THE
TRUST
for
PUBLIC
LAND

Connecticut River Program
One Short Street
Suite 9
Northampton, MA
01060
T. 413-584-6686
F. 413-584-6687
www.tpl.org/ctriver

OVERVIEW

This appendix provides details on the data and methods used to produce maps and analytical results for the body of the report. Some of this information is provided in the report section titled Figure and Map Data Sources, but this document provides supplementary detail for those interested. This information was developed primarily for internal use and sharing with organizational partners and as such is not edited for easy reading. It is ordered by map in the sequence in which they appear in the report, but presents the housing density methodology conducted by David Theobald at the end of the appendix. Please contact The Trust for Public Land Connecticut River Program with any questions.

MAP 1: CONNECTICUT RIVER WATERSHED

Standard map data sources; city populations from US Census Bureau (2000 Census), with Lenbanon and Hanover combined due to their proximity.

MAP 2: BUILT INFRASTRUCTURE

Data from The National Map and ESRI standard datasets, widely available free of charge. Airports and dams selected based on size. Aqueducts from Connecticut Department of Environmental Protection (1:24,000 hydrography, 1994 data processed 2005) and MassGIS (1:25,000 hydrography, February 2005). Urban areas are “densely settled areas” made up of urbanized areas with total population greater than 50,000 and urban clusters with total population between 2,500 and 49,999. Both areas “generally consist of a geographic core of block groups or blocks that have a population density of at least 1,000 people per square mile, and adjacent block groups and blocks with at least 500 people per square mile.” (http://www.census.gov/geo/www/tiger/glossary.html)

MAP 3: CONSERVED LANDS

Purpose

This dataset is a collection of conserved lands throughout the 4-state region of Connecticut, Massachusetts, New Hampshire, and Vermont.

Distribution Rights

Some data included in the dataset has restricted distribution conditions. Unless otherwise noted, this data may be used for TPL analysis only. It may not be distributed.

Attributes

The following unique attributes are included in this dataset:

- CanDisplay
  - 1 = Can display and distribute this record
  - 0 = Restricted rights for display and distribution of the record
- State
  - State from whom this data was acquired
- DataSrc
  - Source data file from which this feature was derived. See state-by-state description of source data below
- CodeAttr
  - Attribute within DataSrc above, used to determine appropriateness of this data for denoting conserved lands. See state-by-state description of source data below.
- Code
  - Code retrieved from attribute CodeAttr within DataSrc above, used to determine appropriateness of this data for denoting conserved lands. See state-by-state description of source data below.
- LastUpdate
  - Last known update of this DataSrc.

Vermont Data

VT_ConsPri.shp (includes both public and private)

Downloaded with restricted permissions from David.Capen@uvm.edu
Last updated: January 2005

Coordinate System: NAD_1983_StatePlane_Vermont_FIPS_4400 Meters

Coded based on attribute PPTYPE (Primary Protection Type):

- All codes included EXCEPT:
  (60) Partially protected through current land use
  (99) Not protected

Full Code Description of attribute PPTYPE:

(01) Fee Ownership, (02) Fee Ownership Except Timber Rights, (02.1) Fee Ownership Except Lifetime Wood Rights, (03) Fee Ownership Except Mineral Rights, (04) Fee Ownership Except Oil Rights, (05) Empty, (06) Fee Ownership Except Hunting Rights, (07) Empty, (08) Empty, (09) Fee Ownership Except Multiple Rights, (10) Conservation Easement (General), (10.1) Vermont Land Trust Conservation Easement, (10.2) The Nature Conservancy Conservation Easement, (10.3) Green Mountain Club Conservation Easement, (10.4) Upper Valley Land Trust Conservation Easement, (10.5) State of Vermont Conservation Easement, (10.6) US Forest Service Conservation Easement, (10.7) US Dept. of Agriculture Conservation Easement, (10.8) Conservation Easement Held by Vermont Municipality, (10.9) Conservation Easement Held by Other, (11) Trail Easement, (11.1) Winter Trail Easement, (12) Historical Preservation Easement, (13) Scenic Easement, (14) Flowage Easement, (15) Rails to Trails Easement, (16) Ecological Protection Zone, (17) Empty, (18) Agricultural Easement, (19) State of Vermont Hunting Rights Conservation Easement, (20)

