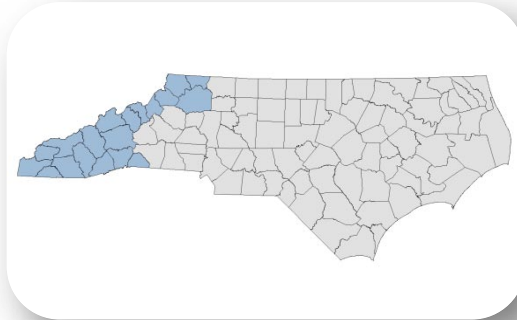

The Center for Applied GIScience at UNC Charlotte

Mapping historical development patterns and forecasting urban growth in Western North Carolina

1976-2030

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EXECUTIVE SUMMARY

The encroachment and subsequent conversion of natural and rural lands by the rapid expansion of development over the past 30 years has significantly altered the landscape throughout the Carolinas. Policy makers and planners responsible for managing growth struggle to accommodate demands for infrastructure and economic growth yet maintain the natural amenities that provide essential ecosystem services and constitute important "Quality of Life" assets. Often a lack of targeted analyses forces these managers to work with incomplete information in regards to the nature, determinants, and costs of our current patterns of land consumption.

This study of urban growth dynamics focused on identifying trajectories of land consumption in Western North Carolina to build an understanding of factors contributing to the patterns seen in the landscape today and develop tools for forecasting urbanization over the next 20 years. With funding and support provided by local, state, and federal collaborators[1], we mapped historical patterns of development at four decadal time steps (1976, 1985, 1995, and 2006) for a 19-county region using satellite image analysis. The application of a spatially-explicit urban growth model specifically developed for the project allowed us to forecast and map future regional patterns of growth through 2030 (Figure 1) at 5 year intervals. The urban growth forecasts provide an

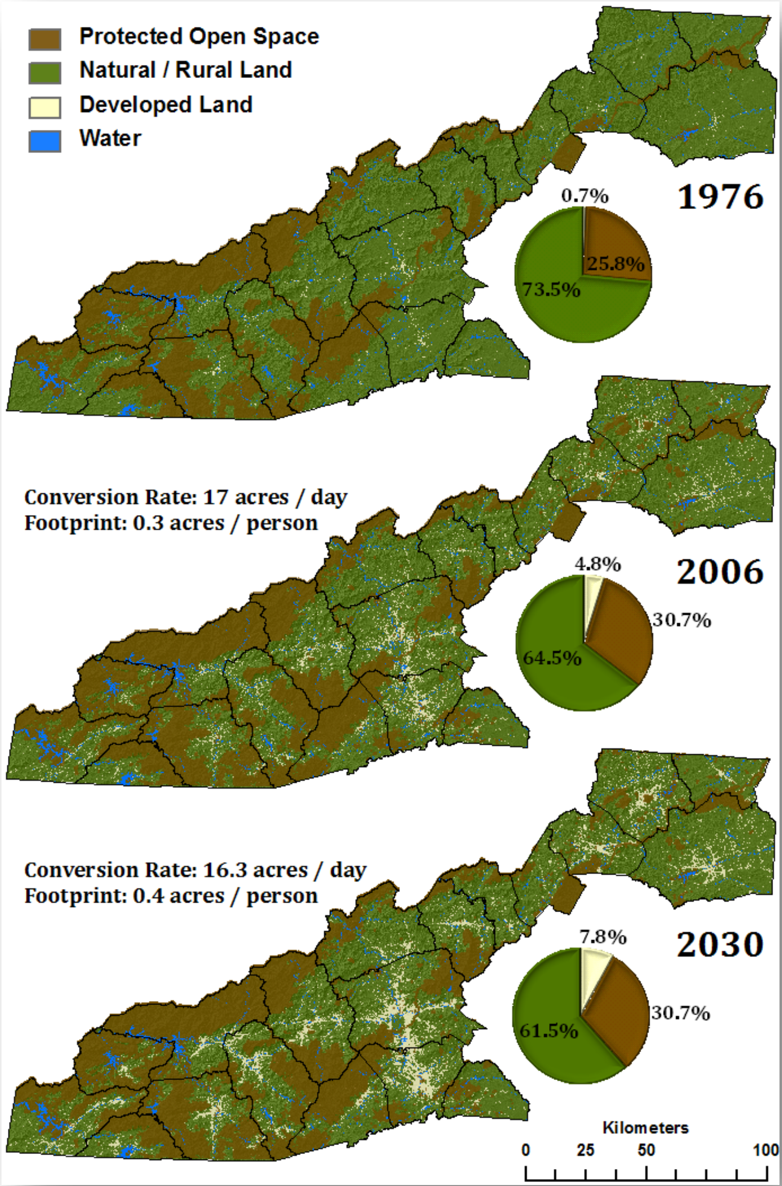

Figure 1. Three snapshots of historical and forecast development patterns and average conversion rates for 1976 - 2030 time period in Western NC.

[1] City of Asheville, USDA Forest Service (Southern Research Station), the Renaissance Computing Institute (RENCI), the RENCI Engagement Center at UNC Asheville, the RENCI Engagement Center at UNC Charlotte, and the Center for Applied GIS at UNCC.

opportunity to quantify and visualize land use outcomes before they are realized on the landscape. By analyzing these historical and forecast patterns of development we determined the rates (acres / day) at which natural and rural agricultural lands converted to developed lands through time. When combined with historical population data and population projections, we also estimated how much developed land is required on a per capita basis (i.e. the "human footprint", or acres per person).

Development in the region increased 570% at an average rate of 17 acres per day between 1976 and 2006 (Table 1), outpacing population growth by nearly 14-to-one! This dichotomy of density is reflected in human footprint values that increased 400%, indicating that on a per-capita basis each person is using significantly more land despite significant increases in population over the same time period. At current land consumption trajectories, an additional 145,374 acres of primarily forested and rural agricultural lands are forecast to be developed between 2006 and 2030 at an average rate of 16.3 acres per day (see Figure 9 for forecast maps). By 2030, when population in the region is projected to approach 1 million, undeveloped lands are expected to convert to developed lands at 15 acres / day, each inhabitant will require nearly a ½ -acre of developed land, and new development will consume around 5% of the region's remaining land not currently protected by federal, state, or local entities as of 2006 (see Figure 1 and Figure 9). Protected open space comprised around 31% of the region in 2006.

Buncombe and Henderson Counties experienced the greatest historical growth in absolute number of acres gained and also account for the greatest anticipated growth. Between 1976 and 2006, Buncombe and Henderson Counties added 31,149 and 27,186 acres of development, respectively, each accounting for over 10% of the total developed acres gained in the region (nearly 200,000 acres gained by 2006). Of the 145,374 acres of forecast development in the region, Buncombe and Henderson Counties are expected to contribute 24,647 and 19,004 acres, respectively, or 17% and 13% of total forecast gains. These two counties also stand out in terms of average land conversion rates, each well exceeding 2 acres of development per day in both historical and forecast development (Table 1). Henderson County saw the greatest percent increase in population (92%) between 1976 and 2006 and is projected to have a 41% increase between 2006 and 2030, second only to Clay County with a 42% increase.

Ashe, Madison, and Yancey Counties share the distinction of relatively high percent increases in developed acres between 1976-2006, with Ashe County experiencing a 2100% increase, Madison County a 1130% increase, and Yancey County a 1600% increase. Alleghany, Ashe, and Madison Counties all top 100% increases in forecast development by 2030. Ashe County saw the greatest change by far in human footprint between 1976-2006, increasing from 0.03 to 0.59 acres per person, a nearly 1900% increase, and is the only county forecast to top 1 acre per person by 2030. In comparison, human footprint in Henderson County is expected to increase 350%, from 0.07 to 0.31 acres per person between 1976 and 2006, and reach 0.35 acres per person by 2030 (Table 1).

Findings presented in this full report are the second phase of a larger effort to analyze and forecast development patterns for all of North Carolina. Understanding growth patterns in Western North Carolina is an important step in understanding urbanization statewide. These results, when combined with a similar completed study of the Southern Piedmont / Greater Charlotte Metropolitan region and the forthcoming funded analyses of the Piedmont Triad and Research Triangle regions, are expected to cover two-thirds of the state by 2011.

Table 1. Key measures of development, population, and human footprint: 1976 - 2030.

