TECHNICAL DOCUMENT

LOSING GROUND

BEYOND THE FOOTPRINT

Patterns of development and their impact on the nature of Massachusetts

Fourth Edition of the Losing Ground *Series*

Mass Audubon
Protecting the Nature of Massachusetts

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Losing Ground, Beyond the Footprint Technical Document

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Appendices

Land Use Change Estimates (1999 – 2005)

The analyses of land use change presented in our Losing Ground series are based on land use/land cover (LULC) data produced by MassGIS. The LULC data classifies every part of the state as one of 21 types of land use based on analysis of aerial photos. In geographic information system (GIS) mapping parlance, each 'area' so classified is called a *polygon*. In the past, LULC classifications were based on visual inspection of aerial photos (those taken in 1975, 1985, and 1999) resulting in hand-drawn land use polygons. Losing Ground analyses were based on simple comparisons of the changes in these datasets. The most recent LULC analysis, however, utilized computerized image analysis to render more precise land use polygons. This change in method created challenges in working with the 1999 and 2005 Land Use / Land Cover (LULC) data layers in order to extract meaningful information. Nevertheless, with the methods described below, we feel confident that the final estimates provide us with a good picture of change between 1999 and 2005.

The primary discrepancies between 1975/85/99 and 2005 land use classification that concern us are:

Problem 1. The 1999 and earlier land use polygons were often more generous than 2005 in their depiction of development, e.g. a sliver of forest around a mall would be included in the 'commercial' category. The 2005 data are more accurate. As a result, a fair amount of land was mapped as developed in 1999 but as undeveloped in 2005 in places where there has been no actual change.

Our solution: we burned any land depicted as undeveloped in 2005 into the previous three time steps, thus developed land was not allowed to revert to undeveloped. This completely solves problem 1. Although developed land obviously does sometimes revert to undeveloped (note all those stone walls through the woods), we believe that such change is very minor in the 34 year span covered by the land use data.

Problem 2. Thanks to misalignment in earlier land use data and differences in mapping between the two methods, quite a bit of land that is mapped as forest in 1999 and developed in 2005 hasn't really changed at all. Most of these polygons are in the form of slivers of "new" development on the edges of existing development, where there has been no actual change. Most of these slivers of "new" development are quite small, but they add up to a large number of acres statewide.

Our solution: Use a statistical analysis based on a visual inspection of sample areas to detect and remove many of these bogus slivers; use an error analysis to correct for remaining slivers.

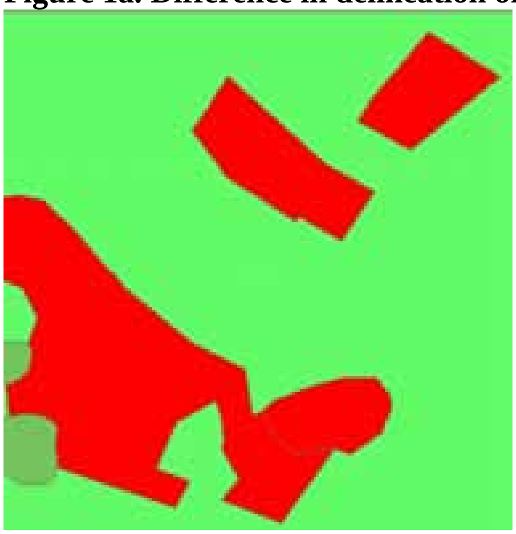
Problem 3. For various reasons, a fair amount of land that was developed prior to 1999 was not mapped as developed in 1999, but is finally picked up in the 2005 land use. This "deferred" development inflates estimates of new development between 1999 and 2005.

Our solution: Assess the amount of deferred development from the error analysis (above), and correct estimates accordingly.

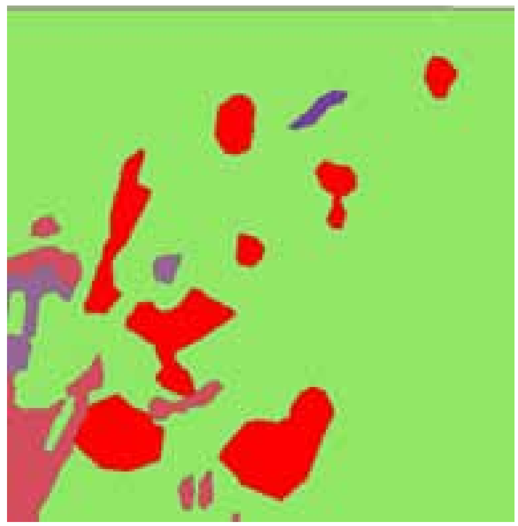
Overestimates of development in 1999 and earlier land use

Figures 1a and 1b depict areas in Massachusetts as measured by the 1999 LULC and the 2005 LULC (red is residential development). In Figure 1a, we can see how the 2005 LULC delineates development much more tightly around the building envelope. The result is that the 1999 LULC estimates 30.7 acres of development while the 2005 LULC depicts the same area as 10.5 acres. The differences are not always that great. Figure 1b shows an area that is 31.7 acres in 1999 vs 24.4 acres in 2005.

Figure 1a. Difference in delineation of one area in 1999 and 2005

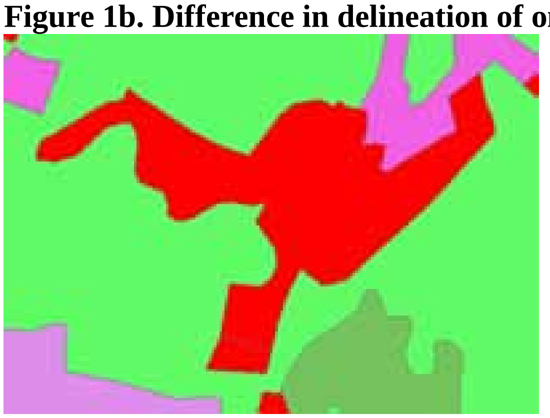


1999 polygon of development
30.7 acres



2005 polygon of development
10.5 acres

Figure 1b. Difference in delineation of one area in 1999 and 2005



1999 polygon of development
31.7 acres

2005 polygon of development
24.4 acres

The first step in developing estimates of change was to union (in a GIS) the 1999 LULC with the 2005 LULC. We then queried the unioned shapefile to extract all areas that were *not* developed in 1999 that *were* developed in 2005. We used the following query to do this: ("LU99" <> 10 AND "LU99" <> 11 AND "LU99" <> 12 AND "LU99" <> 13 AND "LU99" <> 15 AND "LU99" <> 16 AND "LU99" <> 18 AND "LU99" <> 31 AND "LU99" <> 32) AND("LU05" = 10 OR "LU05" = 11 OR "LU05" = 12 OR "LU05" = 13 OR "LU05" = 15 OR "LU05" = 16 OR "LU05" = 38). We identified all 1999 polygons that were *not* multi-family residential (10), Residential - < 1/4 acre lots (11), Residential - 1/4 - 1/2 acre lots (12), Residential - 1/2 - 1 acre lots (13), Commercial (15), Industrial (16), Transportation (18), Urban public (31), and Transportation facilities (32) that were the following development categories in 2005: multi-family residential (10), Residential - < 1/4 acre lots (11), Residential - 1/4 - 1/2 acre lots (12), Residential - 1/2 - 1 acre lots (13), Commercial (15), Industrial (16), Transportation, and Residential - > 1 acre lots (38).

