide insight in the nature and extent of land cover changes as a result, and establish baseline data for further research to be developed. In addition, the results from retrospective models can provide literature for the research community on the application, methodology, and procedures to be used in the future to conduct temporal land cover analyses. Moreover, data from retrospective studies can be combined with wide array of data sources as inputs into growth models for future analyses. The value in both of these tools is that they provide a means to assess past and address future land policies, and land cover change effects within the environment. By employing such information, municipalities, state organizations, land-use planners, and residents may then advance sound and sustainable land-use practices.

Remotely sensed data also can be used to further explore and develop sustainable development practices. Leading-edge geographic information systems technology has made the development of interactive and realistic GIS-platform based planning decision support toolkits possible. These toolkits are specifically designed to support and foster sound, sustainable, and participatory planning processes, and can provide 2D or 3D site visualizations aimed at reducing impacts on the environment. These tools are not only crucial for municipalities for record keeping, land use monitoring, code enforcement, and permit tracking, these tools provide an effective means to promote an awareness of a wide range of existing environmental conditions, potential issues of alternative scenarios, future predictions, and foster discussion towards appropriate land use planning.

The next chapter will focus on presenting additional web-deployed options for land data dissemination and a conceptual framework for their successful adoption and implementation to assist participation in organizations engaged in natural resource and land planning.

CHAPTER XI. A CONCEPTUAL FRAMEWORK FOR THE SUCCESSFUL ADOPTION AND IMPLEMENTATION OF LEADING-EDGE GEOSPATIAL TECHNOLOGICAL TOOLS

Introduction

Designing computing tools to support land planning is an old idea (Hopkins, 1999). The recent advancement of computers, the Internet, and Geographic Information System (GIS) technologies have provided an important base for the development of online or web deployed GIS mapping tools for a variety of applications (Nedovic-Budic, 2000; Tsou and Buttenfield, 2002; Nedovic-Budic et al., 2006; Nivala et al., 2008). In the past, desktop geographic information systems (GIS) technology has been accused of being an elitist by giving more power to those who already possess it and depriving others, specifically, the general public (Carver et al., 2001).

In response, over the last decade, web-based GIS tools have developed significantly, their functionality has improved substantially, and they have been sought after by many (Brail and Klosterman 2001; Nivala et al., 2008). Online GIS mapping tools have primarily been developed with the intention to lessen the cost of owning GIS software, to remove it from the standalone and proprietary realm, and bring its functionality to the mainstream (Anderson and Moreno-Sanchez, 2003). However, adjusting these tools to meet specific applications can still present a challenge (Vonk et al., 2005), but the existence of these tools can not only encourage the multi-disciplinary collaboration between the GIS and computer science communities, but, foster public participation to evolve their capabilities (Klosterman, 1998; Tsou and Buttenfield, 2002).

Web-based GIS tools have allowed their users with the capability to structure, streamline, and focus computer network resources, benefit from advancing programming capabilities, and acquire, share, store, visualize, and disseminate data from a variety of sources (Dragicevic and Balram, 2004). However, some of these tools have ultimately failed because they were built on earlier GIS technology platforms which may have been better suited for a small workgroup environment rather than for large-scale deployment (Microsoft, Inc, 2009).

Building online tools for planners and for the public as sources of information and inquiry is a long-term goal of the GIS and remote sensing communities, and many tools that have been built fail to attract an audience or meet the needs of their target constituencies. In order to dissolve egocentric views of the environment and facilitate an open land planning process across a wide audience, development of user-friendly, inexpensive, appropriately functioned online GIS mapping tools is essential (Dragicevic and Balram, 2004). This paper will discuss methods to improve these tools, giving examples of some successful and failed online tools, the costs/benefits of building tools for specific purposes rather than generic tools, and in removing barriers to their use.

Literature Review

Theories of Technology Adoption

Advancements in geographic information systems (GIS) and other visualization technologies have allowed for the development of numerous planning decision support tools (Nedovic-Budic et al., 2000; Nedovic-Budic et al., 2006). These tools have facilitated the process of urban and suburban planning a draw from multiple technologies to contribute to data management, analysis, problem solving, design, decision-making, visualization of hypothetical situations, and communication activities (Hopkins, 1999; Nedovic-Budic et al., 2006). The development and use of these tools are crucial for land use monitoring, code enforcement, permit tracking, and provide a means to foster articulation and negotiation among stakeholders, consensus building and dispute resolution (Innes, 1996; Klosterman, 1998; Hopkins, 1999; Klosterman, 2001; Nedovic-Budic et al., 2006).

According to Haklay et al. (2008), from 2005 to 2007, 50 million people visited and used online GIS mapping sites like Multimap, Mapquest, Google Map, and Google Earth, for a variety of applications, and over 50,000 integrated tools, derived using these sites, called "mashups", have been developed. There is a variety of literature which discusses the development and implementation of online GIS mapping tools for a variety of applications (Cheng et al., 2004; Sugumaran et al., 2004; Greiling et al., 2005; Blackburn et al., 2008; Gao et al., 2008). However, there is limited or no literature which evaluates the usability, in terms of the failure of specific tools (Nivala, 2008). To understand how to implement online GIS mapping tools successfully, it is critically important to examine the factors of how technology is adopted and or diffused among people.

There are several conceptual frameworks which outline numerous factors which may contribute to the adoption, success, failure, and, use of technology, in general. Rogers (1995) discusses the diffusion of innovation theory which focuses on the conditions which can increase or decrease the likelihood that a new idea, product, or practice will be adopted by members of a given culture. Roger's theory also introduces the idea of early versus late adopters of any innovation. Hartzband (2008) argues that there are four keys which can influence the adoption of technology: (1) technical, (2) social and cultural, (3) cost, and, (4) alignment. Davis et al. (1989) suggests two other factors in the technology acceptance model which includes (1) perceived usefulness and (2) perceived ease-of-use that are critical for the success. This paper will combine, adapt, and apply the conceptual frameworks of both Hartzband (2008) and Davis et al. (1989) and set out to explore how to improve the successful adoption of online GIS mapping tools to meet their target constituencies. Furthermore, this paper also may provide valuable insight to those in the pursuit of the development and improvement of online GIS mapping tools.

Successes and Failures of Technology Adoption

As Hartzband (2008) indicates, there are four keys which may influence the success and failure of the adoption of technology; in this case, online GIS mapping tools for land planning purposes. The keys are: (1) technical, (2) social and cultural, (3) cost, and, (4) alignment. In addition, within each of the four key areas are two factors: barriers and facilitators. Barriers negatively influence the success of adoption of technology, while facilitators enable its success. In the following sections, the four keys areas and factors will be discussed.

Technical

The technical key refers to the systems requirements, capacity, or capabilities (Hartzband, 2008). In developing online GIS mapping tools for many land planning organizations, there may be several technical barriers which may influence a successful development and adoption of the technology: (1) the required network infrastructure is not readily available or in place, (2) there is a perceived need to develop large complex computer systems, (3) there is a possibility of acquiring additional hardware and software to support the tool's development and role-out, and, (4) the acquisition of additional technical staff. In addition, to develop an online GIS mapping tool successfully, which can serve it users effectively, knowledge of computer programming, web development and web design also may be required.

According to Felton and Morgan (2005) and Haklay et al. (2008), there have been several extensive programming improvements in the way web browsers can support or display GIS information in online mapping setting in recent years. These include AJAX (Asynchronous JavaScript and XML), SOAP (Simple Object Access Protocol), XML, (Extensible Markup Language), API (application programming interface), ASP (Active Server Pages), JSP (Java Server Pages), JavaScript, HTML (Hypertext Markup Language), ArcSDE, Oracle SQL Server, Cold Fusion, SDKs (software development kits), as well as KML (Keyhole Markup Language) (Google, Inc., 2009) for two and three-dimensional modeling, and the integration of live camera or sensor feeds. In addition, Haklay et al. (2008) indicates that there are different levels of expertise which may be required to perform "hacking" or customization of these tools and websites to produce more attractive, useful, or purposeful online GIS mapping tools, such as deep technical systems programming, shallow technical end-user programming, use hacking, and meaning hacking. These levels of expertise are essential for developing more successful tool interfaces, change the GIS source code for specific planning functions, author new and/or specific analytical tools, change the of the graphical user interface using macro customization for specific operations, and apply additional programming tools to further information beyond it original design. Furthermore, Felton and Morgan

(2005) indicate implementing online GIS tools effectively may require numerous staff additions, such as GIS specialists, web programmers, network engineers, graphic design, technical writers, data-base administrators, and project managers.

The cities of Boston, Massachusetts, Frisco, Texas, and Hudson, Ohio provide examples of how state organizations involved in land planning activities have developed successful interactive online GIS mapping tools using interfaces from Environmental Systems Research Institute's (ESRI) ArcIMS or ArcServer. Judging from the appearance and functionality provided by these online GIS tools, substantial time, effort, and funding went into the research and development process. In addition, personnel with extensive technical expertise may have been acquired to design and configure the network architecture and infrastructure to support connectivity to the internet, as well as to acquire, install, and configure the necessary GIS software and other supportive software like Apache Tomcat (Java servlets) (Apache, 2009; City of Boston, Ma, 2009; City of Frisco, 2009; City of Hudson, 2009; ESRI, 2009). These tools also may have required subscription of licenses from ESRI's ArcGIS desktop software suite in order to construct the GIS data for public use on each of the sites.

A facilitating factor (facilitator) which may assist the adoption or use of online GIS tools like the previous examples may include the use of open-source platform technologies (Open Source GIS, 2009; Open Geospatial, Inc. 2009). However, these tools also may require additional staffing to provide the technical expertise for their development, but can offer a customizable platform setting which can integrate an existing web tools to provide further functionality for the web-GISs. Some examples include the United States Army's Geographic Resources Analysis Support System

(GRASS), (Anderson and Moreno-Sanchez, 2003), CLUES (Cape Land Use Expert System, 2008), or the Oregon Coastal Atlas, (Oregon Coastal Atlas, 2009), which are built using open-source technologies.

