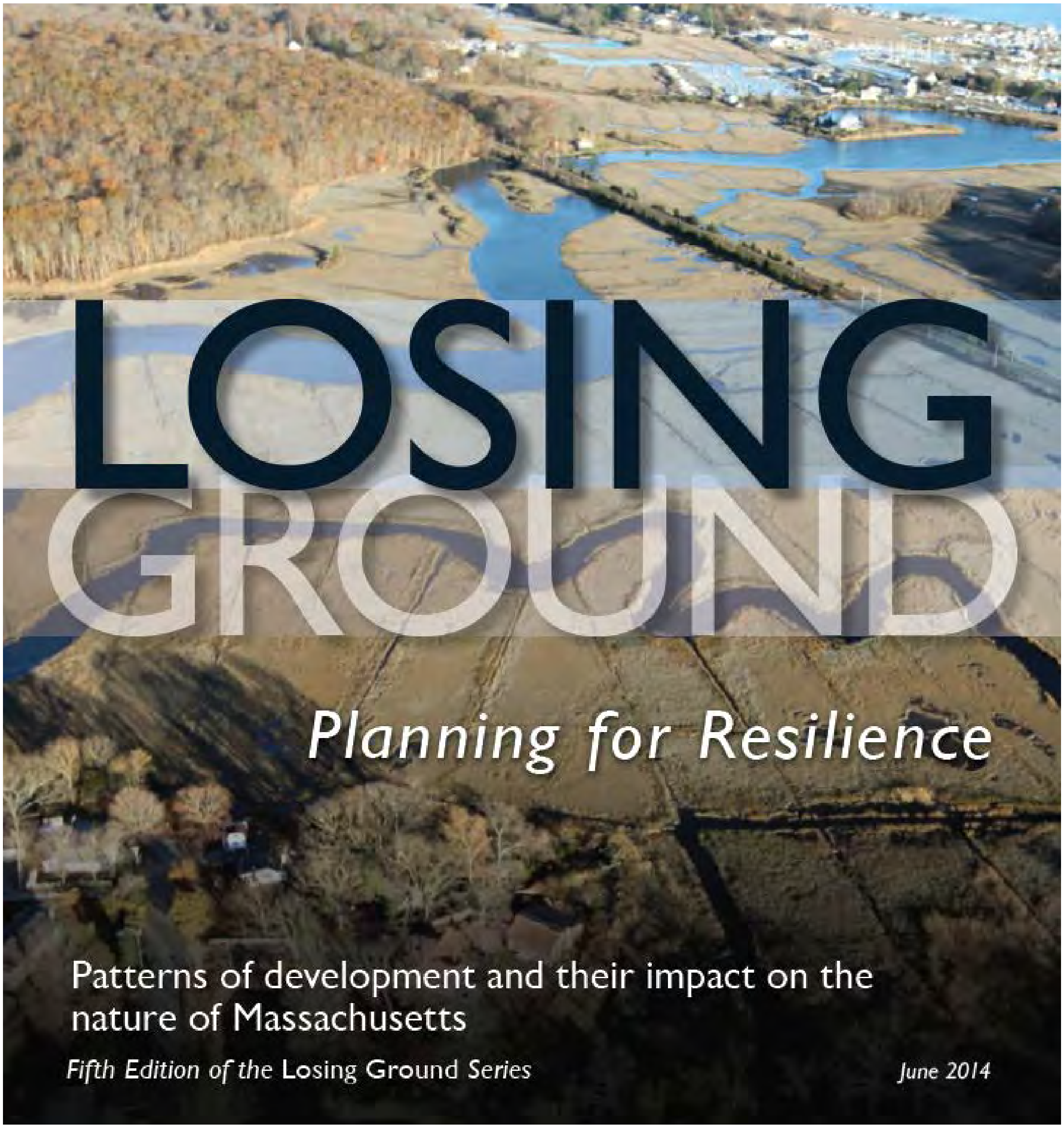

Technical Report

Mass Audubon
Protecting the Nature of Massachusetts

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The analysis presented in *Losing Ground: Planning for Resilience* (Lautzenheiser et al. 2014) relies on four foundational datasets: the land use change model created by the Boston University Department of Earth & Environment; the catalogue of conserved open space recorded in the Protected and Recreational OpenSpace datalayer from MassGIS; the terrestrial climate change resilience model for Massachusetts developed by The Nature Conservancy (TNC)-Massachusetts Chapter; and the model of priority conservation lands identified in the Natural Heritage and Endangered Species Program (NHESP)/TNC's *BioMap2*. Combining these datasets to obtain an accurate representation of the effects of land use change on the various conservation-related resources necessarily involved many decisions and assumptions that affect the reported results. In turn, the four datasets themselves rest on their own assumptions and decisions, as do their constituent parts. This report describes the various datasets and documents important assumptions, and includes the processing steps used to conduct the *Losing Ground* analysis. All spatial analyses (with the exception of those conducted in the development of the land use change model) were completed with ArcGIS 10.1 or 10.2 software. Additionally, this report describes the analyses of land use planning and zoning techniques in the 37 communities in the 495/MetroWest Development Compact Plan (495 Plan) region, reported in Chapter 4 of the main report.

We are grateful to the following supporters who provided funding for *Losing Ground: Planning for Resilience*: Alces Foundation, American Planning Association—Massachusetts Chapter, Franz and Anne Colloredo-Mansfeld, Epsilon Associates, Inc., Horsley Witten Group, Inc., Susan and Christopher Klem, Massachusetts Association of Planning Directors, Open Space Institute, Judy A. Samelson and William Schawbel, and U.S. Green Building Council—Massachusetts Chapter.

The main report and interactive maps and data are available at: www.massaudubon.org/losingground.

Section 1: Land Cover Change Detection, Classification and Area Estimation

Valerie Pasquarella, June 2014.

The fifth edition of *Losing Ground* is the first report in the series to use time series of Landsat observations for mapping land cover and estimating land cover change. The land cover information was produced in partnership with Boston University (Principal Investigator: Curtis Woodcock) using the Continuous Change Detection and Classification (CCDC) algorithm (Zhu and Woodcock 2014, Zhu et al. 2012).

I. Background & System Characteristics

The Landsat program is a joint effort of the U.S. Geological Survey (USGS) and National Aeronautics and Space Administration (NASA). Since the launch of Landsat 1 in 1972, Landsat satellites have been continuously monitoring the Earth's land surface, building a historical archive of earth observation unparalleled in quality, detail, coverage, and length. The newest Landsat satellite, the Landsat Data Continuity Mission (LDCM), also known as Landsat 8, was just launched in 2013 to continue the legacy of the Landsat program. The LGV analysis presented in this report utilizes data from Landsat 4, Landsat 5, and Landsat 7.

Temporal Resolution: Landsat satellites orbit north to south over the sunlit side of the Earth, imaging the surface of the Earth along a 115-mile-wide swath. Each of the three Landsat satellites used in this study makes a complete orbit every 99 minutes, circling the Earth about 14 times per day and imaging every point on its surface once every 16 days. Between 1999 and 2013, the simultaneous operation and offset orbits of Landsat 5 and Landsat 7 allowed for repeat coverage of the same location every 8 days, doubling the number and frequency of Earth observations available for this period.

Spectral Resolution: The Landsat Thematic Mapper (TM) sensors carried by Landsat 4 and Landsat 5, and the Enhanced Thematic Mapper Plus (ETM+) sensor carried by Landsat 7 are designed to measure light reflectance in 7 portions of the electromagnetic spectrum, typically referred to as "bands". The Landsat spectral bands extend beyond the visible color spectrum perceivable by the human eye into the longer near- and mid-infrared wavelengths, allowing for improved discrimination of land cover types/features (see Table 1.1, Figure 1.1(c)). The TM/ETM+ sensors used in this study also have a thermal band that acquires temperature information.

Table 1.1: Landsat TM and ETM+ band designations. Adapted from the USGS Landsat Project Fact Sheet (http://pubs.usgs.gov/fs/2012/3072/fs2012-3072.pdf)

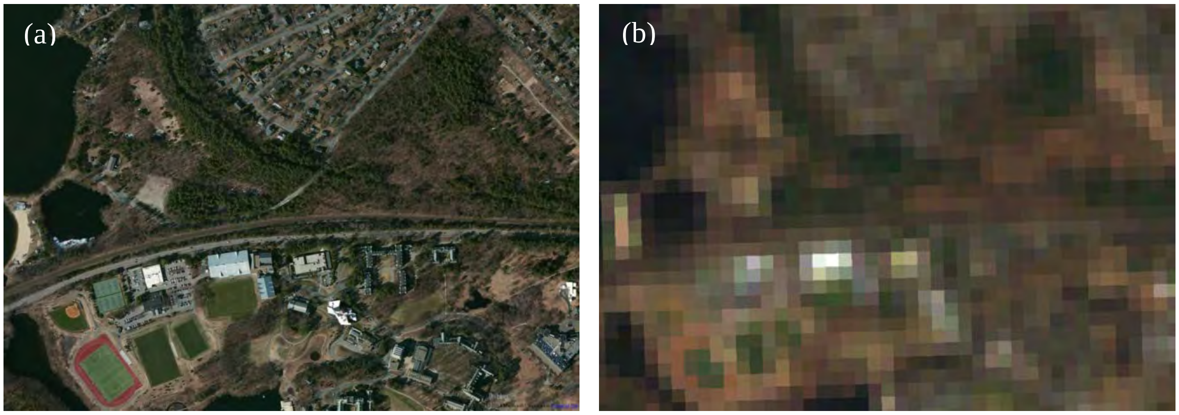
Spectral Band	Wavelength (micrometers)	"Color"	Use
Band 1	0.45-0.52	Blue-green	Distinguishing soil from vegetation; deciduous from conifer vegetation
Band 2	0.52-0.61	Green	Emphasizes peak vegetation, which is useful for assessing plant vigor
Band 3	0.63-0.69	Red	Emphasizes vegetation slopes
Band 4	0.76-0.90	Near-Infrared (NIR)	Emphasizes biomass content and shorelines
Band 5	1.55-1.75	Short-wave Infrared 1 (SWIR1)	Discriminates moisture content of soil and vegetation; penetrates thin clouds
Band 7	2.08-2.35	Short-wave Infrared 2 (SWIR2)	Useful for thermal mapping and estimated soil moisture
Band 6	10.40-12.50	Thermal Infrared	Useful for mapping hydrothermally altered rocks associated with mineral deposits

Spatial Resolution: Spectral reflectance in TM/ETM+ Bands 1 to 5 and 7 is measured over an areal unit, or "pixel" size, of 30m x 30m, while the thermal band (Band 6) is measured at a slightly courser resolution (120m x 120m for Landsat 4 and Landsat 5; 60m x 60m for Landsat 7). As shown in Figure 1.1, the spectral reflectance value for each pixel in a Landsat image represents an average reflectance of all features within that pixel. Though Landsat is unable to resolve (distinguish) features at the sub-pixel scale such as individual houses or tree crowns, its spatial resolution is well suited for analysis of large-scale land cover and land cover change.

II. Data & Pre-processing

A 2008 change in the Landsat data distribution policy has made all new and archived data held by the USGS freely available online (Woodcock et al. 2008). For the *Losing Ground* land cover analysis, all available Level 1 Terrain (L1T) Landsat TM/ETM+ imagery with less than 80% cloud cover for the five Landsat scenes covering Commonwealth of Massachusetts (Figure 1.2) was downloaded via the USGS EROS Science Processing Architecture (ESPA) Global Land Suface (GLS) Visualization Interface - (http://espa.cr.usgs.gov/ui/). Scenes distributed through ESPA are georeferenced, terrain-corrected, and radiometrically calibrated across Landsat sensors, enabling direct comparison of reflectance values of individual pixels over time. All imagery also underwent standard preprocessing steps to reduce unwanted/ephemeral noise in the signal. Atmospheric effects were removed and observations were converted to surface reflectance using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) (Masek et al. 2006), and the Fmask 3.2 algorithm (Zhu and Woodcock 2012) was used to automatically identify and mask clouds, cloud shadows, and snow.

Figure 1.1: Three views of a Massachusetts landscape



(a) Aerial photo, 30cm pixels

(b) Landsat "true color" composite, 30m pixels
Red=Band 3 (red) reflectance
Green=Band 2 (green) reflectance
Blue=Band 1 (blue) reflectance

(c) Landsat "false color" composite, 30m pixels
Red=Band 4 (NIR) reflectance
Green=Band 3 (red) reflectance
Blue=Band 2 (green) reflectance
Note: Vegetation appears red in false color composites due to strong reflectance in the NIR.

III. Change Detection & Classification

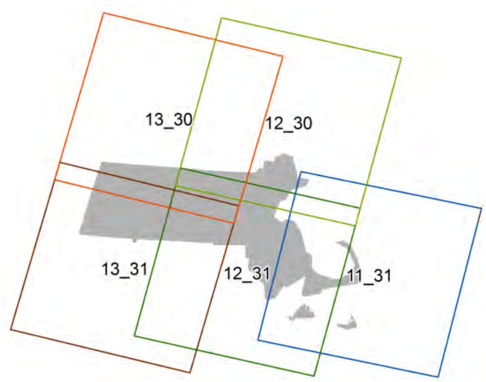


Figure 1.2: Massachusetts Scene IDs, labeled by WRS-2 Path_Row

Change detection and classification was performed using the CCDC algorithm version 9.3 (Zhu and Woodcock 2014, Zhu et al. 2012). The CCDC algorithm uses complete time series of Landsat surface reflectance to detect pixel-level changes in the landscape and to characterize land cover types over continuous time horizons. The CCDC analysis proceeds in two steps:

Change Detection: During the change detection stage, an 8-parameter Fourier model with terms for slope, intercept, and three sine/cosine harmonics is iteratively fit to time series of surface reflectance observations for each pixel in the image dataset. At each fitting step, the observed values are compared to the modeled fit. If surface reflectance significantly deviates from the predicted values more than three times in a row, a change point is flagged, and a new model is initialized. The end result is a time series for each band of each pixel segmented into one or more stable periods, each with its own Fourier model.

Classification: Once the model fits have been determined, the 56 Fourier fit parameters (8 parameters x 7 bands) for each stable segment are used to classify (label) the associated land cover. A Random Forest Classifier (RFC) trained with ground truth examples from across the state was used to generate thematic land cover maps. The ground truth examples used for the *Losing Ground* analysis represent a modified version of a 16-class dataset produced by Clark University and previously used to calibrate the HERO Massachusetts Forest Monitoring Program (MaFoMP) 2000 land cover product (Rogan et al. 2010). The stable land use/land cover classes used in *Losing Ground* and their definitions are provided in Table 1.2. Due to its continuous nature, the CCDC approach makes it possible to generate a land cover map for virtually any date in the time series; for *Losing Ground*, land cover maps were generated for April 1 of each year.

Table 1.2: Stable Land Use/Land Cover Class Definitions. Note: In the final analysis, Bare, Herbaceous/Grassland, and Agriculture classes were combined into a single "Open" class.

