3 Demographic Trends in the Eastern US and the Wildland Urban Interface: Implications for Fire Management

John A. Stanturf
Center Forest Disturbance Science, US Forest Service, 320 Green St., Athens, GA 30602, USA
Email: jstanturf@fs.fed.us

Michael C. Wimberly
GISc Center of Excellence, South Dakota State University, Brookings, SD 57007-3510, USA
Email: michael.wimberly@sdstate.edu

Abstract Over the last century, the United States has evolved from a predominantly rural to an urbanized society with an exurban area currently referred to as the wildland urban interface (WUI). This WUI is critical as it occupies three to five times as much land area as urban areas with emerging and latent conflicts between traditional resource management and preferences of new residents. The effect of development on wildland fire management has received the most attentions. Increasingly, one of the most effective tools in the manager's kit, fuel reduction by frequent understory burning, is off-limits because of safety and liability risks or public dislike of smoke. Fire risk in the WUI is greater than in wildland because there is a higher risk of catastrophic wildfire. The WUI, however, cannot be defined by simple proximity of forest to urban areas but more realistically is conceptualized as a set of complex social, physical, and biotic gradients. The Southern US exemplifies the problems of mixing urbanized land uses with fire-affected natural vegetation. Remote sensing and geographic information systems, along with spatial information at appropriate scale, will play a critical role in providing managers with monitoring capability that can also be used to educate the public about the wildland urban interface.

Keywords Prescribed burning, hazardous fuel reduction, smoke management, WUI Index, forest land management

3.1 Introduction

Over the last century, the United States has evolved from a predominantly rural to an urbanized society (Hobbs and Stoops, 2002). Since the World War Ⅱ, growth of exurban areas has dominated: beyond the suburbs, not exactly rural and not quite urban. Today this exurban area, currently referred to as the wildland urban interface (WUI) is critical as it occupies three to five times as much land area as urban areas (Theobald, 2001; Radeloff et al., 2005). Although there are many emerging emergent and latent conflicts in the WUI between traditional resource management and preferences of new residents, the effect of development on wildland fire management has attracted the greatest attention from policymakers. As human populations expand farther into fire-affected natural landscapes, more people, more natural ecosystem area, and greater capital investment are at risk from wildfire. Fragmentation of forest land due to land use change driven by population growth constrains many traditional methods of forest management, particularly the use of prescribed burning to manage fuel loads. Prescribed fire is used routinely in conifer forests in the South, Lake States, and Northeast to reduce fuel loads and decrease the risk of catastrophic wildfires, improve forest health, and manage habitat for threatened and endangered species. Increasingly, one of the most effective tools in the manager's kit, fuel reduction by frequent understory burning, is off-limits because of safety and liability risks (Achtemeier et al., 1998; Wade and Brenner, 1995) or public dislike of smoke (Macie and Hermansen, 2002).

Demographic changes in the Eastern United States affect natural resources and the attitudes of the public toward traditional management practices such as prescribed burning (Cordell et al., 1998). The WUI, however, is not a discrete management unit that can be defined, more or less, by simple proximity of forest to urban areas. Because of heterogeneous patterns of both forest cover and human settlement across broad landscapes, the WUI is more realistically conceptualized as a set of complex social, physical, and biotic gradients (Wimberly et al., 2005). Our objectives in this chapter are to briefly describe the changing demographics of the Eastern United States (focusing on the South), characterize the growing WUI, and describe the implications for the land manager of the expansion of dense human settlements into fire-affected forests.

3.2 Demographics

The population of the United States grew 270% over the course of the 20th century, from approximately 76 million to 281 million and growth in the 1990s was the greatest increase in population for any decade in history (Hobbs and Stoops, 2002). The South, defined for our purposes as the 13 states in region 8 of the US forest service, showed a greater percentage increase, 319% (from 22 million to almost 92 million) over the same century (Hobbs and Stoops, 2002; Cordell and Macie, 2002). These growth rates are the combined effect of lowered mortality, longer living, and immigration (Cordell et al., 2004). Population increase was not steady, however, and the post World War II "baby boom" shows clearly when increases are viewed at decadal intervals (Fig. 3.1). Applying the rate of increase for the decade from 1990 – 2000 (13.1%) to future growth, the United States population is predicted by the bureau of census to double in size in the next 100 years, to 570 million (Cordell et al., 2004).