Another alternative to the ESRI, Inc. or open source routes is Google, Inc. (Google, 2009). Since the development of *Google Maps* and *Google Earth*, Google, Inc. has provided extensive online mapping capabilities with access to a wide variety of libraries of information, including imagery for location purposes, trip planning capabilities, and three-dimensional environment simulation. In addition, recently, Google, Inc. has been promoting an awareness of GIS, by coupling their existing web programming capabilities and online mapping services with standard cartographic principles and evolving GIS technologies. In addition, Google, Inc. also has providing its users with free web-space to facilitate website development. *Google Earth* provides GIS capabilities to and solicits input from a wealth of mainstream users, and has provided many solutions for non-profit organizations, states and municipalities, as well as for the research community. An example is Virtual Alabama, which was introduced on the website for the State of Alabama's Homeland Security Program (The State of Alabama, 2009). Both Google, Inc. and the State of Alabama partnered to develop this online mapping tool to provide an "affordable, scalable, maintainable, and capable of employing the power of existing and evolving internet based applications" for land planning and homeland security preparedness (The State of Alabama, 2009). Another example includes *Google Earth's* recent application to assist a field researcher in studying one of earth's most ancient trees, the bristlecone pine (Google, 2009).

The advent of these new “turn-key” solutions, which have been called by some as Web Mapping 2.0, (Bissett, 2009), allow many individuals and organizations to conduct informed land planning, site investigation, and field research without the large investment in the systems resources and personnel. They do so by harnessing the power of Google-owned systems infrastructure, technical expertise, and advancing web programming capabilities and access to a wealth of geographic data sources within an open and participatory setting.

Social and Cultural

The social and cultural key or domain refers to the workforce, training, and leadership (Hartzband, 2008). In developing online GIS mapping tools for many land planning organizations, there are social and cultural barriers which may influence the successful adoption or sustained use of the technology. These barriers may include (1) the presence of close-minded individuals who illustrate an unwillingness to learn about the capabilities of these tools, dislike their interfaces, and/or distrust their outputs, (2) hierarchical or non-collaborative environments which do not promote or support group participation in the tool selection, development of its functions, or ongoing refinement processes, and, (3) absence of a “champion” who believes in or can promote the development and use of the technology.

There are numerous ways to facilitate the adoption and use of these tools under this domain. First, the organization could keep staff well-trained, well-prepared, and committed to process of improvement. In addition, to design an online GIS planning tool with the appropriate functions, input of experts from different fields are required, and stakeholders within the organization who have diverging interests need to be involved, as the results derived from these outputs can affect a large number of people (Voss et al., 2004). Therefore, participation in the development of and access to online GISs can minimize, if not remove, the barriers of access, diverse motivations, and competing views (Dragicevic and Balram, 2004; Kitzito et al., 2009). Carver et al. (2001) indicates that carefully designed interfaces resulting from public participation can empower its users in a more positive way. Involvement in the design in the web-based GISs can provide an open service for many people, which will foster interaction, discussion, and will assist in advancing and embracing the technology (Cobb and Olivera 1997; Plewe 1997).

Cost

The cost key refers to the initial financial investment in the technology and its ongoing operations (Hartzband, 2008). In developing online GIS mapping tools for many land planning organizations, there are several cost barriers which may influence the successful adoption or sustained use of the technology. These barriers include: (1) the large cost of the tools being offered, (2) mounting costs associated with their ongoing development, (3) unjustifiable costs, (4) limited or no continued organizational funding, and (5) little or no observable return on investment (ROI). For instance, according to Gateway Horizons in 2009, it costs $10,000 per year for a private company to purchase a license to operate ESRI's ArcIMS for one computer processor in order to develop a web-based GIS mapping tool. In addition, depending on the network configuration, to successfully operate ArcIMS, additional server hardware and other web supportive software (like Apache), or database software like ArcSDE (to serve up metadata) or Oracle, (to supply attribute data) may be required (ESRI, 2009; Jakarta Project, 2009; Oracle, Inc. 2009).

For some planning organizations with limited budgets, the costs may be prohibitive, and these agencies may be forced to not develop the tools, implement a phased-development approach, or sacrifice certain modules or components in order to establish a base system. In addition, many organizations do not have the funding resources to adequately support and conduct the necessary needs assessment process, which may negatively affect the adoption or successful implementation of the tool.

A key facilitating factor to address cost issues may be, as mentioned earlier, to use open-source web GIS mapping tools as provided by the Open GIS Consortium, or develop a partnership with Google to develop a few "light" GIS capabilities as a starting point since most of tools provided are free to the public (Google, 2009; Open Source GIS, 2009; Open GIS Consortium, 2009). Both open-source and partnered-source tools may provide potential users with enough of a valuable showcase to illustrate the benefits of the technology and its potential application, thereby increasing the likelihood of establishing ongoing funding support for additional applications development.

Alignment

The alignment key refers to the functional alignment of the technology to the organization's existing workflow (Hartzband, 2008). The careful selection or promotion of products is essential to ensure their adoption and effective use. A barrier to the successful adoption to the technology or acceptance of the tool is that its functionality poorly matches the workflow, styles, and needs of the organization. For instance, in several planning organizations, GIS is often used to provide an extension to computer aided drawing (CAD) functions: to make ground surveys more visually appealing, or to develop presentation materials for marketing purposes. Hence, many planning organizations want to develop online GIS mapping tools only to illustrate their organization's seemingly forward thinking, rather than to perform in depth and useful analyses. In other words, GIS is often put in place for aesthetic reasons, and not applied to the extent of its capabilities.

A key facilitating factor to address the alignment issue would be to acquire a system which closely matches the workflow, styles, integrates the data commonly used, and produces products which resemble those that are familiar to the organization. *Mapguide,* which is sponsored by AutoDesk, is an open-source tool that can effectively interact with any web browser. *Mapguide* supports DWF (design web format), utilized in most CAD applications, for light-weight mapping and exceptional plotting, a full suite of geospatial analyses capabilities, a studio application for the development of geospatial data and attractive websites, integration with *Google Earth,* and web-based site/server administration. Therefore, *Mapguide* can be used to display a vast amount of computer-assisted design data derived from AutoDesk's AutoCAD software suite, which is most commonly used in land planning agencies, as well as GIS data generated from ESRI's ArcGIS (AutoDesk, 2009; ESRI, 2009; Mapguide, 2009).

Perceived Usefulness

Davis et al. (1989) indicate that perceived usefulness is defined as the prospective user's view that using a specific application system will increase his or her job performance with an organizational context. Perceived usefulness is related to the social and culture key area. A barrier to the successful adoption of technology or acceptance of a certain tool may relate to an inaccurate perception that the tool offers little value to the existing or future workflow. A key facilitating factor to address the perceived usefulness issue is to openly discuss the numerous and varied potential uses of the product. Open discussion could also illustrate how this tool may improve or automate specific day-to-day operations, provide a means to ease the workflow by providing additional structure, or to communicate the importance or significance of these tools for the greater good.

Perceived Ease of Use

Davis et al. (1989) indicate that "perceived ease of use" refers to the degree to which a prospective user expects the target system to be free of effort. A barrier to the successful adoption of technology or acceptance of a certain tool may be its reputation. If a certain tool is defined by many as being difficult to use, complex, or does not function or operate properly, its chances for adoption will be small. A key facilitating factor to address the perceived ease of use issue is to provide awareness or introductory training, or develop literature for a wide audience. This would assist staff or public users in acquiring general knowledge on some of the benefits and challenges of using the tool, navigating its interface, and customization capabilities for desired output. A second key facilitating factor for adopting technology borrows from Rogers' theory of technology diffusion (1995): early adopters of the technology can serve as "champions", and can confirm the perceived ease of use, and perceived usefulness. In doing so, more people will likely adopt the tool.

Cost and Benefit of specifics vs. generic online GIS mapping tools

A benefit to using generic solutions like Chameleon, CartoWeb or Mapguide, (CartoWeb, 2009; Mapguide, 2009; Maptools, 2009), or ArcIMS or ArcServer, (ESRI, 2009), is that they are either free to the public, or could be acquired at a relatively fixed cost. In general, generic tools have been time and user-tested, debugged, and troubleshooting fixes for software glitches have most likely been resolved. In theory, generic tools may be less expensive as their costs for development have been spread-out over many entities over time. However, some additional functions, which may exist in the "tailor-made" or specific tools, may not accompany, or may not be easily added into the generic tool.

"Tailor-made" or specific tools are designed to meet certain requirements of a particular organization, and often require further customization. Tailor-made tools may have a higher likelihood of alignment with the organization's workflow, may have had key staff stakeholder input during its development, which may lead to higher perceived usefulness with staff readily championing its adoption. However, these tools often require periodic customization. Without further funding support for additional updates such tools can easily become isolated, standalone, and rigid. Moreover, tailor-made tools require additional expenses in staff, hardware and software infrastructure to develop.

Conclusion

Cartographers have long recognized the need to develop software which could provide the capability to generate thematic maps to communicate a "visual thinking" about spatially referenced data to a large audience (Andrienko and Andrienko, 1999). The advent and ongoing development of many online GIS mapping tools are rapidly providing this capability. This paper discussed six concepts from two conceptual frameworks which can influence the successful adoption and use of these tools. In addition, this paper provided a framework for those who are pursuing the successful development and adoption of online GIS mapping tools for a variety of applications.

An extensive review of the literature reveals that there many generic open-source tools, which are free and available for download from the Internet, and a variety of proprietary tools, which readily available for purchase by the public. In addition, most of the tools which have been discussed provide a stable platform which can be further developed to provide its users with a range of basic and complex GIS mapping functions. However, to ensure the successful adoption of these tools, several factors such as the technical, social and cultural, cost, alignment, perceived usefulness, and perceived ease of use should be carefully considered. In addition, the presence of barriers, as discussed within each these key areas, can have negative impact on the success, adoption, and advancement of these tools for a variety of users in a multitude of applications. Therefore, the removal of these barriers will ensure that a successful adoption and sustained use of these tools will occur.

CHAPTER XII. OVERALL DISCUSSION AND CONCLUSION

This dissertation set out to: 1) detect, quantify, and document the nature and extent of land development and land cover change within Essex and Middlesex Counties in Massachusetts from 1990 to 2007, 2) compare and contrast the demographic and/or population dynamics within areas of land cover change, and 3) assess the effects from land development on the environment (e.g., on specific areas of environmental concern, wildlife habitat areas and associated wildlife species). This dissertation also reviewed literature on the scientifically-derived guidelines to assist the protection of threatened or imperiled species, terrestrial vertebrates, lakes, rivers and stream ecosystems, and the effects impervious surfaces have on the environment. This dissertation also presented several existing land cover models which could employ the research findings for future land cover change investigations and assessments, presented various web-deployed data dissemination options to facilitate environmental awareness through public access, and provided a strategy for the successful adoption and implementation of these technological options for organizations engaged involved natural resource or land planning and management.