Class	Land Use/Land Cover Label	Description
1	**Bare***	Non-vegetated land comprised of above 60% rock, sand, or soil
1	**Herbaceous/Grassland***	Non-woody naturally occurring or slightly managed plants; includes pastures and hayfields
1	**Agriculture***	Non-woody cultivated plants; includes cereal and broadleaf crops
2	**Commercial / Industrial / High-Density Residential**	Area of urban development; impervious surface area target 50-100%
3	**Low-Density Residential**	Area of residential urban development with significant vegetation; impervious surface area target 1-50%
4	**Forest**	Forested land with at least 40% tree canopy cover containing any mix of tree leaf or phonological type. This class includes both natural and cultivated or managed trees including orchards, tree farms, plantations, and landscaping. This class also includes forested wetlands, areas that may be seasonally or permanently inundated, provided that the percent tree cover is > 40%.
5	**Wetland**	Area of land covered by mostly non-woody, herbaceous vegetation with either seasonal or permanent inundation. This class includes saltwater and freshwater marshes; river, lake, and pond banks; as well as tidal rivers and mudflats.
6	**Water**	Areas of high water cover including lakes, ponds, rivers and oceans.
7	**Cranberry Bog**	Manmade cultivated cranberry bogs.

The CCDC process and results for just one of the 23,261,392 pixels in the Commonwealth are illustrated in Figures 1.3, 1.4, and 1.5. Figure 1.3 shows a time series of Google Earth imagery for an example pixel (30m x 30m square, outlined in red). This pixel was initially dominated by mixed forest (note seasonal differences between Panels 3b and 3c). Around 2006 (Panel 3d), the adjacent area is cleared to create a dirt road. By 2008 (Panel 3e), this road has been paved and the lot within the pixel boundaries has been partially cleared. By 2009 (Panel 3f), a house has been built on the cleared lot, completing the pixel's transition from forest to low-density residential housing.

Figure 1.3: Example of Land Cover Change as illustrated by Google Earth.

Figure 1.4 shows the CCDC change detection model fits in each of the seven Landsat bands for the same pixel shown in Figure 1.3. In these figures, black points represent the observed surface reflectance values, the point circled in red represents a marked change point, and the solid blue lines represent the CCDC Fourier model fit. Note the difference between the stable forest model (dark blue) and the subsequent low-density residential model (light blue), as well as the different model fits for the seven different Landsat bands.

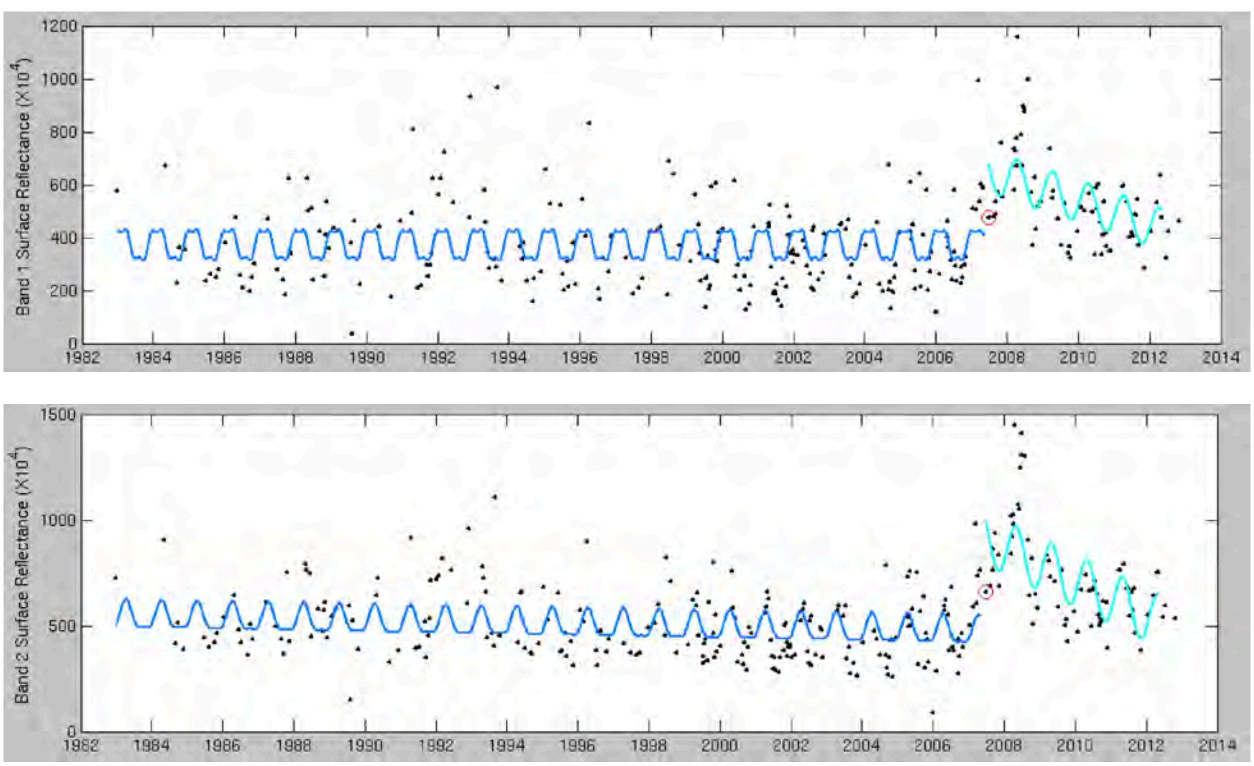


Figure 1.4: Surface reflectance data and CCDC model fit

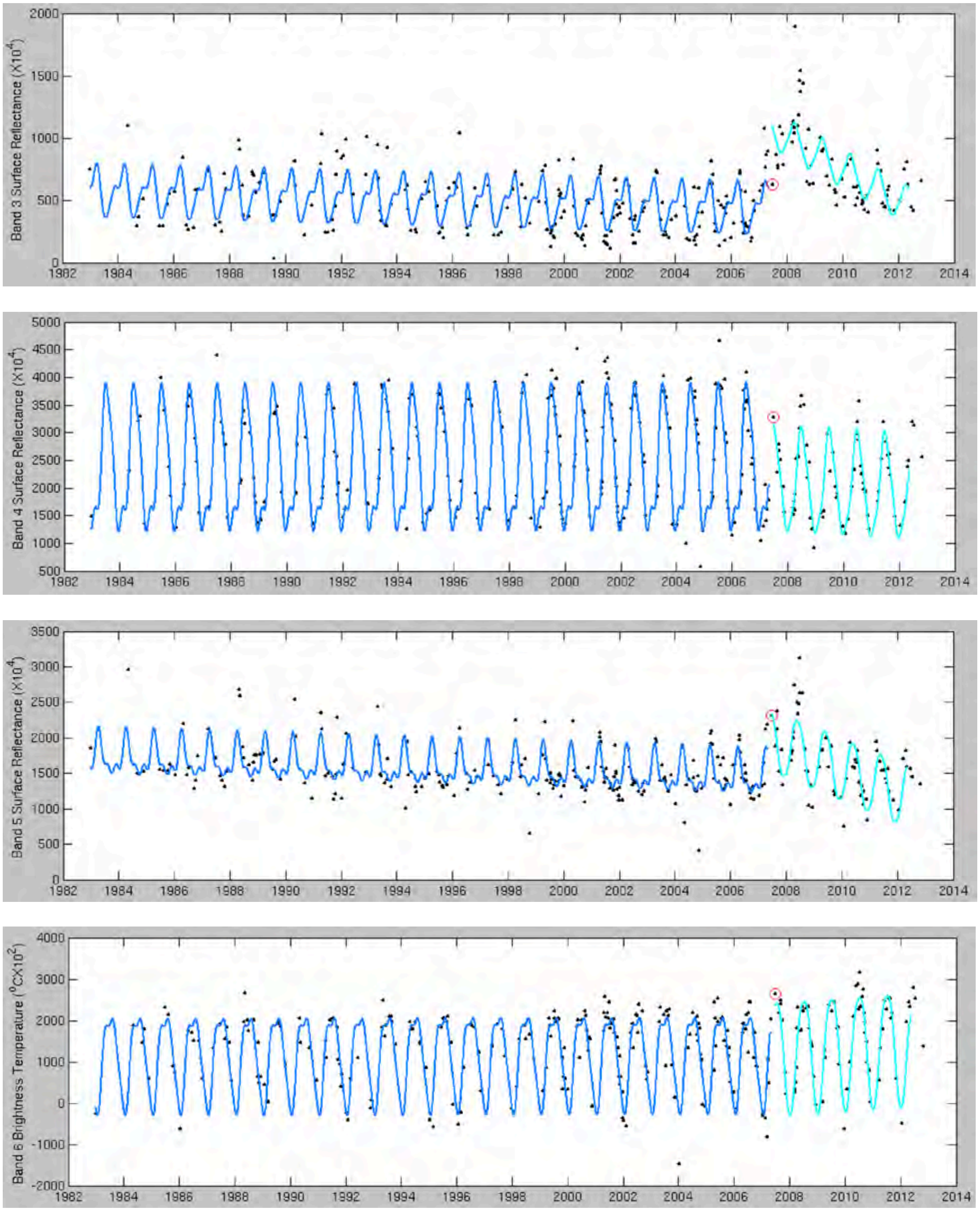


Figure 1.4: Surface reflectance data and CCDC model fit (cont'd).

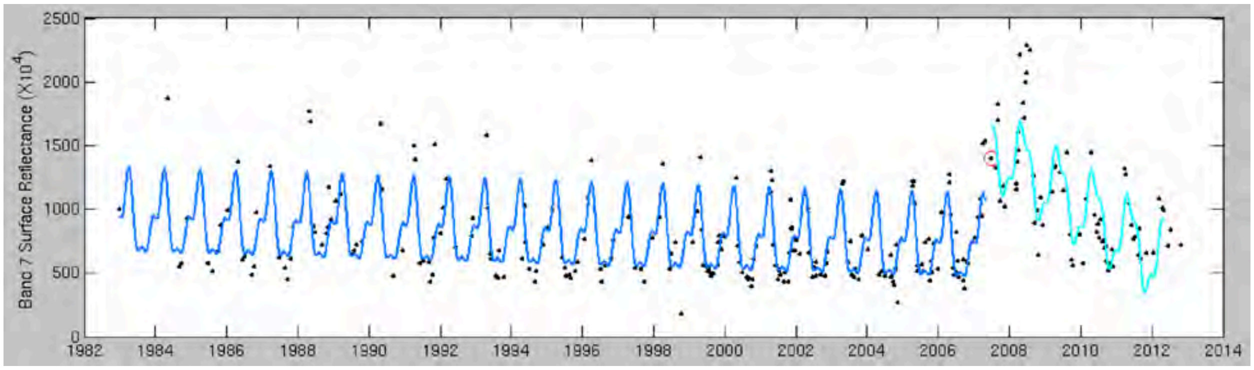


Figure 1.4: Surface reflectance data and CCDC model fit (cont'd).

Figure 1.5 shows the mapped CCDC results and corresponding Google Earth imagery for the landscape surrounding the pixel highlighted in Figure 1.3, again outlined in red. Panels 5a and 5b show the CCDC classification output for 2005 and 2013, respectively, while Panels 5d and 5e show the corresponding high-resolution imagery from Google Earth. Panel 5c provides a map of changed locations between the two periods.

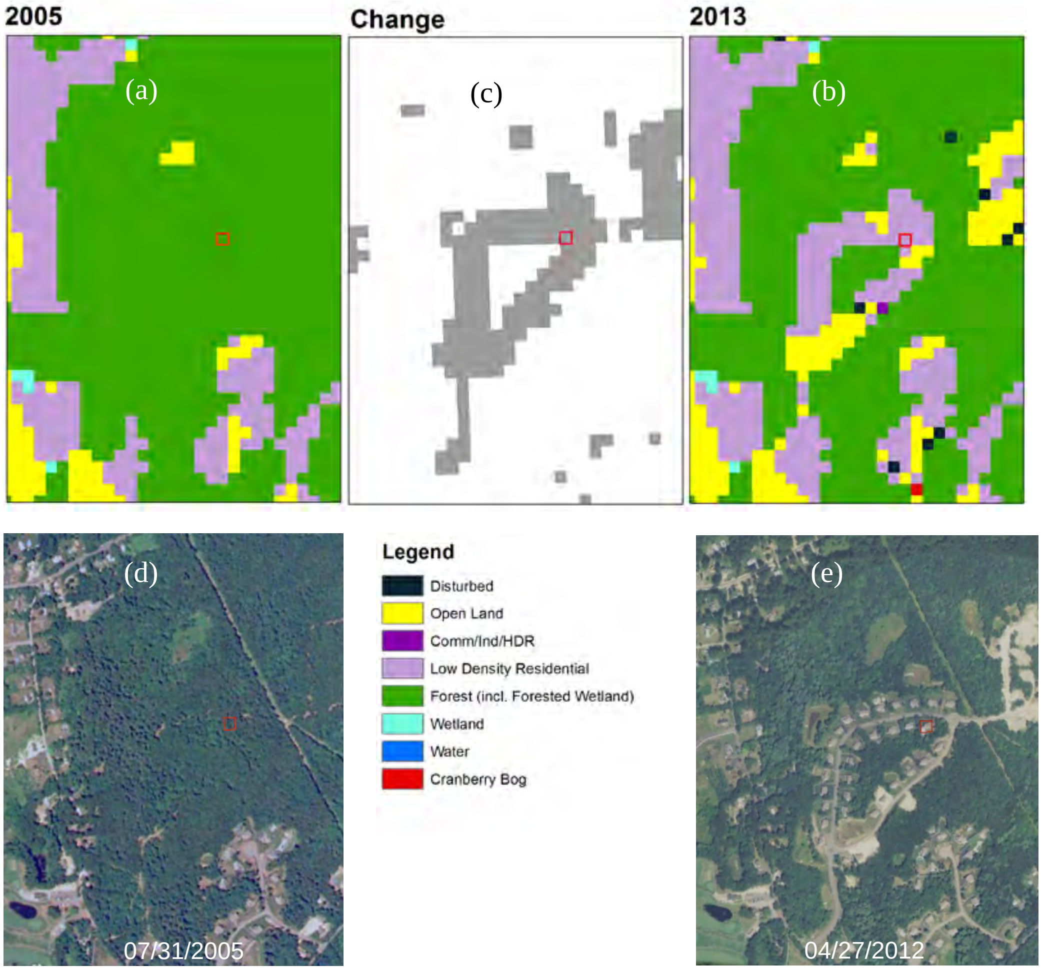


Figure 1.5: Classification Output and Google Earth Reference Data

IV. Area Estimation & Agreement Assessment

In the final stage of analysis, the change detection and classification results output by the CCDC were used to guide an area estimation and agreement assessment. A random stratified sample of 1,750 pixels was drawn based on seven stable and four change classes following the good practices outlined by Olofsson et al. (2014). Samples were allocated based on the proportional mapped area of each class, with a minimum of 50 samples per class.

Each pixel in the assessment sample was independently reviewed by three experts who used surface reflectance time series and historical Google Earth imagery to determine (a) whether the land cover of the pixel had changed, (b) if so, when the change occurred, and (c) the correct land cover label(s) (1 label for stable pixels; 2 labels [before and after] for changed pixels). The sample dataset was then compared to the corresponding map results to determine classification biases and compute adjusted estimates of class areas as well as 95% confidence intervals. The results of this analysis are provided in Table 1.3.