Deed Restrictions (General), (21) Agricultural Preservation Deed Restrictions, (22) Archeological Preservation Deed Restrictions, (23) Set Aside area of Development Deed Restriction, (24) Flowage Deed Restrictions, (25) Act 250 Deed Restrictions, (26) Conservation Deed Restrictions, (27) Recreation easement, (28) Empty, (29) Empty, (30) Reverter, (31) Management Agreement, (32) State of Vermont 'Natural Area' Designation, (33) Executory Interest, (34) Remainder Interest, (35) Lease, (36) Empty, (37) Covenant, (37.1) No Development Zone within Covenant, (38) Parcel to be conveyed to other entity, (39) Empty, (39.1) No Development Zone within Easement, (50) NA (SEE SPTYPE1), (51) NA, (51.1) NA, (52) NA, (53) NA, (54) NA, (55) NA, (56) NA, (57) NA, (58) NA, (59) NA, (60) Partially protected through current land use, (70) NA, (71) NA, (72 NA), (73) NA, (74 NA), (75) NA, (76) NA, (77) NA, (78) Public Access Easement, (79) NA, (80) NA, (81) NA, (82) Empty, (83) Empty, (84) Empty, (85) Vermont Use Value Appraisal Program, (86) Empty, (87) Empty, (88) Water, (89) Empty, (90) Miscellaneous (Explained in PPTYPEDESC), (99) Not protected (See EXCLUDED).

Connecticut Data

Depproperty.shp (downloaded from http://dep.state.ct.us/gis/dataguides/dep/layers/propdep.htm)
Last updated: 2004
FederalProperty.shp (downloaded from http://dep.state.ct.us/gis/dataguides/dep/layers/propfed.htm)
Last updated: 1997
MunicipalProperty.shp (downloaded from http://dep.state.ct.us/gis/dataguides/dep/layers/propmun.htm)
Last updated: 1997

Coordinate System: NAD_1983_StatePlane_Connecticut_FIPS_0600_Feet
Codes included:

DEP
All features included.

Federal
All features included.

Municipal
Coded based on attribute CATEGORIES.
All features included EXCEPT:

CATEGORY	**Largest Area (Acres)**
School	154
General Recreation	951
Cemetery	278
Uncategorized	4,623

Massachusetts Data

OPENSPACE_POLY.shp (downloaded from http://www.mass.gov/mgis/osp.htm)
Last updated: Jan 2005

Coordinate System: NAD_1983_StatePlane_Massachusetts_Mainland_FIPS_2001_Meters

Codes included:
Coded based on attribute Lev_Prot.
Codes included:
- P=Perpetuity

Codes EXCLUDED:

Lev_Prot	Largest Area (Acres)
X=Unknown	617
T=Term Limited	297
N=None	1218
L=Limited	1377

New Hampshire Data

consp.shp and **conspadf.dbf** (downloaded from http://www.granit.sr.unh.edu/cgi-bin/nhsearch)

Last updated: 2004

Coordinate System: NAD_1983_StatePlane_New_Hampshire_FIPS_2800_Feet

Codes included:

Coded based on attribute LEVEL.

Codes included:

- 1=Permanent conservation land
- 4= Developed public land

Codes EXCLUDED:

LEVEL	Largest Area (Acres)
2-Unofficial Consv Land	26,773
2A-Water Supply Lands	2,716
3-Unprot Pub OS	2,910
9-Unknown	632

1 - Permanent conservation land.
Land protected from development through conservation easement, restriction, or outright ownership by an organization or agency whose mission includes protecting land in perpetuity; more than 50% of area will remain undeveloped.
2 - Unofficial conservation land.
Owned by an agency or organization whose mission is not conservation, but whose intent is to keep the land for conservation, passive recreation, or educational purposes. Not permanently protected.
2A - Water supply lands.
Lands owned or controlled by suppliers of public drinking water. Includes all supplies owned by a municipality or a subdivision of a municipality, and all private water systems which serve 500 people or more.
3 - Unprotected public open space land.
4 - Developed public land
including land having active recreational use on more than 50% of its area, e.g. beaches, picnic areas.
9 - Unknown.