The results derived from the change detection analyses performed indicate that land cover change occurred within Essex and Middlesex Counties from 1990 to 2007. In addition, the historical patterns of development (e.g., placement of settlement, agriculture, industry, transportation corridors) have undoubtedly influenced the counties present day landscape. From 1990 to 2007, the development of land in these counties increased as a result of marked decreases in the existing land cover classes within the image classification scheme (e.g., bareland, forest, grassland, wetland, and water). The change detection results indicate that 23,436.66 acres of land changed from non-developed to developed, and 22,923.60 acres of developed land changed to non-developed representing a 0.56% (415.46 acres or 0.64 square miles) (net) increase of developed land areas during this period. Among the land cover class changes that occurred, grasslands exhibited the largest change in acreage as 40.0% of these areas changed into developed, bareland, forested, wetland, and water areas; land development was responsible for 13.63% (or 7,794.19 acres) of this change.

This dissertation also compared three population data types with "new" development in county cities and towns to investigate whether an association can be made between population change and land development. This research has shown that changes in population type (e.g., population number, families with children and median household income) during this period may have influenced land development and/or land cover change within this region. The combined results from the post-classification technique and GIS analyses indicate that communities with larger increases in families with children exhibited moderate to high increases of land development, while communities with higher increases in median household income exhibited low to moderate land development. Land cover change detection over the 17-year period indicates that land development occurred in many areas, but level of development in the cities and towns varied by socio-demographic factors. Although, this dissertation only compared three population data types to investigate associations between population and land development its more profound contribution is that it provided the methodology and data considerations for future comparative land cover change detection analyses.

The dissertation also determined that land development has affected several Commonwealth of Massachusetts delineated "environmentally-sensitive" areas within Essex and Middlesex Counties. Results from comparison of the remotely sensed and the Commonwealth's environmental GIS data analyses indicate that land development did occur, encroached upon, and/or fragmented many of these areas: 722 acres in areas of critical environmental concern, 670 acres in priority habitats of rare species, 1,092 acres in living waters core habitats and critical supporting watersheds, 1,318 acres in protected and recreational open spaces, and within 0-1000 feet of 600 certified vernal pool areas.

In addition, through advanced GIS overlay and data intersect analyses, "hyper-sensitive" areas, areas where one or more threatened or imperiled wildlife species are or will likely to be affected by land development, also were identified. This dissertation has illustrated that analyses of this nature can be valuable and can serve to: 1) refine previously delineated or develop "new" "environmentally-sensitive" areas, 2) identify areas susceptible or conditions acceptable to promote invasive species development, 3) incorporate wildlife "footprint" data to enhance monitoring and levels of habitat suitability for specific species, 4) gain more knowledge at the ecosystem-level, 5) develop more comprehensive protection and conservation measures, 6) conduct annual/bi-annual threat assessments, 7) develop "citizen-scientist" and/or student outreach monitoring or research opportunities, and 8) to monitor the progression of land development and its impact over time.

Remote sensing and GIS technologies can not only provide the means to explore the nature and extent of land development within many areas, but also can be used to identify areas where specific land cover type changes (e.g., fragmented forest areas and early-successional grassland habitats) may affect or influence wildlife persistence in areas experiencing habitat encroachment, alteration, fragmentation, disruption, and destruction. Assessing land cover change through the use of remotely sensed data can often be challenging and the results uncertain, and extensive processing of satellite imagery is required in order to produce accurate change detection results. This dissertation has shown that the integrated use of satellite remote sensing and geographic information systems (GIS) technology is suitable for the detection and quantification of the nature and extent of land cover change. Finally, the ultimate goal of this research was to promote environmental awareness through a demonstration of the application of remotely sensed data, geographic information systems, and ancillary data sources, to assist in dissolving environmentally-egocentric views and to promote the development of considerate, participatory, sound and sustainable land use, planning, and management strategies, initiatives, and practices.

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APPENDIX A – LANDSAT SATELLITES

The currently operating Landsat 5 satellite scans the Earth's surface in a descending polar sun-synchronous orbital track (moving from north to south) at an altitude of 705 km. Landsat 5 has a 16-day orbit cycle and is designed to collect data over a 185 km swath and use the Path and Row Worldwide Referencing System (WRS) to assist data users in locating and obtaining imagery for any given area on the Earth.

The Landsat 5 satellite carries both the Multi-Spectral Scanner (MSS) and the Thematic Mapper (TM) sensors. The MSS sensor was turned off in the early 1990's, but, while operational its spatial resolution was approximately 80 meters, with four bands of spectral coverage ranging from the visible green to the near-infrared (IR) wavelengths. The Thematic Mapper (TM) sensor includes several additional bands in the shortwave infrared (SWIR) and an improved spatial resolution of 120 meters for the thermal-IR band and 30 meters for the other six bands. Additional satellite data, as used for a change detection assessment within Tardie (2005), is available as it was acquired from the Landsat 7 satellite which carries the Enhanced Thematic Mapper Plus (ETM+) sensor, with 30 meter visible and IR bands, a 60 meter spatial resolution thermal band, and an additional 15 meter panchromatic band (Band 8).

Landsat 5

Launched: March 1, 1984
Status: Operational
Sensors: Multi-Spectral Scanner (MSS) & Thematic Mapper (TM)

Landsat 7

Launched: April 15, 1999
Status: Operational
Sensors: Enhanced Thematic Mapper Plus (ETM+)

MSS Band Designation

Spectral Bands	Spatial Resolution	Application
Band 4 - Green	80 meters	Healthy vegetation
Band 5 - Red	80 meters	Vegetation/bare soil, rock differentiation
Band 6 - Near Infrared (NIR)	80 meters	Emphasizes vegetation boundary between land and water, and landforms
Band 7 - Near Infrared (NIR)	80 meters	Penetrates atmospheric haze; emphasizes vegetation, water body delineation

TM & ETM+ Sensor Band Designation

Spectral Bands	Spatial Resolution	Application
Band 1 - Blue	30 meters	Coastal water mapping, soil/vegetation differentiation
Band 2 - Green	30 meters	Healthy vegetation
Band 3 - Red	30 meters	Chlorophyll absorption
Band 4 - Near Infrared (NIR)	30 meters	Biomass surveys, water body delineation
Band 5 - Mid-Infrared (MIR)	30 meters	Water moisture measures
Band 6 - Thermal Infrared (TIR)	**120m ***60m	Thermal mapping and estimated soil moisture
Band 7 - Mid-Infrared (MIR)	30 meters	Hydrothermal mapping altered rocks associated with mineral deposits
*Band 8 - Panchromatic	15 meters	Sharpening of multi-spectral images

* On the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) sensor only.
** For the Landsat 5 Thematic Mapper (TM) sensor.
*** Improved in the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) sensor.

For further information:

United States Department of the Interior United States Geological Survey Landsat Project Site
http://landsat.usgs.gov/index.php

NASA: Landsat 7 Project Science Office Goddard Space Flight Center
http://landsat.gsfc.nasa.gov/

USGS: National Center for Earth Resources Observation and Science (EROS)
http://edcsns17.cr.usgs.gov/EarthExplorer/

APPENDIX B – CLIMATOLOGICAL DATA

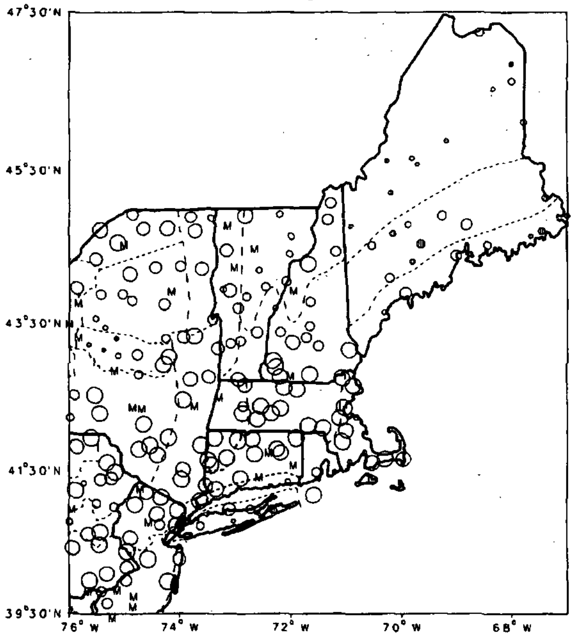
DEPARTMENT OF COMMERCE UNITED STATES OF AMERICA

ISSN 0364-5339

CLIMATOLOGICAL DATA
NEW ENGLAND
SEPTEMBER 1990
VOLUME 102 NUMBER 9

MONTHLY PRECIPITATION DEPARTURE FROM
INDIVIDUAL STATION NORMALS (1951–1980)

M	INCOMPLETE DATA FOR THE MONTH
•	EXACTLY NORMAL
∘○◯	5,10,20,...50% OR MORE BELOW NORMAL
•●⬤	10,20,40,...100% OR MORE ABOVE NORMAL



CIRCLE DIAMETER IS PROPORTIONAL TO DEPARTURE ON A CONTINUOUS SCALE

"I CERTIFY THAT THIS IS AN OFFICIAL PUBLICATION OF THE NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA). IT IS COMPILED USING INFORMATION FROM WEATHER OBSERVING SITES SUPERVISED BY NOAA/NATIONAL WEATHER SERVICE AND RECEIVED AT THE NATIONAL CLIMATIC DATA CENTER (NCDC), ASHEVILLE, NORTH CAROLINA 28801."