We ultimately added "urban public" as a developed category in 1999 because it was so poorly delineated. Almost all of the 1999 urban public polygons were overestimating the amount of park land, so that a union with the 2005 LULC made it appear that the parks were being developed when in fact, they were just much more accurately depicted in 2005. We also removed "transportation" (18) from "developed" in 2005. All of the "new" transportation polygons that were being identified were sliver polygons surrounding transportation polygons that were already well depicted in 1999. Overlay of the two time steps resulted in long sliver polygons of "new" development near roads/highways.

The above query allowed us to generate the "new development shapefile". It identified 134,370 acres of land across the Commonwealth that was "new development". However, even a quick glance at this data layer made it obvious that it would have to be heavily filtered and analyzed. Ultimately, we ended up with a two step correction of this initial shapefile. 1) We removed polygons based on their shape or based on their overlap with the "impervious surface" layer developed by MassGIS. 2) We then applied correction coefficients to the data to "deflate" the acreage estimates further.

Validation data and sliver correction

In order to accomplish both step 1 and step 2, we used a stratified sampling approach where we selected twenty 4 km by 4 km blocks (selected from the MassGIS orthophoto quad index) across a gradient of development (shown in Figure 2). Within each decile of "percent developed", two blocks were randomly selected from all of the blocks within that decile. In each of these *error assessment quads* we manually inspected 4,517 polygons adding up to 2,265 acres to determine which of the following categories the polygon fit into:

- **1** = was undeveloped in 1999, is developed in 2005 (correctly classified in both years). (= **correct**)
- **2** = pre-1999 development that was missed in 1999 land use. This is real development but detection is deferred until 2005 (= **deferred**)

3 = undeveloped both years, but marked as developed in 2005. These are slivers where 2005 land use was more liberal than 1995. (= **sliver**)
4 = developed in 1999, and undeveloped in 2005. None of these occur, because undeveloped 2005 polygons have been projected back to earlier years (solution to problem 1, above).

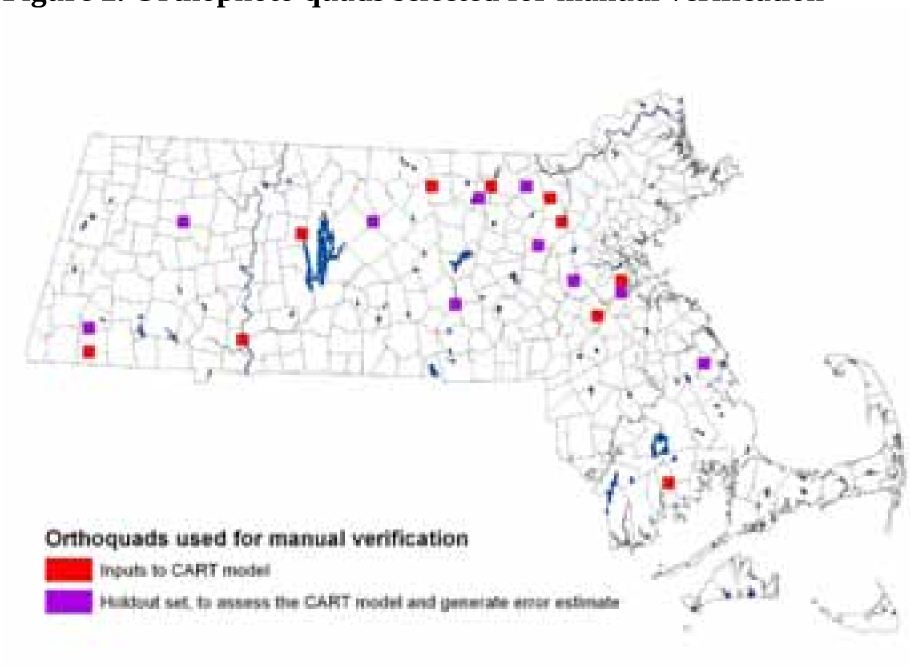
Throughout the rest of this section, the colors depicted below are used to help orient the reader when we are distinguishing between real change, deferred change, and slivers.

Real change (Not developed in 1999, Developed 2005)

Deferred change (Developed in 1999, Developed 2005)

Slivers (Not developed in 1999, Developed 2005)

Figure 2. Orthophoto quads selected for manual verification



We then developed a statistical model that could filter out the false positives. We ultimately chose a CART model (Classification and Regression Tree) because it is free of many of the assumptions of a linear model. CART models also allow for contingent relationships to be analyzed. For example, if impervious polygons (as identified by MassGIS using 2005 LULC data) overlap the “new development” polygon we can investigate perimeter / area ratio, but if there is no impervious polygon we do not have to investigate perimeter / area ratio. In messy real-world models, (non-normal data, strange contingent relationships, missing data, etc.), CART often can build more robust (and often easier to interpret) models than a parametric model.

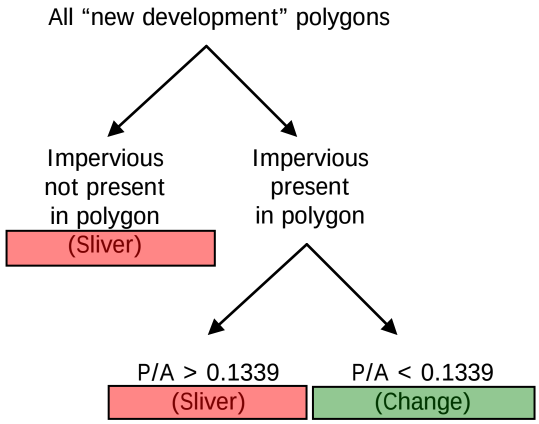
A variety of variables were tested in an attempt to develop a model that could be used to filter out false positives. These variables included:

- Adjacency to existing development
- A variety of FRAGSTATS metrics
- Perimeter to area ratio
- Presence of impervious data in the polygon

Ultimately, it was a very simple model that was the most robust. It included:

- Perimeter to area ratio
- Presence of 2005 impervious data in the polygon

Figure 3. Diagram of the final CART model used



The above model was applied to all of the polygons in the "new development shapefile" and provided a good filter. Of the original 134,370 acres, it removed 34,794 acres or 26% of the polygons, leaving 99,576 acres. Figure 4 shows one cluster of polygons to which the CART filter was applied. All of the pink polygons were removed from further analysis while the green polygons remained. While the data was improved, it was still necessary to apply a correction coefficient to the acreage results. Note that "deferred" polygons were excluded from the CART analysis, because there are no plausible spatial variables that could differentiate pre-1999 development from post-1999 development.