Region/ County	1976 - 2006				Forecasts 2006 - 2030				Human Footprint* (acres/person)		
	Development#		Pop†	Rate‡	Development#		Pop†	Rate‡	1976	2006	2030
19-County	195,074	570%	42%	17.0	145,374	63%	25%	16.3	0.06	0.30	0.39
Alleghany	3,104	700%	18%	0.26	3,622	102%	17%	0.41	0.05	0.32	0.56
Ashe	14,488	2100%	23%	1.3	15,650	103%	20%	1.78	0.03	0.59	1.00
Avery	4,443	510%	28%	0.39	1,082	20%	4.8%	0.13	0.06	0.29	0.34
Buncombe	31,149	350%	44%	2.75	24,647	62%	29%	2.77	0.06	0.18	0.23
Cherokee	10,898	835%	46%	0.94	9,132	75%	28%	1.01	0.07	0.46	0.62
Clay	3,143	830%	75%	0.27	3,017	86%	42%	0.34	0.07	0.35	0.46
Graham	2,478	435%	20%	0.21	1,631	54%	12%	0.18	0.08	0.38	0.52
Haywood	13,853	467%	26%	1.21	5,983	36%	9.3%	0.68	0.07	0.30	0.37
Henderson	27,186	730%	92%	2.36	19,004	61%	41%	2.1	0.07	0.31	0.35
Jackson	12,900	670%	49%	1.1	12,638	85%	33%	1.4	0.08	0.41	0.57
Macon	9,185	287%	80%	0.8	7,694	62%	40%	0.9	0.18	0.38	0.43
Madison	4,994	1130%	23%	0.4	5,947	109%	24%	0.7	0.03	0.27	0.45
Mitchell	3,926	722%	11%	0.34	934	21%	3.5%	0.1	0.04	0.28	0.33
Polk	4,478	570%	51%	0.4	556	11%	5%	0.06	0.06	0.28	0.29
Swain	4,590	418%	37%	0.4	4,153	73%	24%	0.47	0.11	0.41	0.57
Transylvania	5,637	600%	38%	0.5	2,604	40%	15%	0.3	0.04	0.22	0.26
Watauga	12,755	813%	45%	1.1	8,928	62%	31%	1.0	0.05	0.33	0.40
Wilkes	19,299	530%	18%	1.7	11,615	51%	11%	1.3	0.06	0.35	0.47
Yancey	6,566	1600%	25%	0.6	6,537	94%	20%	0.74	0.03	0.38	0.62

Acres gained and percent increases. See Appendix B for comprehensive metrics.
† Percent increases in population; data obtained from the State Demographics Branch of NC Office of State Budget and Management

‡ Average number of acres per day
* Human footprint, or per-capital land consumption, is calculated by dividing the total number of acres of developed land for a particular area (county, region) and year by the total population for that same area and year.

CONTENTS

1. DATABASE DEVELOPMENT

1.1. Acquire and process satellite imagery: 1976 – 2006

To map historical development patterns in the Western North Carolina region, we obtained Landsat satellite imagery distributed by the US Geological Survey's Earth Resource Observation and Science Center (USGS-EROS) for 10-year intervals corresponding to years 1976, 1985, 1995, and 2006 and during "leaf-on" conditions ranging between May - September. The 1970s era imagery was captured using the Landsat 1 Multispectral Scanner (MSS) satellite sensor and delivered at a spatial resolution of 60 meters and image extent of 185km x 185km. Landsat 5 Thematic Mapper (TM) imagery with a spatial resolution of 30 meters and image extent of 185km x 172km was obtained for the 1985, 1995, and 2006 time steps. Coverage for the entire regional extent required at least 5 Landsat scenes per time step (Figure 2). In the majority of cases, even the highest quality scenes contained clouds or other image anomalies/errors, particularly in the mountainous areas. Thus, secondary companion scenes were obtained as close as possible to the dates of the original scenes in order to patch these problem areas[2]. A total of thirty-four scenes were acquired for the region and the four time steps.

Image preprocessing is necessary to standardize the satellite images and prepare them for further analysis and classification. Following an initial evaluation of image quality, each image was geo-referenced to the State Plane Coordinate System using North American Datum 1983 and units of meters in order to align with other state GIS datasets. Images were then subset to the study area boundary and radiometrically calibrated to convert original image pixel values to at-sensor (above atmosphere) reflectance. Water bodies, major rivers and streams, clouds and cloud shadows were removed from each of the images using semi-automated preprocessing (Martinuzzi et al., 2007). An across-band image brightness normalization was applied whereby the pixel values within each image band (3 visible and 3 infrared bands) are normalized relative to the values of coincident pixels in the other bands of the scene (Wu, 2004). Finally, a

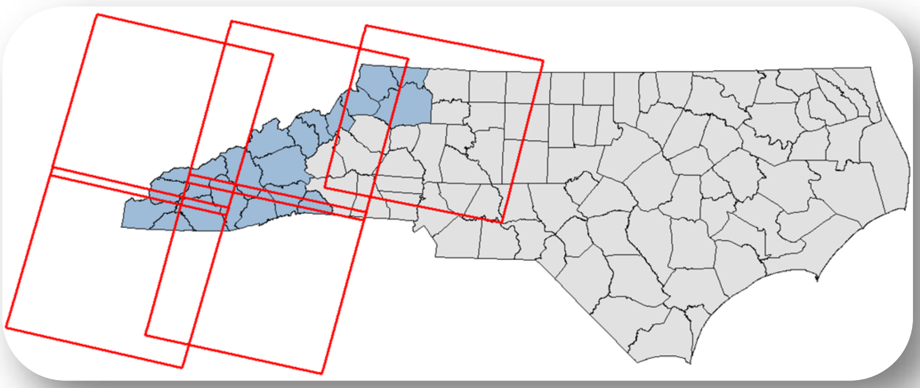

Figure 2. Western North Carolina counties highlighted in blue with Landsat scene extents superimposed in red. The 19-county region extends into 5 Landsat scenes.

[2] Images acquired in 1995 and 1996 analyzed and results merged; a majority of the region covered by 1995 imagery. Images acquired in 2005 and 2006 analyzed and results merged; a majority of the region covered by 2006 imagery.

principal component analysis (PCA) was performed on each image, which reduced the dimensionality of the original image data from 6 bands to 3 bands of new data that capture the maximum variance in the original image bands. PCA bands aided in the selection of pure training sites used to classify the normalized images into vegetation, impervious surface, and soil components.

1.2. Develop spatial predictor variables

In anticipation of analysis of hypothesized predictors of changes in development patterns, we assembled a collection of GIS datasets for the region from collaborators and government sources or by in-house development. Using these datasets, we generated a suite of spatial variables (see Appendix A for details) that we evaluated statistically for their potential to explain the observed changes in development patterns between 1995 and 2006. In addition, high resolution, color orthophotos for the years 2006 and 2008 were obtained from the National Agricultural Imagery Program (NAIP) for the entire region. NAIP orthophotos and high-resolution imagery available in Google Earth provided critical ground truth information for assessing the accuracy of image classifications.

2. DEVELOP FORECAST MODELS

2.1. Map historical development patterns: 1976 – 2006

Exploration of future development patterns requires an understanding of past development trends. We mapped development patterns in the region at four decadal time steps from 1976 through 2006 via analysis of historical Landsat satellite imagery. This approach allowed us to capture significant landscape features typically missing in Census geographies and associated tabular data, such as parking lots, utility corridors, and the clearing of private lands. Using calibrated and normalized Landsat satellite images from 1976, 1985, 1995 and 2006, we classified the imagery into developed and undeveloped categories at a resolution of 0.22 acres, or a 30 X 30 meter pixel. Classification was based on the vegetation - impervious surface - soil (V-I-S) model of urban environments, which characterizes the landscape according to the percentage of these three components comprising each image pixel (Ridd, 1995). The fractions of the V-I-S components that comprise each image pixel were estimated via spectral mixture analysis (Wu, 2004; Lee and Lathrop, 2005). This analysis allows for identification of even small amounts of impervious surface, indicative of development, despite the presence of tree canopy typical in many mature residential areas. The undeveloped class includes both forest and rural agricultural lands. All buildings and paved areas, as well as golf courses, managed lawns, and industrial agriculture (e.g., poultry), were considered developed. Accuracy of the mapping was assessed by systematic comparison of a random set of sample locations with high resolution color orthophotography acquired from the National Agriculture Imagery Program (NAIP) and historical orthophotography available in Google Earth. Overall classifications accuracies for 1976, 1985, 1995, and 2006 map products were 75%, 87%, 84%, and 84%, respectively.

Figure 3 shows the historical development patterns and conversion rates (decade averages) based on the analysis of satellite imagery over the 30-yr period. The percentage of the region that is developed increased from 0.7% in 1976 to nearly 5% by 2006. Protected open space[3] comprised a full quarter of the region in 1976 due to the presence of large tracts of federal and state-owned land. This percentage increased to approximately 31% by 2006. These protected spaces effectively reduce the amount of available land for future development. For example, in 1976 Swain County had approximately 77%, or over three quarters, of its total land area classified as protected open space due primarily to the establishment