Kenneth D Hadeen

DIRECTOR, NATIONAL CLIMATIC DATA CENTER

noaa

NATIONAL
OCEANIC AND
ATMOSPHERIC ADMINISTRATION

NATIONAL
ENVIRONMENTAL SATELLITE, DATA
AND INFORMATION SERVICE

NATIONAL
CLIMATIC DATA CENTER
ASHEVILLE NORTH CAROLINA

MONTHLY SUMMARIZED STATION AND DIVISIONAL DATA

NEW ENGLAND
SEPTEMBER 1990

STATION	TEMPERATURE (°F)														PRECIPITATION (IN)									
											NO. OF DAYS								SNOW, SLEET			NO. OF DAYS		
											MAX		MIN											
	AVERAGE MAXIMUM	AVERAGE MINIMUM	AVERAGE	DEPARTURE FROM NORMAL	HIGHEST	DATE	LOWEST	DATE	HEATING DEGREE DAYS	COOLING DEGREE DAYS	90 OR ABOVE	32 OR BELOW	32 OR BELOW	0 OR BELOW	TOTAL	DEPARTURE FROM NORMAL	GREATEST DAY	DATE	TOTAL	MAX. DEPTH ON GROUND	DATE	.10 OR MORE	.50 OR MORE	1.00 OR MORE
EAST BRIMFIELD LAKE	71.6	48.1	59.9		83	3	34	20+	184	36	0	0	0	0	1.30		.35	16	.0	0		7	0	0
HAVERHILL	71.9	50.7	61.3	-2.6	85	2	34	19	142	38	0	0	0	0	1.46	-2.11	.40	15	.0	0		5	0	0
LAWRENCE	72.8	51.1	62.0	-.8	86	3	38	19	135	51	0	0	0	0	2.51	-1.18	1.06	12	.0	0		4	2	1
LOWELL	74.5	50.1	62.3		88	3	34	19	135	63	0	0	0	0	1.12		.46	16	.0	0		3	0	0
PEPPERILL	74.4	45.5	60.0		88	3	31	19	185	38	0	0	2	0	1.20		.49	16	.0	0		4	0	0
READING	71.8	50.9	61.4		85	2	35	19	141	39	0	0	0	0	1.64		.46	15	.0	0		6	0	0
SOUTHBRIDGE 3 SW	69.1	47.7	58.4		80	3+	34	19	215	27						.00			M	M				
TULLY LAKE	74.0	45.8	59.9	1.2	87	3	32	20+	190	44	0	0	3	0	1.32	-2.30	.36	16	.0	0		5	0	0
WALPOLE 2	72.0	52.0	62.0		86	2	34	19	136	56	0	0	0	0	1.67		.68	23	.0	0		4	2	0
WEST MEDWAY	74.5	45.6	60.1		86	3	31	19	177	36	0	0	3	0	1.36		.60	16	.0	0		5	1	0
WORCESTER WSO AP R	68.4	50.2	59.3	-1.0	81	2	34	18	192	25	0	0	0	0	1.73	-2.52	.70	15	.0	0		6	1	0
--DIVISIONAL DATA------->			60.4	-1.0											1.50	-2.25			.0					
COASTAL 03																								
BOSTON WSFO AP R	72.3	56.9	64.6	.0	87	2	44	18	84	77	0	0	0	0	1.67	-1.74	.57	22	.0	0		6	1	0
BROCKTON	74.1	51.3	62.7		88	2	34	19	131	69	0	0	0	0	2.25	-1.74	1.56	22	.0	0		3	1	1
CHATHAM WSMO	68.7	56.7	62.7	.6	77	2	45	19	91	31	0	0	0	0	2.08	-1.66	1.26	22	.0	0		4	1	1
EAST WAREHAM	72.0	53.6	62.8	.6	83	1	37	19	115	58	0	0	0	0	3.88	.08	1.80	23	.0	0		4	3	1
EDGARTOWN	69.9	55.3	62.6	-.4	78	16+	41	19	102	39	0	0	0	0	2.96	-.69	1.57	23	.0	0		5	2	1
HINGHAM	71.9	52.9	62.4		85	2	36	19	128	57	0	0	0	0	2.28		1.20	23	.0	0		5	2	1
HYANNIS	70.3	54.4	62.4	-.4	82	3	42	19	108	36	0	0	0	0	1.63	-1.87	1.08	23	.0	0		4	1	1
MARBLEHEAD	71.9	54.4	63.2		85	2	39	19	96	49	0	0	0	0	1.85		.52	22	.0	0		6	1	0
MIDDLETON	73.4	53.8	63.6	1.0	85	2	36	9	94	59	0	0	0	0	1.46	-2.07	.44	23	.0	0		3	0	0
NEW BEDFORD	74.4	57.2	65.8	.1	87	2	42	19+	63	94	0	0	0	0	3.69	.34	1.85	22	.0	0		6	2	1
PEABODY	72.6	52.5	62.6		86	2	38	19+	123	56	0	0	0	0	1.65		.52	23+	.0	0		4	2	0
PLYMOUTH	72.6	54.4	63.5	.6	87	2	40	19+	99	59	0	0	0	0	2.65	-1.51	1.32	22	.0	0		5	1	1
PROVINCETOWN	66.7	53.1	59.9		78	3	45	19	155	9	0	0	0	0	2.29		1.32	23	.0	0		3	2	1
ROCHESTER	73.5	53.4	63.5	1.6	89	3	35	19	110	69	0	0	0	0	3.10	-.73	1.69	23	.0	0		5	2	1
TAUNTON	74.0	52.0	63.0	1.3	88	3	34	19	132	78	0	0	0	0	1.94	-1.90	1.17	23	.0	0		4	1	1
--DIVISIONAL DATA------->			63.0	.1											2.36	-1.27			.0					
NEW HAMPSHIRE																								
NORTHERN 01																								
BENTON 5 SW	66.2	48.3	57.3		77	2+	35	19+	232	10	0	0	0	0	2.22		.53	15	.0	0		7	1	0
BERLIN	67.7	45.5	56.6		81	2	34	20+	252	7	0	0	0	0	2.38	-.82	.87	16	.0	0		6	2	0
BETHLEHEM	66.1	46.4	56.3	.1	77	2+	33	8	261	4	0	0	0	0	1.70	-1.64	.36	10	.0	0		6	0	0
COLEBROOK	65.1	44.8	55.0		78	1	31	19+	299	6	0	0	3	0	2.05		.62	15	.0	0		6	1	0
FIRST CONNECTICUT LAKE	62.7	41.9	52.3	-.1	76	1	29	19	374	0	0	0	3	0	2.85	-1.08	.68	23	.0	0		6	2	0
GRAFTON	69.8	44.7	57.3		83	3	32	25+	238	14	0	0	3	0	2.82		.64	30+	.0	0		8	2	0
LANCASTER	67.2	47.5	57.4		80	1	35	19+	237	15	0	0	0	0	2.48		.45	15	.0	0		8	0	0
MONROE 5 NNE	67.1	48.2	57.7		85	1	38	8	227	16	0	0	0	0	2.99		.65	16	.0	0		9	1	0
NORTH STRATFORD	67.1	43.9	55.5		81	1	32	20+	282	6	0	0	2	0	2.43		.63	23	.0	0		6	1	0
PINKHAM NOTCH	62.7	44.9	53.8	.4	75	2+	34	18	326	0	0	0	0	0	4.30	-.31	1.31	16	.0	0		7	2	2
YORK POND	65.8	42.6	54.2		78	2	30	19	320	4	0	0	4	0	2.64		.48	23	.0	0		9	0	0
--DIVISIONAL DATA------->			55.8	.5											2.62	-.97			.0					
SOUTHERN 02																								
BLACKWATER DAM	69.7	48.2	59.0	.8	84	3	34	19	204	27	0	0	0	0	2.52	-.89	.57	13	.0	0		7	2	0
CONCORD WSO AIRPORT R	71.4	47.9	59.7	.6	87	2	30	19	183	30	0	0	1	0	2.31	-.81	1.26	15	.0	0		6	1	1
DEERING	67.6	50.6	59.1		80	2	35	18	193	22	0	0	0	0	1.74		.84	15	.0	0		5	1	0
DURHAM	71.4	49.7	60.6	.1	85	2	34	19	157	33	0	0	0	0	1.75	-1.62	.47	15	.0	0		5	0	0
EPPING	72.2	49.7	61.0		86	2	33	19	154	41	0	0	0	0	1.49		.69	15	.0	0		4	1	0
FRANKLIN FALLS DAM	71.6	47.6	59.6		86	3	34	19+	188	32	0	0	0	0	2.51	-.66			.0	0		5	1	0
GREENLAND	72.3	51.1	61.7		86	2	33	19	139	47	0	0	0	0	2.45		.65	23	.0	0		6	2	0
HANOVER	70.2	50.3	60.3	.9	81	5	36	18	166	33	0	0	0	0	3.16	-.15	1.35	30	.0	0		6	1	1
KEENE	72.9	49.9	61.4	.9	85	2	32	18	154	53	0	0	1	0	1.56	-1.88	.51	16	.0	0		4	1	0

SEE REFERENCE NOTES FOLLOWING STATION INDEX

DAILY PRECIPITATION (INCHES)