Correction of remaining sliver errors and deferred development errors

After building a CART model (based on the first 10 error assessment quads) to correct the GIS data (by dropped slivers), we used the second 10 error assessment quads to assess the remaining error in the change estimate, and used this to adjust estimates. This was necessary because correction of slivers was imperfect, and because we have no other way to account for polygons of deferred development.

Correction factors were calculated as the mean proportion of area across the 10 error assessment quads for each of four possible combinations of GIS data and assessment data. This resulted in four correction factors. Corrected acreages of change and deferred can be estimated by multiplying these correction factors by the areas in change and slivers for any arbitrary area.

Type in corrected GIS data	Type in hand-scored error assessment quads
change	change
change	deferred
sliver	change
sliver	deferred

We estimated uncertainty in the final estimates with the standard error of the difference between each correction factor and the mean across group of polygons in each error assessment quad in the test data set. Error is used to construct a 95% confidence interval on the estimate.

Figure 3. Example application of the CART filter

The CART model was derived using the first 10 error assessment quads of data, while the correction coefficients were generated using the second 10 error assessment quads of data. Figure 4 shows the correction coefficients that were applied to the data from the "newly developed shapefile". Figures 5 and 6 provide examples as to exactly how we applied these correction coefficients. In this example, we use a hypothetical 100 acres of polygons.

Figure 4. Correction coefficients applied to the "new development shapefile" acreage estimates

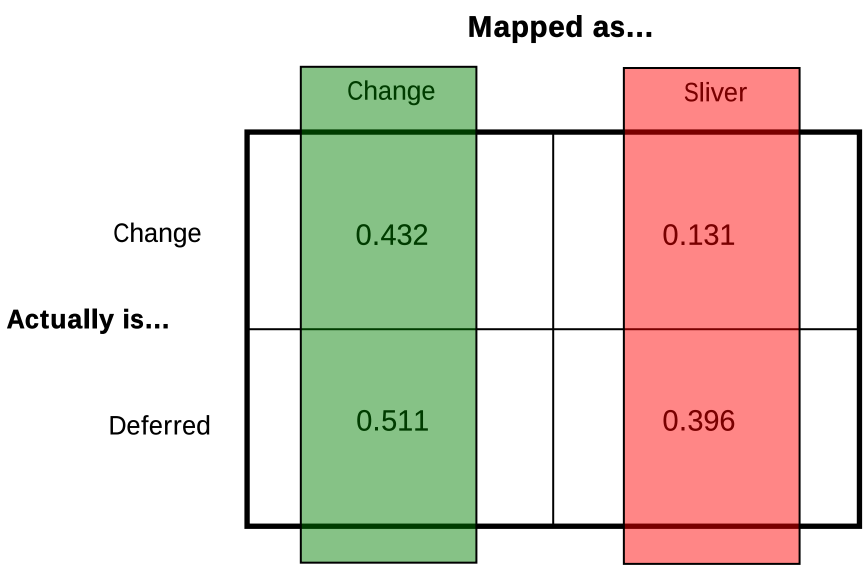


Figure 5. Example showing how the correction coefficients are applied to the data