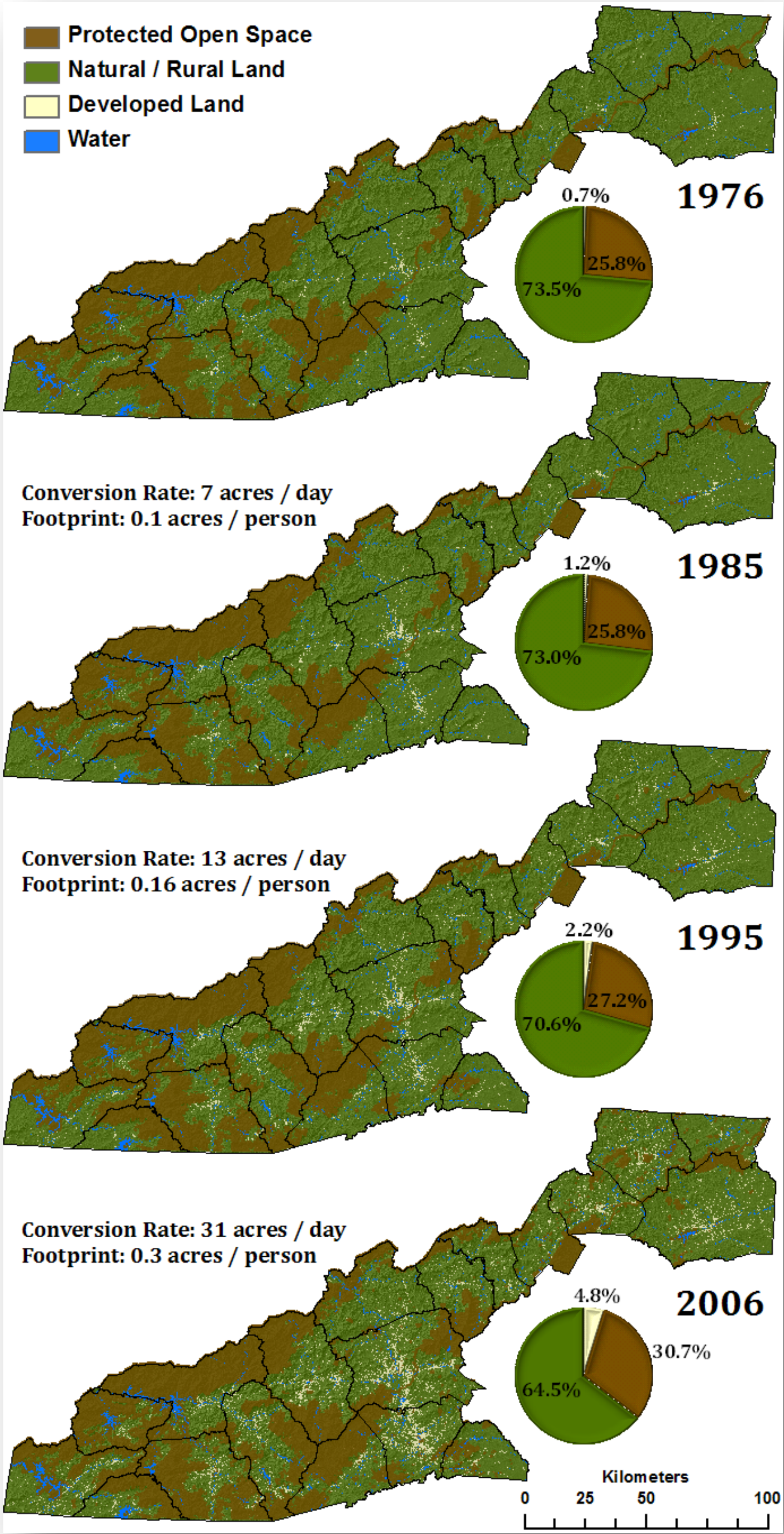

Figure 3. Historical development patterns and conversion rates: 1976 - 2006.

[3] Protected open space based on collection of spatial datasets referred to as Open Space and Conservation Lands and distributed by the NC Center for Geographic Information & Analysis. Data sources include state and local agencies as well as private conservation organizations and land trusts.

of the Great Smoky Mountains National Park in the 1930s. Other counties in the region also have significant protected open spaces (Figure 3) that limit new development to the remaining unprotected lands.

Total developed acres in the region increased from 34,348 in 1976 to 229,422 acres in 2006 (see Appendix B for more detailed data), a nearly 570% increase in developed acres at an average conversion rate of 17 acres per day. Over the same time period, the total population in the region increased from 545,100 to 774,281, a 42% increase, indicating that development outpaced population growth by nearly 14-to-1. Analysis of population-development trends over the 30-yr time period revealed a dichotomy of density, which is reflected in human footprint values that increased 400% from 0.06 acres / person in 1976 to 0.3 acres / person by 2006. Thus, on a per-capita basis each person required significantly more land despite significant increases in population over the same time period.

At the county level, Buncombe and Henderson Counties experienced the greatest historical growth in absolute number of acres gained. Between 1976 and 2006, Buncombe and Henderson Counties added 31,149 and 27,186 acres of development, respectively, each accounting for well over 10% of the total developed acres gained in the region (nearly 200,000 acres gained by 2006). These two counties also stand out in terms of average land conversion rates, each well exceeding 2 acres per day in historical development (Table 1). Henderson County also saw the greatest percent increase in population (92%) between 1976 and 2006 with Macon and Clay Counties following at 80% and 75% population increases, respectively. When considering increases in total developed acres relative to county area, Henderson again tops the list by converting 11.6% of its undeveloped lands to developed lands between 1976 and 2006, a jump from 1.6% to 13.2% over the 30-yr period. Developed lands comprised 2.1% of Buncombe County in 1976 and 9.7% of the county by 2006, a difference of 7.5%. Watauga County follows closely, increasing from 0.8% developed lands in 1976 to 7.3% in 2006, a difference of 6.5%

Ashe, Madison, and Yancey Counties share the distinction of relatively high percent increases in developed acres between 1976-2006, with Ashe County experiencing a 2100% increase, Madison County a 1130% increase, and Yancey County a 1600% increase. These notable percent increases are the result of the counties' meager numbers of developed acres in 1976 relative to the gains made by 2006. For example, each of these 3 counties had well under 1000 acres of developed land in 1976. Ashe County saw the greatest change by far in human footprint between 1976 and 2006, increasing from 0.03 to 0.59 acres per person, a nearly 1900% increase. In comparison, human footprint in Henderson County, which experienced the greatest percent increase in total population over the 30-yr period, is expected to increase 350%, from 0.07 to 0.31 acres per person between 1976 and 2006 (Table 1). Interestingly, Buncombe County experienced the smallest jump in human footprint in the region, increasing from 0.06 acres per person in 1976 to 0.18 acres per person by 2006, a difference of 0.12 acres, and a 200% increase.

The historical development patterns in Figure 3 are used to elucidate the driving factors underlying the conversion of natural and rural agricultural lands to urbanized landscapes. When coupled with county population data and projections, the historical development patterns and analysis of population-development trends can inform how much demand for land there is likely to be in the future. The next question is: where are these conversions to developed land most likely to occur over the next 20 years?

2.2. Evaluate development potential: 1995 – 2006

To develop a statistical understanding of factors associated with conversion of natural and rural agricultural lands to developed lands, we looked specifically at locations that developed between 1995 and 2006 (Figure 4) and asked why these areas converted. Understanding the factors that possibly caused these areas to convert aided in evaluating development potential of available land. Statistical analyses were completed in phases with each county falling into one of three sub-regions based on analysis of relationships between 1995-2006 conversions and the hypothesized predictor variables. We developed a logistic regression model for each of three sub-regions within the study extent (Figure 5). We analyzed a suite of thirty-seven geographic, socioeconomic, and environmental datasets hypothesized as possible predictors of development (see Appendix A), sampling values from these raster datasets using thousands of points located via a stratified random sampling design.

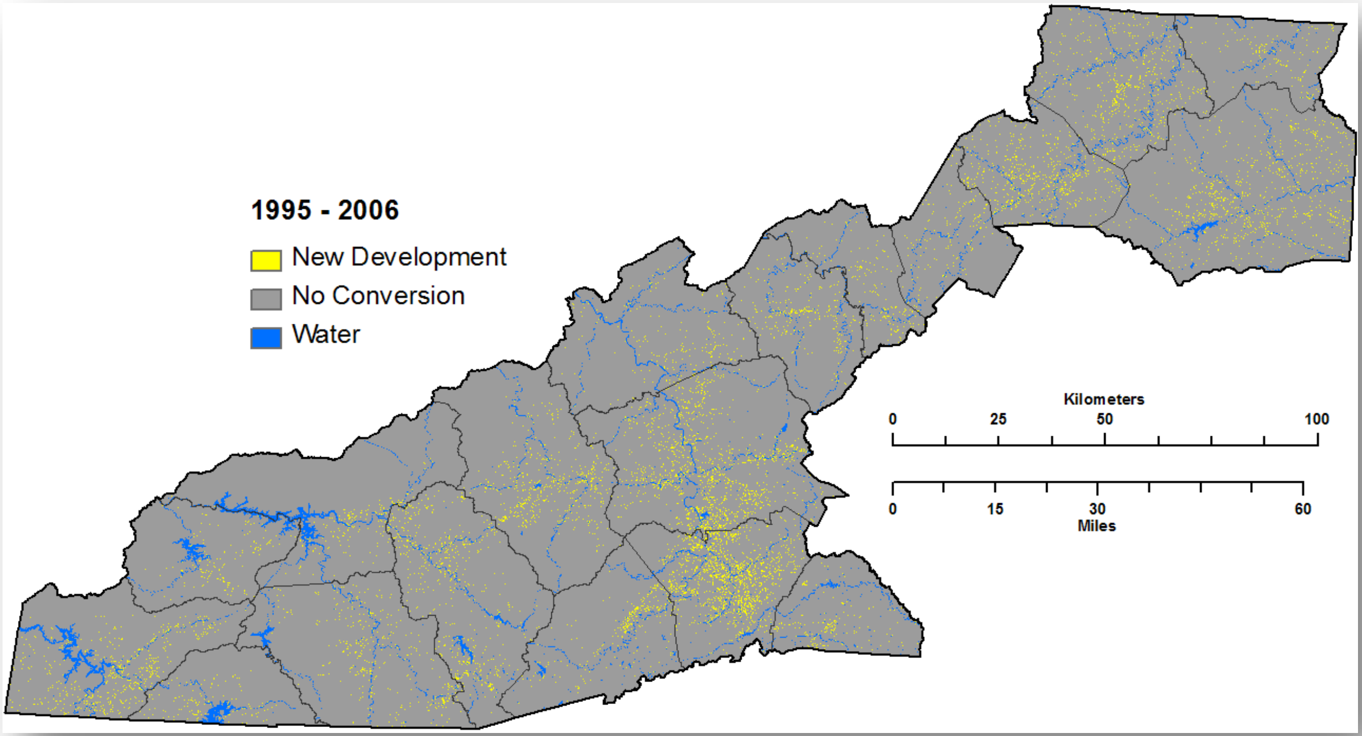

Figure 4. Locations (in yellow) that converted from natural / rural land to developed land between 1995 and 2006.