TPL Connecticut Headwaters Project

\ConsLand\TPL (raster) – from previous work by Lexi Shear, TPL Consultant

Coordinate System: NAD_1983_StatePlane_Massachusetts_Mainland_FIPS_2001_Meters

MAPS 4 AND 5: WATERSHED HOUSING DENSITY AND CHANGE

Map 5 shows areas where density crosses a threshold between 2000 and 2020, from rural to exurban, exurban to suburban, and so on. These areas are used in maps 7, 9, 11, and 13 to represent the threat associated with current trends in landscape change. While valuable for assessing trends across a wide area that includes the full spectrum of housing densities, the results should not be interpreted at a local level. Actual housing density data resulting from this analysis are available to partner organizations upon request.

Methodology Overview

A. Spatially Explicit Regional Growth Model Methodology as developed by:
David M. Theobald, Ph.D.
Natural Resource Ecology Lab, Colorado State University
Fort Collins, Colorado, 80523-1499
davet@nrel.colostate.edu
Please see, at the end of this appendix:
Theobald, D.M. 2005. Spatially Explicit Regional Growth Model (SERGoM) v2. Unpublished report, Natural Resource Ecology Lab, Colorado State University.

B. Development Threat Crossover Analysis
This analysis examined PROJECTED CHANGE in housing density between 2000 and 2020.

Classifications were defined as follows:
2 = Rural (>40 acres/unit), 0, or NoData
3 = Exurban (10-40)
4 = Suburban (1.7-10)
5 = Urban (0.6 - 1.7)
6 = Dense Urban (<0.6)

A “crossover” analysis was performed, showing where a range of density thresholds were projected to be crossed (thresholds shown above). This analysis is distinct from the more traditional approach of highlighting a single threshold defined as "urbanization," "suburbanization”. Therefore, this approach captures the full gradient of landscape change, including exurbanization or "rural sprawl”. One downside in this analysis is that changes of equal magnitude that happen *within* a given density category are not highlighted, so there is a bias towards highlighting change in places that happen to already be close to an arbitrary density threshold in the base year.

Result Rasters

BINARY Rasters:
threat_bin   High Potential for New Development

MAP 6: FARMLAND RESOURCES

Methodology Overview

Identify areas that have prime agricultural soils

Analysis Detail

Step A: Identify areas that have prime agricultural soils:

Analysis Summary:

Where SSURGO data exists, use prime farmland attribute provided in the data.

Where SSURGO data does not exist (Franklin County and parts of Worcester County in Massachusetts, Caledonia and Essex Counties in Vermont, and Coos County in New Hampshire), use a multivariate approach based on landform, substrate, and landcover characteristics provided in TNC's System30 dataset, to statistically predict where prime agricultural lands are likely present.

Detailed Methodology

Where SSURGO data exists:

Use attribute FARMINDCL from SSurgo table MAPUNIT to identify SSurgo polygons classified as prime farmland. Note that over the 4-state study area, values provided in attribute FARMINDCL are not consistent.

Used only the **All areas are prime farmland** value as an indicator of prime farmland, to be consistent across entire study area.

Other possible values included in some states were:

- Not prime farmland
- Farmland of statewide importance
- Farmland of local importance
- Prime farmland if drained
- Prime farmland if protected from flooding

Where SSURGO does not exist:

Use a multivariate approach based on landform, substrate, and landcover characteristics provided in TNC's System30 dataset, to statistically predict where prime agricultural lands are likely present.

ESRI's Multi-variate analysis tools were applied. Spatial variables used for the predictive model include substrate, landform, and landcover. Predictive model was "trained" to best match known SSURGO values on an area in central Connecticut within CT River Watershed. Then this same model was used to predict areas within MA, VT, and NH where SSURGO data is not yet available. Model results were validated using Statsgo data and County-specific prime-soil acreage counts.

Data Sources:

2003 System30 raster dataset:
The Nature Conservancy (TNC) Conservation Science Support, Survey, US Geological , US Environmental Protection Agency, and Geological Surveys of ME, NH, VT, NY, MA, CT, RI, PA, NJ, DE, 2003, systems30. Copyright © 2003 The Nature Conservancy. All rights reserved.