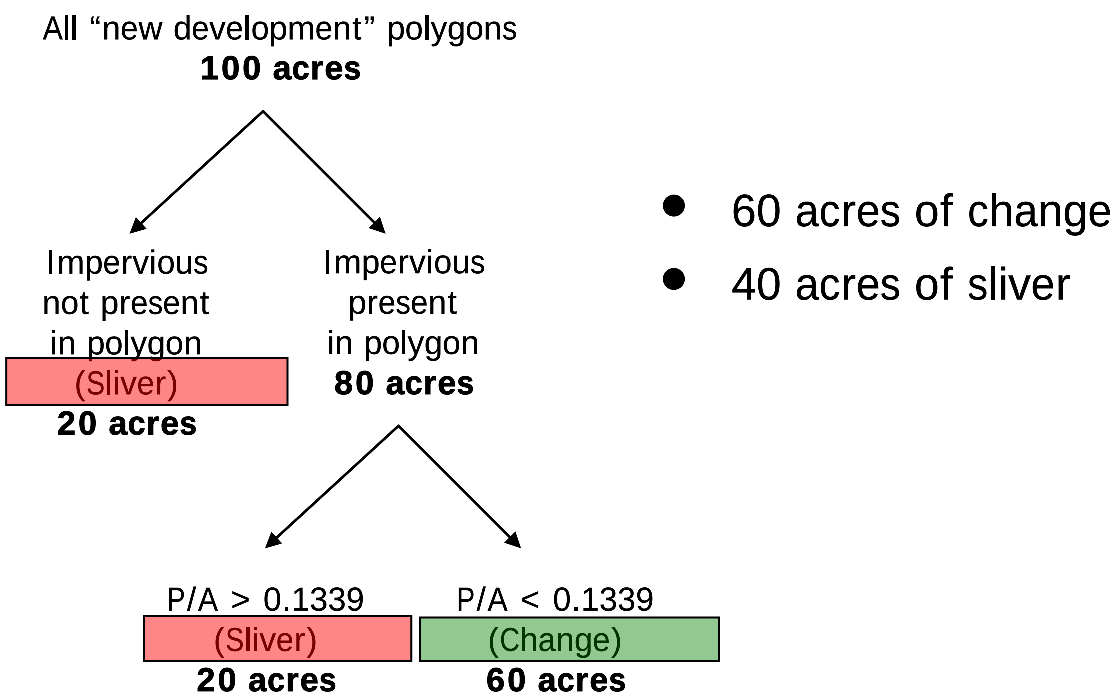


Figure 6. Application of coefficients to shapefile polygons

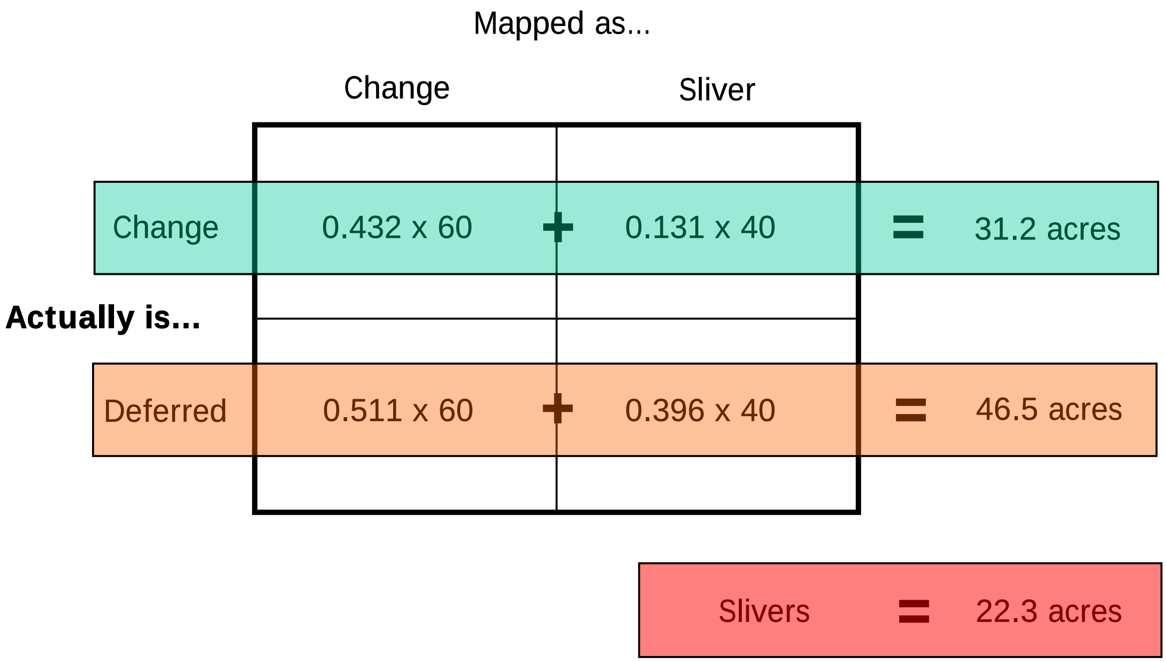
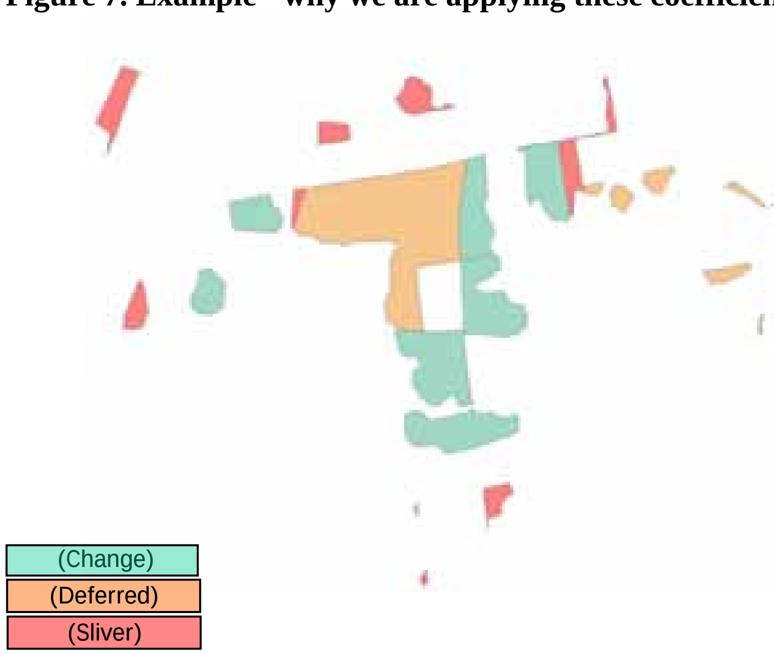


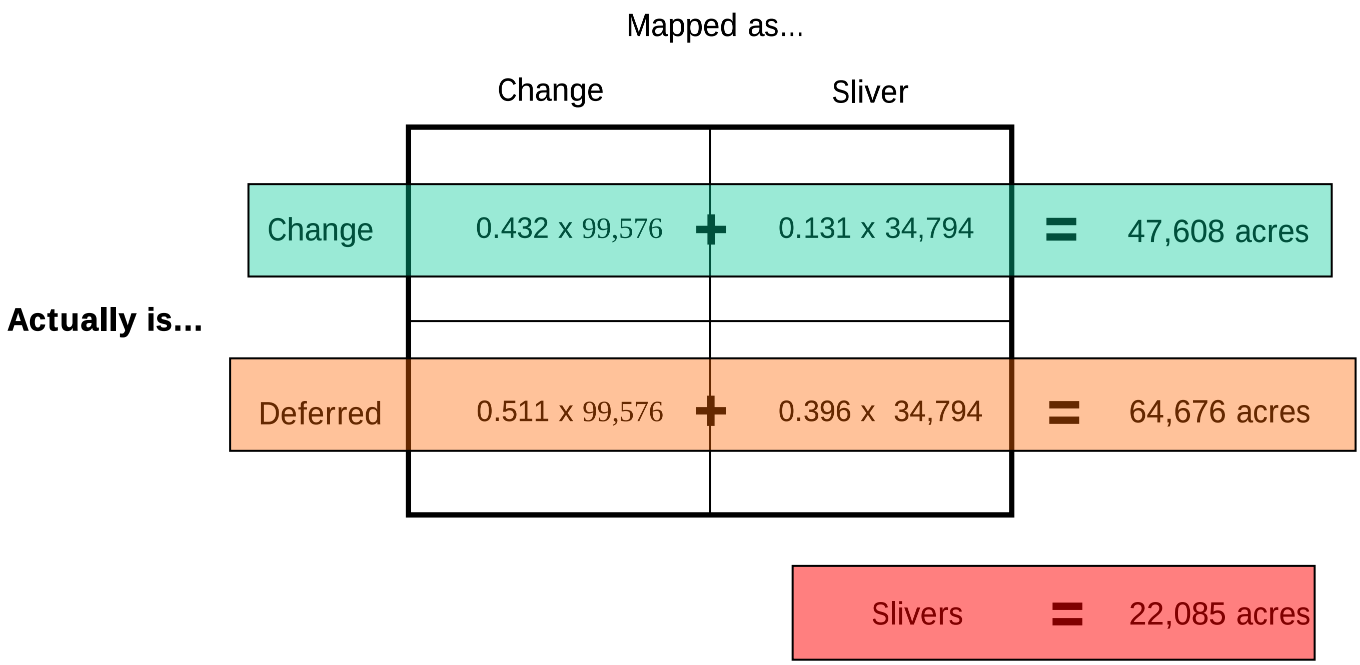
Figure 7 returns to the polygons shown in Figure 3. It shows what inspection of late 1990s and 2005 aerial photography revealed about these “new development” polygons. The orange polygons were already developed in 1999, while the blue polygons represent real new development. This example spatially depicts what we attempted to do with our correction coefficients. By applying the coefficients, we are stripping away acres that were really already developed in 1999, leaving only those acres of real new development.