Within each sub-region (Figure 5) 2000 points were randomly located in areas that converted between 1995 and 2006 (the response, or dependent variable). A second set of 2000 points was randomly located in areas that remained undeveloped as of 2006. A very small percentage of these sample points fell on roadways or road cuts where further development is not permitted. Those points were removed. The resulting sample point datasets were then exported for statistical analysis and model development.

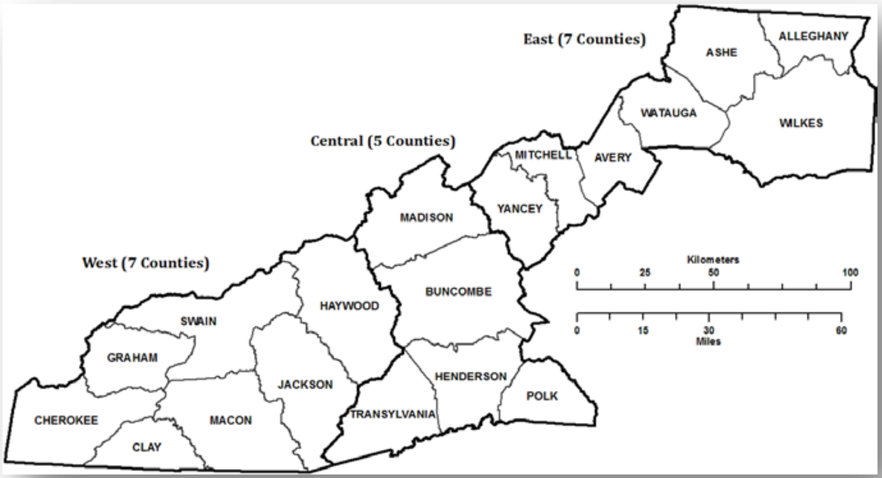

Figure 5. Logistic regression models developed for 3 multi-county sub-regions.

Logistic regression was used to evaluate the potential for undeveloped land to convert to developed land. Forward and backward stepwise regression techniques aided in the initial selection of a high performing yet parsimonious set of predictor variables. Binary logistic regression produced a final statistical model for each sub-region for evaluation of development potential. Analysis of the 5-county Central sub-region resulted in a statistical model that accounts for 50% of variability using six, highly significant ($p < 0.0001$) predictor variables (see Figure 6 for examples): development pressure; employment attraction[4] (at 100km alpha); distance to nearest road (primary or secondary); topographic slope; distance to the nearest urban center; and distance to the nearest highway interchange. The resulting regression equation is:

C = -12.8864 + (0.13808*DP) + (0.00002*EA) - (0.00209*DR) - (0.12298*S) - (0.00003*DU) - (0.00010*DI)

Where C is the probability of conversion from undeveloped to developed land, DP is development pressure within a 250m window, EA is attraction to employment centers, DR is distance to nearest primary or secondary road, S is topographic slope, DU is distance to the nearest urban center, DI is distance to the nearest highway interchange.

The equation may be described in non-statistical terms as:

Probability of conversion to development = development pressure + employment attraction - distance to nearest road - slope - distance to nearest urban center - distance to nearest highway interchange

[4] We tested job-weighted employment attraction at distances of 6km, 15km, and 100km and found employment attraction at 15km and 100km to be most significant with clear geographic trends of increasing attraction toward Asheville, NC (at 15km alpha) and the Greenville-Spartanburg region of South Carolina at 100km alpha.

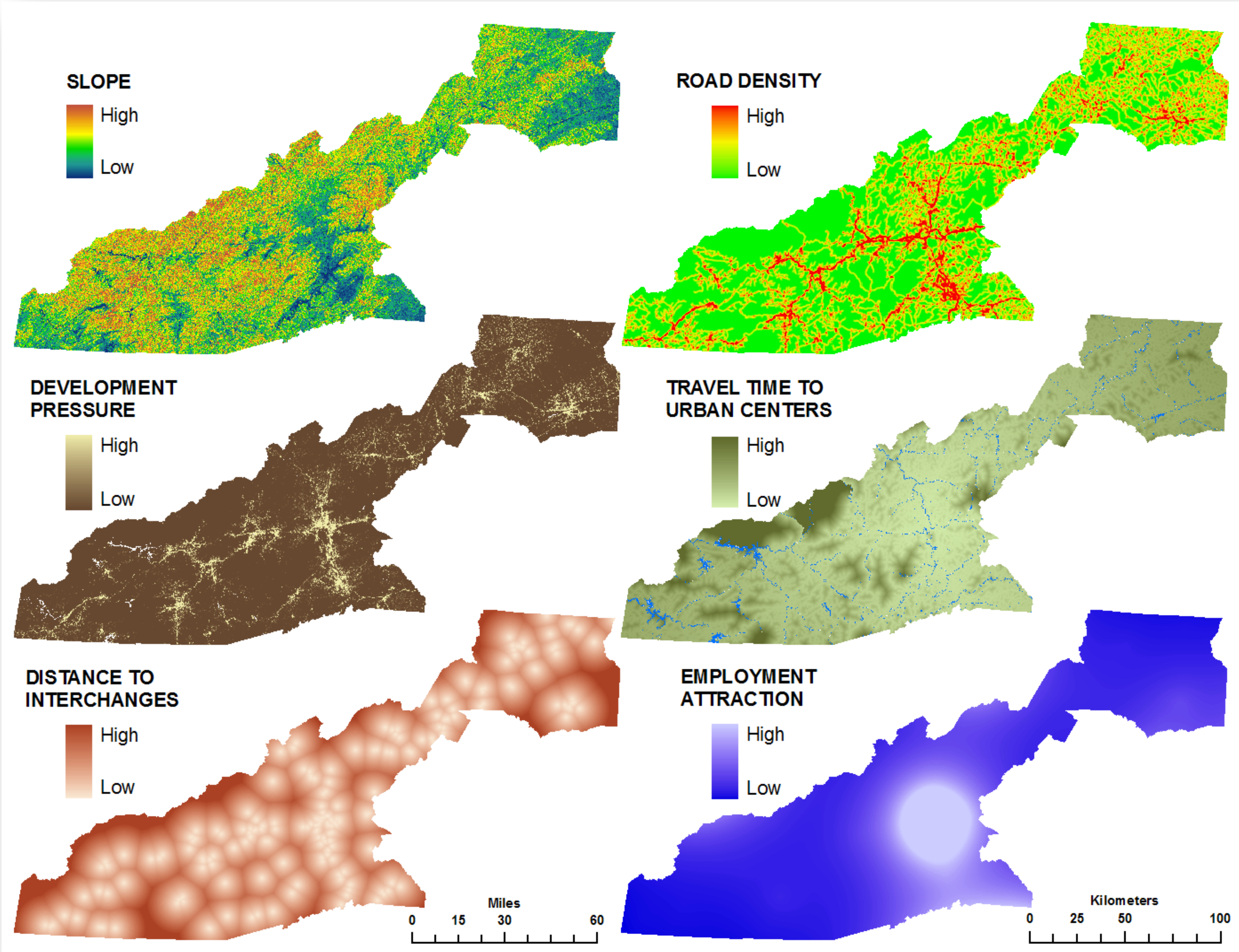

Figure 6. Subset of variables found to be most significant predictors of conversion from natural / rural land to development.

Analysis of the 7-county West sub-region resulted in a similar statistical model that accounts for 47% of variability using six, highly significant ($p < 0.0001$) predictor variables: development pressure (DP); employment attraction (EA; at 15km alpha); distance to nearest highway interchange (DI); road density (RD); topographic slope (S); and travel time to nearest urban center (TTU). The resulting regression equation is:

C = 2.91529 + (0.23157*DP) + (0.00005*EA) - (0.00016*DI) + (0.20380*RD) - (0.09935*S) - (0.00849*TTU)

The equation may be described in non-statistical terms as:

Probability of conversion to development = development pressure + employment attraction – distance to nearest highway interchange + road density - slope - travel time to nearest urban center

Finally, analysis of the 7-county East sub-region produced a statistical model that accounts for 36% of variability using five, highly significant ($p < 0.001$) predictor variables: development pressure (DP); employment attraction (EA; at 100km alpha); road density (RD); topographic slope (S); and travel time to nearest highway interchange (TTI). The resulting regression equation is:

C = -1.43438 + (0.30605*DP) + (0.000003*EA) + (0.16555*RD) - (0.08669*S) - (0.02356*TTI)

The equation may be described in non-statistical terms as:

Probability of conversion to development = development pressure + employment attraction + road density - slope - travel time to nearest highway interchange

We assessed statistical model performance using several metrics, including the r^2 value and the area under the curve (AUC) of the receiver operating characteristic (ROC). Table 2 lists the key assessment metrics for each of the sub-regional regression models. Overall internal model accuracies were approximately 86.3%, 84.5%, and 81.4% for the Central, West, and East sub-regions, respectively, meaning, for example, the estimated regression model for the Central sub-region correctly classified 1,668 of 2,000 (83.4%) of the undeveloped sample points and 1,754 of the 1,966 (89.2%) of the developed sample points, for an average model accuracy of 86.3%.