Table 1.3: Area Estimation and Agreement Assessment Results

Class	Class ID	% of Map Area	Mapped Area (in pixels)	Adjusted Area (in pixels)	95% Confidence Interval (in pixels)	Margin of Error	Adjustment %
"Open"	1	10.34%	2,405,288	2,479,261	262,973	10.61%	103.08%
Commercial / Industrial / HDR	2	4.16%	967,340	1,123,286	230,049	20.48%	116.12%
Low-Density Residential	3	16.80%	3,908,009	3,547,245	430,258	12.13%	90.77%
Forest	4	60.29%	14,023,683	13,824,799	418,300	3.03%	98.58%
Wetland	5	4.05%	941,494	915,236	112,007	12.24%	97.21%
Water	6	3.16%	734,142	748,747	72,064	9.62%	101.99%
Cranberry Bog	7	0.36%	84,744	53,115	12,694	23.90%	62.68%
Change in Forest Forest2Built + Forest2Open + Forest2Wetland + Forest2CBog	8	0.65%	151,765	225,621	54,941	24.35%	148.66%
Change in Built Forest2Built + Open2Built	9	0.35%	81,458	167,517	46,637	27.84%	205.65%
Change in Open Forest2Open - Open2Built	10	0.27%	62,299	49,988	13,957	27.92%	80.24%
Change in Other Forest2Wetland + Forest2Cbog	11	0.03%	8,008	8,116	4,561	56.19%	101.35%

Overall agreement between sample and map = 86.3%

V. Discussion

Landsat time series approaches such as the CCDC approach used for LGV represent a new paradigm for dynamic land cover mapping. While the LGV analysis made the best possible use of preexisting datasets such as the classification training dataset, which was adapted from a 16-class dataset previously produced by Clark University, there remains significant room for improvement as Landsat time series analysis methods continue to develop and evolve. Future work on land cover change analysis in Massachusetts will focus on developing new training datasets that capture the full range of landscape variability present in Landsat time series data (Kennedy et al. 2014) and reducing the margins of error in land cover/land cover area estimation.

VI. References

Kennedy, R.E., Andréfouët, S., Cohen, W.B., Gómez, C., Griffiths, P., Hais, M., Healey, S.P., Helmer, E.H., Hostert, P., Lyons, M.B., Meigs, G.W., Pflugmacher, D., Phinn, S.R., Powell, S.L., Scarth, P., Susmita, S., Schroeder, T.A., Schneider, A., Sonnenschein, R., Vogelmann, J.E., Wulder, M.A., & Zhu, Z. (2014). Bringing an ecological view of change to Landsat-based remote sensing. *Frontiers in Ecology and the Environment*.

Lautzenheiser, T.E., Collins, J.M., Ricci, E.H., & Clarke, J. (2014). Losing Ground: Planning for Resilience. Massachusetts Audubon Society, Inc., 32 pp.

Masek, J.G., Vermote, E.F., Saleous, N.E., Wolfe, R., Hall, F.G., Huemmrich, K.F.,Gao, F., Kutler, J., & Lim, T.. (2006). A Landsat Surface Reflectance Dataset for North America, 1990-2000. *IEEE Geoscience and Remote Sensing Letters*, 3(1), 68–72. doi:10.1109/LGRS.2005.857030

Olofsson, P., Foody, G.M., Herold, M., Stehman, S.V., Woodcock, C. E., & Wulder, M.A. (2014). Good practices for estimating area and assessing accuracy of land change. *Remote Sensing of Environment*, 148, 42-57.

Rogan, J., Bumbarger, N., Kulakowski, D., Christman, Z., Runfola, D.M., & Blanchard, S. D. (2010). Improving forest type discrimination with mixed lifeform classes using fuzzy classification thresholds informed by field observations. *Canadian Journal of Remote Sensing* 36(6), 699–708.

Woodcock, C.E., Allen, R., Anderson, M., Belward, A., Bindschadler, R., Cohen, W.B., Gao, F., Goward, S.N., Helder, D., Helmer, E., Nemani, R., Oreopouluos, L., Schott, J., Thenkabail, P.S., Vermote, E.F., Vogelmann, J., Wulder, M.A., & Wynne, R. (2008). Free access to Landsat Imagery. *Science* 320: 1011.

Zhu, Z., & Woodcock, C. E. (2012). Object-based cloud and cloud shadow detection in Landsat imagery. *Remote Sensing of Environment*, 118, 83–94.

Zhu, Z., Woodcock, C. E., & Olofsson, P. (2012). Continuous monitoring of forest disturbance using all available Landsat imagery. *Remote Sensing of Environment*, 122, 75–91.

Zhu, Z., & Woodcock, C. E. (2014). Continuous change detection and classification of land cover using all available Landsat data. *Remote Sensing of Environment*, 144(25), 152–171.

Section 2: Land Protection Analysis

Jeffrey Collins, June 2014.

I. Open Space

We used MassGIS Protected and Recreational OpenSpace data to report on land protection. This database includes parcels that are not permanently protected and includes some land under water. To limit our analyses to permanently protected land above water, we used the following Definition Query: "LEV_PROT" = 'P' AND "PRIM_PURP" <> 'U'.

We further limited OpenSpace data to parcels that were protected within our project timeframe. We used the CAL_DATE_R field to define the date of land protection. We created a new field called DateOut, selected all features where CAL_DATE_R was before April 30, 2005, and for those features set DateOut=0. We then switched the selection so that all features with CAL_DATE_R after April 1, 2005, were selected. We then manually deselected features where CAL_DATE_R was after April 30, 2013. The remaining selected features were set DateOut=1; these were the parcels used in our analysis. We chose to include only lands with CAL_DATE_R through April 30, 2013, to remain consistent with the period of our land cover change analysis. While the information in this field is very useful for tracking land protection over time, some dates may reflect a recent transaction that conveys additional protection to an already-protected parcel; for example, a state agency conservation restriction over town-owned land. This “belts-and-suspenders” approach increases protection of the land but may skew our statistics somewhat.

The total area of Massachusetts is 5,175,192 acres when calculated by summing the areas of towns as mapped by MassGIS; this includes all land and water bodies within the various town boundaries. However, since large water bodies are not shown as protected in the MassGIS data, we used a measure of *total land area* of the state when calculating percent of the state that is permanently protected. The U.S. Census 2010 block group datalayer from MassGIS includes the field ALAND10, which gives the area of *land* within each block in square meters. We summed this field and converted to acres to calculate a total Massachusetts land area of 4,992,032 acres.

II. *BioMap2*

The Massachusetts Natural Heritage and Endangered Species Program (NHESP) and The Nature Conservancy’s (TNC) Massachusetts Chapter developed *BioMap2* (Woolsey et al. 2010) to protect the state’s biodiversity in the context of projected effects of climate change. *BioMap2* combines NHESP’s 30 years of rigorously documented rare species and natural community data with spatial data identifying wildlife species and habitats that were the focus of MassWildlife’s 2005 State Wildlife Action Plan (SWAP). *BioMap2* also integrates The Nature Conservancy’s assessment of large, well-connected, and intact ecosystems and landscapes across the Commonwealth, incorporating concepts of ecosystem resilience to address anticipated climate change impacts.

Critical Natural Landscape (CNL) consists of 1,783,000 acres complementing Core Habitat, including large natural Landscape Blocks that provide habitat for wide-ranging native species, support intact ecological processes, maintain connectivity among habitats, and enhance ecological resilience. Buffering uplands around coastal, wetland, and aquatic Core Habitats also help ensure landscapes' long-term integrity.

BioMap2 identifies two complementary spatial layers, Core Habitat and Critical Natural Landscape. Core Habitat identifies key areas that are critical for the long-term persistence of rare species and other Species of Conservation Concern, as well as a wide diversity of natural communities and intact ecosystems across the Commonwealth. Protection of Core Habitats will contribute to the conservation of specific elements of biodiversity. Core Habitat includes:

- Habitats for rare, vulnerable, or uncommon mammal, bird, reptile, amphibian, fish, invertebrate, and plant species;
- Priority Natural Communities;
- High-quality wetland, vernal pool, aquatic, and coastal habitats; and
- Intact forest ecosystems.

Critical Natural Landscape identifies large natural Landscape Blocks that are minimally impacted by development. If protected, these areas will provide habitat for wide-ranging native species, support intact ecological processes, maintain connectivity among habitats, and enhance ecological resilience to natural and anthropogenic disturbances in a rapidly changing world. Areas delineated as Critical Natural Landscape also include buffering upland around wetland, coastal, and aquatic Core Habitats to help ensure their long-term integrity.

The long-term persistence of Massachusetts biological resources requires a determined commitment to land and water conservation. Protection and stewardship of both Critical Natural Landscapes and Core Habitats are needed to realize the biodiversity conservation vision of *BioMap2*.

More information can be found at the *BioMap2* website.

III. References

Woolsey, H., A. Finton, J. DeNormandie. 2010. BioMap2: Conserving the Biodiversity of Massachusetts in a Changing World. MA Department of Fish and Game/Natural Heritage & Endangered Species Program and The Nature Conservancy/Massachusetts Program.

Section 3: TNC Resilience Analysis

Jessica Dyson, December 2013

This analysis aims to identify the most resilient examples of key geophysical settings within Massachusetts. It draws on the methods and input data layers of The Nature Conservancy's regional resilience analysis, which is described in detail in the reports and materials available on the Conservation Gateway.

Four steps in this process are described here:

1) Defining Geophysical Settings
2) Rescaling Landscape Complexity and Landscape Connectedness
3) Calculating Resilience Scores
4) Stratification of Resilience Scores by Geophysical Settings

Unit of Analysis**:** The final scale of the resilience scores is a 90 meter grid cell, which is the resolution of the coarsest input layer. Geophysical settings and landscape complexity were each developed at a 30 meter scale, while landscape connectedness was developed at a 90 meter scale.

Z-scores: Throughout this analysis, metrics are consistently converted to standardized normalized scores (z-scores) so that each has a mean of zero and a standard deviation of 1. This ensures that datasets are on a common scale. Z-scores are obtained by subtracting the mean of a grid and dividing by the standard deviation. The units of z-scored grids are in standard deviations, for example a value of .5 means that cell is .5 standard deviations above the mean.

I. Defining Geophysical Settings:

Geophysical settings are combinations of geology types and elevation zones that correlate with species diversity patterns. The definition and mapping of geophysical settings for this project drew heavily on Ecological Land Units (ELUs), which were described and mapped by Charles Ferree and Mark Anderson (Anderson and Ferree 2010). In brief, ELUs are combinations of the following elevation, geology, and landform zones.

Table 3.1. Elevation zones used in resilience analysis

ELEVZONE	ZONE_DESC1	ZONE_DESC2
1000	< 20'	Coastal zone
2000	20-800'	Low elevation
3000	800-1700'	Low to mid elevation transitional
4000	1700-2500'	Mid to upper elevation transitional
5000	2500-3600'	High elevation
6000	> 3600'	Subalpine-alpine

Table 3.2. Geology zones used in resilience analysis

Geology	Geology Class	Geology Description
100	ACIDIC SEDIMENTARY / METASEDIMENTARY	Fine- to coarse-grained, acidic sed/metased rock
200	ACIDIC SHALE	Fine-grained acidic sedimentary rock with fissile texture
300	CALCAREOUS SEDIMENTARY / META-SEDIMENTARY	Basic/alkaline, soft sed/metased rock with high calcium content
400	MODERATELY CALCAREOUS SEDIMENTARY / METASED	Neutral to basic, moderately soft sed/metased rock with some calcium but less so than above
500	ACIDIC GRANITIC	Quartz-rich, resistant acidic igneous and high-grade meta-sedimentary rock; weathers to thin coarse soils
600	MAFIC / INTERMEDIATE GRANITIC	Quartz-poor alkaline to slightly acidic rock, weathers to clays
700	ULTRAMAFIC	Magnesium-rich alkaline rock
800	FINE SEDIMENTS	Fine-grained surficial sediments
900	COARSE SEDIMENTS	Coarse-grained surficial sediments

Table 3.3. Landform zones used in resilience analysis

LF_TYPE	LFTYPE_DES	Landform30	LF30_Desc
1	Summit/ridgetop	11	Flat summit/ridgetop
		13	Slope crest
2	Cliff/steep slope	5	Cliff
		4	Steep slope
3	Sideslope	23	Sideslope cooler aspect
		24	Sideslope warmer aspect
4	Cove/footslope	43	Cove/footslope cooler aspect
		44	Cove/footslope warmer aspect
		41	Flat at bottom of steep slope
5	Hill/valley: gentle slope	22	Hill (gentle slope)
		21	Hilltop (flat)
		32	Valley/toeslope
6	Dry flats	30	Dry flats
7	Wet flats	31	Wet flats
8	Open water	54	Chesapeake Bay, outer Delmarva shore
		52	Lake/pond/reservoir
		53	Lower rivers, Chesapeake Bay
		51	Stream/river

The first goal of this project was to develop a geophysical settings dataset at a 30 meter scale, drawing upon the ELU categories. Before attempting to crosswalk these categories to geophysical settings, we reviewed the data sources used for the ELUs to ensure that we were using the best available data for Massachusetts.

Geology - Bedrock: We found that the best digital bedrock geology layer available for Massachusetts is the 1:250 bedrock lithology data distributed by MassGIS. This data is derived from the same source data that was used to develop the regional ELU data. Although this data is coarse, we proceeded with this since it is the best currently available and captures the geologic patterns across the state.

Bedrock units were crosswalked into 7 general classes, following the crosswalk developed by Charles Ferree. That crosswalk is based on information about weathering properties, mineral content, texture, and hardness in the descriptions of bedrock units in the original USGS paper map from 2004. A general description of bedrock types is given in Table 3.2.

Geology - Surficial Sediments: The ELU dataset relies on a modeled approach to identify where surficial sediments are deep and mask the effect of underlying bedrock. In Massachusetts, we saw that in areas like the relatively flat coastal outwash of the Plymouth area this model did not capture the actual sediment pattern. Instead, we used a combination of statewide data sources for surficial sediments; the 1:24K USGS surficial sediments data obtained from MassGIS as well as 1:250K surficial sediments data, also distributed by MassGIS. The 1:24K layer does not cover the full extent of Massachusetts. The map below shows where data is available. In the Berkshires, the Worcester Plateau, and in the greater Boston area, the best data available is at 1:250K. Since the deep surficial sediments are mostly constrained to narrow river valleys in these areas, we felt comfortable using this data to fill in the gaps where the finer scale 1:24K data is not available.