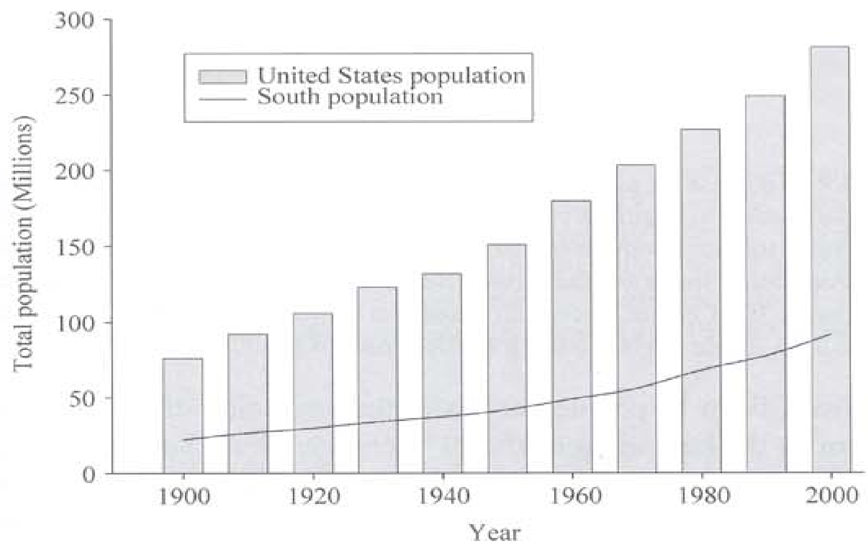

Figure 3.1 Decade to decade population increases for the entire United States and the 13 Southern states in region 8 of the US forest service. Population totals for the United States exclude Alaska and Hawaii through 1950. Source: US census, decennial census of population, 1900 – 2000 presented in Appendix A Table 1 of Hobbs and Stoops (2002)

More than 70% of the current population lives east of the 100th Meridian, i.e. in the East. Increasingly, the US population lives within a metropolitan area. In 1910, only 28% lived in a metropolitan area but by 2000, the US population was 80% metropolitan (Hobbs and Stoops, 2002). The growth of metropolitan population in the South has increased, especially since World War II, and now approaches the national average (Fig. 3.2). Since World War II, growth has been concentrated outside of the central cities; half the US population now lives in suburban areas (Hobbs and Stoops, 2002). In the South, 20.8% of the increase between 1990 and 1999 has been in metropolitan areas outside of the central cities (Mackun and Wilson, 2000).

Increased population levels do not tell the whole story, however. Given a fixed area of land, increasing population means higher population density. The US

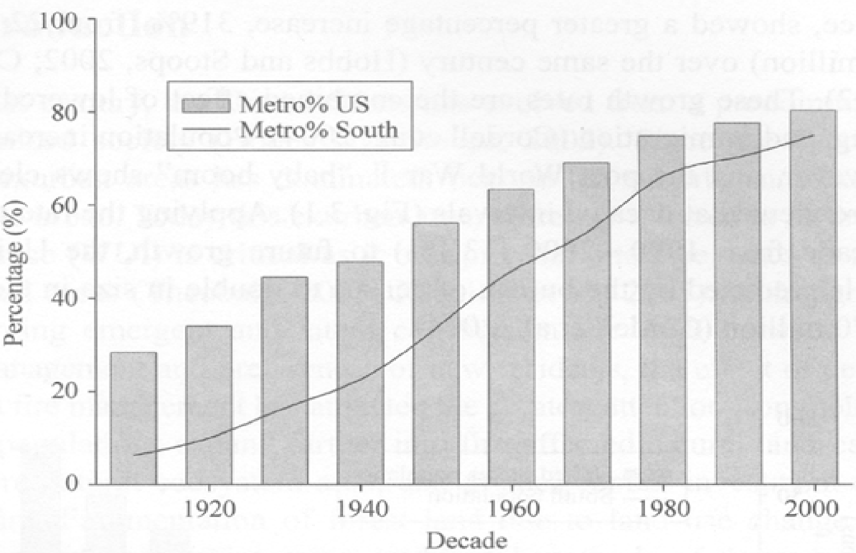

Figure 3.2 Increase in the metropolitan population of the United States and the 13 Southern states in region 8 of the US forest service, 1910 – 2000, shown as the percentage of the total population that lived in metropolitan areas at each decennial census. Population totals for the United States exclude Alaska and Hawaii through 1950. Source: US Census, decennial census of population, 1900 – 2000 presented in Appendix A Table 3 a and b of Hobbs and Stoops (2002)

tripled in density, from 10 people per km^2 at the beginning of the 20^{th} century to 31 people per km^2 at the beginning of the 21^{st} century. The US remains relatively less densely populated, however, in comparison with most countries and is lower than the average world population density of 46 people per km^2 (Hobbs and Stoops, 2002). The average population density in the South exceeds the national average, and has increased more rapidly than the national rate since World War Ⅱ (Fig. 3.3).