Of the highly significant predictor variables across all models, development pressure, employment attraction and road density exhibited a positive relationship with conversion to developed land. Development pressure is a measure of the location effects of previously existing development on adjacent and nearby undeveloped land. Thus, a positive relationship with conversion indicates that undeveloped areas are more likely to develop if there is a significant amount of development within 250 meters. Employment attraction measures the weighted effect of employment centers (defined as urban areas with > 40,000 people and weighted by employment data from US Census) in the study area and up 100km away from each location within the study area. Centers with higher employment rates generate a greater effect. A positive relationship indicates greater likelihood of development near areas of higher employment. Road density measures the density of linear features (ie., roads) within a specific search distance (250m up to 5km) around each location in the study area. A positive relationship indicates greater likelihood of conversion to development for those undeveloped areas with a greater density of existing roads in the surrounding area.

Conversely, the remaining predictor variables exhibited a negative relationship with conversion to developed land. Increasing distance (straight-line Euclidean distance) or increasing travel time (measured in minutes along road networks) to nearest roads, urban centers, and highway interchanges has a negative effect on the likelihood of conversion, indicating that the further a site is (measured in distance or time) from these features the less likely it is to develop. Topographic slope of an area also has a negative relationship with conversion, indicating that places with steeper slopes are less likely to develop. Thus, each predictor variable exhibits a relative influence on the resulting geography of subsequent development in the region. To visualize this concept, the significant predictor variables for each sub-region were combined in their final logit models, which were applied across all undeveloped space (excluding protected open space and water bodies) in the study extent to produce a development potential surface for 2006 (Figure 7) based on the conversion history between 1995 and 2006 (Figure 4). Development potential is simply a transition probability surface with cell values ranging from 0 (low probability of conversion) to 1 (high probability of conversion).

Table 2. Assessment metrics for sub-regional logistic regression models.

Region	r^2	ROC	CC-0	CC-1	errC	errO	CC
Central	0.50	0.92	83.4%	89.2%	16.6%4	10.8%	86.3%
West	0.47	0.92	85.6%	83.4%	14.4%	16.6%	84.5%
East	0.36	0.88	84.9%	78.0%	15.1%	22%	81.4%

r^2 = Overall model R-Squared.
ROC = Area Under ROC (Receiver Operating Characteristic) Curve
CC-0 = Percentage of undeveloped (0) sample points correctly classified.
CC-1 = Percentage of developed (1) sample points correctly classified.
errC = Errors of commission, or % undeveloped samples misclassified as developed
errO = Errors of omission, or % developed samples misclassified as undeveloped
CC = Overall percentage of sample points correctly classified

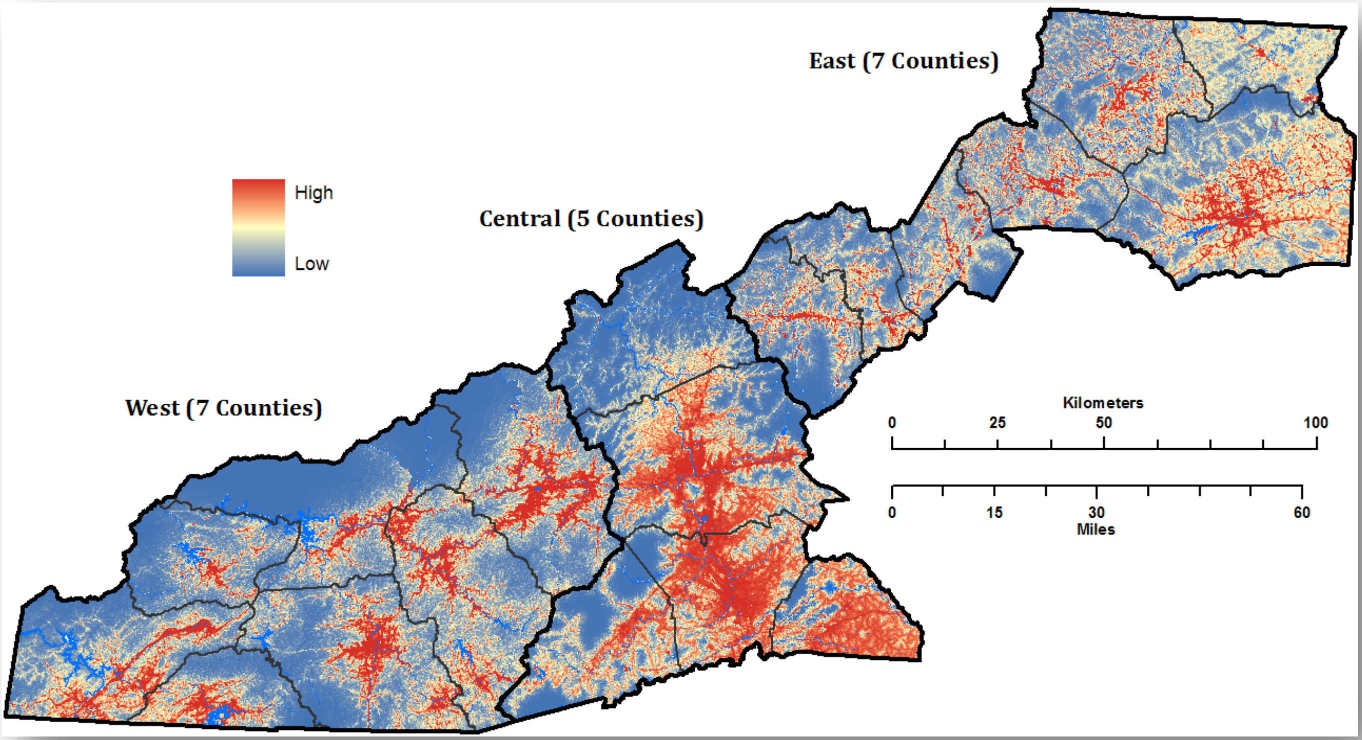

Figure 7. Development potential (transition probability surface) for 2006 based on logistic regression models applied to three multi-county sub-regions (West, Central, and East).

3. FORECAST URBAN GROWTH

3.1. Evaluate population-development trends: 1976 – 2030

Regional population is projected to increase from 774,281 to 969,805 between 2006 and 2030, a 25 percent increase to nearly 1 million people. The infrastructure required to support this population growth is expected to cause a substantial increase in the amount of developed land within this region. Past trends in per-capita land consumption are very likely to be indicative of the amount of development that will be observed in the region given future population projections. In order to determine these historical trends in land demand, the amount of developed land per person in 1976, 1985, 1995, and 2006 was quantified by comparing satellite image-derived development amounts (acres per county) with their concurrent historical population figures (people per county) from the State Demographics Branch of the North Carolina Office of State Budget and Management (NCOSBM). The amount of development expected in future years was estimated by extrapolating from the observed relationship between historical population figures and observed historical development patterns, producing a trend line of future per-capita land consumption (Figure 8) based on population projections for each county from the State Demographics Branch of the NCOSBM (see Appendix B for projections).

3.2. Map future development patterns: 2006 – 2030

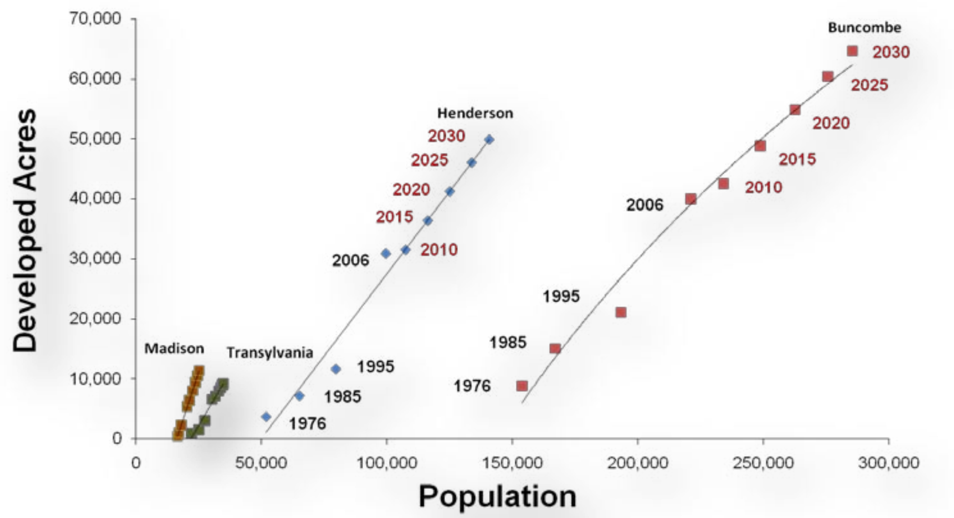

Figure 8. Historical trends in per capita land consumption and county population projections were used to estimate the amount of development expected in each county at each future time step. Madison, Transylvania, Henderson, and Buncombe Counties' historical and extrapolated trend lines are shown as examples.