Contact: Charles Ferree, GIS Analyst/Ecoregional Cons Planner, TNC Eastern US Region, Boston, MA

USDA NRCS SSURGO, http://soildatamart.nrcs.usda.gov
Publication dates:

VT 2005
NH 2004
MA 2004-2005
MA 2006 Pre-release SSURGO for Hamp_Central and Hampden_Central
CT 2005 Pre-release SSURGO
(http://dep.state.ct.us/gis/Data/data.asp)

USDA NRCS STATSGO
http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/metadata/ct.html
Publication date: 1994

Step B: Delineate results based on areas that are currently farmed

Analysis Summary:
Use land cover data to extract currently farmed areas based on attribute codes.

Detailed Methodology
Retrieve most recent land cover data from each state (see data source below)
Most recent datasets are given precedence.
Extract agricultural codes as follows:

CT: 2, 3
MA: 4, 5
VT: 24, 61, 211, 212
NH: 211, 212, 221, 412
NLCD: 81, 82, 83, 85

Data Sources:
NLCD – National Land Cover Data 1992 (http://seamless.usgs.gov/)
Connecticut: 2002 Land Cover, Greater Connecticut (http://clear.uconn.edu/)
Massachussetts: Massachusetts Land Cover 1997 Analysis for June 23, 1997 from NOAA Coastal Services Center/Coastal Change Analysis Program (C-CAP)
New Hampshire: NH land cover assessment 2001 (http://www.granit.sr.unh.edu/cgi-bin/load_file?PATH=/data/datacat/funclist.html)
Vermont: LandLandcov_LCLU from VCGI and Mt Holyoke College; modified variant of 1992 NLCD base imagery, (http://www.vcgi.org/dataware/default.cfm?layer=LandLandcov_LCLU>)

All five datasets were reprojected to Albers Conic Equal Area Contiguous USA, NAD 1983.

MAP 7: FARMLAND STATUS

Combines all prime and farmed lands (Map 6) and segments them according to coincidence with the 2000-2020 density change model results (Map 5).

MAP 8: FOREST RESOURCES

Methodology Overview

Define Large Blocks of Roadless, Non-Steep Forest

Analysis Detail

Define Large Blocks of Roadless, Non-Steep Forest:

Summary of Analysis Steps:

A1 - Roadless Areas
- 100m buffer on highways
- 50m buffer on other roads

A2 - Forest Blocks from Land Cover
- Codes 41-Deciduous Forest, 42-Evergreen Forest, 43-Mixed Forest

A3 – Steep slope exclusion
- less than 35%

A All - Large Blocks of Roadless, Non-Steep, Forests
- Contiguous blocks > **1000** acres

Detailed Methodology

A1 - Roadless Areas

Using Street-Map data as input, considers highways and other roads. Eliminates trails and private roads. Creates 50 m buffer on roads and a 100m buffer on highways. Creates a mask using the gaps.

Data Source:
ESRI's Streetmap Data -
Ground Condition: 2000, Publication data: 2002, 1:50K resolution

A2 - Forest Blocks from LandCover

Retrieves most recent land cover data from each state.
Combines data with 1992 NLCD to cover entire 4-state region (most recent data given precedence)
Extracts Forest only codes: 41 Deciduous Forest, 42 Evergreen Forest, 43 Mixed Forest.

Data Sources:
NLCD – National Land Cover Data 1992 (http://seamless.usgs.gov/)
Connecticut: 2002 Land Cover, Greater Connecticut (http://clear.uconn.edu/)
Massachussetts: Massachusetts Land Cover 1997 Analysis for June 23, 1997 from NOAA Coastal Services Center/Coastal Change Analysis Program (C-CAP)
New Hampshire: NH land cover assessment 2001 (http://www.granit.sr.unh.edu/cgi-bin/load_file?PATH=/data/datacat/funclist.html)
Vermont: LandLandcov_LCLU from VCGI and Mt Holyoke College; modified variant of 1992 NLCD base imagery, (http://www.vcgi.org/dataware/default.cfm?layer=LandLandcov_LCLU>) All five datasets were reprojected to Albers Conic Equal Area Contiguous USA, NAD 1983.