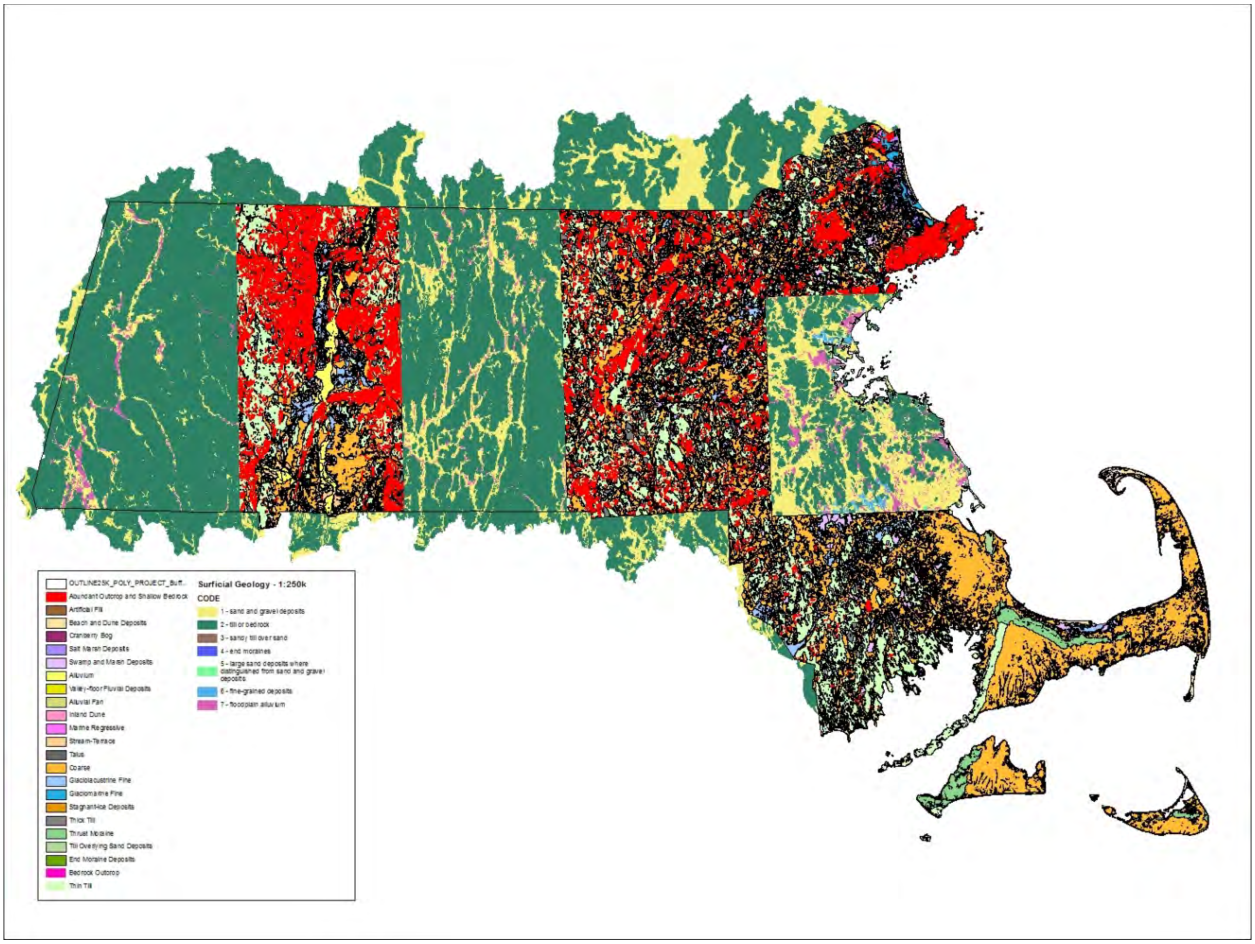


Figure 3.1. Surficial sediments in Massachusetts; data from MassGIS

For both surficial datasets, we classified sediments as either “coarse” or “fine”. Details on those classifications are given in Table 3.2 and Table 3.3. The 1:24K sediments consist of 4 data layers: till/bedrock, stratified deposits, postglacial deposits, and early postglacial deposits. These data layers stack on top of one another, from till/bedrock on the bottom to early postglacial sediments closest to the surface (with the exception of shallow bedrock outcrops that are at the very surface). The 4 datalayers were unioned together and a new field was created in the unioned dataset (Final Class), which is the uppermost sediment type in this stack. It includes only the surficial sediments that we are interested in capturing (i.e., it leaves out artificial fill, cranberry bogs, talus slopes). The final sediment type (fine or coarse) of an area is determined by the uppermost layer, as classified in Table 3.2. In a similar way, 1:250K surficial sediments were classified as “coarse” or “fine” as described in Table 3.3. Then coarse and fine sediments were combined with the bedrock dataset, and the resulting data converted to a 30 meter raster containing 9 geology classes.

Elevation: We classified the 1:5K MassGIS Digital Elevation Model (DEM) into the elevation zones used in the ELU dataset. Five zones occur in Massachusetts because there are no lands over 3,600 feet in elevation.

Landform: No modifications were made to the landforms mapped in the ELU dataset. Of those landforms only the "steep" slopes were used to define geophysical settings. However, landforms were used extensively in developing the landscape complexity metric in the following..

II. Crosswalking to geophysical settings

Elevation and the geology data were then combined into a single raster at a 30 meter resolution. We crosswalked these into the geophysical settings, using the 32 groups defined in the regional analysis as a starting point (see Table 3.4). In some cases regional geophysical settings did not apply to Massachusetts, such as shale bedrocks, which are not prevalent here. Since the regional analysis used 1,000-acre hexagons as the unit of analysis, some hexagons necessarily contained a mix of geologies and elevation zones. That resulted in some settings with mixed geologies such as "Low Elevation Granitic and Coarse Sand," which we chose not to use in our finer scale analysis. Where settings were altered in the Massachusetts analysis, they are noted with an asterisk in Table 3.4 and an explanation is given.

Beyond these alterations, we made several additional modifications to geophysical settings after reviewing the Massachusetts data on screen and by acreage. Our intention in grouping or splitting geology/elevation combinations was to identify settings that are truly ecologically unique.

The main differences from the regional settings were as follows.

- All bedrocks at high elevation (> 2,500 feet) were combined into a single setting, since they all have a very small extent. In addition, we thought the high elevation zone would be a stronger ecological driver than distinctions between calcareous, moderately calcareous, and sedimentary bedrocks.

- At mid-elevations, coarse and fine sediments are separate settings. This was done because they are distinct geophysical settings, and at this finer scale of analysis it was possible to split them apart whereas at the coarser 1,000-acre hexagon scale it was not.

- Ultramafic settings were grouped at low and mid-elevations. This has a very restricted range in Massachusetts. Yet since it is so ecologically distinct, we wanted to preserve it as a separate setting rather than combine it with another geology type.

- We considered splitting "mid-elevation" and "mid-high-elevation" zones but ultimately decided to maintain this grouping in this Massachusetts dataset. Although areas above 1,700 feet start to see a transition to more northern hardwoods species, we did not want to create more geophysical settings classes that would result in overstratifying the resilience results. We felt the 1700-foot threshold does not produce an ecological distinction dramatic enough to warrant splitting geophysical settings.

Once those edits were made, a final step was to identify and superimpose "Steep slopes" as a separate setting that overrode geology and elevation. Steep slopes and cliffs were selected from the landform types identified in the regional ELU dataset and compared to a slopes derived from the 1:5K

Massachusetts DEM. Since the regional ELU grid did a good job of capturing the steepest slopes shown in the Massachusetts DEM, we used the regional ELU data to define steep geophysical settings.

A few final modifications were done to make sure that the geophysical settings layer matched the extent of the landscape complexity and connectedness grids. A gap in the bedrock data in the southeast corner of the state was coded as mid-elevation moderately calcareous, and gaps along the northern coastline of Buzzards Bay were filled in with geology from the regional ELU dataset. Also, a buffer of 90 meters around the edge of the state was filled in with the geology values from the regional ELU dataset.

Table 3.7 and Figure 3.2 show the final set of 20 geophysical settings used in the Massachusetts analysis.

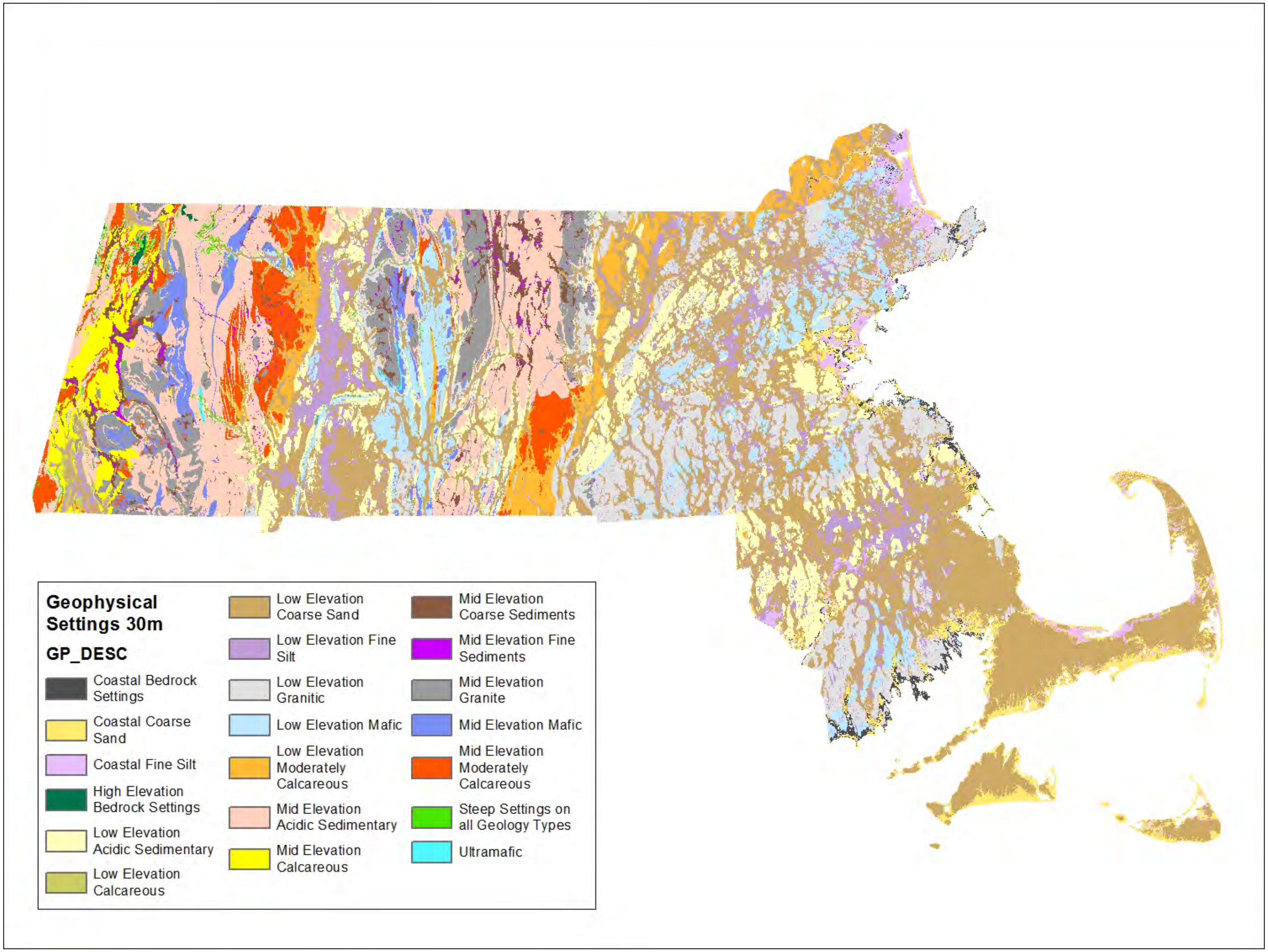


Figure 3.2. Geophysical settings in Massachusetts; data from MassGIS

III. Rescaling Landscape Complexity and Landscape Connectedness

Landscape Complexity

Landscape Complexity scores are based on landform variety, elevation range, and wetland density. Methods for developing each of those inputs are described in The Nature Conservancy's regional resilience report.

It was necessary to create a landscape complexity grid that has a standard normal distribution for Massachusetts (what exists as an input to the regional analysis is scaled to the region). To do this, the statewide extent was extracted from each of the regional input grids, rescaled (or z-scored) each, and combined according to the same formula used in the resilience report. That process is described for each of the input grids here.

- Wetland density is measured by the percentage of wetlands within both a 100-acre (denwet100f) and a 1,000-acre (denwet1000f) radius of each cell.

- For coastal areas where much of the area within the search radius was actually ocean, the density of wetlands is based on only the percent of the land area (not ocean area) within the search radius of each cell. For land areas with no wetlands within 100 acres, these areas were given values of zero.

- Each of these grids was extracted to the extent of Massachusetts (with a 90-meter buffer). They were then added together, with the 100-acre search radius weighted twice: (denwet100f x 2) + (denwet1000f). The resulting grid was log transformed, and divided by the maximum value, in order to approximate a normal distribution. The resulting grid has values ranging from 0-1, with a mean of 0.49 and a standard deviation of 0.25. Finally this grid was z-scored, using this mean and standard deviation, before being combined with the other landscape complexity inputs.

- We chose not to recalculate wetland density using the finer scale 1:12K Department of Environmental Protection (DEP) wetland data available in Massachusetts. The regional wetland density grids were based on National Wetlands inventory, National Land Cover Database (NLCD) 2001 wetlands, and Southern Atlantic Gap programs wetlands datasets. These datasets were compared onscreen, and the regional dataset appeared to capture most of the DEP wetlands, thus we did not feel it was warranted to generate new wetland density grids based on the Massachusetts wetland data.

1) Elevation range measures the elevation range in a 100-acre circle around a central cell and compares it to the regional average. To prepare this input the regional grid (elevrng_100ac) was extracted to the Massachusetts extent. Values for Massachusetts range from 0 to 435, with a

mean of 40.21 and a standard deviation of 37.19. This grid was z-scored before being combined with the other landscape complexity inputs.

2) The landform variety metric is a measure of topographic diversity that offers a variety of microclimates and moisture gradients. Scores in the landform variety grid reflect the number of landforms within a 100-acre radius of each cell, with the maximum possible 11 landform types. (Types are as follows: 1-Open water, 2-Summit or ridgetop, 3-Cliff, 4-Cool slope, 5-Warm slope, 6-Cove, 7-Low hilltop, 8-Low hill slope, 9-Valley toeslope, 10-Dry flats, 11-Wet flats). Values in Massachusetts ranged from 1 to 11, with a mean of 6.45 and a standard deviation of 1.42. The landform variety grid was extracted to Massachusetts extent and z-scored according to this mean and standard deviation.

Once input grids had been z-scored, the state was split into "flats" and "slopes" using landform categories from the ELU grid. "Flats" were landforms 1) hilltop (flat), 2) hill (gentle slope), 3) wetflat, 4) dry flat, and 5) valley/toeslope: gentle slope. "Slopes" were defined as all remaining landform types, excluding open water and streams.

Then the input grids were combined using the following formula:

Landscape Complexity= Flats (2*LV + 1* ER + 1 WD)/4) + Slopes (2*LV + 1* ER/3).

Where LV = landform variety, ER = elevation range, and WD = wetland density. Landscape Complexity was calculated separately for slopes and flats.

Landscape Complexity (slopes): mean .76, standard deviation .61

Landscape Complexity (flats): mean -.09, standard deviation .53

The two resulting grids were merged, and the final landscape complexity grid was z-scored *after* combining scores for flats and slopes, using the mean (.09) and standard deviation (.65) of the combined grid.