Figure 7. Example - why we are applying these coefficients



Application of the coefficients to the acreages in the “new development” shapefile is shown below:

Figure 8. Correction coefficients applied to the “new development” shapefile



We used the above coefficients to generate estimates of change statewide, but also at the town, ecoregion, watershed, regional planning agency, and county level. In addition, we used these coefficients to calculate acreages of the undeveloped land use types that were converted to development. Table 1 below shows the land use types that were converted to development in 2005.

Table 1. 1999 Land uses converted to residential or commercial development

1999 Types converted	Acres
Forest	28,201
Cropland	6,303
Open Land	3,670
Pasture	3,148
Urban Open	2,146
Mining	577
Participation Recreation	542
Waste Disposal	538
Orchard	408
Non forested wetland	360
Powerlines	339
Nursery	247
Golf	201
Water	189
Cemeteries	176
Cranberry bog	162
Salt Wetland	116
Marina	92
Water Based Recreation	80
Heath	25
Spectator Recreation	25

In hindsight, I would have removed several of these land use types that amount to 912 acres from the statewide estimate of change between 1999 and 2005 (spectator recreation, water-based recreation, marina, cemeteries, and waste disposal).

CAPS Analysis

In order to investigate the ecological impacts of development in Massachusetts, Mass Audubon partnered with a team of researchers at the University of Massachusetts. Dr. Kevin McGarigal, Scott Jackson, Brad Compton, and Kasey Rolih have developed the Conservation and Assessment Prioritization System (CAPS) model (for more information, see www.masscaps.org).

How does CAPS work?

CAPS is a spatial model designed to assess the ecological integrity of lands and water for all of Massachusetts. Ecological integrity can be thought of as the ability of an area to support plants and animals and the natural processes necessary to sustain them over the long term. The CAPS model rests on the assumption that by conserving intact, ecologically-defined natural areas of high integrity, we can conserve most species and ecological processes. CAPS is a "coarse-filter" approach, based on GIS data that are available statewide. It does not consider any information on rare species or other site-specific information (typically considered "fine-filter"). Results should be interpreted with the understanding that areas of low ecological integrity are often in need of conservation effort (e.g., fragmented wetlands in eastern Massachusetts contain many rare species).

The CAPS model was run for 1971, 1985, 1999, and 2005 using the MassGIS land use land cover data sets. This made it possible to investigate the changes in the ecological integrity of the Massachusetts landscape over the past 35 years.

The CAPS model divides the entire state into small cells (30 by 30 meters) and then calculates an index of ecological integrity score (IEI) for each cell. The IEI varies in value from 0 to 1, 1 being a high score and 0 being a low score. An IEI score of 1 indicates maximum integrity, and an IEI score of 0 indicates minimum integrity. A cell with an IEI of 1 would typically be in natural cover, far from roads or development. Development, whether it is a lone house or within an urban center, is given an IEI of 0.

For the Losing Ground analysis, we selected eight CAPS metrics (from a total of about two dozen). Limitations from our four-time step land use data precluded using other metrics (e.g., Road traffic intensity requires traffic rate data, available only for the most recent time step). Each metric was run for the entire state, resulting in a grid with a value between 0 and 1 for each cell. Stressor metrics are meant to capture things that will decrease the ecological integrity of an area if they are present, such as roads, invasive species, and edge predators. Resiliency metrics are meant to quantify an areas ability to bounce back from degradation. For instance, the connectedness metric would score a large patch of isolated forest lower than an equal sized patch of forest that was well connected to adjacent natural patches. The patch would be less "resilient" because of its isolation from other intact habitat. The stressor metrics include: Habitat loss; microclimate alterations; impacts from domestic predators such as cats and dogs; impacts from edge predators such as raccoons, blue jays, and cowbirds; non-native invasive plants; and non-native earthworms. The resiliency metrics calculated were:

connectedness of the landscape and similarity of the landscape. Appendix C defines each of these metrics; parameterization details are given in Appendix D.

Each metric is scaled by percentiles within the study area (statewide in this analysis), and metrics are integrated in a weighted linear combination, which is then scaled again by percentiles, resulting in IEI. Interpretation of scaled metrics and IEI is straightforward: an IEI of 0.95 means that this cell is in the 95th percentile of highest integrity across the state. When comparing across multiple time steps, metrics and IEI are scaled to the first time step, thus less than 5% of cells for later steps will have values of 0.95 or higher.

Additional Assumptions

The CAPS analysis was designed to measure the impact of development on "the nature of Massachusetts." To arrive at overall impact, we grouped various land cover types into six general categories: natural, residential, commercial/industrial, transportation, other developed, and open water. The "natural" class captures most of the land use types that are of interest to the conservation community, including forests, wetlands, non-forested uplands, agricultural land, orchards, and shrublands. An initial run of the CAPS model attempted to distinguish among these undeveloped types. However, shifts between these undeveloped types through time due to delineation error produced results that contained unrealistic changes in IEI. In essence, the "signal" of land use change over time was lost in the "noise" of arbitrary shifts in land use due to mapping errors. The classes ultimately used in this analysis allow an examination of the impacts of development on natural/undeveloped land.

Ideally, we would have assembled a unique road layer for each time step in order to capture the changing impacts due to development of new roads. Unfortunately, such a detailed undertaking was not feasible given the project budget/timeline. For this reason, we included all highways (Class 1), numbered routes (Class 2 and 3), and major roads (Class 4) as present in all years of analysis and minor streets were omitted.