NEW ENGLAND
SEPTEMBER 1990

STATION	TOTAL	DAY OF MONTH																														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
CENTRAL 02																																
AMHERST	1.42		.03					T			.07		.29		.02	.43					.31		.02	.25								
ASHBURNHAM	1.48							.02		T	.06		.07		.01	.67		T		.10	.13		.15	.04							.23	
ASHFIELD	2.35			.04					.01		.35		.20		.01	1.03	.05				.22			.44								
BARRE FALLS DAM	1.52					T	T		.02		.10	T	.14			T	.86	.03			.25			.12								
BEDFORD	1.33							.01			.09		.10			.46	T	.06		.08	.16		.17	.02							.18	
BELCHERTOWN	1.50			.01					.15		.05	.01	.04		T	.03	.78	.02			.28			.13								
BIRCH HILL DAM	1.10										.26		.13		T	T	.40		T		.26		T	.05								
BLUE HILL R	1.86		T	T				.02			.01					.53		.18		.10	.05		.80	T				.01			.16	
BUFFUMVILLE LAKE	1.33										.22		T			T	.58	.17	.09		.15		.03	.09								
COLRAIN 5 N	2.40							.03	.02		.32		.01		.10	.50	.39				.22		.01	.44	.01			.35				
EAST BRIMFIELD LAKE	1.30										.25					.20	.35	.10			.15		.10	.15								
FRANKLIN	1.44								T			T					.56				.17			.50				.21				
GARDNER	1.14		T						T		.05		.11		T	.02	.61	T			.16			.19								
HARDWICK	1.51	T							.07		.10		.04			.15	.82	.03			.24		T	.06								
HAVERHILL	1.46		T	.07				T			.08		.06			.40	T	.02		.13	.24		T	.23							.23	
HOLYOKE	1.61	.19									.01	T	.05				.59				.25			.51						.01		
LAWRENCE	2.51										.06	.03	1.06				.72	.03			.38			.23								
LOWELL	1.12			T						*	.02		.28	T		T	.46	.02			.29			*	.05				T			
MILFORD	1.54			T							.03	T					.64	.15			.18		.16								.38	
NATICK	1.24										.07						.55	.12			.21			.20				.09				
NEW SALEM	2.85							.01	.08		.06		.46				.44	.54	.08		.28		.38	.19							.33	
NORTHBRIDGE 2	1.25										.06						.79	T		.15	.16			.09								
PEPPERELL	1.20								T		.04	T	.29	T			.49	.03			.24			.11							T	
PETERSHAM 3 N	1.12							T	.01				.18		T	.37	.21				.22		T	.13								
READING	1.64			T				.01			.10		.03		T	.46	T	07		.17	.12		.44								.24	
SOUTHBRIDGE 3 SW	M		.01	.14					T		.09	.18				.01	.81	15			.19			.12								
SUNDERLAND	1.38		T		T			T	.04		.15		.14		.02	.05	.41	T	T		.27		T	.30	T							
TULLY LAKE	1.32										.26		.28			T	.36				.31			.11								
WALPOLE 2	1.67		T						.01		T	T				T	.62	.18	T		.18		T	.68								
WARE	1.22								.11		.11	.03				.01	.62	.08			.23	T	.03									
WESTFIELD	.97			T				T	T		.08		*	*	*	.40	.05				.20		T	.24	T			T				
WEST MEDWAY	1.36								T			T					.60	.20	T		.18			.22				.16				
WORCESTER WSO AP R	1.73		.01					.27		T	.18		.02		T	.70		.04		.13	T		.12								.26	
COASTAL 03																																
BEECHWOOD	3.96											.02					1.95	.40	.29	T				1.30	T						T	
BOSTON WSFO AP R	1.67			.01				.01			.16	T		T	T	.39	T	.10		.12	.08		.57	T							.23	
BROCKTON	2.25										T				.01	.43		.23		.02			1.56									
CHATHAM WSMO	2 08		.03					T	T		.08			T		.33		.01		.01	.16		1.26	.20					T	T		
EAST WAREHAM	3.88								.04		.76	T		.03			.72	.04			.48			1.80			01					
EDGARTOWN	2.96								.25		T					T	.58	.02	T		.26			1.57				.28		T		
HATCHVILLE	1.94											T					.57	.08	T		.21			1.08				T				
HINGHAM	2.28			.02				T			.04				T	.57		17			.12		.15	1.20				.01			T	
HYANNIS	1.63											T			I		.22	.20	T		.12			1.08			.01					
IPSWICH	1.60			.24				.04			.06						.32	.06			.25	T		.63								
MARBLEHEAD	1.85							T			.27		T			.37	.01	.13			.30		.52	.25					T		T	
MIDDLEBORO	3.42											.61			.01		.54	.21			.21			1.78				.06				
MIDDLETON	1.46				.07			T			.05		.07			.40	T	.07			.31		T	.44							.05	
NEW BEDFORD	3.69		T					.03			.18				T	.97		.14		.05	.35		1.85					.12				
NEWBURYPORT	1.53			.08					T		.05	.01	.03	.07			.45	.03			.32			.49							T	
PEABODY	1.65							T			.18		.03	T		.52		.09			.31		T	.52								
PLYMOUTH	2.65							.03			.01					.35		.13		T	.32		1.32	.49				T				
PROVINCETOWN	2.29								.02		.01					.14	.75				.00			1.32					.05			
ROCHESTER	3.10								.10		T				.01		.74	.14			.33			1.69	.01			.08				
TAUNTON	1.94														T	T	.44	.17			.16			1.17				T				

SEE REFERENCE NOTES FOLLOWING STATION INDEX
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STATION INDEX

NEW ENGLAND
SEPTEMBER 1990

STATION	INDEX NO.	DIVISION	COUNTY	LATITUDE	LONGITUDE	ELEVATION (IN FEET)	OBSERVATION TIME AND TABLES LOCAL STD TIME				OBSERVER
							TEMP	PRECIP	EVAP	SPECIAL (SEE NOTES)	
WEST BUXTON 2 NNW	9314	02	YORK	43 42	70 37W	150	MID	MID			CENTRAL MAINE POWER CO
WEST PARIS	9538	02	OXFORD	44 20	70 35W	541		07			LEE E FARRAR
WEST ROCKPORT 1 NNW	9593	03	KNOX	44 12	69 9W	381	09	09		H	CAMDEN-ROCKLAND WTR CO
WOODLAND	9891	02	WASHINGTON	45 9	67 24W	138	07	07			GA PACIFIC CORP
MASSACHUSETTS											
AMHERST	0120	02	HAMPSHIRE	42 23	72 32W	180	14	14		C H	TOWN OF AMHERST WTP
ASHBURNHAM	0190	02	WORCESTER	42 37	71 53W	1100		MID		H	THOMAS MATTUS
ASHFIELD	0213	02	FRANKLIN	42 31	72 47W	1250		07		H	RUSSELL FESSENDEN
BARRE FALLS DAM	0408	02	WORCESTER	42 26	72 2W	910	08	08		C H	US CORPS OF ENGINEERS
BEDFORD	0535	02	MIDDLESEX	42 29	71 17W	160	MID	MID		H	WEATHER SERVICES CORP
BEECHWOOD	0551	03	NORFOLK	42 14	70 49W	59		08			MA WATER RESOURCES COMM
BELCHERTOWN	0562	02	HAMPSHIRE	42 17	72 21W	560		08			METRO DIST WATER COMM
BIRCH HILL DAM	0666	02	WORCESTER	42 38	72 7W	864	08	08		C H	US CORPS OF ENGINEERS
BLUE HILL	R 0736	02	NORFOLK	42 13	71 7W	630	MID	MID		C H J	NATL WEATHER SERVICE
BORDEN BROOK RESERVOIR	0759	01	HAMPDEN	42 8	72 56W	1110	07	07			SPRINGFIELD WATER WORKS
BOSTON WSFO AP #	R 0770	03	SUFFOLK	42 22	71 2W	20	MID	MID		C H J	NATL WEATHER SERVICE
BROCKTON	0860	03	PLYMOUTH	42 3	71 0W	79	MID	MID			CITY OF BROCKTON
BUFFUMVILLE LAKE	0998	02	WORCESTER	42 7	71 54W	500	08	08		C H	US CORPS OF ENGINEERS
CHATHAM WSMO	1386	03	BARNSTABLE	41 40	69 58W	50	MID	MID		H	NATL WEATHER SERVICE
CHESTERFIELD	1436	01	HAMPSHIRE	42 23	72 51W	1425		08			MA WATER RESOURCES COMM
COLRAIN 5 N	1611	02	FRANKLIN	42 44	72 43W	750		07		H	RUTH M GILDERDALE
CUMMINGTON HILL	1774	01	HAMPSHIRE	42 28	72 56W	1610	08	08		H	FRANK C HERRON
EAST BRIMFIELD LAKE	2107	02	WORCESTER	42 7	72 8W	680	08	08		C H	US CORPS OF ENGINEERS
EAST WAREHAM	2451	03	PLYMOUTH	41 46	70 40W	20	MID	08		H	UNIV OF MASSACHUSETTS
EDGARTOWN	2501	03	DUKES	41 23	70 31W	20	08	08		H	MARK LOVEWELL
FRAMINGHAM	2975	02	MIDDLESEX	42 17	71 25W	171	07	07			INACTIVE 01/01/90
FRANKLIN	2997	02	NORFOLK	42 5	71 25W	240		08			MA WATER RESOURCES COMM
GARDNER	3052	02	WORCESTER	42 35	71 59W	1110		08			MA WATER RESOURCES COMM
GREAT BARRINGTON ARPT	3213	01	BERKSHIRE	42 11	73 24W	730	08	08			WALTER J KOLADZA
HARDWICK	3401	02	WORCESTER	42 21	72 11W	991		08			MA WATER RESOURCES COMM
HATCHVILLE	3471	03	BARNSTABLE	41 37	70 32W	69		08			MA WATER RESOURCES COMM
HAVERHILL	3505	02	ESSEX	42 46	71 4W	18	MID	MID		H	WASTEWATER TRTMT PLANT
HEATH	3549	01	FRANKLIN	42 40	72 49W	1590		08			RALPH DICKINSON
HINGHAM	3624	03	PLYMOUTH	42 14	70 55W	30	19	19		H	F ROBERT SKILLING
HOLYOKE	3702	02	HAMPDEN	42 12	72 36W	102		08			HOLYOKE WATER POWER CO
HYANNIS	3821	03	BARNSTABLE	41 40	70 18W	50	08	08		C H	TOWN-BARNSTABLE WWCF
IPSWICH	3876	03	ESSEX	42 40	70 52W	80		08			MA WATER RESOURCES COMM
KNIGHTVILLE DAM	3985	01	HAMPSHIRE	42 17	72 52W	630	07	07		C H	US CORPS OF ENGINEERS
LANESBORO	4075	01	BERKSHIRE	42 33	73 14W	1236	06	06		C H	ROBERT J WIRTES
LAWRENCE	4105	02	ESSEX	42 42	71 10W	60	08	08		H	ESSEX COMPANY
LOWELL	4313	02	MIDDLESEX	42 39	71 22W	110	07	07			CITY OF LOWELL
MARBLEHEAD	4502	03	ESSEX	42 30	70 52W	40	21	21		C H	RICK TRACY
MIDDLEBORO	4711	03	PLYMOUTH	41 53	70 55W	59		08			RICHARD E TINKHAM
MIDDLETON	4744	03	ESSEX	42 36	71 1W	90	16	16		H	DANVERS WTP
MILFORD	4760	02	WORCESTER	42 10	71 31W	280		08			MILFORD WATER COMPANY
NATICK	5175	02	MIDDLESEX	42 18	71 22W	150		07		H	JOHN SLAMIN

SEE REFERENCE NOTES FOLLOWING STATION INDEX

DAILY TEMPERATURES(°F)