Development forecasts are completed at five year intervals from 2010 – 2030 using 2006 development patterns as initial conditions. Current population projections extend only to the year 2030, making development forecasts beyond this point increasingly uncertain. Future development patterns are mapped for each county using the dynamic urban growth model that allocates new development to available undeveloped areas based on their development potential (see Figure 7). Beginning with the 2010 time step, the undeveloped cells with the highest probability for conversion (based on 2006 development potential) are changed to a developed state followed by conversion, if necessary, of additional undeveloped cells with the next highest probability and continuing until the estimated land demand for the 2010 time step is fulfilled. With land demand achieved, a 2010 development pattern forecast map is output. The development pressure variable is recalculated to account for the influence of the newly forecast development in the 2010 output map. A new development potential surface is generated by combining in a logit model both the updated development pressure variable (a dynamic variable that updates at each time step) and the remaining predictor input variables. The resulting development potential surface is used to allocate new development for the 2015 time step. This process repeats for all remaining time steps. Apart from the dynamic development pressure, other predictor variables in the model of development potential are assumed to remain constant (static variables) due to lack of accurate future data on these variables. New development was not allowed to occur in water bodies, protected open space, nor previously developed areas. Protected open space was held constant from the 2006 time step due to a lack of information on future protected lands.

Figure 9 shows the forecasts of future development patterns in the region with corresponding conversion rates at each future time step[5]. The 2006 historical map is provided for baseline

[5] Figure 9 provides static snapshots of geographic patterns and diffusion of forecast development in the region. More detailed maps and animations are available on the RENCI@UNC Charlotte website at http://renci.uncc.edu/category/projects/urbangrowthmodel.

comparison. Forecast development patterns reflect the combined influence of the predictor variables used to allocate new development on the landscape. Application of the dynamic urban growth model resulted in new development generally emerging in areas directly adjacent to or in close proximity to existing development, major employment centers, and major roads and areas of denser road networks; near highway interchanges and urban cores (in both distance and travel time), and on gentler slopes where clearing land, new infrastructure development, and public and private construction projects are presumably more cost efficient. New development tended to diffuse out from these highly favorable areas into surrounding undeveloped, natural and agricultural lands and coalesce with other areas of new development.

Total developed land is forecast to increase from 4.8% of the region in 2006 to 7.8% of the land area in 2030. This increase of 3% in total developed land corresponds to an additional 145,374 acres with conversion occurring at an average rate of 16.3 acres per day. And the increase is equivalent to nearly 5% of the region's undeveloped land not currently protected by federal, state, or local entities as of 2006. By 2030, when population in the region is projected to approach 1 million, undeveloped lands are expected to convert to developed lands at 14.5 acres per day, and each inhabitant will require nearly a ½ -acre (0.4) of developed land, a 30 percent increase in human footprint from 2006.

Of the approximately 145,000 acres of forecast development in the region, Buncombe and Henderson Counties are expected to contribute 24,647 and 19,004 acres, respectively, or 17% and 13% of total forecast gains. These two counties also stand out in terms of average land conversion rates, each well exceeding 2 acres of development per day in forecast development (Table 1). Henderson County saw the greatest percent increase in population (92%) between 1976 and 2006 and is projected to have a 41% increase between 2006 and 2030, second only to Clay County with a 42% increase. Alleghany, Ashe, and Madison Counties all top 100% increases in forecast development by 2030, with Avery, Mitchell and Polk Counties posting relatively modest gains of 20%, 21%, and 11%, respectively, each at or below 1000 total acres of forecast development by 2030. Ashe County saw the greatest change by far in human footprint between 1976-2006, increasing from 0.03 to 0.59 acres per person, a nearly 1900% increase, and is the only county forecast to top 1 acre per person by 2030. Cherokee and Yancey Counties share a distant second place with human footprint at 0.62 acres per person in 2030. In comparison, human footprint in Henderson County is forecast to reach 0.35 acres per person by 2030, and Buncombe County is expected to have the smallest footprint in the region at 0.23 acres per person (Table 1). Alleghany County tops all counties in the region with a 75% increase in footprint between 2006 and 2030, rising from 0.32 to 0.56 acres per person. Ashe, Madison and Yancey Counties follow Alleghany with increases in footprint of 69%, 67%, and 63%, respectively.

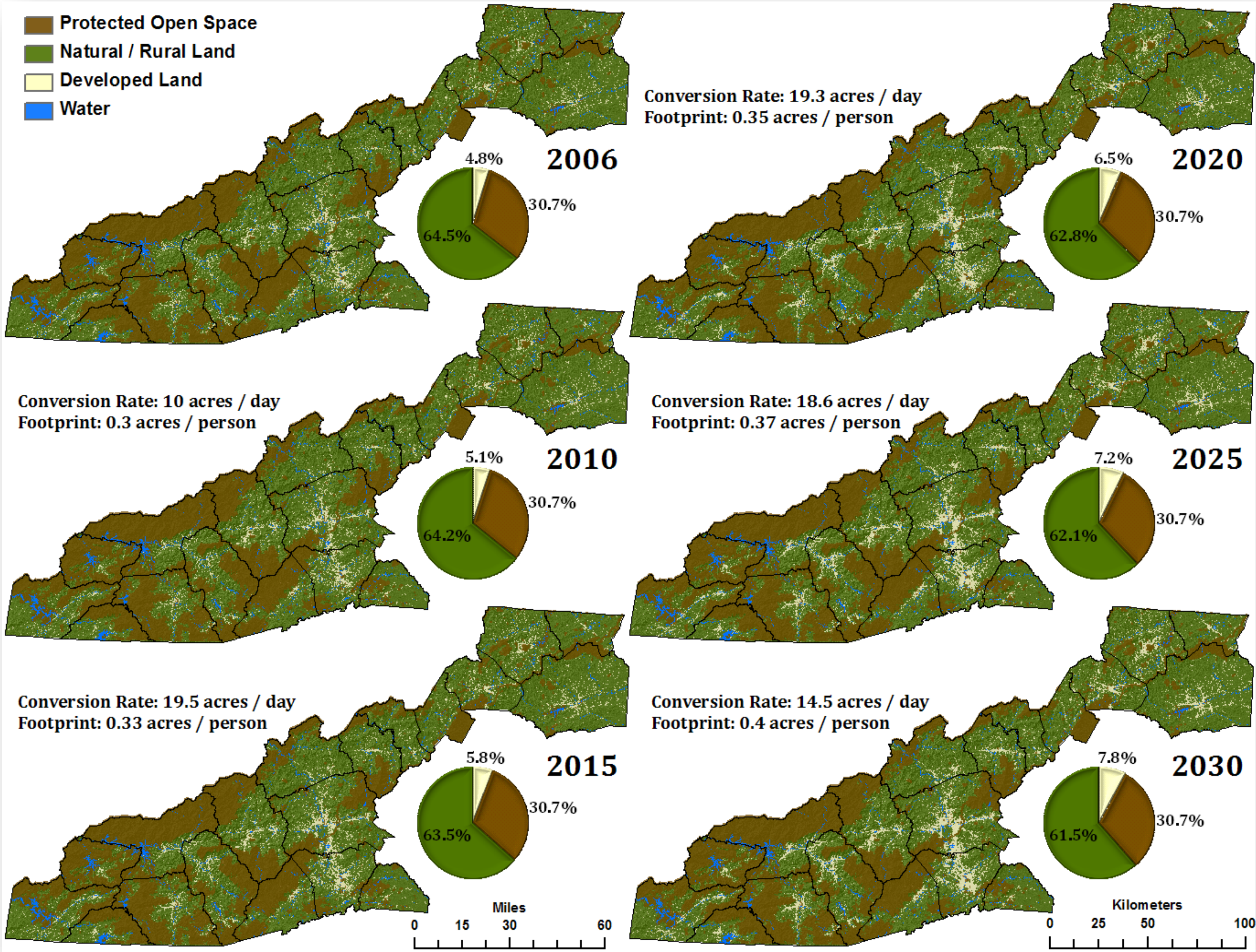

Figure 9. Forecast maps show expected patterns of development and conversion rates at 5-year time steps from 2010 – 2030 with 2006 shown for comparison.

4. CONCLUSION and FUTURE WORK

The forecasts of development patterns presented in this report are based on 1) analysis of historical satellite imagery, 2) historical population data and population projections, 3) analysis of population-development trends in per-capita land consumption, and 4) statistical models of urbanization driven by relationships between a parsimonious set of significant explanatory variables and the observed conversions of natural and rural agricultural lands to developed lands. This approach is unbiased, objective, and repeatable. These types of spatially-explicit models and forecast maps provide stakeholders, decision makers, planners, conservationists and the public with powerful tools for quantifying and visualizing land use outcomes before they are realized on the landscape. These tools also improve our understanding of the consequences of current growth trends, including possible losses of regional character, natural and wildlife heritage, and ecosystem services. The results presented here are the second phase of a larger effort to analyze and forecast development patterns for all of North Carolina. Combined with the original Southern Piedmont / Charlotte Metropolitan Region study, and with plans to expand this research to the Piedmont Triad and Research Triangle regions with funding from the Z. Smith Reynolds Foundation (Winston-Salem, NC) and support from the Renaissance Computing Institute in Chapel Hill, NC, similar analyses covering two-thirds of North Carolina are expected in 2011.