A3 – Steep slope exclusion

Converts digital elevation model data into percent slope using standard ArcGIS algorithm. Extracts only those areas with slope less than or equal to 35%, Rationale – slopes greater than 35% are unharvestable.

Data Source:
1:250,000 DEMs from the USGS (http://edc.usgs.gov/geodata/)

Preprocessed to create a mosaic of 22 quads to cover the study area.
Reprojected to Albers Conic Equal Area Contiguous USA, NAD 1983

A All - Large Contiguous Blocks of Roadless, Non-Steep, Forests
Intersect results from A1, A2, A3 above
Extract contiguous blocks > **1000** acres

Result Rasters

forblks_bin	Code 1=Large forest blocks (>1000ac), Code 0=Other
forblks_tht	as above, except Code 99 = Threatened Forest Blocks

MAP 9: FOREST STATUS

Combines all forest blocks over 1,000 acres (Map 8) and segments them according to coincidence with the 2000-2020 density change model results (Map 5).

MAP 10: HABITAT PRIORITIES

Methodology Overview

C. Identify Federal Habitat Priorities
D. Identify State Habitat Priorities
E. Determine Critical Aquatic Habitat

Analysis Detail

Step A: Federal Habitat Priorities

Analysis Summary:
Conte National Wildlife Refuge Focus Areas

Detailed Methodology
Used data collected by Lexi Shear, April 2004. Data files used include rasters conteland, contefish, contestream.

Data Sources
Bandolin, L. 1995. The Silvio O. Conte National Fish and Wildlife refuge Final Action Plan and Environmental Impact Statement. US Fish and Wildlife Service, Turners Falls, MA. Data received from Conte National Wildlife Refuge June, 2003.

Step B: State Habitat Priorities

Analysis Summary:
State Natural Heritage Inventories

Detailed Methodology
Used data collected by Lexi Shear, April 2004. Subtracted Federal Habitat areas (defined above) from combined habitat layer in raster Habitat3.shp, to derive state only.

Data Sources
Vermont Biodiversity Program, 2000. Biodiversity Hotspot Metadata. University of Vermont Spatial Analysis Lab, Burlington, VT. Retrieved August, 2003 from http://www.vcgi.org/metadata/EcologicHabitat_HOTSPOTS.htm.
Natural Heritage and Endangered Species Program, 2003. Retrieved August, 2003 from http://www.state.ma.us/mgis/prihab.htm.
New Hampshire point occurrence data was received directly from the New Hampshire Natural Heritage Inventory, March, 2003.
Massachusetts Priority Habitats of Rare Species data was received from the Massachusetts Natural Heritage and Endangered Species Program, May, 2003.
Vermont point occurrence (endanger.eoo) data was downloaded January, 2003 from http://www.vcgi.org/
Connecticut Department of Environmental Protection Environmental and Geographic Information Center, 2003. Environmental GIS Data for Connecticut, 2003 Edition. DEP Bulletin 37. 7 CD set.

Step C: Critical Aquatic Habitat

Analysis Summary:
Create graduated buffers along waterways to identify aquatic habitat, as well as areas important for water quality, erosion management, flood plains protection, and other land-water interface concerns.

Detailed Methodology
- CT River mainstem was buffered 400 meters on each side (1/4 mi)
- Primary Tributaries were buffered 200 meters
- Minor Tributaries were buffered 100 meters

Segments listed above were extracted from the EPA Reach File using the stream order attribute (“Lev”):

Category	Stream Order
Mainstem	1
Primary Tributary	2
Minor Tributary	3+

Data Sources
U.S. EPA Reach File 1 (RF1) for the Conterminous United States distributed with EPA BASINS http://www.epa.gov/waterscience/basins

Result Rasters

BINARY Rasters:

habste_bin	State Habitat Priorities
habfed_bin	Federal Habitat Priorities
habbuf_bin	Critical Aquatic Habitat
haball_bin	Combined Habitat(state, fed, aquatic)

Rasters showing resource threat :

habste_tht	State Habitat Priorities
habfed_tht	Federal Habitat Priorities
habbuf_tht	Critical Aquatic Habitat
haball_tht	Combined Habitat(state, fed, aquatic)

MAP 11: HABITAT STATUS

Combines all identified habitat areas (Map 10) and segments them according to coincidence with the 2000-2020 density change model results (Map 5).