NEW ENGLAND
SEPTEMBER 1990

STATION	OB. TIME	MAX/MIN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	AVERAGE
BEDFORD	MID	MAX	82	85	74	71	77	79	78	65	68	72	82	75	81	74	74	67	59	58	65	67	68	64	69	59	69	70	72	77	76	73		71.7
		MIN	54	62	54	50	50	59	60	44	37	59	57	63	60	63	55	47	44	36	34	48	42	51	51	43	40	50	52	54	58	57		51.1
BIRCH HILL DAM	08	MAX	80	82	86	73	73	77	79	75	68	70	75	82	77	82	73	70	65	55	57	63	66	67	68	65	56	67	70	74	75	76		71.5
		OBS																													***	***		
		MIN	44	55	55	40	42	55	56	36	31	36	49	49	60	59	61	42	41	28	27	28	32	32	35	40	31	31	41	42	41	52		42.4
		OBS										56																			***	***		
BLUE HILL	MID	MAX	83	84	69	66	78	78	77	61	71	72	81	73	76	76	76	68	57	58	63	67	68	61	68	58	68	70	72	77	76	73		70.8
		MIN	63	63	58	52	52	62	56	48	47	59	61	61	62	62	55	50	43	37	41	50	46	52	50	43	46	53	58	58	59	55		53.4
BUFFUMVILLE LAKE	08	MAX	81	82	85	72	71	79	78	78	66	69	77	81	74	81	76	76	66	56	58	62	67	68	60	67	57	67	70	75	76	77		71.7
		MIN	51	54	61	49	49	49	59	46	36	40	54	56	60	63	65	48	46	37	34	35	41	44	50	41	37	38	49	49	49	60		48.3
EAST BRIMFIELD LAKE	08	MAX	79	81	83	72	71	77	77	77	65	69	75	81	74	81	76	74	65	65	58	63	67	68	66	66	57	66	71	74	75	76		71.6
		MIN	51	59	61	48	50	58	59	44	38	47	54	54	60	60	64	48	45	35	34	34	39	40	40	41	37	43	51	46	47	57		48.1
		OBS										59																						
HAVERHILL	MID	MAX	83	85	73	68	79	80	77	69	69	76	82	76	78	72	76	66	58	58	66	67	69	64	68	60	70	72	71	75	78	71		71.9
		MIN	54	55	52	48	48	60	59	42	38	56	55	61	61	60	58	48	48	37	34	52	44	46	53	45	40	47	48	55	59	57		50.7
LAWRENCE	08	MAX	84	83	86	70	71	80	80	79	68	70	76	83	77	81	75	70	66	59	58	65	65	69	67	68	60	71	73	75	76	78		72.8
		MIN	54	54	59	55	54	57	62	47	41	41	56	57	63	61	64	49	48	39	38	40	45	50	53	45	41	44	53	53	56	55		51.1
		OBS																65																
LOWELL	07	MAX	82	83	88	76	76	81	81	78	70	72	76	83	77	83	76	78	69	69	59	68	68	69	66	70	59	71	74	75	80	79		74.5
		OBS		***							***														***									
		MIN	55	55	64	47	53	59	62	47	37	40	55	58	61	62	65	48	47	37	34	37	45	44	52	47	39	39	47	53	55	58		50.1
		OBS									***														***									
PEPPERILL	06	MAX	85	81	88	76	75	82	82	78	70	74	77	83	79	84	73	77	69	59	59	69	67	70	61	69	61	72	74	76	81	81		74.4
		MIN	49	50	58	44	44	53	60	42	32	33	53	52	59	58	63	44	43	35	31	33	38	38	47	42	36	35	42	48	51	51		45.5
READING	MID	MAX	82	85	73	71	78	78	78	66	70	72	81	76	80	72	75	66	58	58	66	68	68	63	69	58	71	71	73	77	77	74		71.8
		MIN	54	63	52	48	51	59	57	42	38	58	56	62	60	63	55	47	45	37	35	48	42	51	50	43	41	51	51	53	59	57		50.9
SOUTHBRIDGE 3 SW	07	MAX	78	80	80	70	70	75	77	77	65	68	72	79	74	78	74	73	63	53	55	60	64	63	59	64	57	64	66	70	72	74		69.1
		OBS	88																															
		MIN	50	51	60	49	49	56	58	48	37	37	58	58	61	61	63	47	47	37	34	35	41	42	49	40	37	37	42	45	45	57		47.7
TULLY LAKE	08	MAX	84	84	87	77	77	80	81	75	72	74	79	85	80	85	75	72	68	58	62	65	68	69	60	68	59	71	72	77	78	77		74.0
		OBS																														***		
		MIN	48	49	56	45	45	55	58	43	36	37	54	54	61	62	63	45	42	32	32	32	37	38	46	42	35	37	47	45	45	53		45.8
		OBS			46																											***		
WALPOLE 2	19	MAX	84	86	75	70	79	79	80	69	72	72	80	75	79	77	75	67	58	58	62	68	68	62	68	58	69	71	74	77	76	72		72.0
		MIN	53	63	62	48	50	58	67	48	37	59	56	60	60	63	60	49	47	37	34	52	41	50	52	42	39	50	53	50	59	61		52.0
WEST MEDWAY	07	MAX	82	84	86	74	72	85	80	80	69	73	76	85	76	82	78	77	78	60	62	66	70	70	62	71	59	70	72	79	79	79		74.5
		MIN	48	49	62	47	45	52	55	45	32	33	53	53	56	56	60	44	45	33	31	32	38	40	48	38	37	38	43	47	47	60		45.6
WORCESTER WSO AP	MID	MAX	79	81	70	68	74	75	74	63	68	74	79	74	79	72	70	62	52	54	60	62	63	57	64	54	65	69	71	74	74	71		68.4
		MIN	60	60	54	50	51	59	53	43	42	56	58	59	61	60	52	46	40	34	38	49	47	47	44	40	39	49	53	54	55	53		50.2
COASTAL 03																																		
BOSTON WSFO AP	MID	MAX	80	87	72	67	80	80	81	64	67	73	83	77	75	74	79	70	60	60	65	71	65	64	70	60	70	72	71	76	80	77		72.3
		MIN	63	67	62	56	56	64	61	52	48	63	62	63	63	65	61	56	50	44	45	55	52	56	56	50	48	56	58	55	61	58		56.9
BROCKTON	MID	MAX	85	88	74	69	80	81	81	65	71	74	83	83	79	80	78	73	59	59	65	70	71	71	70	61	70	73	78	79	78	75		74.1
		MIN	53	63	53	48	47	57	59	43	39	60	57	61	64	65	65	49	42	39	34	54	43	43	47	41	39	48	53	53	61	58		51.3
		OBS							69																									
CHATHAM WSMO	MID	MAX	75	77	71	66	72	76	75	65	68	68	76	66	72	65	74	70	61	59	64	69	65	65	69	62	66	67	70	71	69	67		68.7
		MIN	62	64	64	58	55	62	64	56	46	56	61	59	59	61	63	56	53	46	45	56	52	55	54	50	51	58	59	57	59	61		56.7
		OBS									56																							
EAST WAREHAM	MID	MAX	83	81	76	68	75	79	76	62	72	71	80	75	76	80	70	71	61	60	64	69	67	67	70	63	67	70	77	75	73	73		72.0
		MIN	57	67	62	48	45	57	65	45	40	60	57	61	66	66	59	54	48	42	37	51	44	56	53	46	42	55	56	52	60	58		53.6
EDGARTOWN	08	MAX	77	77	78	68	69	72	77	77	63	67	72	78	72	75	76	78	66	61	58	63	67	64	67	66	61	66	71	70	72	70		69.9
		MIN	55	61	67	62	48	58	62	56	54	56	57	60	62	65	65	53	55	46	41	53	53	53	57	45	43	50	56	51	54	61		55.3
HINGHAM	19	MAX	79	85	75	66	79	79	78	73	69	72	78	77	73	77	77	69	59	58	66	69	66	63	69	59	70	72	69	78	77	75		71.9
		MIN	53	64	62	52	47	58	68	47	37	61	57	62	62	64	62	48	49	40	36	54	42	50	54	43	42	50	53	51	59	61		52.9

SEE REFERENCE NOTES FOLLOWING STATION INDEX
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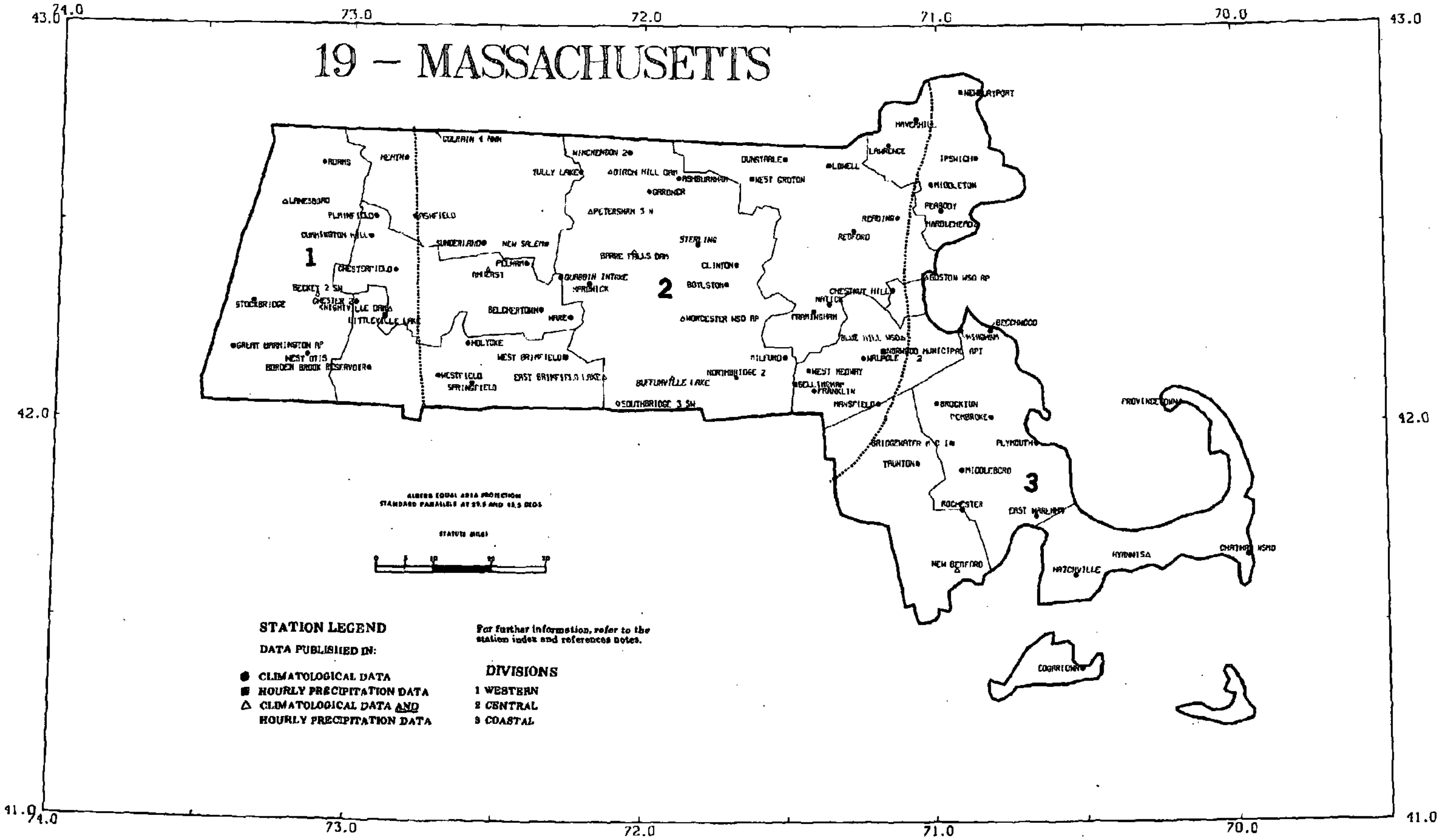
19 – MASSACHUSETTS