Despite the danger of extending past trends into the future, we see no reason to expect that population levels will decline in the United States, or even that the rate of growth will decline (Nowak et al., 2005). Another trend besides the growth of population that is likely to continue is the increase in per capita footprint. Since the 1960s, conversion from rural to urban land use has exceeded the rate of population growth (Hirschorn, 2000), with a preference for non-urban settings (Sullivan, 1994). This trend is due to the combined effects in exurban versus urban areas of lower housing density, larger average lot size, and the expansion of supporting infrastructure such as roads, schools, and commercial area (Cordell et al., 2004). In the decade and a half from 1982 – 1997, developed area in the US increased 34%, with the largest regional increase in the South (Alig et al., 2004). Thus demographics can be visualized through the effect of human population growth on land use, both in terms if the present distribution of people on the landscape in urban, exurban, and rural areas and the likely changes in land use patterns over the next century.

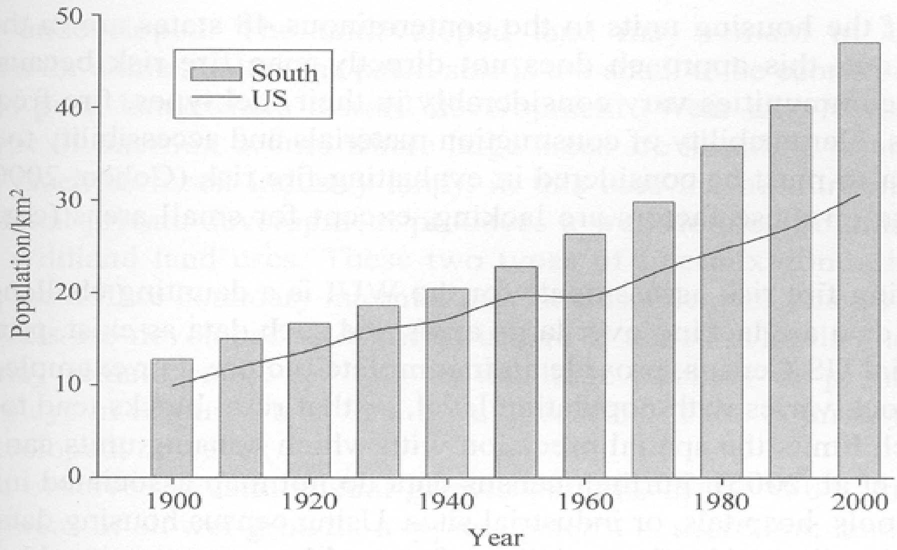

Figure 3.3 Average population density per km^2 of the United States and the 13 Southern states in region 8 of the US forest service, 1910 – 2000, shown as the average density at each decennial census. Density levels for the United States exclude Alaska and Hawaii for 1900 – 1950. Density levels are based on census 2000 land area measurements. Source: US census bureau, geography division; decennial census of population, 1900 – 2000 presented in Appendix A Table 2 of Hobbs and Stoops (2002)

3.3 The Wildland Urban Interface

The traditional concept of the WUI is that of an area of urban sprawl where new housing developments abut large areas of public or private wildland. Recreation managers view this interface in terms of adjacency of people seeking recreational opportunities and access to backcountry. Fire managers view the interface in terms of adjacency of flammable wildland fuels and structures (Long et al., 2005). The federal government defined the interface as "…the area where houses meet or mingle with undeveloped wildland vegetation" and described three types of interface communities: ① the "interface community" where structures about wildland fuels, ② the "intermix community" where structures are dispersed within a wildland matrix, and ③ the "occluded community" where wildland fuels are patches within a matrix of structures, for example a park (USDA and USDI, 2001).

Attempts to map the interface and intermix conditions based on this definition use the threshold set in the Federal register of one house per 40 acres (Radeloff et al., 2005). Further assumptions must be made about the nature of the wildland vegetation. The WUI map for 2000 produced by Radeloff and colleagues (2005) used a 50% threshold for wildland vegetation: greater than 50% for the interface community, less than 50% wildland vegetation but within 1 mile of wildland vegetation for the intermix community type. They estimated that 10% of the area and 33% of the housing units in the conterminous 48 states are in the WUI. As they point out, this approach does not directly map fire risk because wildland vegetation communities vary considerably in their fuel types, fire frequency, and fire regimes. Flammability of construction materials and accessibility to firefighting equipment also must be considered in evaluating fire risk (Cohen, 2000); spatially explicit data on these factors are lacking, except for small areas (e.g., Haight et al., 2004).