MAP 12: WATER SUPPLY AREAS

Methodology Overview

A. Identify Water Supply Lands
B. Delineate Company-Owned Lands

Analysis Detail

Step A: Water Supply Lands

Analysis Summary:
Water Supply Lands for the 4-state region, but unavailable for Vermont.

Detailed Methodology
Used data collected by Lexi Shear, April 2004. Data files used include NH_wq_protected.shp, NH_wq_protected.shp, CT_wq_protected.shp.

Data Sources
Information is not available from the state of Vermont because of national security concerns.
Information on New Hampshire water supply Lands was received in August, 2002 as a GIS layer from NH DES.
Information on Massachusetts water supply lands was received in August, 2002 as a GIS layer from Mass DEP.

Step B: Company Owned Lands

Analysis Summary:
Company Owned Lands within NH and CT.

Detailed Methodology
nh_wq_companyowned.shp, ct_wq_companyowned.shp

Data Sources
See above.
Information on Connecticut water supply lands was received as a GIS layer from CT DEP.

Result Rasters

BINARY Rasters:

watsup_bin	Watershed Water Supply Areas

Rasters showing resource threat :

watsup_tht	Watershed Water Supply Areas

NB: Company owned lands within NH and CT derived from water system attributes. Company owned water supply land in Massachusetts open space datasets is listed as "permanently protected" and is therefore is counted as conserved. The question of developability of company owned water supply lands is controversial and varies by state law and culture, as well as by individual case. To the extent possible, TPL aimed to distinguish lands that are protected through public ownership or legal protections from those that are not.

MAP 13: WATER SUPPLY STATUS

Combines all water supply areas (Map 12) and segments them according to coincidence with the 2000-2020 density change model results (Map 5), classifying them as threatened, conserved, or neither.

MAPS 14 AND 15: RESOURCE ASSESSMENT, RESOURCE STATUS

All data are from previously described sources. Water supply lands were excluded because Vermont data were not available. Areas of overlap between critical resources were calculated on a 100-meter square algebraic analysis that assigned one "point" for each of the following characteristics attributed to each square in the raster grid: prime farm soil, currently farmed, within forest block of at least 1,000 acres, within a riparian buffer, within a state rare species habitat area, within a federal (Conte Refuge) habitat focus area. TPL intentionally avoided applying weights to particular resources, but there is inherent bias in such an analysis based on the data available and chosen for inclusion.

The first raster, resrc_sum (for Map 14), was created by performing the following weighted sum operation:

```
Sum(
1 * primag_bin,
1 * farmed_bin,
1 * forblks_bin,
1 * habbuf_bin,
1 * habfed_bin,
1 * habste_bin)
```

The 2nd raster, resrc_bin, is in binary raster format. In this datasets, a "1" represents a score of at least 2 or greater from the above calculation. A "0" denotes a score of less than 2.

The 3rd raster, resrc_tht (for Map 15) denotes threatened lands within overlapping resources. A "1" represents the presence of two or more overlapping resources, a "99" denotes the presence of threatened overlapping resources, and a "0" denotes absence of overlapping resources.

resrc_sum	Overlapping critical resources (as defined above)
resrc_bin	Binary: 1 = two or more overlapping resources
resrc_tht	Threatened overlapping resources

In map 15, all grid squares with a score of two or higher in Map 14 are displayed as "high-value land" because they provide multiple conservation benefits. This map segments those high-value areas according to coincidence with the 2000-2020 density change model results (Map 5), classifying them as threatened, conserved, or neither.

Spatially Explicit Regional Growth Model (SERGOM) v2 methodology

David M. Theobald, Ph.D.
Natural Resource Ecology Lab, Colorado State University, Fort Collins, Colorado, 80523-1499, USA
davet@nrel.colostate.edu

Note: this is an excerpt from a paper in review in Ecology & Society called "Landscape patterns of exurban growth in the USA from 1980 to 2020"

Exurban or rural sprawl has been equated with rural residential development at exurban densities (Theobald 2001a). Based on the Census definition of urban areas, I define *urban* housing densities as less than 0.1 ha per unit and s*uburban* as 0.1 – 0.68 ha per unit. I define *exurban* density as 0.68 – 16.18 ha per unit to capture residential land use beyond the urban/suburban fringe that is composed of parcels or lots that are generally too small to be considered productive agricultural land use (though some high-value crops such as orchards are a notable exception). *Rural* is defined as greater than 16.18 ha per unit where the majority of housing units support agricultural production. In some states where farming can be productive even for small acreage farms (~8-10 ha), exurban areas can be defined as having between 0.68 – 8.09 ha per unit.