STATION LEGEND

DATA PUBLISHED IN:

- ● CLIMATOLOGICAL DATA
- ■ HOURLY PRECIPITATION DATA
- △ CLIMATOLOGICAL DATA AND HOURLY PRECIPITATION DATA

For further information, refer to the station index and references notes.

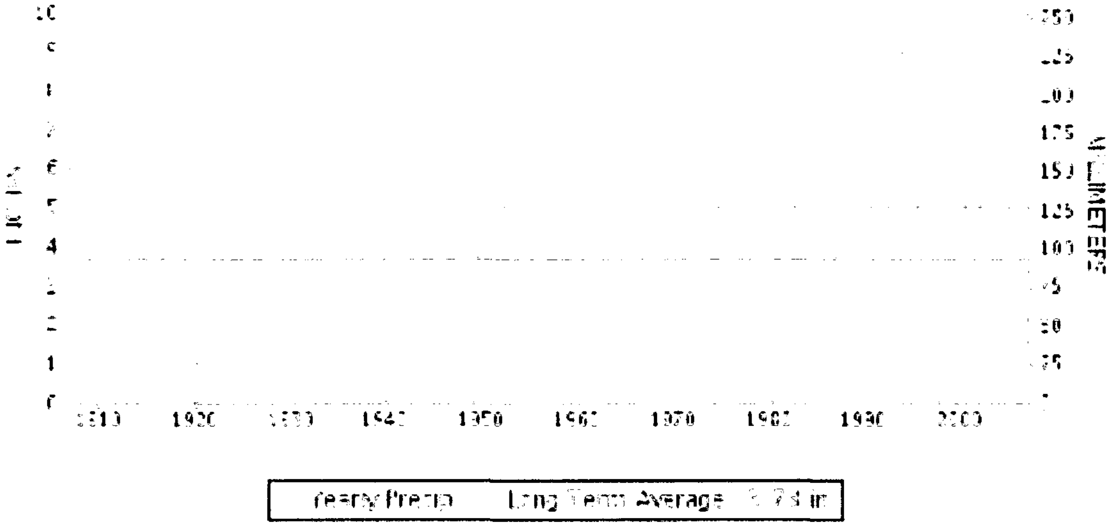
DIVISIONS

1 WESTERN
2 CENTRAL
3 COASTAL

CLIMATOLOGICAL DATA
NEW ENGLAND

SEPTEMBER 2007
VOLUME 119 NUMBER 09
ISSN [illegible]

SEPTEMBER PRECIPITATION BY YEAR



TEMPERATURE AND PRECIPITATION EXTREMES

[illegible]			
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]		[illegible]
[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

"I certify that this is an official publication of the National Oceanic and Atmospheric Administration (NOAA). It is compiled using information from weather observing sites supervised by NOAA National Weather Service and received at the National Climatic Data Center (NCDC), Asheville, North Carolina 28801."

Thomas R. Karl
Director
National Climatic Data Center

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National
Oceanic and
Atmospheric Administration

National
Environmental Satellite, Data
and Information Service

National
Climatic Data Center
Asheville, North Carolina

NEW ENGLAND
SEPTEMBER 2007

MONTHLY STATION AND DIVISION SUMMARY

STATION	TEMPERATURE (°F)	PRECIPITATION (IN)
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
EAST BRIMFIELD LAKE	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
HAVERHILL	[illegible]	[illegible]
LAWRENCE	[illegible]	[illegible]
LOWELL	[illegible]	[illegible]
MAYNARD	[illegible]	[illegible]
NATICK	[illegible]	[illegible]
READING	[illegible]	[illegible]
SOUTHBRIDGE 3 SW	[illegible]	[illegible]
TULLY LAKE	[illegible]	[illegible]
WALPOLE 2	[illegible]	[illegible]
WESTBOROUGH	[illegible]	[illegible]
WORCESTER WSO AP	[illegible]	[illegible]
DIVISIONAL DATA	[illegible]	[illegible]
COASTAL 03		
BEVERLY	[illegible]	[illegible]
BOSTON WSO AP	[illegible]	[illegible]
BRIDGEWATER	[illegible]	[illegible]
BROCKTON	[illegible]	[illegible]
CHATHAM	[illegible]	[illegible]
EAST WAREHAM	[illegible]	[illegible]
EDGARTOWN	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
HINGHAM	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
TAUNTON	[illegible]	[illegible]
DIVISIONAL DATA	[illegible]	[illegible]
NEW HAMPSHIRE		
NORTHERN 01		
[illegible]	[illegible]	[illegible]
BERLIN	[illegible]	[illegible]

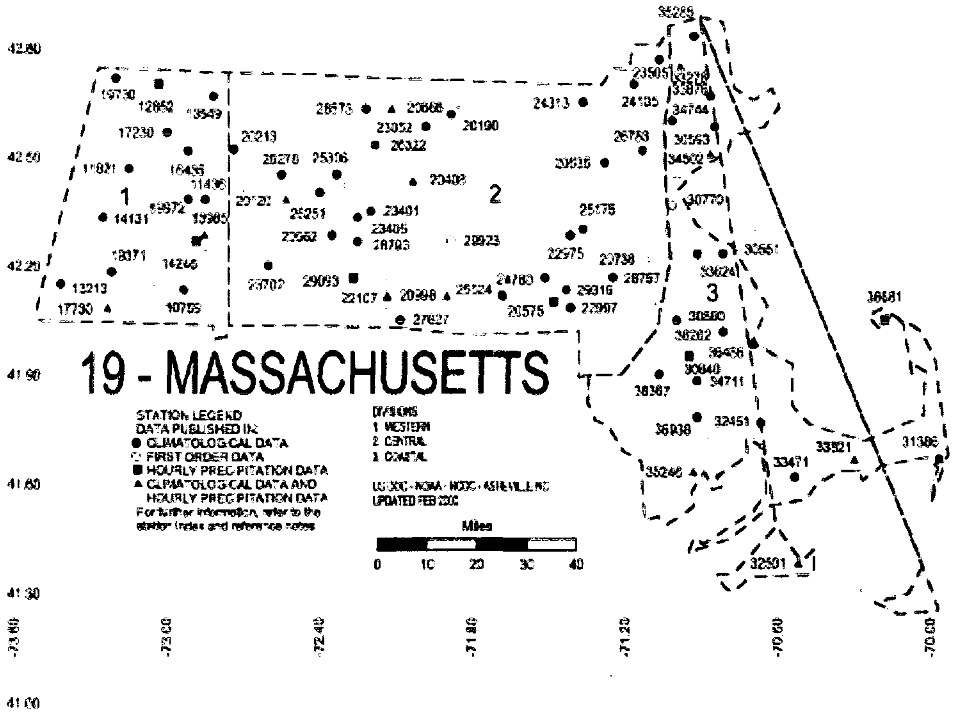
NEW ENGLAND
SEPTEMBER 2007

DAILY PRECIPITATION (INCHES)

STATION	TOTAL	DAY OF MONTH
MASSACHUSETTS		
WESTERN 01		
DALTON	3.83	[illegible]
LENOX DALE	1.7?	[illegible]
SANDY	M	[illegible]
WORTHINGTON	2.18	[illegible]
CENTRAL 02		
AMHERST	2.5?	[illegible]
ASHBURNHAM	3.26	[illegible]
ASHFIELD	2.5?	[illegible]
BARRE FALLS DAM	2.82	[illegible]
BEDFORD	2.14	[illegible]
BELCHERTOWN	2.09	[illegible]
BIRCH HILL DAM	4.56	[illegible]
BLUE HILL	1.89	[illegible]
BRIMFIELD LAKE	M 2.00	[illegible]
EAST BRIMFIELD LAKE	1.54	[illegible]
FRANKLIN	1.95	[illegible]
GREENFIELD	3.81	[illegible]
HARDWICK	3.45	[illegible]
HAVERHILL	M	[illegible]
LAWRENCE	2.58	[illegible]
LOWELL	3.7?	[illegible]
MAYNARD	2.04	[illegible]
MILFORD	2.15	[illegible]
NATICK	1.84	[illegible]
NEWBURYPORT	2.43	[illegible]
READING	2.97	[illegible]
SOUTHBRIDGE 3 SW	1.29	[illegible]
SUNDERLAND	3.48	[illegible]
TULLY LAKE	3.08	[illegible]
WALPOLE 2	2.10	[illegible]
WARE	2.44	[illegible]
WESTBOROUGH	2.24	[illegible]
WORCESTER WSO AP	1.98	[illegible]
COASTAL 03		
BEVERLY	3.14	[illegible]
BOSTON WSO AP	1.81	[illegible]
BRIDGEWATER	1.57	[illegible]
BROCKTON	2.96	[illegible]
CHATHAM	2.91	[illegible]

DAILY TEMPERATURES (°F)