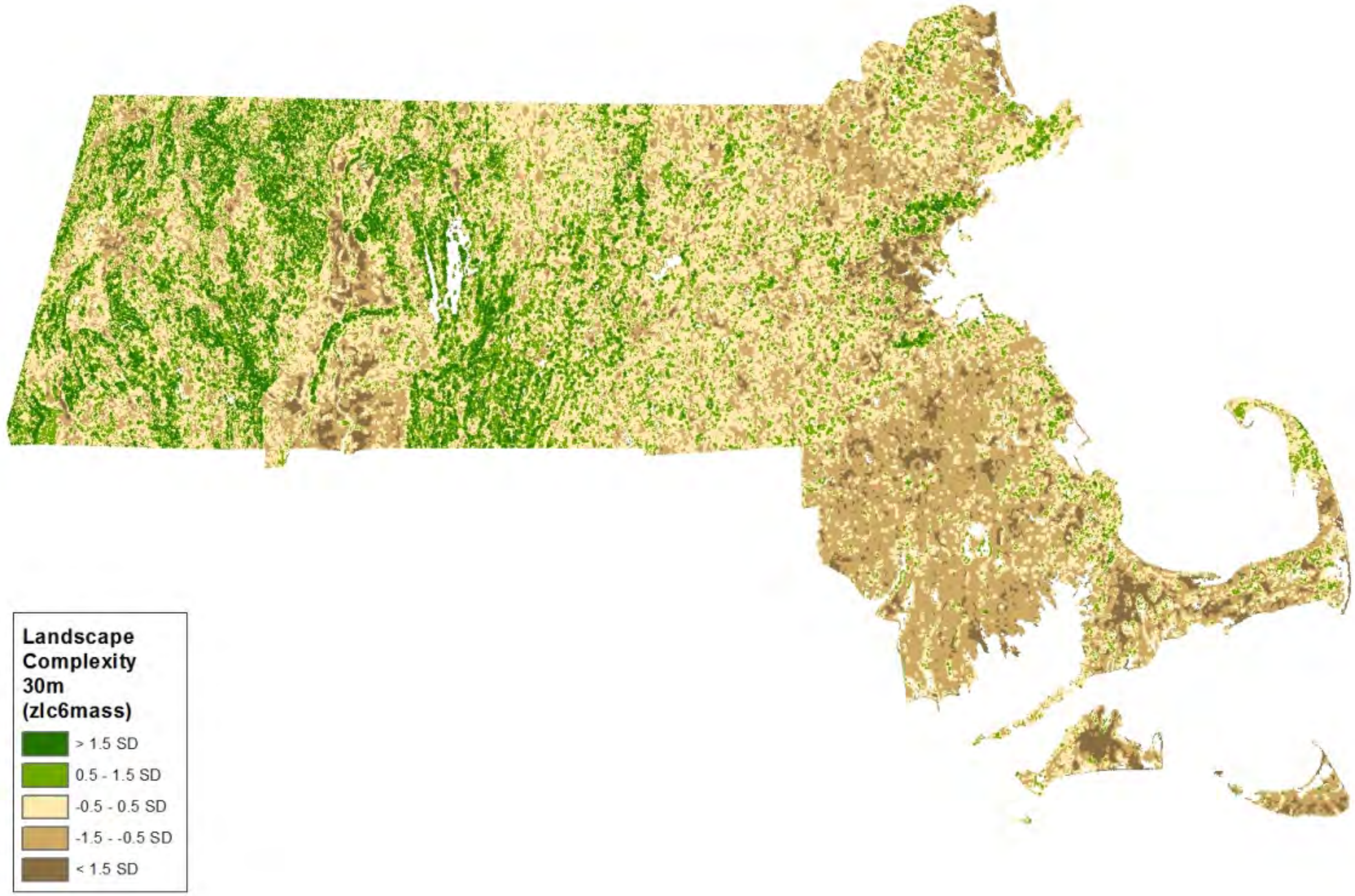


Figure 3.3. Landscape complexity.

Landscape Connectedness

The regional connectedness metric (prmlc_stdnrm) was extracted to Massachusetts. The extracted grid had values ranging from -1037 to 2165, with a mean of -405.63 and a standard deviation of 682.13. The extracted grid was z-scored, with the resulting grid shown in Figure 3.3.

We considered using the UMass Conservation Assessment and Prioritization System (CAPS) connectedness grid, which has a resolution of 30 meters, rather than the coarser regional metric. Upon comparison, the major patterns are consistent between the two datasets, but there are some discrepancies. Regional scores are much higher than the CAPS metric at the center of Martha's Vineyard, the Elizabeth Islands, the Wellfleet area on Cape Cod, and around the Quabbin Reservoir.

However, the UMass version is already stratified by ecological settings, and we did not want to "overstratify" the results. The UMass CAPS connectedness layer does not score areas that are developed. Based on an onscreen review of areas that were excluded, this seemed overly restrictive since it excluded areas of open fields and pastures that seemed relevant to terrestrial resilience.

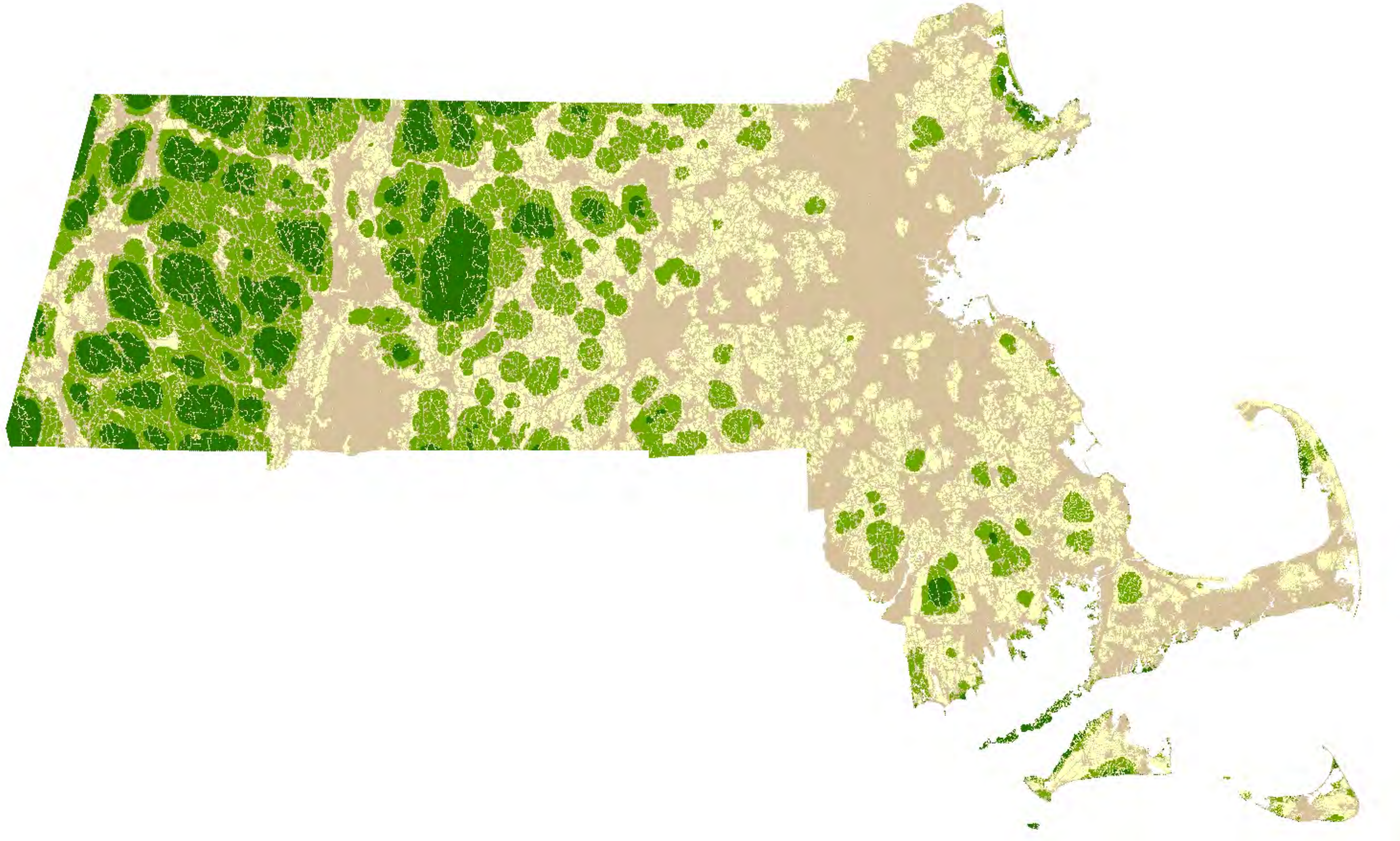


Figure 3.4. Landscape connectedness.

IV. Calculating Resilience Scores

The landscape connectedness grid and landscape complexity grids were combined according to the formula used in the regional analysis:

Estimated Resilience = (Landscape Complexity + Landscape Connectedness)/2

The resulting grid was recentered by z-scoring. The z-scored grid is shown in figure 3.5.

V. Stratification of Resilience Scores by Geophysical Settings

Resilience scores were stratified by the 20 geophysical settings defined for Massachusetts. Zonal statistics were used to find the mean and standard deviation of the estimated resilience scores for each setting. These statistics were then used to z-score each setting, so that final resilience scores are in z-score units around the mean for that particular setting. The final stratified scores are shown in Figure 3.6.

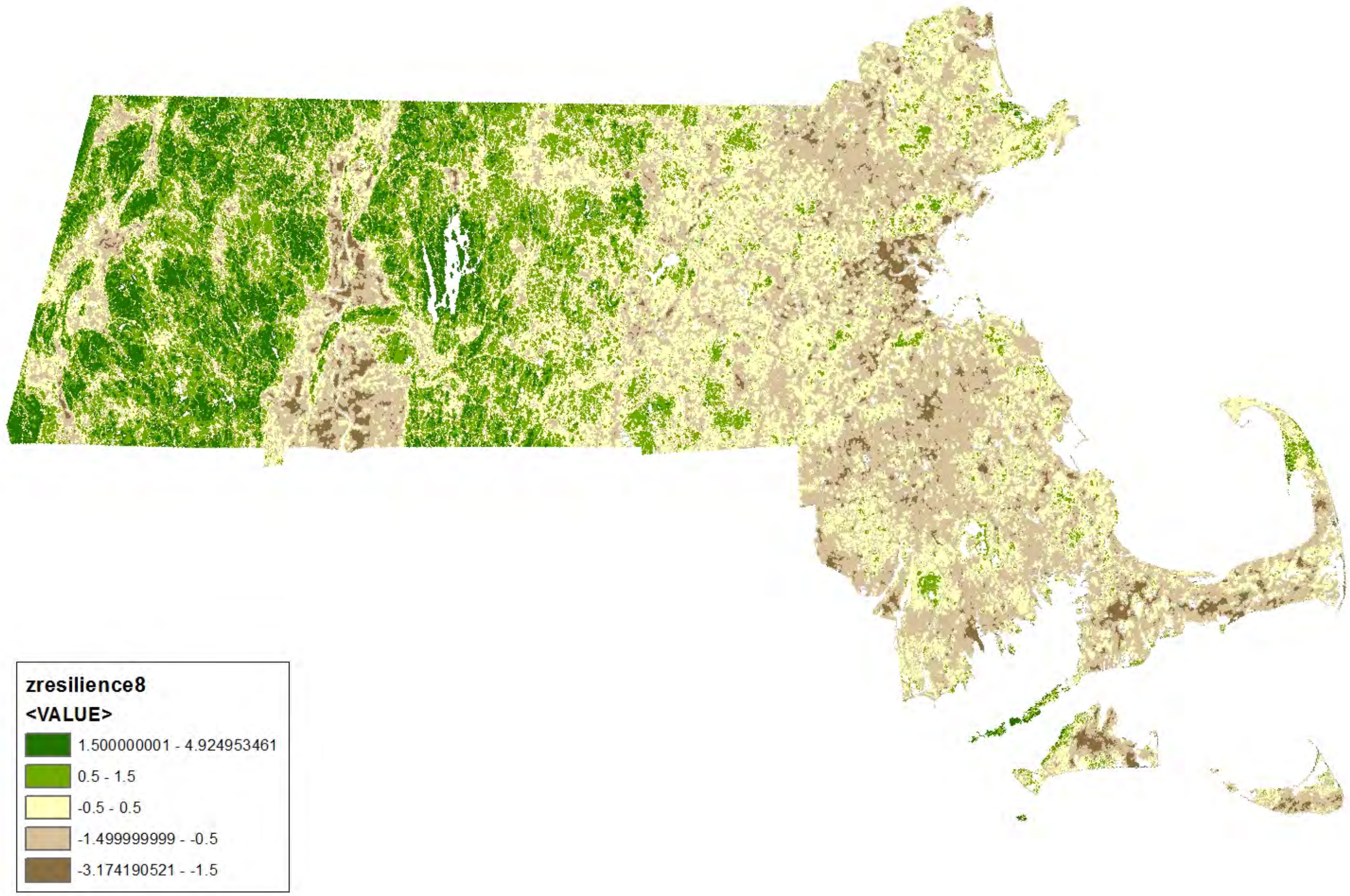


Figure 3.5. Estimated resilience scores (z-scored)