The 2005 LULC, as described above, delineates polygons in a much tighter manner than was done in previous time steps. As a result, there were many developed polygons from 1971, 1985, and 1999 that were depicted as reverting to undeveloped categories, thought there was no actual change on the ground. For example, 224,000 acres coded as developed by the 1999 LULC was delineated as forest by the 2005 LULC. The accuracy of the 2005 LULC is much higher than any previous LULC. For this reason, we reverted the "developed" polygons in previous time steps to the soft land uses (forested, cropland, pasture, etc.) delineated by the 2005 LULC. The result is a much more accurate portrayal of actual development. The down-side is that any reversions of developed land to natural (e.g., an abandoned house site reverting to forest) were removed from the data. We believe that such reversions between 1971 and 2005 were exceedingly rare. Table 4 below shows the 2005 land use types that were "burned" into previous timesteps if they were developed in 1999, 1985, or 1971.

Table 4. Land use types "burned" into 1971, 1985, and 1999 from 2005

Cropland	1
Pasture	2
Forest	3
Openland	6
Salt wetland	14
Water	20
Cranberry bog	23
Saltwater sandy beach	25
Golf courses (if adjacent to golf course in the "base" year)	26
Cemeteries	34
Orchard	35
Nursery	36
Forested wetland	37

Additional editing of the data to reduce noise included:

- We burned cells mapped by DEP as open water and cells mapped in any year as open water into all years as open water. This avoids introducing errors by open water moving around slightly across time steps; the assumption is that open water is invariant from 1971-2005.
- We dropped first order stream centerlines. These are small and essentially part of matrix type; they created a mess in salt marshes and cranberry ponds.
- If either sequence of three successive years is developed → natural → developed, change inner natural to developed, assuming this change is the result of an error. This cleans up a handful of obvious errors where cells flicker between developed and natural.

We captured all of the queries that were used during this process. Please contact the author if you have further questions.

IEI-Acre and its applications

Throughout the CAPS analysis, a unit called the "IEI-acre" is used. This unit was created to facilitate comparison of one area to another. It is calculated so that an acre of grid cells (roughly 5 cells), each with a perfect score of 1, would be given a value of 1 IEI-acres. Likewise, an acre of cells with a value of 0.5 would be given a value of 0.5 IEI-acres. For instance, the town of Townsend 12,000 IEI-acres in 1971. This means that the sum of IEI for all of the cells in the town's 21,100 acres adds up to 12,000. By 2005, Townsend's had dropped to 8,700 IEI-acres. You can think of this as Townsend losing 3,300 acres of land with high ecological integrity. In reality, this loss occurred throughout the entire 21,100 acres of the town, rather than on 3,300 acres, but it allows comparison of Townsend to other towns and also allows the calculation of the change in IEI over time.

We used the IEI-acre values for each town to calculate the percent change in IEI through time. This very useful statistic resulted in Figure 3.5 in the main document, which was key in the delineation of the Sprawl Danger Zone. The IEI-Acre was also used to compare the indirect impacts of development to the direct impacts of development. In order to generate Figure 3.7, we calculated the change in IEI-acres on all land that remained natural from one time step to another and compared it to the change in IEI-acres directly under the cells of new development. We then made a ratio of these two figures for each town.

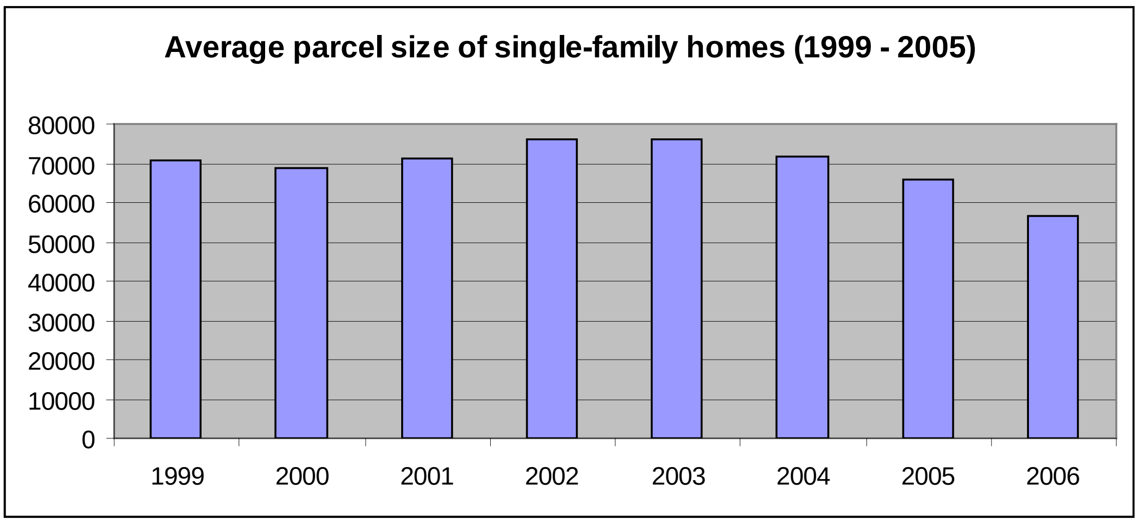
Housing Data and Zoning Information

Housing Data

MassGIS provided us with an analysis of the Warren Group real property listing data from 1999 to 2005. We extracted all units with a "Year Built" attribute that fell between 1999 and 2005. This allowed us to get an estimate of the number of homes built over this period and the average living area of the homes. Figure 2.2 in the main document depicts the average living area of single-family homes built between 1999 and 2005.

We also analyzed the average parcel size on which these new homes were built. Between 1971 and 2003 (3rd edition) it was determined that the average parcel size on which homes were being built was increasing. We investigated this trend in this edition as well. Unlike in past editions of Losing Ground, we were not able to detect that parcel sizes are continuing to grow. Figure 10 below shows the average parcel size, by year, for single-family homes.

Figure 10.



Zoning

The zoning analysis was based on information obtained from MassGIS Zoning data layers. Zoning data changes frequently and assembling zoning data for all towns is not regularly undertaken by MassGIS. For this reason, the zoning information depicted in figure 2.3 may not represent the current state of zoning for all towns in the Commonwealth. However, we feel use of MassGIS data is appropriate to illustrate statewide trends in zoning.

In order to generate Figure 2.3 we used residential zoning categories R1 – R5 and RA (Residential / Agricultural mix). Table 5 shows these zoning types.

Table 5. Zoning types included in Figure 2.3 (main document)

Category	Definition
R1	Single Family Residential, >= 80,000 sq. ft.
R2	Single Family Residential, 40,000 - 79,999 sq. ft.
R3	Single Family Residential, 20,000 - 39,999 sq. ft.
R4	Single Family Residential, 15,000 - 19,999 sq. ft.
R5	Single Family Residential, 5,000 - 14,999 sq. ft.
RA	Residential/Agricultural Mix

Towns “Predominantly zoned for 2-acre lots” had at least 50% of the town area in R1 and/or RA zoning types. Towns “Predominantly zoned for 1- to 2-acre lots” had at least 50% of the town area in R2. Towns “Predominantly zoned for < 1-acre lots” had at least 50% of the town area in R3, R4, or R5.