5. DISCLAIMER

We have attempted to gather, develop and analyze the most reliable data available for producing the spatial variables, historical and forecast data products and maps discussed and displayed in this report. Where possible, we have reported the level of accuracy for data and statistical analyses and derived products. Forecasts of development patterns are based on the probability of what is likely to occur in the future by extrapolating from historical trends in population and development patterns and by using population projections. Moreover, the predicted spatial patterns of development should be interpreted as representations of landscape-scale trends of urbanization processes rather than actual, site-specific outcomes. Inherent uncertainty exists in these urban growth forecasts. Therefore, users of these datasets and map products should exercise caution when interpreting the results or basing subsequent work or decision making on these forecasted development patterns.

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8. APPENDIX A

Spatial variables evaluated for potential for explaining changes in development patterns between 1995 and 2006.

File Name	Description	Base Data Source
aspect30m	Slope direction derived from NED elevation dataset; output cell values in compass direction (0 - 360 degrees)	USGS NED[1]
d2_at_th	Euclidean distance to the nearest Appalachian Trail trailhead	ATC & ATPO[2]
d2_hydro24k	Euclidean distance (meters) to the nearest river / stream (1:24,000 scale)	NC OneMap[3]
d2_hydromaj	Euclidean distance (meters) to the nearest major rivers and water bodies	NC OneMap
d2_int_95*	Euclidean distance (meters) to the nearest major highway interchange	NC DOT[4]
d2_ldfl95c	Euclidean distance (meters) to the nearest landfill (only those closed as of 1995-96 considered)	NC OneMap
d2_ldflw95o	Euclidean distance (meters) to the nearest landfill (only those open as of 1995-96 considered)	NC OneMap
d2_ldflw95oc	Euclidean distance (meters) to the nearest landfill (those closed and open as of 1995-96 considered)	NC OneMap
d2_mst_th	Euclidean distance (meters) to the nearest Mountains-to-Sea Trail trailhead	FMST[5]; Google Earth
d2_protected	Euclidean distance (meters) to the nearest protected area	Various[6]
d2_ps95*	Euclidean distance (meters) to the nearest primary or secondary road as of 1995-96	NC DOT
d2_pway_ent	Euclidean distance (meters) to the nearest Blue Ridge Parkway entrance	NPS[7]
d2_swr_srv	Euclidean distance (meters) to the nearest available municipal sewer service line	NC OneMap; Conservision-NC[8]
d2_urban*	Euclidean distance (meters) to the nearest urban center (population > 40,000)	US Census[9]
d2_wtr_srv	Euclidean distance (meters) to the nearest available municipal water service line	NC OneMap; Conservision-NC
devp_250m*	Development pressure: Number of neighboring cells classified as developed within a 250 meter window	Satellite image analysis[10]
devp_500m	Development pressure: Number of neighboring cells classified as developed within a 500 meter window	Satellite image analysis
devp_1k	Development pressure: Number of neighboring cells classified as developed within a 1 kilometer window	Satellite image analysis
devp_1500m	Development pressure: Number of neighboring cells classified as developed within a 1.5 kilometer window	Satellite image analysis
devp_2k	Development pressure: Number of neighboring cells classified as developed within a 2 kilometer window	Satellite image analysis

devp_2500m	Development pressure: Number of neighboring cells classified as developed within a 2.5 kilometer window	Satellite image analysis
devp_5k	Development pressure: Number of neighboring cells classified as developed within a 5 kilometer window	Satellite image analysis
emp_100k*	Euclidean distance to the nearest urban area within 100 km weighted by the number of jobs provided by that center	US Census
emp_15k*	Euclidean distance to the nearest urban area within 15 km weighted by the number of jobs provided by that center	US Census
emp_6k	Euclidean distance to the nearest urban area within 6 km weighted by the number of jobs provided by that center	US Census
ned30m	Elevation (meters) above sea level	USGS NED
perm	Soil permeability	CONUS-SOIL[11]
poro	Soil porosity	CONUS-SOIL
rd95_250m*	Density (km / km^2) of DOT primary and secondary roads (as of 1995-96) within a 250 meter window	NC DOT
rd95_500m*	Density (km / km^2) of DOT primary and secondary roads (as of 1995-96) within a 500 meter window	NC DOT
rd95_1k	Density (km / km^2) of DOT primary and secondary roads (as of 1995-96) within a 1 kilometer window	NC DOT
rd95_2500m	Density (km / km^2) of DOT primary and secondary roads (as of 1995-96) within a 2.5 kilometer window	NC DOT
rd95_5k	Density (km / km^2) of DOT primary and secondary roads (as of 1995-96) within a 5 kilometer window	NC DOT
rd95_10k	Density (km / km^2) of DOT primary and secondary roads (as of 1995-96) within a 10 kilometer window	NC DOT
slope30m*	Topographic slope derived from NED elevation dataset; values range from 0-90 degrees	USGS NED
tt95_i*	Travel time (meters per minute) to nearest DOT primary highway interchange as of ‘95-96	NC DOT
tt95_u*	Travel time (meters per minute) to nearest urban center (population > 40,000 as of 1995)	US Census

*significant ($p < 0.001$) explanatory variables used in all transition probability models

1 United States Geological Survey National Elevation Dataset (ned.usgs.gov)
2 Appalachian Trail Conservancy & National Park Service Appalachian Trail Park Office (www.appalachiantrail.org)
3 North Carolina ONEmap distributed by NC Center for Geographic Information & Analysis (www.nconemap.com)
4 North Carolina Department of Transportation via NC ONEmap distribution & digitized from historical, hardcopy NC road maps (www.ncdot.org; www.nconemap.com)
5 Friends of the Mountains-To-Sea Trail (www.ncmst.org)
6 NC Dept of Environment & Natural Resources; NC ONEmap; Conservision-NC - One NC Naturally's Conservation Planning Tool

(www.conservision-nc.net)
7 National Park Service Geographic Information Systems (www.nps.gov/gis)
8 Conservision-NC - One NC Naturally's Conservation Planning Tool (www.conservision-nc.net)
9 United States Census (www.census.gov)
10 Historical development patterns derived from analysis and classification of Landsat satellite imagery
11 Miller, D.A. and R.A. White, 1998: A Conterminous US Multi-layer Soil Characteristics Data Set for Regional Climate and Hydrology Modeling. Earth Interactions, **2.** (www.soilinfo.psu.edu).

8. APPENDIX B

Population, development data, and conversion rates for the 19-county region and individual counties of Western North Carolina based on historical data and population projections from the State Demographics Branch of the North Carolina Office of State Budget and Management, analysis of satellite imagery, and analysis of development trends in per-capita land consumption.

Year	Population	Developed Land (%)	Developed Land (acres)	Developed Land (ha)	Rate of Development (acres/day)	Rate of Development (ha/day)
19-County Region						
1976	545,100	0.7	34,348	13,900	N/A	N/A
1985	601,439	1.2	57,057	23,091	6.91	2.80
1995	675,801	2.2	105,434	42,669	13.25	5.36
2006	774,281	4.8	229,422	92,846	30.88	12.50
2010	811,319	5.1	243,583	98,577	9.70	3.93
2015	855,457	5.8	279,099	112,950	19.46	7.88
2020	897,725	6.5	314,249	127,175	19.26	7.79
2025	938,353	7.2	348,273	140,944	18.64	7.54
2030	969,805	7.8	374,796	151,678	14.53	5.88
Alleghany County						
1976	9,300	0.3	446	181	N/A	N/A
1985	9,549	0.4	605	245	0.05	0.02
1995	9,877	0.8	1,131	458	0.14	0.06
2006	10,946	2.4	3,550	1,437	0.60	0.24
2010	11,242	2.7	4,040	1,635	0.34	0.14
2015	11,660	3.3	4,863	1,968	0.45	0.18
2020	12,080	3.9	5,689	2,302	0.45	0.18
2025	12,498	4.4	6,512	2,636	0.45	0.18
2030	12,833	4.9	7,172	2,902	0.36	0.15
Ashe County						
1976	20,900	0.3	681	275	N/A	N/A
1985	22,723	0.4	1,160	469	0.15	0.06
1995	23,202	2.5	6,761	2,736	1.53	0.62
2006	25,630	5.7	15,169	6,139	2.09	0.85
2010	26,705	6.6	17,544	7,100	1.63	0.66
2015	27,787	7.9	21,040	8,515	1.92	0.78
2020	28,868	9.2	24,532	9,928	1.91	0.77
2025	29,948	10.5	28,021	11,340	1.91	0.77
2030	30,814	11.5	30,819	12,472	1.53	0.62
Avery County						
1976	14,200	0.6	877	355	N/A	N/A
1985	14,726	0.9	1,379	558	0.15	0.06
1995	15,462	1.8	2,854	1,155	0.40	0.16
2006	18,214	3.4	5,320	2,153	0.61	0.25
2010	18,341	3.6	5,576	2,257	0.17	0.07
2015	18,538	3.7	5,793	2,345	0.12	0.05
2020	18,734	3.9	6,010	2,432	0.12	0.05
2025	18,932	4.0	6,228	2,520	0.12	0.05
2030	19,090	4.1	6,402	2,591	0.10	0.04