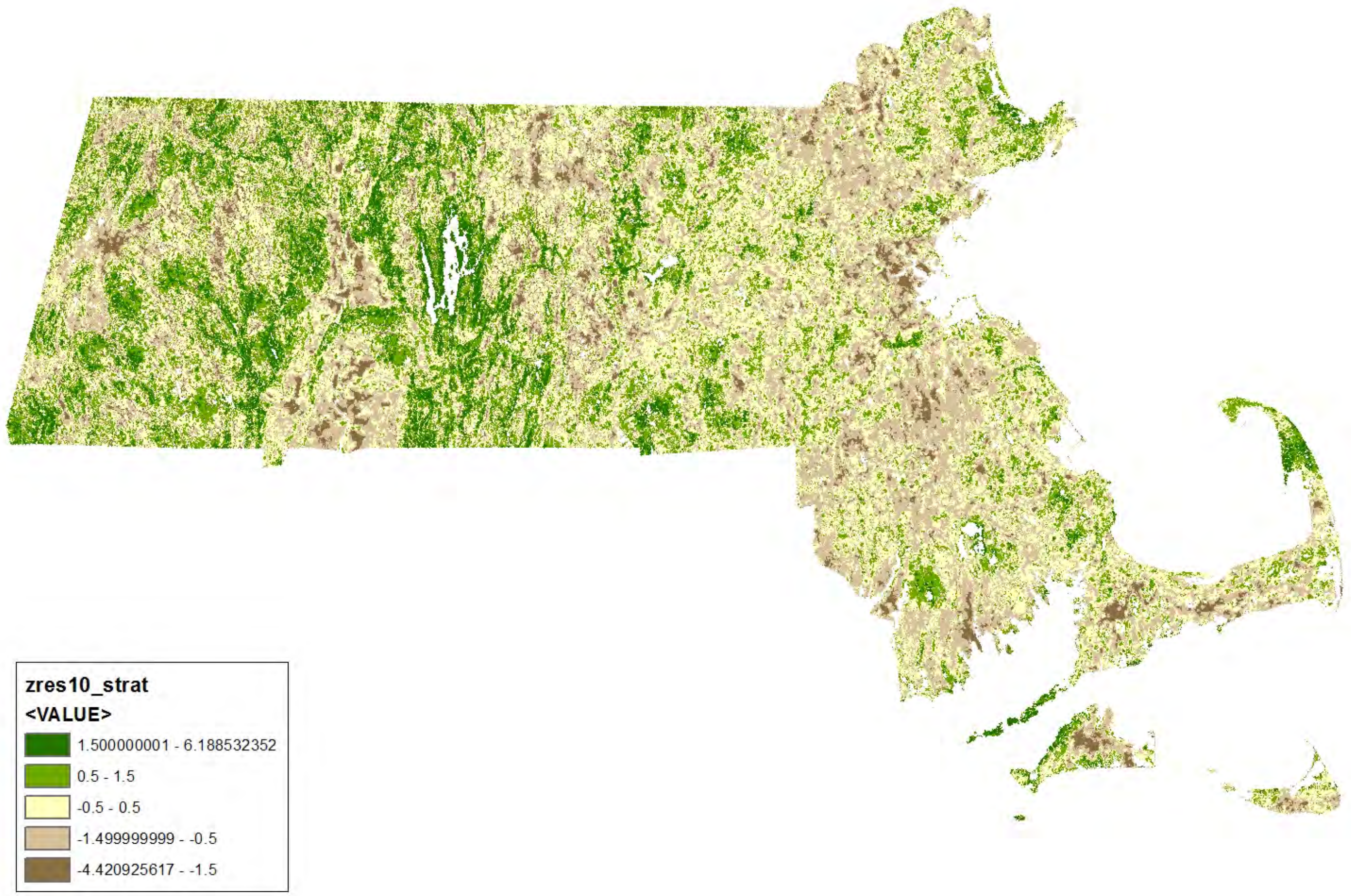


Figure 3.6. Estimated resilience scores, stratified by geophysical settings

Table 3.4. Geophysical Settings from Regional Analysis. This table lists the 32 Geophysical Settings used in the regional analysis. Where settings were altered in the Massachusetts analysis, they are noted with an asterisk.

Geophysical Setting Code	Description	Change made in Massachusetts
EDGE*	Edge Cells	Did not need because of fine resolution of data
L:COAST	Coastal Bedrock Settings	
L:COAST/COARSE	Coastal Coarse Sand	
L:COAST/FINE	Coastal Fine Sand	
L:SED	Low Elevation Acidic Sedimentary	
L:CALC	Low Elevation Calcareous	
L:COARSE	Low Elevation Coarse Sand	
L:FINE	Low Elevation Fine Silt	
L:GRAN	Low Elevation Granite	
L:GRAN/CALC*	Low Elevation Granitic and Calcareous	Split apart Granitic and Calcareous
L:GRAN/COARSE*	Low Elevation Granitic and Coarse Sand	Split apart Granitic and Coarse Sand
L:MAFIC	Low Elevation Mafic	
L:MODCALC	Low Elevation Moderately Calcareous	
L:SED/COARSE	Low Elevation Sedimentary and Coarse Sand	
L:SHALE*	Low Elevation Shale	Does not occur in Massachusetts
L:ULTRA*	Low Elevation Ultramafic	Grouped with Mid Elevation Ultramafic because of small extent
M:CALC	Mid Elevation Calcareous	
M:GRAN	Mid Elevation Granite	
M:MAFIC	Mid Elevation Mafic	
M:MODCALC	Mid Elevation Moderately Calcareous	
M:SED	Mid Elevation Sedimentary	
M:SHALE*	Mid Elevation Shale	Does not occur in Massachusetts
M:SURF*	Mid Elevation Surfical Sediments	Split apart fine and coarse sediments
M:ULTRA*	Mid Elevation Ultramafic	Grouped with Low Elevation Ultramafic
H:CALCMOD*	High Elevation Calcareous and Moderately Calcareous	Grouped with High Elevation Bedrock
H:GRAN*	High Elevation Granite or Mafic	Does not occur in Massachusetts
H:SED/CALC	High Elevation Mixed Sedimentary and Calcareous	
H:SED	High Elevation Sedimentary	
H:ULTRA*	High Elevation Ultramafic	Does not occur in Massachusetts
H:SHALE*	Settings on stable and unstable Shale Slopes	Does not occur in Massachusetts
STEEP:SED	Steep Slopes on all Sedimentation	
ALP:ALL	Alpine and Subalpine	Does not occur in Massachusetts

Table 3.5. Crosswalk of Surficial Sediments. All data from MassGIS at http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/

Data Source	Sediment Type Crosswalk	Metadata description
Till Bedrock: SURFGEO24K_TB_POLY .shp		
Sb – areas of abundant outcrop and shallow bedrock	Bedrock	Areas of shallow bedrock or areas where small outcrops are too numerous to map individually; in areas of shallow bedrock surficial materials are less than 5 - 10 ft thick.
Postglacial Deposits: SURFGEO24K_PG_POLY .shp		
'Af' – artificial fill	Not included	Earth materials and manmade materials that have been artificially emplaced, primarily in highway and railroad embankments, and in dams; may also include landfills, urban development areas, and filled coastal wetlands.
Al – alluvium	Fine	Sand, gravel, silt, and some organic material, stratified and well sorted to poorly sorted, beneath the floodplains of modern streams. The texture of alluvium commonly varies over short distances both laterally and vertically, and generally is similar to the texture of adjacent glacial deposits. Along smaller streams, alluvium is commonly less than 5 ft thick. The most extensive deposits of alluvium on the map are along the Nashua, Squannacook, and Nissitissit Rivers where the texture is predominantly sand, fine gravel, and silt, and total thickness is as much as 25 ft. Alluvium typically overlies thicker glacial stratified deposits.
B and Bd – Beach and dune deposits	Coarse	Sand and fine gravel deposited along the shoreline by waves and currents, and by wind action. The texture of beach deposits varies over short distances and is generally controlled by the texture of nearby glacial materials exposed to wave action. Sand beach deposits are composed of moderately sorted very coarse to fine sand, commonly laminated. Coarser layers may contain some fine gravel particles; finer layers may contain some very fine sand and silt. Gravel beach deposits are composed of granule-to-cobble-sized clasts in moderately sorted thin beds. Minor amounts of sand within gravel beds, and thin beds of sand as alternating layers. Beach deposits are rarely more than a few feet thick. Sand dune deposits are composed of moderately to well sorted, fine to medium sand, variably massive, laminated, and cross bedded. Dune deposits are as much as 35 ft thick. Unit includes artificial sand deposits in locally replenished beaches.
Cb – cranberry bog	Not included	Some natural freshwater swamps or peat bogs overlain locally by artificially emplaced sand or other fill; in many places in southeastern Massachusetts, cranberry bogs are created by excavation into sand and gravel deposits that form the bed; peat and other organic material have been artificially emplaced over the bed and water drainage pathways are diverted into the area to control seasonal flooding of the bog.
Ff – valley floor fluvial deposits	Coarse	Sand, gravel, and minor silt, stratified and moderately to poorly sorted, beneath flat floors of valleys, called furrows (Mather et al. 1942) that are eroded into glacial outwash plains. The texture of the fluvial deposits commonly varies over short distances both laterally and vertically and generally is similar to the texture of adjacent glacial deposits. The fluvial deposits overlie thick glacial stratified deposits in the upper, dry reaches of the furrow valleys and probably are less than 20 ft thick. Swamp deposits and deformation of bedding related to melting of buried ice in kettles interrupt the fluvial deposits. The deposits probably extend beneath salt-marsh deposits in coastal valley reaches. The most extensive valley fluvial deposits are along Quaker Run and Coonamessett, Childs, and Quashnet Rivers on upper Cape Cod, and Quampachje Bottom on Martha's Vineyard.

Data Source	Sediment Type Crosswalk	Metadata description
Sm – salt marsh deposits	Fine	Peat and organic muck interbedded with sand and silt, deposited in environments of low wave energy along the coast and in river estuaries. Marsh deposits are dominantly peat and muck, generally a few feet to 25 ft thick. In the major estuaries, marsh deposits locally overlie estuarine deposits (not mapped), which are sand and silt with minor organic material as much as 30-80 ft thick. The marsh and estuarine deposits generally are underlain by adjacent glacial material, either till, coarse stratified deposits, or glaciomarine fine deposits.
Sw – swamp and marsh deposits	Fine	Organic muck and peat that contain minor amounts of sand, silt, and clay, stratified and poorly sorted, in kettle depressions or poorly drained areas. Most swamp deposits are less than about 10 ft thick. Swamp deposits overlie glacial deposits or bedrock. They locally overlie glacial till even where they occur within thin glacial meltwater deposits.
Early postglacial deposits: SURFGEO24K_EPG_POLY.shp		
Alf – alluvial fan deposits	Coarse	Generally coarse gravel and sand deposits on steep slopes where high-gradient streams entered lower-gradient valleys. Some alluvial fans in this area were graded to lowering levels of glacial Lake Hitchcock. Some fans continue to form today.
D – early postglacial inland dune deposits	Coarse	Fine to medium, well-sorted sand, in transverse, parabolic, and hummocky dunes as much as 30 ft thick. Occur most commonly in large glacial lake basins where sand was derived from extensive glacial-lake deltas that were not yet vegetated and deposited in dune forms by early postglacial winds. Dune sand is now fixed by vegetation except where disturbed by human activities.
Mr – early postglacial marine regressive deposits	Coarse	Sand and gravel deposited along former, higher shorelines in northeastern Massachusetts by waves and currents, and by wind action, as well as sand and gravel deposited by fluvial and wave action in lower estuarine valleys. The fluvial estuarine-terrace deposits are shown on the map where they overlie glaciomarine fine deposits; elsewhere, sand and gravel in postglacial terrace deposits are included in the glacial coarse stratified map unit. The fluvial terrace deposits are mixtures of gravel and sand within individual layers, and as alternating layers. Sand and gravel layers generally range from 25 to 50 percent gravel particles and from 50 to 75 percent sand particles. Layers are well to poorly sorted. Beach and near-shore deposits are composed of moderately sorted very coarse to fine sand, commonly laminated. Coarser layers may contain some fine gravel particles; finer layers may contain some very fine sand and silt. Regressive beach and near-shore deposits are rarely more than a few feet thick. Regressive spit deposits are 10-30 ft thick..
St – stream-terrace deposits	Coarse	Sand, gravel, and silt deposited by meteoric water (locally distal meltwater) on terraces cut into glacial meltwater sediments along rivers and streams. Most stream-terrace deposits are less than 10 ft thick and overlie thicker glacial deposits; textures are usually similar to underlying glacial meltwater deposits. Many stream terraces in the Connecticut River valley are composed of fine to medium sand and overlie lake-bottom silt and clay.
Ta – talus deposits	Not included	Angular, loose blocks of basalt and diabase accumulated by rockfall and creep at the base of bedrock cliffs along linear traprock ridges in the Mesozoic lowland. Talus deposits form steep, unstable slopes. Generally less than 20 ft thick

Data Source	Sediment Type Crosswalk	Metadata description
Glacial stratified deposits: SURFGEO24K_SD_POLY .shp		
Sd-c – glacial stratified deposits, coarse	Coarse	Sorted and stratified sediments composed of gravel, sand, silt, and clay (as defined in particle size diagram) deposited in layers by glacial meltwater. These sediments occur as four basic textural units – gravel deposits, sand and gravel deposits, sand deposits, and fine deposits. On this interim map, gravel, sand and gravel, and sand deposits are not differentiated and are shown as Coarse Deposits where they occur at land surface. Textural changes occur both areally and vertically, however subsurface textural variations are not shown on this interim map. Coarse deposits include: Gravel deposits composed mainly of gravel-sized particles; cobbles and boulders predominate; minor amounts of sand within gravel beds, and sand comprises few separate layers. Gravel layers generally are poorly sorted and bedding commonly is distorted and faulted due to postdepositional collapse related to melting of ice. Sand and gravel deposits composed of mixtures of gravel and sand within individual layers and as alternating layers. Sand and gravel layers generally range from 25 to 50 % gravel particles and from 50 to 75 % sand particles. Layers are well to poorly sorted; bedding may be distorted and faulted due to postdepositional collapse. Sand deposits composed mainly of very coarse to fine sand, commonly in well-sorted layers. Coarser layers may contain up to 25 percent gravel particles, generally granules and pebbles; finer layers may contain some very fine sand, silt, and clay.
Sd-f – glacial stratified deposits, fine	Fine	Sorted and stratified sediments composed of gravel, sand, silt, and clay (as defined in particle size diagram) deposited in layers by glacial meltwater. These sediments occur as four basic textural units – gravel deposits, sand and gravel deposits, sand deposits, and fine deposits. Fine Deposits are shown where they occur at land surface. Textural changes occur both areally and vertically, however subsurface textural variations are not shown on this interim map. Glaciolacustrine fine deposits include very fine sand, silt, and clay that occur as well-sorted, thin layers of alternating silt and clay, or thicker layers of very fine sand and silt. Very fine sand commonly occurs at the surface and grades downward into rhythmically bedded silt and clay varves. Locally, this map unit may include areas underlain by fine sand.
Sd- fm – glacial stratified deposits, glaciomarine fine	Fine	Sorted and stratified sediments composed of gravel, sand, silt, and clay (as defined in particle size diagram) deposited in layers by glacial meltwater. These sediments occur as four basic textural units – gravel deposits, sand and gravel deposits, sand deposits, and fine deposits. Fine Deposits also are shown where they occur at land surface. Textural changes occur both areally and vertically, however, subsurface textural variations are not shown on this interim map. Glaciomarine fine deposits include silty clay, fine sand, and some fine gravel deposited in a higher level sea in environments of low wave energy along the coast and in river estuaries. Fine to very fine sand, massive and laminated, commonly is present at the surface and grades downward into interbedded very fine sand, silt, and silty clay. Lower silty clay and clay is massive and thinly laminated. Total thickness is generally a few feet to 75 ft.
Sid – stagnant ice deposits	Coarse	Surface coarse sediments bounded by ice-contact slopes, present on tops of till hills or extending > 30 ft above the altitudes of adjacent meltwater morphosequences in lowlands. Deposits are aligned in belts parallel to the retreating ice margin .Surface coarse sediments include scattered large surface boulders, gravel deposits and sand and gravel deposits, totaling 5-30 ft thick, that overlie chiefly sand deposits. Sand deposits contain deltaic foreset bedding and interlayered beds of fine sand, silt, and little clay. Sand and silty sand deposits extend downward to basal till and bedrock. Flowtill sediments are interlayered under ice-contact slopes. Stratification in surface and underlying sediments is generally distorted and faulted due to postdepositional collapse related to