Developing fire risk assessments for the WUI is a daunting challenge; most of the needed data are lacking over large areas and such data as exist, primarily from the decennial US Census, provide an incomplete picture. For example, the size of a census block varies with population level, so that rural blocks tend to be of large areas, which limits the spatial precision with which housing units can be mapped (Wimberly et al, 2005). Further, census data do not map associated infrastructure such as schools, hospitals, or industrial sites. Using census housing data to map the WUI is further limited by the omission of second-home, recreational housing; only primary abodes are listed in the census data. Spatial information on the pattern of roads is useful in mapping the WUI, and in combination with census data can overcome some of these limitations. Roads tend to be correlated with housing in rural areas; individual buildings are more likely to be located close to roads, and roads themselves have an impact on probability of ignition (Forman, 2002).

Attempts to map the WUI to date have produced static snapshots of land use and population density. Other predictors of fire risk related to the socioeconomic environment are even harder to map, such as labor markets, law enforcement, and socioeconomic conditions (Prestemon et al, 2002; Mercer and Prestemon, 2005; Butry and Prestemon, 2005). Because it is impractical for managers to redo a WUI map for each fire season, a dynamic view of the WUI is needed, one that identifies where change is most likely to occur (e.g., growth clusters—Hammer et al., 2004). We propose a new typology that defines the WUI along two axes: from wildland to urban land use and private to public land ownership. At one extreme is dispersed urban development within a wildland matrix, typified by second home or summer recreation development, the interface zone. Often these are private in-holdings within large areas of public ownership. The Wildland Island at the other extreme is a park or forest stand within an urban area. These remnant natural areas frequently are rich in plant species; the pine rocklands in South Florida exemplify this form of the WUI (O'Brien, 1998; Snyder et al., 1990).

Between these extremes is the intermix zone of areas undergoing a transition from natural resource uses such as forestry or agriculture to urban uses. We distinguish two types based on the sharpness of the boundary between wildland and urban land uses: the diffuse boundary and defined boundary intermix zones. In both types, developed parcels are small relative to forested land. The diffuse boundary intermix zone occurs where private ownership predominates and parcel sizes are relatively small. Typical leapfrog urban development creates zones of development well beyond the edge of urban development, with land between remaining undeveloped. The undeveloped land may remain in active forest management for a time, unless the patch size is too small to be economical or rising land values push landowners toward development (Wear and Newman, 2004). Another type of intermix occurs where large areas are in public or single private ownership (such as forest industry land); in this case the mixture of forest land with individual private development produces a well-defined boundary between urban and wildland land uses. These two types of intermix zone differ in their dynamism; the diffuse boundary intermix may be unstable over time as individually owned parcels are developed and infrastructure is added. The distinct boundary intermix may remain stable as long as the large publicly or privately owned forestland stays in resource use. The developed side of the boundary likely will be fully developed, however.

We have observed several spatial growth patterns in the WUI. Around small towns and areas of slower growth, a typical pattern is accretion; land at the edge of town is developed, particularly along major roads. Accretion generally develops a defined boundary with wildland. In larger towns undergoing more rapid development, a typical pattern is leapfrog and fill-in; development occurs beyond the outskirts of older development, leaving a sizeable area of undeveloped land between, resulting in a diffuse boundary. Over time, the gap is closed. Analysis of county-level census data illustrates this phenomenon: counties mapped as 40% – 60% urban in the 1990 census saw the greatest increase in urban area in 2000 (Nowak and Walton, 2005). In the southeastern U. S., 35% of the census blocks that converted from rural to WUI between 1990 and 2000 were not adjacent to existing WUI blocks, indicating a leapfrog pattern of development (Zhang and Wimberly, 2007). Another common development pattern seen especially in rapidly developing areas of the South such as Florida and along the Atlantic and Gulf coasts is concentrated development. This is called variously a planned unit development, or a gated or golf course community. Sometimes these developments result from large blocks of forest owned by industry being converted to up-scale real estate development. Vacation home development can occur within the intermix zone on large lots, or be truly dispersed in private forest areas (Stein et al., 2005).