Estimating historical and current housing density

To estimate historical and current housing density patterns, I used the best available, fine-grained and national-extent spatial database on population and housing from the Census Bureau's block-group and block data for 2000 (US Census Bureau 2001a). Maps of past and current housing density were computed using dasymetric mapping techniques that have been detailed in previous work (Theobald 2001, 2003). Here, I describe census geography basics and refinements to these basic dasymetric techniques.

Using census geography, the familiar census tract is subdivided into a block-group (containing roughly 250 to 550 housing units). Block-groups are in turn subdivided into blocks that are roughly a block or so in size in urban areas, but may be many square kilometers in rural areas. These block-groups and blocks tessellate or cover the entire US (US Census Bureau 2001a). Nationwide in 2000, there were 207,469 block groups and 8,185,004 blocks. The boundaries of census blocks typically follow visible physical features such as streets, roads, streams, railroad tracks, and ridgelines, and occasionally are based on city or county limits, property lines, or short extensions of streets (US Census 2001a).

Blocks vary in shape and size from small (roughly less than 1 to 2 ha), but the grain or resolution is finer in urban areas. Estimates of exurban development computed from these data are conservative because units are assumed to be roughly spread evenly throughout a block. Therefore, estimated housing density will tend to be lower because higher density areas within a block are "averaged out". Moreover, the varying sized analytical units cause possible inaccuracies, which is widely recognized as the modifiable areal unit problem (Openshaw 1984). Analyses based on Census data are subject to these limitations, but to date there is no easy, practical solution to these difficulties (Longley et al. 2001). It is important to note that the resolution or "grain" of refined blocks is coarser than land cover information from USGS

National Land Cover data (30 x 30 m), but because the boundaries of blocks are often based visible physical boundaries, their shapes often conform to important features on the landscape.

Because houses are not allowed on public and protected lands, I removed the portions of blocks that overlapped with protected lands identified in the Protected Areas Database (from Conservation Biology Institute). In addition, housing units were precluded from occurring in so-called "water blocks", which represent hydrological features such as streams, rivers, ponds, lakes, and reservoirs.

Although the refined blocks result in a finer-grained resolution, an assumption must be made about the spatial distribution of units within a refined block. Typically, dasymetric mapping techniques assume a homogenous distribution ("spread evenly") (e.g., Theobald 2001). Here I modified the spatial distribution of housing units based on density of major roads. All other things being equal, houses are more likely to be located near roads and less likely to be in portions of blocks that are distant (>~1 km) from roads.

The allocation of housing units were weighted based on road density (km/km^2) computed using a moving neighborhood with an 800 m radius. Density was computed using a commonly available nationwide dataset of major roads generated from the US Census TIGER dataset (ESRI Data & Maps 2004). Road density was classified into four arbitrary categories to distinguish different levels of development based on an ad hoc comparison of road densities and housing densities around the nation. The classes were: very low (0.0 – 0.25 km/km^2), low (0.25 – 1.0 km/km^2), medium (1.0 – 5.0 km/km^2), and high (>5.0 km/km^2). Weights of 1, 2, 3, and 4 were assigned to very low to high (respectively) and were used to allocate housing density values to cells within a block.

The number of housing units per block was obtained from the 100% sample data from the 2000 Census STF1 (US Census Bureau 2001b). Historical patterns of housing density (decadal from 1940 to 1990) were generated from estimates obtained from the "Year Housing Built" question from the sample data Summary File 3 dataset (US Census Bureau 2001c). Because the geography of tracts and blocks changes with each census, I estimated historical housing units based on the 2000 Census geography using established methods (Theobald 2001). Housing unit counts for each decade are provided at the block-group level and were adjusted to ensure that the sum of units by block-groups in a county equaled the counts from decadal census. This ensures that systematic underestimation of historical units is minimized (Theobald 2001).