It would be very useful to periodically recreate Figure 2.3 to see if towns are shifting their zoning strategies over time. Zoning is one of the drivers of land use. The conservation community should have multiple zoning indicators that it is monitoring as new zoning tools are made available through legislation or tested in other towns.

Land Protection Analysis

In order to generate the statistics on protection, a copy of the Openspace and Recreation Data Layer was initially downloaded from MassGIS in April, 2008. These tables were subsequently updated using data from December, 2008. Permanently protected land was identified as all polygons where the attribute "LEV_PROT" had a value of "P". This includes some polygons that are not usually considered when analyzing protection of wildlife habitat, such as agricultural preservation. However, the analysis of Losing Ground was broadened to consider the protection of agricultural land in this edition, so it was appropriate to consider all permanently protected lands.

The estimates of the number of acres protected between 1999 and 2005 were generated using the December, 2008 version of the Openspace and Recreation Data Layer. Again, we considered all polygons where "LEV_PROT" = "P".

Analysis of Threats to Natural and Agricultural Resources

These analyses are described in enough detail within the Losing Ground document that they could be reproduced. Tables 4.4 and 4.6 list the land use types that were included in our definition of "natural" and "agricultural" lands.

Appendix A: Land Cover Classes

Land cover classes are listed below, with numeric codes for each class. Sources include land use (1971, 1985, 1999, 2005), EOT roads, trains, and stream centerlines.

Developed

5 Mining
7 Participatory recreation [and from 26]
8 Spectator recreation
10 Multi-family residential
11 High-density residential
12 Medium-density residential
13 Low-density residential [and from 38]
15 Commercial
16 Industrial
17 Urban open [from 17, 34]
18 Transportation [and from 32]
19 Waste disposal [and from 39]

Roads [from EOT roads]

71 Expressway
72 Primary highway
73 Secondary highway
76 Railroad [from trains]

Natural

111 Forests & forested wetlands [from 3, 37], Powerline/old field/successional [from 6, 24, 40], Pasture [from 2], Woody Perennial [from 21], Heath [from 33], Cropland [from 1], Nonforested freshwater wetland [from 4], Salt marsh [from 14, 27, 28], Water based recreation [from 9; mostly beaches]

Open water

333 Open water [from 0 (lower Merrimack and some estuaries), 20, 30, and from stream centerlines]

Appendix B: Input Data Layers

Land use – Land cover is from UMass Resource Mapping Unit's 1971, 1985, and 1999 Land Use: pasture, powerlines, and old fields (from open land).

Streams and Rivers – Streams and rivers are based on our work for Natural Heritage and Endangered Species Projgram's Living Waters project. MassGIS 1:25k stream centerlines were used to define streams. Streams are classified by order and gradient. Order is calculated from the stream centerline data; and gradient is based on the digital elevation model. We identified rivers that flow into the state to correct the order of these stream networks. For rivers wider than 30 m, the open water class from Land Use was used to represent the entire river basin, and the class based on order and gradient was applied to the entire width.

Developed Land – Developed land comes directly UMass Resource Mapping Lab's 1999 Land Use.

Roads and Railroads – Roads are railroads are from MassGIS's 1:25k EOT roads and trains layers. Roads were reclassified into five types based on original road classes as well as surface type (for unpaved roads). We also used interpolated traffic rates from the EOT roads layer.

Appendix C: CAPS Integrity Metrics

The following ecological integrity metrics from the Conservation Assessment and Prioritization System (CAPS) were used for the Losing Ground analysis. Integrity metrics include both anthropogenic *stressor* metrics that measure the level of anthropogenic activities exclusively and *resiliency* metrics that measure the combined effect of anthropogenic stressor and landscape context. Note that this is a subset of CAPS metrics that were appropriate given our input data and focus on forest communities.

Stressor Metrics

Development & roads

Habitat loss	Measures the intensity of habitat loss caused by all forms of development in the neighborhood surrounding the focal cell, based on a logistic function of Euclidean distance. This metric assumes that the conversion of natural communities to developed land in the neighborhood of a focal cell will reduce that cell's ecological integrity, regardless of how similar the focal cell is to the communities lost to development.
Microclimate alterations	Measures the adverse effects of induced (human-created) edges on the integrity of patch interiors; that is, factors that negatively intrude on the patch from its surroundings. The edge effects metric is based on the "worst" edge effect among all adverse edges in the neighborhood surrounding the focal cell, where each adverse edge is evaluated using a "depth-of-edge" function in which the "effect" is scaled using a logistic function of distance.

Biotic alterations

Domestic predators	Measures the intensity of development associated with sources of domestic predators (e.g., cats) in the neighborhood surrounding the focal cell, based on a logistic function of distance to development classes. This metric is a surrogate for domestic predator abundance measured directly in the field.
Edge predators	Measures the intensity of development associated with sources of human commensal mesopredators (e.g., raccoons, skunks) in the neighborhood surrounding the focal cell, based on a logistic function of distance to development classes. This metric is a

	surrogate for mesopredator abundance measured directly in the field.
Non-native invasive plants	Measures the intensity of development associated with sources of non-native invasive plants in the neighborhood surrounding the focal cell, based on a logistic function of distance to development classes. This metric is a surrogate for non-native invasive plant abundance measured directly in the field.
Non-native invasive earthworms	Measures the intensity of development associated with sources of non-native invasive earthworms in the neighborhood surrounding the focal cell, based on a logistic function of distance to development classes. This metric is a surrogate for non-native invasive earthworm abundance measured directly in the field.

Resiliency Metrics

Connectedness	Measures the disruption of connectivity caused by ecological dissimilarity and all forms of development between each focal cell and surrounding cells. A hypothetical organism in a highly connected cell can reach a large area with minimal crossing of “hostile” cells. This metric (a form of resistant kernel) uses a least-cost path algorithm to determine the area that can be reached from each focal cell. The focal cell gets a “bank account,” which represents the distance a hypothetical organism could move through a nonresistant landscape. Each cell is assigned a travel cost, based on a resistance matrix, as a function of its ecological dissimilarity to the focal cell. The algorithm then creates a least-cost hull around the focal cell, representing the maximum distance that can be moved from the cell until the “bank account” is depleted. Connectedness uses the ecological distances times a multiplier to come up with resistances values. The user can also specify resistance values for particular cover types (e.g., development types) to supercede ecological distance. Connectedness is defined as the ratio of the area of the observed least cost hull to the area of the least cost hull under a homogeneous nonresistant landscape. In the Losing Ground analysis, large highways (expressway, primary and secondary highway) are given the highest resistance values; developed types and open water are given high values, and natural types are given low resistance.
Similarity	Measures the amount of similarity between the ecological setting at the focal cell and those of neighboring cells, weighted by a logistic function of distance. Similarity is based on the ecological distance between the focal cell and each neighboring cell, where ecological distance is a multivariate distance across all ecological setting

variables. In the Losing Ground analysis, similarity is primarily used to distinguish large highways (expressway, primary and secondary highway) from other types; these larger roads are assumed to have existed for all time steps.