Each type of WUI is dynamic and local factors of economics, access, and proximity to naturalness and scenery largely determine the rate of conversion from wildland to developed land within the national context of capital availability. The types of vegetation communities, stand structures, fuel types and loads vary as well by physiographic province, from the coast to the mountains. There is no single parameter, or simple set of parameters, that adequately describe the WUI environment. As noted by Wear and Bolstad (1998), "…coarse-scale measures of the human drivers of landscape change (for example, population growth measured at the county level) appear to be poor predictors of changes realized at finer scales." The characteristics and significance of the WUI for fire managers at a given location may vary depending upon the spatial scale of the effects considered. Whereas forest patch sizes and interspersion with housing can be assessed at the local level, the potential influences of escaped fires and smoke dispersion must be analyzed over much larger areas. Additionally, fire managers need to be aware of the likelihood of land use changes in intermix areas.

In many ways, the entire South is a WUI. Much of the South was once cleared, farmed, or grazed. Past land use has left many legacies, including an extensive road system (Fig. 3.4). Population growth since the middle of the last century has caused increasing urbanization and fragmentation of the forested landscape (Wear, 2002),

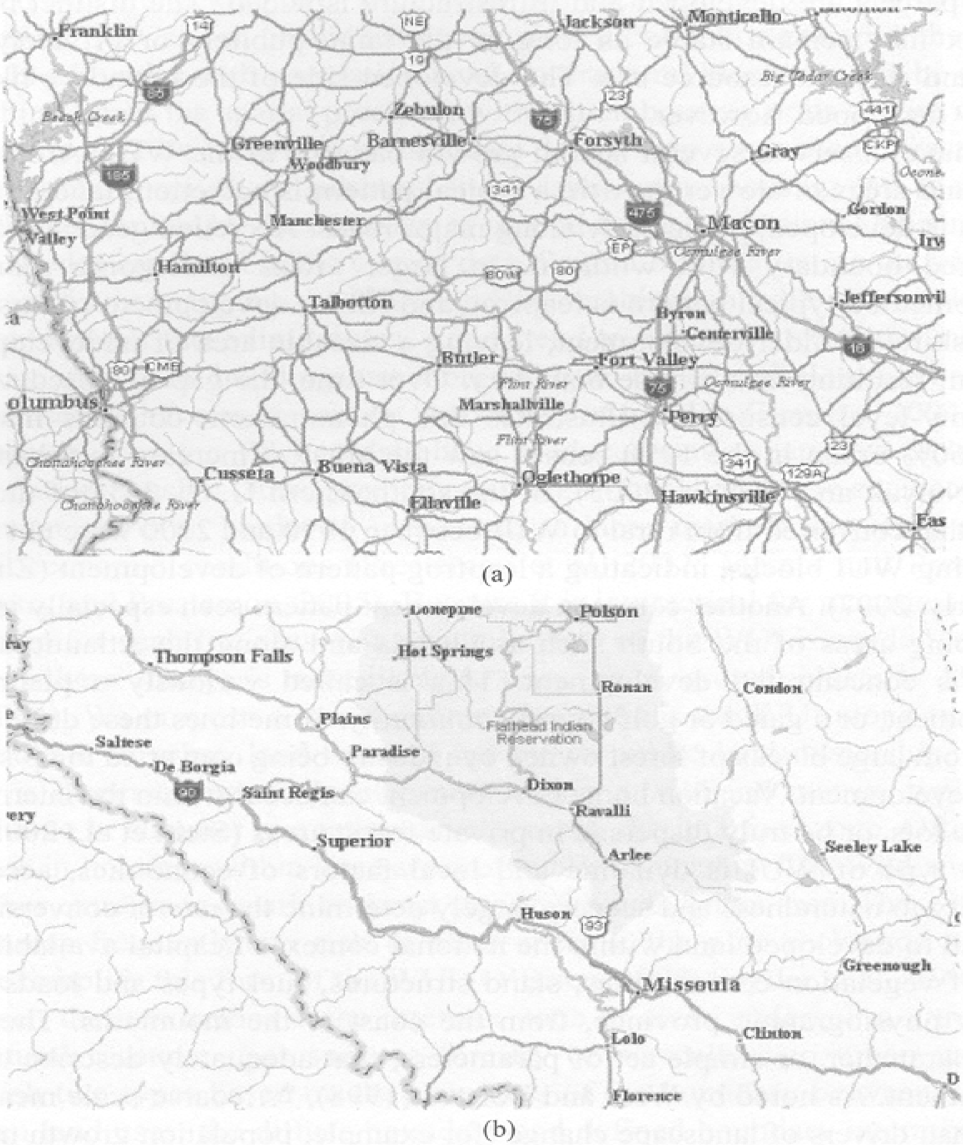

Figure 3.4 A legacy of roads in the South as compared to the West: Roads in an approximately 26,000 km^2 area of southwestern Georgia, the Flint River Valley (a), compared to a similar area of the Bitterroot Valley in Montana (b)