STATION	OB TIME	MAX/MIN	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	AVERAGE
[illegible] LAKE	[illegible]	MAX	[illegible]				[illegible]	[illegible]	[illegible]	[illegible]					[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]											M
		MIN	[illegible]				[illegible]	[illegible]	[illegible]	[illegible]			[illegible]		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]											M
EAST BRIMFIELD LAKE	[illegible]	MAX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
		MIN																																M
		OBS																											[illegible]					
[illegible]	[illegible]	MAX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
		OBS	[illegible]																															
		MIN	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
		OBS				[illegible]					[illegible]																							
HAVERHILL	[illegible]	MAX																																M
		MIN																																M
LAWRENCE	[illegible]	MAX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
		MIN	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
		OBS									[illegible]							[illegible]					[illegible]											
LOWELL	[illegible]	MAX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
		OBS					[illegible]																								[illegible]			
		MIN	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
MAYNARD	[illegible]	MAX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
		MIN	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
NATICK	[illegible]	MAX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
		OBS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
		MIN	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
		OBS				[illegible]			[illegible]																									
READING M	MID	MAX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
		MIN	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
SOUTHBRIDGE 3 SSW	[illegible]	MAX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
		OBS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	***	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	***		
		MIN	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]
TULLY LAKE	[illegible]	MAX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
		MIN	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
WALPOLE 2	[illegible]	MAX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
		MIN	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
WESTFIELD 3 SW	[illegible]	MAX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
		OBS	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
		MIN	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
WORCESTER WSO AP M	MID	MAX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
		MIN	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
COASTAL 03																																		
BEVERLY	[illegible]	MAX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
		MIN	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
BOSTON WSO AP M	MID	MAX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]



APPENDIX C – FROM-TO LAND COVER CHANGES

Change Matrix Category	Pixel Count	September 8th, 1990 Land Cover Class From	September 7th, 2007 Land Cover Class To	Class Change (In Acres)
1	306127	Developed	Developed	51,429.34
2	25083	Developed	Bareland	4,213.94
3	91230	Developed	Forest	15,326.64
4	14849	Developed	Grassland	2,494.63
5	5110	Developed	Water	858.48
6	178	Developed	Wetland	29.90
7	12726	Bareland	Developed	2,137.97
8	15927	Bareland	Bareland	2,675.74
9	31731	Bareland	Forest	5,330.81
10	12213	Bareland	Grassland	2,051.78
11	5179	Bareland	Water	870.07
12	346	Bareland	Wetland	58.13
13	77277	Forest	Developed	12,982.54
14	30190	Forest	Bareland	5,071.92
15	3100779	Forest	Forest	520,930.87
16	93874	Forest	Grassland	15,770.83
17	32524	Forest	Water	5,464.03
18	956	Forest	Wetland	160.61
19	46394	Grassland	Developed	7,794.19
20	20527	Grassland	Bareland	3,448.54
21	182024	Grassland	Forest	30,580.03
22	80228	Grassland	Grassland	13,478.30
23	8517	Grassland	Water	1,430.86
24	1485	Grassland	Wetland	249.48
25	2858	Water	Developed	480.14
26	628	Water	Bareland	105.50
27	17339	Water	Forest	2,912.95
28	1138	Water	Grassland	191.18
29	114122	Water	Water	19,172.50
30	84	Water	Wetland	14.11
31	243	Wetland	Developed	40.82
32	249	Wetland	Bareland	41.83
33	1313	Wetland	Forest	220.58
34	434	Wetland	Grassland	72.91
35	1978	Wetland	Water	332.30
36	423	Wetland	Wetland	71.06

1 Landsat Thematic Mapper Pixel = 28.5 Meters or 0.168 Acres

APPENDIX D – RECOMMENDED BUFFER GUIDELINES

Range of Recommended Buffer Widths for Waterways

Aquatic Habitat			
Function		Reference	Minimum width (each side of stream)
Temperature regulation and shade	Shade	FEMAT 1993	100 ft
	Shade	Castelle et al. 1994	50-100 ft
	Shade	Spence et al. 1996	98 ft
	Shade	May 2000	98 ft
	Shade	Osborne and Kovacic 1993	33-98 ft
	Shade/reduce solar radiation	Brosofske et al. 1997	250 ft.
	Control temperature by shading	Johnson and Ryba 1992	39-141 ft
Bank stabilization and sediment control	Bank stabilization	Spence et al. 1996	170 ft
	Sediment removal and erosion control	May 2000	98 ft
	Ephemeral streams	Clinnick et al. 1985	66 ft
	Bank stabilization	FEMAT 1993	½ SPTH
	Sediment control	Erman et al. 1977	100 ft
	Sediment control	Moring 1982	98 ft
	Sediment removal	Johnson and Ryba 1992	10 ft (sand) – 400 ft (clay)
	High mass wasting area	Cederholm 1994	125 ft
Pollutant removal	Nitrogen	Wenger 1999	50-100 ft
	General pollutant removal	May 2000	98 ft
	Filter metals and nutrients	Castelle et al. 1994	100 ft
	Pesticides	Wenger 1999	>49 ft
	Nutrient removal	Johnson and Ryba 1992*	13 – 141 ft
Large woody debris and organic litter	Large woody debris	FEMAT 1993	1 SPTH
	Large woody debris	Spence et al. 1996	1 SPTH
	Large woody debris	Wenger 1999	1 SPTH
	Large woody debris	May 2000*	262 ft
	Large woody debris	McDade et al. 1990	150 ft
	Small woody debris	Pollock and Kennard 1998	100 ft
	Organic litterfall	FEMAT 1993	½ SPTH
	Organic litterfall	Erman et al. 1977	100 ft
	Organic litterfall	Spence et al. 1996	170 ft

Terrestrial Habitat			
Function		Reference	Minimum width (each side of stream)
	Fish and Wildlife	FEMAT 1993	Two-site potential tree heights; 300 ft
	General wildlife habitat	May 2000	328 ft
Edge effect	Interior bird species	Tassone 1981	164 ft
	Neotropical migrants	Keller et al. 1993	328 ft
	Effect of increased predation	Wilcove et al. 1986	2,000 ft
	Noise reduction of a mature evergreen buffer	Harris 1985	20 ft
	Reduce commercial noise	Groffman et al. 1990	100 ft
LWD and structural complexity	Snags and downed wood	FEMAT 1993	1 SPTH outside the buffer
	Width necessary to minimize nonnative vegetation	Hennings 2001	650 ft
Movement corridors	Travel corridor for red fox and marten	Small 1982	328 ft
	Minimum to allow for interior habitat species movement	Environmental Canada 1998	328 ft
Microclimate	Maintain microclimate	May 2000	328 ft
	Prevent wind damage	Pollock and Kennard 1998	75 ft
	Approximate natural conditions	Brosofske et al. 1997	250 ft
	Maintain microclimate	Knutson and Naef 1997	200-525 ft
	Maintain humidity and soil temperature	Chen et al. 1995	98-787 ft
	Maintain microclimate	REMAT 1993	3 SPTH

By: Metro (Authors Carol Krigger, Malu Wilkinson, Lori Hennings)
Source: Oregon Planners' Journal, Vol. 18, No. 2, June/July 2001

Acronyms:

Acronyms:	SPTH:	Site Potential Tree Height
	NMFS:	National Marine Fisheries Service
	NRCS:	National Resource Conservation Service
	USFWS:	U.S. Fish and Wildlife Service
	FEMAT:	Forest Ecosystem Management Assessment Team

Aquatic Habitat			
Function		Reference	Minimum width (each side of stream)
Aquatic Wildlife	Cutthroat trout	Hickman and Raleigh 1982	98 ft
	Brook trout	Raleigh 1982	98 ft
	Chinook salmon	Raleigh et al. 1986	98 ft
	Rainbow trout	Raleigh et al. 1984	98 ft
	Cutthroat trout, rainbow trout and steelhead	Knutson and Naef 1997	50 – 200 ft
	Maintenance of benthic communities (aquatic insects)	Erman et al. 1977	100 ft
	Shannon index of macroinvertebrate diversity	Gregory et al. 1987	100 ft
	Trout and salmon influence zone (Western Washington)	Castelle et al. 1992	200 ft

Terrestrial Habitat			
Function		Reference	Minimum width (each side of stream)
Wildlife needs	Willow flycatcher nesting	Knutson and Naef 1997	123 ft
	Frogs and salamanders	NRCS 1995	100 ft
	Full complement of herpetofauna	Rudolph and Dickson 1990	>100 ft
	Belted Kingfisher roosts	USFWS HEP Model	100 -200 ft
	Deer	NRCS 1995	200 ft
	Smaller mammals	Allen 1983	214 – 297 ft
	Birds	Jones et al. 1988	246 – 656 ft
	Beaver	NRCS 1995	300 ft
	Minimum distance needed to support area-sensitive neotropical migratory birds	Hodges and Krementz 1996	328 ft
	Western pond turtle nests	Knutson and Naef 1997	330 ft
	Pileated woodpecker	Castelle et al. 1992	450 ft
	Bald eagle nest, roost, perch. Nesting ducks, heron rookery and sandhill cranes.	Castelle et al. 1992	600 ft
	Pileated woodpecker nesting	Small 1982	328 ft
	Mule deer fawning	Knutson and Naef 1997	600 ft
	Rufous-sided towhee breeding populations	Knutson and Naef 1997	656 ft

Range of Recommended Buffer Widths for Waterways

Aquatic Habitat			
Function		Reference	Minimum width (each side of stream)
Temperature regulation and shade	Shade	FEMAT 1993	100 ft
	Shade	Castelle et al. 1994	50-100 ft
	Shade	Spence et al. 1996	98 ft
	Shade	May 2000	98 ft
	Shade	Osborne and Kovacic 1993	33-98 ft
	Shade/reduce solar radiation	Brosofske et al. 1997	250 ft.
	Control temperature by shading	Johnson and Ryba 1992	39-141 ft
Bank stabilization and sediment control	Bank stabilization	Spence et al. 1996	170 ft
	Sediment removal and erosion control	May 2000	98 ft
	Ephemeral streams	Clinnick et al. 1985	66 ft
	Bank stabilization	FEMAT 1993	½ SPTH
	Sediment control	Erman et al. 1977	100 ft
	Sediment control	Moring 1982	98 ft
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Large woody debris and organic litter	Large woody debris	FEMAT 1993	1 SPTH
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