Appendix D: Metric Parameterizations

This table gives relative weights for each metric by community. Weights were based on the 2008 CAPS analysis of Western Massachusetts.

Weight		Grid name	Metric
2	(11%)	habloss	Habitat loss
1	(6%)	edges	Microclimate alterations
1	(6%)	cats	Domestic predators
2	(11%)	edgepred	Edge predators
2	(11%)	badplants	Non-native invasive plants
2	(11%)	worms	Non-native invasive earthworms
5	(28%)	connect	Connectedness
3	(17%)	sim	Similarity

Metric parameterization details

Metric	D_{50} (m)	D_s (m)	bandwidth (m)
Habitat loss	500	100	
Microclimate alterations			
Domestic predators	200	40	
Edge predators	100	20	
Non-native invasive plants	100	20	
Non-native invasive earthworms	200	40	
Connectedness			2000
Similarity	700	140	

Landcover metric parameters

	Habitat loss	Microclimate alterations	Domestic predators	Edge predators	Non-native invasive plants	Non-native invasive worms	Connectedness (resistance)	Similarity (contrast)
Mining	1	180,60	0	1	1	0	10	1
Participatory recreation	1	180,60	0	2	1	0	10	1
Spectator recreation	1	180,60	0	2	1	0	10	1
Multi-family residential	1	180,60	1	3	2	1	10	1
High-density residential	1	120, 40	1	3	2	1	10	1
Medium-density residential	1	120, 40	1	3	2	1	10	1
Low-density residential	1	120, 40	1	3	2	1	10	1
Commercial	1	180,60	1	3	2	1	10	1
Industrial	1	180,60	1	3	2	1	10	1
Urban open	1	120, 40	1	3	2	0	10	1
Transportation	1	180,60	0	2	2	0	10	1
Waste disposal	1	120, 40	0	3	1	1	10	1
Expressway	1	120, 40	0	2	1	0	70	7
Primary highway	1	120, 40	0	2	1	0	60	6
Secondary highway	1	120, 40	0	2	1	0	50	5
Railroad	1	120, 40	0	2	1	0	10	1
Natural							1	0
Water							10	1

Appendix E: History of Applications of CAPS model

Since its creation, the CAPS model has been applied by a variety of groups including the Massachusetts Executive Office of Environmental Affairs, the Massachusetts Division of Fisheries and Wildlife, the Connecticut Department of Transportation, The Trustess of Reservations, the Environmental Protection Agency, the Massachusetts Department of Environmental Protection, The Nature Conservancy, and the Federal Highway Administration via Massachusetts Executive Office of Transportation. These projects are briefly described below.

Project: Housatonic *Year(s)*: 1999-2001
Funder: Massachusetts Executive Office of Environmental Affairs
Description: Develop the initial conceptual framework and software for CAPS, conduct intensive field sampling in the Housatonic watershed (2000 field season), use field data, satellite, and terrain data to map natural communities, and run a CAPS analysis for the watershed.

Project: Living Waters *Year(s)*: 2002-3
Funder: Massachusetts Division of Fisheries and Wildlife
Description: Develop conceptual methods, data and software used to develop "critical supporting watersheds" for Natural Heritage's Living Waters statewide assessment. These methods later became the basis of the CAPS watershed metrics.

Project: Route 11 *Year(s)*: 2003-4
Funder: Connecticut Department of Transportation
Description: Do a scenario analysis on the current landscape and three alternative road alignments for the Route 11 extension in southeastern Connecticut. Results were used to help set mitigation targets.

Project: Highlands *Year(s)*: 2004-5
Funder: Trustees of Reservations
Description: Run a CAPS assessment of the 38-town Highlands region of western Massachusetts. This analysis later became the basis of the initial MassDEP important habitat maps.

Project: Western Massachusetts assessment, forest SLAM, and wetland SLAM pilot
Year(s): 2007-8
Funder: Environmental Protection Agency, Massachusetts Department of Environmental Protection
Description: Run a CAPS assessment for the western 40% of Massachusetts and produce important habitat maps for MassDEP. This project marks our first serious attention to field validation/calibration of CAPS metrics, and includes field work in forested uplands and a pilot wetland season (2007 field season). Field work was designed to develop Indices of Biological Integrity (IBIs) that can be combined into a Site-Level

Assessment Method (SLAM). SLAMs are intended to be used by DEP to assess the condition of wetlands in the field; they are also used to validate and refine CAPS metrics.

Project: Losing Ground *Year(s)*: 2008-9
Funder: Massachusetts Audubon Society
Description: Run eight CAPS metrics in a comparative analysis of undeveloped land across Massachusetts for 1971, 1985, 1999, and 2005. Results will be included in the fourth edition of Mass Audubon's Losing Ground series.

Project: Forested wetland SLAM *Year(s)*: 2008-ongoing
Funder: Environmental Protection Agency, Massachusetts Department of Environmental Protection
Description: Continuation of field work in forested wetlands (2008 and 2009 field seasons) and development of a SLAM for field-based assessment of forested wetlands.

Project: Coastal wetland SLAM + Statewide CAPS run *Year(s)*: 2008-ongoing
Funder: Environmental Protection Agency, Massachusetts Department of Environmental Protection
Description: Continued development of CAPS (including new metrics and settings variables) to support analyses in coastal communities; work with Massachusetts Coastal Zone Management (CZM) to develop a SLAM for salt marshes (2009 and 2010 field seasons); statewide CAPS run and DEP important habitat maps (preliminary run, spring 2009; final run, fall 2009).

Project: Linkages *Year(s)*: 2009-ongoing
Funder: Federal Highway Administration via Massachusetts Executive Office of Transportation [funding pending], The Nature Conservancy
Description: Develop a scenario analysis capability to assess large numbers of road segments, stream crossings, and dams across Massachusetts for potential improvements in connectivity by mitigation (e.g., road passage structures, culvert upgrades, dam removal).