Data Source	Sediment Type Crosswalk	Metadata description
		melting of buried ice. Ice Stagnation Deposits are confined to irregular hummocky hills, bounded by ice-contact slopes, present on tops of till hills or extending >30 ft above the altitudes of adjacent meltwater morphosequences in lowlands. Deposits are aligned in belts parallel to the retreating ice margin.
Till Bedrock: SURFGEO24K_TB_POLY .shp		
Em – end moraine deposits	Coarse	Composed predominantly of boulders and ablation facies sandy upper till; lenses of stratified sand and gravel occur locally within the till. Surface boulders on end moraine deposits are generally more numerous than on adjacent till surfaces; dense concentrations of boulders are present in some places. Deposits occur as free-standing hummocky landforms, commonly in ridges that trend NE/SW, and range in thickness from 10 to 60 ft.
T/s – till overlying sand deposits	Coarse	In the Pine Hills area, Manomet quadrangle, surface deposits of till and overlying thin colluvium, both consisting of nonsorted, nonstratified matrix of sand, some silt, and little clay containing scattered gravel clasts and few large boulders; loose to moderately compact, generally sandy, commonly stony. The surface nonsorted deposits, 6 to 30 ft thick, overlie sand, gravel, and silty sand deposits that extend >250 ft downward to basal till and bedrock (Hansen and Lapham 1992). These subsurface stratified deposits crop out in the sides of Pine Hills and Indian Hill, where they appear to be coarse-grained glacial meltwater sediments
Tm – thrust moraine	Coarse	Surface deposits of nonsorted, nonstratified matrix of sand, some silt, and little clay containing scattered gravel clasts and large boulders; predominantly till of the last glaciation; loose to moderately compact, generally sandy, commonly stony. Two facies of till are present in some places: a looser, coarser grained ablation facies, melted out from supraglacial position; and an underlying more compact, finer grained lodgement facies deposited subglacially (Oldale 1975). Both ablation and lodgement facies of till are stony, containing boulders, and are derived from coarse-grained crystalline rocks. The surface nonsorted deposits, 6 to 30 ft thick, overlie sand, gravel, and silty sand sediments that compose the large meltwater deposit extending to the south and downward to basal till and bedrock. Surface deposits and stratification in underlying sediments commonly are distorted and faulted due to readvance of the ice margin (Oldale and O'Hara 1984) postdepositional collapse related to melting of buried ice.
Tt – thick till	Bedrock	Nonsorted, nonstratified matrix of sand, some silt, and little clay containing scattered gravel clasts and few large boulders at the surface; in the shallow subsurface, compact, nonsorted matrix of silt, very fine sand, and some clay containing scattered small gravel clasts in areas where till is greater than 10-15 ft thick, chiefly drumlin landforms in which till thickness commonly exceeds 100 ft (maximum recorded thickness is 230 ft). Although upper till is the surface deposit, the lower till constitutes the bulk of the material in these areas. Lower till is moderately to very compact, and is commonly finer grained and less stony than upper till. An oxidized zone, the lower part of a soil profile formed during a period of interglacial weathering, is generally present in the upper part of the lower till. This zone commonly shows closely spaced joints that are stained with iron and manganese oxides.
Bk – bedrock outcrop	Bedrock	Extent of individual bedrock outcrops

Data Source	Sediment Type Crosswalk	Metadata description
T - thin till	Bedrock	Nonsorted, nonstratified matrix of sand, some silt, and little clay containing scattered gravel clasts and few large boulders; in areas where till is generally less than 10-15 ft thick and including areas of bedrock outcrop where till is absent. Predominantly upper till of the last glaciation; loose to moderately compact, generally sandy, commonly stony. Two facies are present in some places; a looser, coarser grained ablation facies, melted out from supraglacial position; and an underlying more compact, finer grained lodgement facies deposited subglacially. In general, both ablation and lodgement facies of upper till derived from fine-grained bedrock are finer grained, more compact, less stony and have fewer surface boulders than upper till derived from coarser grained crystalline rocks. Fine-grained bedrock sources include the red Mesozoic sedimentary rocks of the Connecticut River lowland, marble in the western river valleys, and fine-grained schists in upland areas.

Table 3.6. Geophysical Settings from MA analysis.

Code description	Sediment Type
Sand and gravel deposits	Coarse
Till or bedrock	
Sandy till over sand	Coarse
End Moraines	Coarse
Large sand deposits where distinguished from sand and gravel deposits	Coarse
Fine-grained deposits	Fine
Floodplain alluvium	Fine

Table 3.7. Geophysical settings used in the Massachusetts analysis.

GP Code	GP Description	Total Acres
L: CALC	Low Elevation Calcareous	13,011
L: COARSE	Low Elevation Coarse Sand	1,452,046
L: COAST	Coastal Bedrock Settings	37,064
L: COAST/COARSE	Coastal Coarse Sand	141,787
L: COAST/FINE	Coastal Fine Silt	83,836
L: FINE	Low Elevation Fine Silt	409,066
L: GRAN	Low Elevation Granitic	559,893
L: MAFIC	Low Elevation Mafic	312,503
L: MODCALC	Low Elevation Moderately Calcareous	207,616
L: SED	Low Elevation Acidic Sedimentary	469,880
M: CALC	Mid Elevation Calcareous	111,938
M: COARSE	Mid Elevation Coarse Sediments	96,406
M: FINE	Mid Elevation Fine Sediments	21,956
M: GRAN	Mid Elevation Granite	277,061
M: MAFIC	Mid Elevation Mafic	116,471
M: MODCALC	Mid Elevation Moderately Calcareous	202,546
M: SED	Mid Elevation Acidic Sedimentary	658,441
H: BED	High Elevation Bedrock Settings	3,740
STEEP	Steep Settings on all Geology Types	22,857
ULTRA	Ultramafic	3,926
Grand Total		5,202,045

VI. References

Anderson, M.G., & Ferree, C. (2010). Conserving the stage: climate change and the geophysical underpinnings of species diversity. *PLOS ONE* 5(7): e11541.

Hansen, B.P., & Lapham, W.W. (1992) Geohydrology and simulated ground-water flow, Plymouth-Carver Aquifer, southeastern Massachusetts. U.S. Geological Survey Water-Resources Investigations Report 90-4204, 69 p.

Mather, K.F., Goldthwait, R.P., and Theismeyer, L.R., 1942, Pleistocene geology of western Cape Cod, Massachusetts. *Geological Society of America Bulletin*. 52: 1127-1174.

Oldale, R.N. (1975) Geologic map of the Sandwich quadrangle, Barnstable County, Cape Cod, Massachusetts. U.S. Geological Survey Geologic Quadrangle Map GQ-1222.

Section 4: Development and Protection of Critical Landscapes: Resilience and *BioMap2*

Tom Lautzenheiser, June 2014.

Generating statistics for land protection and development within land of greater than average climate resilience, as well as *BioMap2* Core Habitat and Critical Natural Landscape, by towns and other geographical regions, required additional processing in ArcGIS. The primary inputs for this analysis included TNC Massachusetts Chapter resilience, NHESP/TNC *BioMap2*, MassGIS OpenSpace, and Boston University land use change datasets previously described. All resilient land with a z-score of ≥1 standard deviation above average was selected; this relatively high resilience land was the basis for further analysis. Major water features were removed from the primary input datasets using the USGS Major Ponds polygons (MAJPOND_POLY) available from MassGIS (February 2013) to limit the analysis to terrestrial features; preliminary analyses indicated that results that included large waterbodies such as the Quabbin and Wachusett Reservoirs misrepresented the development and land protection histories of the adjacent communities.

After major water bodies were removed, 4-class rasters were developed for resilience, *BioMap2* Core Habitat, and *BioMap2* Critical Natural Landscape following identical processing steps:

1) land neither protected nor developed between 2005 and 2013
2) land protected prior to 2005
3) land protected between 2005 and 2013
4) land developed between 2005 and 2013

- The raster for land developed between 2005 and 2013 was extracted from the full land use change dataset. Values extracted were Commercial/Industrial/High Density Residential; X to Commercial/Industrial/High Density Residential; Low Density Residential; X to Low Density Residential; Cranberry Bog; X to Cranberry Bog (where X is Open, Forest, Wetland, or Water).
- The raster for land protected between 2005 and 2013 was extracted from MassGIS's full OpenSpace dataset, and included all properties conserved between April 1, 2005, and April 1, 2013, based on the CAL_DATE_R attribute.

Zonal statistics were then computed via the tabulate area command for each of the 4-class rasters for six geographical regions:

1) towns (TOWNSSURVEY_POLY, 2013)
2) counties (COUNTIES_POLY, 1991)
3) watersheds (WATERSHEDS_POLY, 2000)
4) regional planning agencies (RPAS_POLY, 2007)
5) US EPA ecoregions (ECOREGIONS_POLY, 1999)
6) geophysical settings (an input into the resilience model)

Shapefiles for all but the last of these regions were from MassGIS, and all were dissolved to aggregate features into unique records (e.g., the four polygons comprising the town of Amesbury in the town's shapefile were combined into a single multipart polygon, etc.) prior to tabulating the statistics.

The resulting data tables were then joined to their respective zonal shapefile by zone name.

Section 5: Adopting Innovative Planning and Zoning Techniques

E. Heidi Ricci and Valerie Massard, June 2014

The 495/MetroWest Development Compact Plan (495 Plan) region consists of 37 communities stretching roughly along Route 495 from Plainville at the southern end to Westford on the north, east to Natick and west to Worcester (Figure 5.1). Mass Audubon selected this area for analysis of local land use plans and rules because it is in the Sprawl Frontier and the 495 Plan engaged the communities in planning for future development and land protection priorities.

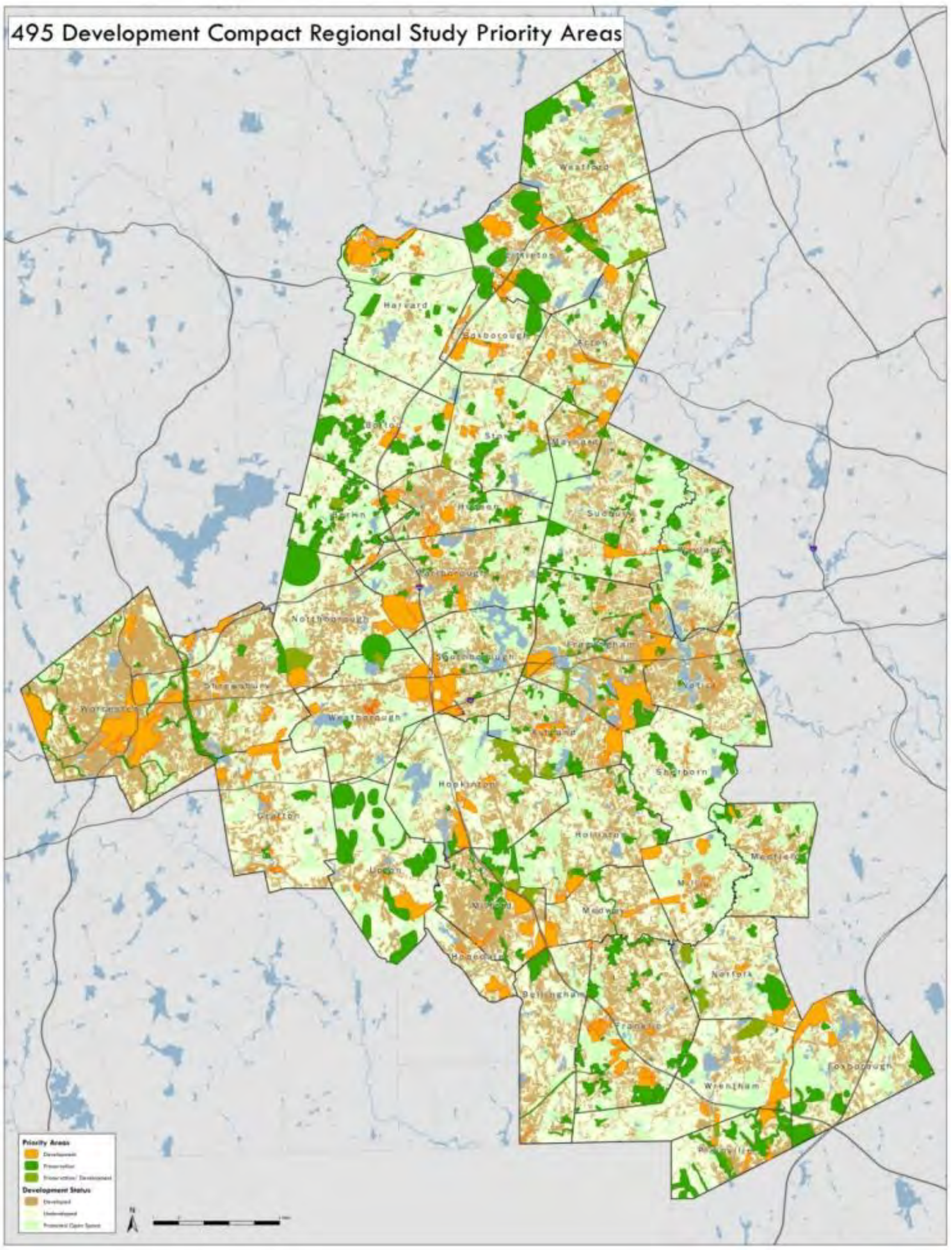


Figure 5.1. The 495 Plan region with Priority Protection Areas shown in green and Priority Development Areas shown in orange.

I. Smart Growth Tools in the 495 Region

We analyzed local adoption of several smart growth tools that have been widely promoted by the state and regional planning agencies. Smart growth tools were grouped into three categories: Land and Water Protection; Priority Development Techniques, and Energy and Climate Change. We examined municipal websites and contacted local officials to determine whether each community had in place certain land use tools in 2012. Some communities may have subsequently updated their local plans, zoning, or regulations, and our analysis did not examine policies or procedures.

We examined whether each community had the following tools and techniques:

- Land and Water Protection
    - Up-to-date Open Space Plan approved by the Massachusetts Division of Conservation Services
    - Open Space Design, Conservation Subdivision, Cluster, or Natural Resource Design Zoning Bylaw
    - Wetlands Protection Bylaw
    - Community Preservation Act
    - Agricultural Commission
    - Transfer of Development Rights Bylaw
- Targeted Development Areas
    - Mixed Use Zoning
    - Designated Growth District (e.g. 43D or 40R, or other district specifically designated for concentrated development)
- Energy and Climate Change
    - Green Community Act adopted locally
    - Solar Zoning regulating the siting of large-scale ground mounted solar arrays

In the main *Losing Ground* report, we tallied the status of each of these measures in each of the 37 communities, and calculated how many measures were in place across the communities in the region. Table 5.1 shows the detailed information.

This analysis is intended to provide a general illustration of the degree to which smart growth techniques that the state and regional planning agencies have been promoting for many years have been adopted. It is not intended to be a report card or otherwise reflect on any one individual community's status. We recognize that each community is unique and that these are only a subset of the full suite of planning and land use controls available.