Buncombe County						
1976	153,800	2.1	8,824	3,571	N/A	N/A
1985	167,083	3.6	15,051	6,091	1.90	0.77
1995	193,246	5.1	21,067	8,526	1.65	0.67
2006	221,099	9.7	39,973	16,177	4.71	1.91
2010	234,080	10.3	42,519	17,207	1.74	0.71
2015	248,824	11.8	48,862	19,774	3.48	1.41
2020	262,660	13.3	54,814	22,183	3.26	1.32
2025	275,645	14.6	60,400	24,444	3.06	1.24
2030	285,454	15.6	64,620	26,151	2.31	0.94
Cherokee County						
1976	18,300	0.5	1,305	528	N/A	N/A
1985	19,671	0.8	2,373	960	0.32	0.13
1995	22,386	1.6	4,597	1,860	0.61	0.25
2006	26,684	4.3	12,203	4,938	1.89	0.77
2010	27,578	4.5	12,714	5,145	0.35	0.14
2015	29,341	5.3	15,016	6,077	1.26	0.51
2020	31,084	6.1	17,291	6,998	1.25	0.50
2025	32,813	6.9	19,548	7,911	1.24	0.50
2030	34,182	7.5	21,335	8,634	0.98	0.40
Clay County						
1976	5,800	0.3	378	153	N/A	N/A
1985	7,007	0.5	617	250	0.07	0.03
1995	7,915	1.1	1,420	575	0.22	0.09
2006	10,131	2.6	3,521	1,425	0.52	0.21
2010	10,765	2.8	3,805	1,540	0.19	0.08
2015	11,712	3.3	4,525	1,831	0.39	0.16
2020	12,658	3.9	5,245	2,122	0.39	0.16
2025	13,603	4.4	5,963	2,413	0.39	0.16
2030	14,359	4.8	6,538	2,646	0.32	0.13
Graham County						
1976	6,700	0.3	569	230	N/A	N/A
1985	7,271	0.4	779	315	0.06	0.03
1995	7,639	0.6	1,179	477	0.11	0.04
2006	8,070	1.7	3,047	1,233	0.47	0.19
2010	8,178	1.7	3,133	1,268	0.06	0.02
2015	8,411	1.9	3,540	1,433	0.22	0.09
2020	8,643	2.2	3,946	1,597	0.22	0.09
2025	8,875	2.4	4,352	1,761	0.22	0.09
2030	9,061	2.6	4,678	1,893	0.18	0.07
Haywood County						
1976	44,900	0.8	2,969	1,202	N/A	N/A
1985	47,344	1.1	3,874	1,568	0.28	0.11
1995	50,801	2.4	8,532	3,453	1.28	0.52
2006	56,437	4.8	16,822	6,808	2.06	0.84
2010	57,711	5.1	17,849	7,223	0.70	0.28
2015	58,993	5.6	19,451	7,872	0.88	0.36
2020	60,090	5.9	20,823	8,427	0.75	0.30
2025	61,026	6.3	21,993	8,900	0.64	0.26
2030	61,676	6.5	22,805	9,229	0.45	0.18

Henderson County						
1976	51,800	1.6	3,729	1,509	N/A	N/A
1985	65,085	3.1	7,196	2,912	1.06	0.43
1995	79,569	5.0	11,668	4,722	1.23	0.50
2006	99,559	13.2	30,915	12,511	4.79	1.94
2010	107,402	13.5	31,538	12,763	0.43	0.17
2015	116,240	15.6	36,409	14,735	2.67	1.08
2020	125,032	17.6	41,256	16,696	2.66	1.07
2025	133,781	19.7	46,078	18,648	2.64	1.07
2030	140,749	21.3	49,919	20,202	2.10	0.85
Jackson County						
1976	24,600	0.6	1,936	784	N/A	N/A
1985	26,702	1.0	3,202	1,296	0.39	0.16
1995	30,207	2.1	6,390	2,586	0.87	0.35
2006	36,614	4.8	14,836	6,004	2.10	0.85
2010	38,104	5.2	15,974	6,465	0.78	0.32
2015	40,868	6.1	19,000	7,689	1.66	0.67
2020	43,633	7.1	22,027	8,914	1.66	0.67
2025	46,397	8.1	25,053	10,139	1.66	0.67
2030	48,609	8.9	27,474	11,119	1.33	0.54
Macon County						
1976	18,300	1.0	3,204	1,297	N/A	N/A
1985	22,758	1.4	4,428	1,792	0.37	0.15
1995	26,663	2.1	6,708	2,714	0.62	0.25
2006	32,944	3.8	12,389	5,014	1.42	0.57
2010	35,464	4.1	13,246	5,360	0.59	0.24
2015	38,462	4.6	15,157	6,134	1.05	0.42
2020	41,333	5.2	16,987	6,874	1.00	0.41
2025	44,080	5.7	18,738	7,583	0.96	0.39
2030	46,191	6.2	20,083	8,128	0.74	0.30
Madison County						
1976	16,500	0.2	443	179	N/A	N/A
1985	17,037	0.4	1,059	429	0.19	0.08
1995	18,057	0.8	2,285	925	0.34	0.14
2006	20,316	1.9	5,437	2,200	0.78	0.32
2010	21,322	2.3	6,434	2,604	0.68	0.28
2015	22,563	2.8	8,022	3,246	0.87	0.35
2020	23,631	3.3	9,388	3,799	0.75	0.30
2025	24,549	3.7	10,563	4,275	0.64	0.26
2030	25,191	4.0	11,384	4,607	0.45	0.18
Mitchell County						
1976	14,300	0.4	544	220	N/A	N/A
1985	14,399	0.7	1,007	408	0.14	0.06
1995	15,285	1.6	2,206	893	0.33	0.13
2006	15,884	3.2	4,470	1,809	0.56	0.23
2010	16,074	3.3	4,560	1,846	0.06	0.02
2015	16,208	3.5	4,863	1,968	0.17	0.07
2020	16,312	3.7	5,098	2,063	0.13	0.05
2025	16,394	3.8	5,284	2,138	0.10	0.04
2030	16,447	3.9	5,404	2,187	0.07	0.03

Polk County						
1976	12500	0.5	786	318	N/A	N/A
1985	14021	1.1	1684	682	0.27	0.11
1995	16390	1.8	2671	1081	0.27	0.11
2006	18906	3.5	5264	2130	0.65	0.26
2010	19054	3.6	5301	2145	0.03	0.01
2015	19256	3.7	5441	2202	0.08	0.03
2020	19453	3.7	5577	2257	0.07	0.03
2025	19648	3.8	5711	2311	0.07	0.03
2030	19806	3.9	5820	2355	0.06	0.02
Swain County						
1976	10,200	0.3	1,097	444	N/A	N/A
1985	10,846	0.6	1,941	785	0.26	0.10
1995	11,784	0.9	3,097	1,253	0.32	0.13
2006	13,939	1.7	5,687	2,301	0.64	0.26
2010	14,307	1.9	6,152	2,490	0.32	0.13
2015	15,111	2.2	7,135	2,888	0.54	0.22
2020	15,908	2.5	8,110	3,282	0.53	0.22
2025	16,697	2.7	9,074	3,672	0.53	0.21
2030	17,323	3.0	9,840	3,982	0.42	0.17
Transylvania County						
1976	22,000	0.4	948	383	N/A	N/A
1985	24,948	0.6	1,479	598	0.16	0.07
1995	27,516	1.3	3,068	1,242	0.44	0.18
2006	30,264	2.8	6,585	2,665	0.88	0.35
2010	31,665	3.0	7,131	2,886	0.37	0.15
2015	32,911	3.3	7,960	3,221	0.45	0.18
2020	33,787	3.6	8,542	3,457	0.32	0.13
2025	34,402	3.8	8,951	3,623	0.22	0.09
2030	34,759	3.9	9,189	3,719	0.13	0.05
Watauga County						
1976	30,300	0.8	1,568	634	N/A	N/A
1985	35,071	1.2	2,325	941	0.23	0.09
1995	40,811	3.1	6,141	2,485	1.05	0.42
2006	43,995	7.3	14,323	5,797	2.04	0.82
2010	46,481	7.5	14,705	5,951	0.26	0.11
2015	49,382	8.3	16,271	6,585	0.86	0.35
2020	52,280	9.5	18,763	7,593	1.37	0.55
2025	55,180	10.8	21,257	8,603	1.37	0.55
2030	57,499	11.8	23,251	9,410	1.09	0.44
Wilkes County						
1976	56,200	0.8	3,635	1,471	N/A	N/A
1985	59,852	1.3	6,149	2,488	0.77	0.31
1995	62,491	2.2	10,519	4,257	1.20	0.48
2006	66,455	4.8	22,934	9,281	3.09	1.25
2010	67,936	4.9	23,385	9,464	0.31	0.13
2015	69,496	5.5	26,320	10,651	1.61	0.65
2020	71,060	6.1	29,261	11,842	1.61	0.65
2025	72,622	6.7	32,199	13,031	1.61	0.65
2030	73,871	7.2	34,549	13,982	1.29	0.52

Yancey County						
1976	14,500	0.2	411	166	N/A	N/A
1985	15,346	0.4	751	304	0.10	0.04
1995	16,500	1.6	3,140	1,271	0.65	0.26
2006	18,194	3.6	6,977	2,824	0.96	0.39
2010	18,910	4.1	7,975	3,228	0.68	0.28
2015	19,694	4.8	9,432	3,817	0.80	0.32
2020	20,479	5.6	10,891	4,407	0.80	0.32
2025	21,263	6.3	12,347	4,997	0.80	0.32
2030	21,891	6.9	13,514	5,469	0.64	0.26