Forecasting future patterns

Most efforts to forecast land use change have focused on urban systems (e.g., but see Theobald and Hobbs 1998). In previous work, I created a model to forecast future patterns of housing density across the urban to rural gradient named the Western Futures model (Theobald 2001b; Theobald 2003; Claggett et al. 2004). Here I detail additional refinements that resulted in a new model called SERGoM v2 (Spatially Explicit Regional Growth Model). The full urban-to-rural spectrum of housing densities is modeled in SERGOM at broad regional-to-national extents. It uses a supply-demand-allocation approach and assumes that future growth patterns will be similar to those found in the past decade, although this can be parameterized to reflect alternative scenarios.

There are four basic steps in SERGoM to forecast future patterns on a decadal basis (Figure 1). First, the number of new housing units in the next decade is forced to meet the demands of the projected county-level population. There is significant variability in the population per housing unit ratio (area-weighted mean=2.509, SD= 2.383) so that in the 2000 Census, 440 counties had <2.0 people/unit and 70 counties <1.5 people/unit. Rather than using a single nationwide conversion factor, population growth was converted to new housing units by the county-specific housing unit per population ratio for 2000. For Massachusetts, New Hampshire, and Vermont, population estimates for 1990, 2000, 2010, and 2020 were obtained from TPL for each of 865 municipalities or CCDs in the three states (Clem Clay, personal communication 10 February 2005). For other states, county level population projections were used.

The second step was to compute a location-specific average growth rate from the previous to current time step (e.g., 1990 to 2000). These growth rates were computed for each 100 m cell using a moving neighborhood (radius = 1.6 km). For each state, I computed the average growth rate for each of 16 development classes. These classes were computed by overlaying four density classes -- urban, suburban, exurban, and rural – with four accessibility classes measured as travel time (minutes one way) from the nearest urban core (see below) – 0-10, 10-30, 30-60, and greater than 60 minutes. Growth rates averaged over the classes generated from the housing density and accessibility patterns that reflect previous time step were then joined to a map that depicts the current time step housing density and accessibility pattern. Because these rates are computed locally, both within-county heterogeneity and cross-boundary patterns can be captured. This allows rates of growth to vary across the nation, regionally, and even within a county and does not assume stationarity. New housing units were spatially allocated based on these locally determined growth rates, assuming that areas of future growth are likely to be nearby current high growth areas or “hot spots”. This also allows so-called “leap-frog” development to occur if growth rates are higher in slightly more distant accessibility zones (e.g., at 10-30 minute travel time rather than directly adjacent to developed areas).

The third step was to adjust the distribution of new housing units according to accessibility to the nearest urban core. That is, growth typically occurs at locations on the urban fringe. Accessibility from all developable land to the nearest urban core was computed – based not simply the Euclidean distance – but in terms of minutes of travel time from a location along the main transportation network (major roads and highways) to the nearest urban core. An urban core area is defined here as a contiguous cluster (greater than 100 ha) at urban housing density, but alternative definitions could be developed. Because it is difficult to forecast when roads will be enlarged or where new roads will be constructed, travel time to move across locations that are not on the network of major roads was modeled as an average travel time of 15 miles per hour. Travel speed was assumed to be 70 mph on interstates, 55 mph on highways, and 45 mph on major county roads. An accessibility surface was then created from a cost-weight based on travel time from urban areas along major roads. New housing units are allocated as a function of the accessibility surface. Here the allocation is based on the distribution of new units realized in the previous decade, but other weightings could be applied to develop denser or more dispersed growth scenarios. Accessibility is computed at each decadal time step because new “islands” of urban core may emerge over time. This allows complex growth patterns to be modeled and incorporates the organic nature of development patterns.

The fourth step was to add the map layer of new housing density to the current housing density (e.g., adding new housing units to 2000 housing density). Housing density cannot decline over time in SERGoM. This is a reasonable assumption when examining patterns of expansion in suburban and exurban areas. But, this current implementation is limited when investigating urban-centric processes such as urban decay or expansion of commercial land use into urban and suburban residential areas.

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