Table 5.1. Smart Growth Tools in 37 Communities in the 495 Plan Region as of 2012

	Land & Water Protection					Targeted Development Areas		Energy & Climate Change		
Municipality	**Open Space Plan Status**	**Open Space or Cluster Bylaw**	**Community Preservation Act**	**Wetlands Bylaw**	**Agricultural Commission**	**Transfer of Development Rights Bylaw**	**Mixed Use Zones**	**40R/43D/EOHED Growth District Communities**	**Green Community**	**Solar Zoning Bylaw**
Acton	Expired	Planned Conservation Residential Community / Open Space Development Overlay District (2 separate districts)	Y	Y	N	Y, Zoning Bylaw 5.4	Y in the Village Districts	N	Y	Y
Ashland	2014	Cluster development	Y	Y	N	N	Y	43D	Y	Y
Bellingham	2016	Major Residential Subdivision	N	Y	N	N	Y	N	N	Y
Berlin	2018	N	N	N	Y	N	Y Mixed Commercial /Residential	N	Y	Y

Municipality	Open Space Plan Status	Land & Water Protection Open Space or Cluster Bylaw	Community Preservation Act	Wetlands Bylaw	Agricultural Commission	Targeted Development Areas Transfer of Development Rights Bylaw	Mixed Use Zones	Energy & Climate Change 40R/43D/EOHED Growth District Communities	Green Community	Solar Zoning Bylaw
Bolton	Expired	Farmland and Open Space Planned Residential Development	N	Y	Y	N	N	N	N	Y
Boxborough	Expired	N (but there is Commercial Open Space Zoning)	N	Y	Y	N	Y	N	N	N
Foxborough	2018	Open Space Residential Development	N	Y	N	N	Y	Economic Growth District	N	Y
Framingham	2013	Planned Unit Development	N	Y	Y	N	Y	N	N	N
Franklin	2016	Open Space Development	N	Y	N	N	Y Neighborhood Commercial District	43D	N	N
Grafton	2014	Flexible Development	Y	Y	Y	N	Y Village Mixed Use	40R; 43D	N	N

	Land & Water Protection					Targeted Development Areas		Energy & Climate Change		
Municipality	**Open Space Plan Status**	**Open Space or Cluster Bylaw**	**Community Preservation Act**	**Wetlands Bylaw**	**Agricultural Commission**	**Transfer of Development Rights Bylaw**	**Mixed Use Zones**	**40R/43D/EOHED Growth District Communities**	**Green Community**	**Solar Zoning Bylaw**
Harvard	2015	Open Space and Conservation - Planned Residential Development	Y	Y	Y	N	Y	N	Y	Y
Holliston	2020	Open Space Residential Development	Y	Y	Y	N	Y Village Center Commercial and Village Center Residential	N	N	N
Hopedale	Expired		N	N	N	N	N	N	N	N
Hopkinton	2019	Open Space and Land Preservation	Y	Y	N	N	Y Open Space Mixed Use Development Overlay District (PUD)	N	Y	Y
Hudson	Expired	Open Space Residential Development	Y	N	N	N	Y Adaptive Reuse Overlay District (AROD); allows for mixed use with commercial on the first floor and residential above	43D	N	N

	Land & Water Protection				Targeted Development Areas		Energy & Climate Change		
Municipality	**Open Space Plan Status**	**Open Space or Cluster Bylaw**	**Community Preservation Act**	**Wetlands Bylaw**	**Agricultural Commission**	**Transfer of Development Rights Bylaw**	**Mixed Use Zones**	**40R/43D/EOHED Growth District Communities**	**Green Community**	**Solar Zoning Bylaw**
Littleton	2014	Open Space Development	Y	Y	Y	N	Y Village Center Business District	43D	N Municipal Electric Utility	Y
Marlborough	2016	Open Space Development	N	N	N	N	N	43D	Y	N
Maynard	Expired	N	Y	Y	N	N	Y Mixed Commercial/ Residential	N	Y	N
Medfield	2018	Open Space Residential Zoning	N	Y	N	N	N	N	N	N
Medway	2017	Open Space Residential Development	Y	Y	Y	N	N	43D	Y	N
Milford	Expired	Planned Residential Development	N	Y	N	N	N	N	N	Y
Millis	Expired	Open Space Preservation	Y	Y	Y	N	Y Mixed Use Overlay District	N	N	N

		Land & Water Protection				Targeted Development Areas		Energy & Climate Change		
Municipality	**Open Space Plan Status**	**Open Space or Cluster Bylaw**	**Community Preservation Act**	**Wetlands Bylaw**	**Agricultural Commission**	**Transfer of Development Rights Bylaw**	**Mixed Use Zones**	**40R/43D/EOHED Growth District Communities**	**Green Community**	**Solar Zoning Bylaw**
Natick	2019	Cluster development	N	Y	N	Y bonus development program along portions of Rt 9 with $ for open space acquisition, affordable housing, or transportation improvements	Y Commercial/Industrial Mixed Uses	40R	Y	N
Norfolk	Expired	Open Space Preservation	Y	Y	N	N	N	43D	N	N
Northborough	2017	Open Space Residential Development	Y	Y	N	N	Y	N	N	N
Plainville	Expired	Residential Cluster development	N	Y	N	N	Y Town Center District/ Commercial Interchange District	N	N	Y
Sherborn	Expired	Open Space	N	Y	Y	N	Y Planned Unit Development	N	Y	Y

Municipality	Open Space Plan Status	Open Space or Cluster Bylaw	Community Preservation Act	Wetlands Bylaw	Agricultural Commission	Transfer of Development Rights Bylaw	Mixed Use Zones	40R/43D/EOHED Growth District Communities	Green Community	Solar Zoning Bylaw
		Land & Water Protection				**Targeted Development Areas**		**Energy & Climate Change**		
Shrewsbury	2019	Cluster development	N	N	N	N	Y Mixed Commercial/ Residential, Special Permit	43D	N	N
Southborough	2015	Open Space Residential Design	Y	Y	N	N	N	N	N	N
Stow	2014	Planned Conservation Development	Y	Y	Y	N	N	N	N	Y
Sudbury	2015	Cluster development	Y	Y	Y	N	Y Mixed Commercial/ Residential	N	Y	N
Upton	2017	Open Space Residential Design	Y	Y	N	N	N	N	N	N
Wayland	Expired	Conservation Cluster Development	Y	Y	N	N	Y	N	Y	N
Westborough	2017	Open Space Community	N	Y	N	N	Y Mixed Commercial/ Residential	N	N	Y
Westford	2015	Open Space Residential Design	Y	Y	Y	N	Y Mixed Commercial/Residential; Mill Conversion Overlay District	N	Y	N

	Land & Water Protection					Targeted Development Areas		Energy & Climate Change		
Municipality	Open Space Plan Status	Open Space or Cluster Bylaw	Community Preservation Act	Wetlands Bylaw	Agricultural Commission	Transfer of Development Rights Bylaw	Mixed Use Zones	40R/43D/EOHED Growth District Communities	Green Community	Solar Zoning Bylaw
Worcester	2020	Cluster development	N	Y	N	N	Y Mixed Use Development	43D; Economic Growth District	Y	N
Wrentham	Expired	Open Space Preservation District	N	Y	N	N	N	N	N	Y

II. Open Space Design/Natural Resource Protection Zoning Analysis

One of the most powerful tools available for reducing sprawl and supporting more sustainable development is Open Space Design or Natural Resource Protection Zoning (NRPZ). Other related terms are Cluster or Conservation Subdivision Zoning. All of these types of zoning provide for portions of a development property to be permanently protected, in contrast to conventional residential zoning, which allocates all land within the subdivision to individual house lots. These bylaws enable communities to protect important natural resources and provide amenities such as trails without needing to purchase those lands. At the same time, the landowner and developer benefit from a form of development that typically outperforms traditional subdivisions on marketability and sale price, while reducing costs associated with land clearing and grading and road and utility construction. Other benefits include reduction in the amount of roadway that needs maintenance, reduction in stormwater produced, and improved protection for surface and groundwater resources, forests, farmlands, and wildlife habitat. Greater setbacks to wetlands and floodplains can also be achieved by concentrating development in less vulnerable areas. Such a design also increases resilience in the face of climate change.

As Massachusetts and other states have gained experience with zoning that includes open space protection, much has been learned over the past several decades regarding specific provisions that can be optimized to achieve best results. For example, many older bylaws allow relatively small, disconnected pieces of land to be protected with little natural resource or recreational value, or impose procedural barriers that result in the bylaw rarely being utilized because it is more costly or unpredictable for the developer than the community's conventional zoning provisions.

The Massachusetts Executive Office of Energy and Environmental Affairs (EEA) has a model bylaw in its Smart Growth/Smart Energy Toolkit www.mass.gov/envir/smart_growth_toolkit/pages/mod-osrd.html that provides recommended language, options, and explanations for communities to consider in updating their zoning. This new model incorporates NRPZ principles and provisions that improve upon earlier models in several respects, including making protection of important land and water resources the easiest and preferred method of project design and permitting.

We examined zoning bylaws in the 37 communities in the 495 Plan region, first to determine whether each community had any type of open space protection bylaw and then to analyze those bylaws in relation to criteria adapted from those identified as Good, Better, or Best in the state's model NRPZ bylaw.

An analysis of each community's cluster or open space zoning bylaws (Acton has two applicable bylaws) was performed, ranking the potential options within a bylaw that can strengthen the effectiveness of this type of zoning. We ranked each bylaw according to these criteria. The criteria were divided into four tiers of relative importance in terms of the bylaw's potential overall importance for protecting natural resources. We tallied the scores, then weighted the results. The criteria we utilized and the ranking system was derived in consultation with EEA, and adjustments were made to focus the ranking on factors most essential to natural resource protection and to take into account differences between typical existing bylaws and the state's model. For example, on the minimum open space requirements, we assigned tiers that differ significantly from the state's recommendations. Most of the existing bylaws do not meet even the state's recommended "Good" standard of 50 to 65 %. Rather than ranking communities that only require 20% minimum open space set aside the same as one that requires a minimum 40%, we adjusted these into the following categories: Minimum Percent Open Space - Rank (10-30%=1 point, 30-50%=2, 50-60%=3, > 60%=4). Scores were then normalized to produce a percent score. Berlin, Hopedale, and Maynard have not adopted an open space bylaw. Boxborough has an open space bylaw that only applies to commercial districts and was not comparable for purposes of this analysis.

Tier 1 includes whether the cluster can be done by-right v. require a special permit, how much land is available in that community where the cluster zoning can be applied, the minimum amount of open space set aside required within the bylaw, and the flexibility of the yield planning process. Tier 2 looks at whether a limitation of a minimum acreage to apply the cluster option is in place, and the level of flexibility in dimensional standards applied within the cluster zoning bylaw. Tier 3 ranks contiguity required of the open space set aside, whether the open space is consistent with local priorities, and the level of activity allowed on the open space set aside. Tier 4 looks at whether a density bonus is included for public access to open space, which entity within the municipality governs the special permit process, and whether wastewater treatment and monitoring of the open space are addressed within the language of the bylaw. See Table 5.2 for more detail on the scoring system.

All but one of the bylaws require a special permit for approval of a conservation subdivision design, while allowing traditional cookie-cutter subdivisions "by right." This complicates the process and creates uncertainty for developers. Other issues with older bylaws include inadequate criteria for the selection of the most important areas to conserve from a natural resource perspective, no link between the bylaw and local Open Space Plans, inadequate connectivity among protected open space, and lack of sufficient procedures for securing permanent protection and proper management of the designated open spaces.

This analysis was performed using information available on municipal websites and through an intern (Nathan Spear, under the supervision of Stephanie Elson) making phone calls to local officials when information was difficult to find online. We examined zoning bylaws as of April 2012. The analysis does not include any zoning revisions that may have been adopted after that time, or regulatory or policy-related provisions that may achieve some of these measures outside of what is codified in zoning.

Table 5.5 – Point scoring of Open Space Bylaw Criteria

Tier and Criteria	Scoring
Tier 1 (weighted at 100%)	
Permit type	1=Special Permit, 2=by-right, 3=mandatory
Land Area Available within the community that is undeveloped and cluster zoning can apply	1=only small amount of land in community; 2=much or some; 3=all or all residential
Minimum Percent Open Space Set aside required in the bylaw	10-30%=1, 30-50=2, 50-60%=3, >60%=4 – a higher value is placed on the larger open space set-aside required.
Yield Calculation method for base density	1=full plan, 2=sketch, 3=formula – a higher value is assigned for lesser costs to implement the yield calculations
Tier 2 (weighted at 75%)	
Review Process	1=no pre-selection or general cluster, 2=ID and protect key features, 3=4 step process
Minimum Parcel Size to use cluster bylaw	1=>10 acres, 2=5-10, 3=no min
Dimensional Standard flexibility	1=specified, 2=formulaic reduction or minor, 3=none
Tier 3 (weighted at 50%)	
Contiguity of Open Space included in bylaw	1=not required, 2=consider, 3=required
Specificity of Local Priorities	1=brief statement of purpose; 2=detailed description of purpose; 3=high specificity and cross-reference to local Master Plan and/or Open Space Plan
Allowed Uses	1=not specified, 2=some active recreational uses allowed, 3=natural resource conservation
Tier 4 (weighted at 25%)	
Density Bonus for Public Benefit (such as a contribution to a nearby park or facility, or public access to open space)	1=no, 2=yes
Reviewing Entity	1=Selectmen or ZBA, 3=Planning Board
Wastewater addressed within the bylaw	1=not addressed, 2 discretionary approval possible
Monitoring	0=nonspecified, 1=monitoring provisions

III. 495/MetroWest Development Compact Plan

The 495/MetroWest Development Compact Plan was produced through a collaborative effort of the Massachusetts Executive Office of Housing and Economic Development, Metropolitan Area Planning Council, Central Massachusetts Regional Planning Commission, MetroWest Regional Collaborative, 495 MetroWest Partnership, and Mass Audubon, with extensive input from local officials and a public participation process. Additional information can be found at www.495partnership.org/compact.

Mass Audubon produced an online toolkit to assist communities in this and other regions with similar Priority Development Area/Priority Preservation Area plans to implement, available at http://www.massaudubon.org/495Toolkit.

Executive Office of Housing and Economic Development MAPC CMRPC Central Massachusetts Regional Planning Commission MetroWest Regional Collaborative Fostering Sustainable Communities 495/MetroWest Partnership Leaders for Regional Prosperity Mass Audubon Protecting the Nature of Massachusetts

Appendix: List of Acronyms

AROD	Adaptive Reuse Overlay District
CAPS	Conservation Assessment and Prioritization System
CCDC	Continuous Change Detection and Classification
CPA	Community Preservation Act
DEP	Department of Environmental Protection
DEM	Digital Elevation Model
ELU	Ecological Land Unit
ER	elevation range
ESPA	EROS Science Processing Architecture
ETM+	Enhanced Thematic Mapper Plus
GLS	Global Land Surface
LGV	*Losing Ground* Fifth Edition
L1T	Level 1 Terrain
LV	landform variety
MaFoMP	Massachusetts Forest Monitoring Program
NHESP	Natural Heritage and Endangered Species Program
NIR	Near-Infrared
NLCD	National Land Cover Database
NRPZ	Natural Resource Protection Zoning
OSD	Open Space Design
RFC	Random Forest Classifier
SWIR1	Short-wave Infrared 1
SWIR2	Short-wave Infrared 2
TDR	Transfer of Development Rights
TM	(Landsat) Thematic Mapper
TNC	The Nature Conservancy
WD	wetland density