increasing the size and importance of the WUI. More people now live at the interface and the transportation system is expanding, becoming denser and more pervasive (Riitters and Wickham, 2003). The density of public roads in the US is 0.65 km/km^2 (0.79 km/km^2 for the contiguous US excluding Alaska and Hawaii) and the average for the southern states is 0.98 km/km^2 (US DOT, 2004). The road density in Georgia is 1.22 km/km^2, higher than the national average; the density in Montana is lower than the national average at 0.29 km/km^2. Continuing growth in the South is projected to occur along the Atlantic and Gulf coasts and the Piedmont Crescent, mostly from the conversion of forest to urban land use (Wear, 2002). Besides the physical aspects of the WUI, changing demographic profiles and cultural values (Cordell et al., 1998) have altered attitudes towards natural resource management in general (Bliss et al., 1997; Jacobson et al., 2001; Hull and Stewart, 2002) and prescribed burning in particular (Loomis et al., 2001; Duryea and Hermansen, 2002). In general, Southerners share the same attitudes about the environment as the general population and even small forest landowners are averse to even-aged management practices such as clearcutting and use of herbicides to control competing vegetation (Bliss et al., 1997).

Land ownership in the South and East differs from the West; Eastern forests are predominantly in private ownership, approaching 80% or more in most states. Forest land ownership differences lead to distinctive land cover patterns (e.g., Turner et al., 1996). A distinctive feature of southern forests is the relatively large industrial ownership, especially coastal plain pine plantations. Forest industry has for many years developed or sold parcels with high amenity values, such as coastal islands and lakeshores, and increasingly a significant proportion of new housing starts are vacation homes on wildland/high contrast edges such as abutting national forest or national park land (Theobald, 2004). The 1990s saw a new phenomenon in the wholesale divestiture of industry land to financial and real estate organizations, the Timber Investment Management Organization (TIMO) and Real Estate Investment Trust (REIT) (Ravenel et al., 2002; Stanturf et al., 2003). Although purchased and managed in the short-term for their timber value (Caulfield, 1998; Yin et al., 1998), the long-term fate of this land base is uncertain (Clutter et al., 2005); the question is whether the land will be reforested once the standing value is harvested, or sold for urban development. Again, local and national economics will influence such decisions (Wear and Newman, 2004). Large contiguous blocks of industrial ownership are not limited to the South, and there is concern throughout the Eastern US for the uncertainty of future uses of forest industry land (e.g., Hagan et al., 2005).

3.3.1 Georgia Case Study

To further explore the characteristics of the WUI in the southeastern US, we carried out a GIS modeling exercise for the state of Georgia, in which digital maps of forest cover, housing density, and road density were combined to map the spatial pattern of the WUI. A vector dataset containing housing density from the 2000 census, mapped at the census block level, was obtained from the SILVIS website (Radeloff et al., 2005). The road layer was derived from 1:100,000 digital line graphs (DLGs) originally produced by the USGS. A 18-class land cover map of Georgia, developed by the Institute of Ecology for the Georgia Gap Analysis Project and the Georgia Land Use Trends program, was used to map forest cover (Kramer et al., 2003). This 30 m raster dataset characterized land cover in 1998 and was developed by classifying Landsat TM images from 2 dates representing leaf-on and leaf-off conditions. For this study, cells mapped as deciduous forest, conifer forest, mixed forest, and forested wetlands were reclassified with a value of 1 (forested), and all other pixels were reclassified with a value of 0 (non-forested). Our WUI map for Georgia was developed using the methodology of Zhang (2004). These data sets were transformed spatially using a moving-window analysis. The housing densitymap was converted toa raster dataset with a 30 m cell size to match the land cover dataset. A new housing density value was then assigned to each cell, based on the average housing density within a 2.4 km^2 radius circular neighborhood (Fig. 3.5(a)). This radius was chosen to match the buffer zone for WUI identification that had been used in previous mapping efforts (Radeloff et al., 2005). Road density, computed as km of road per km^2, was also summarized within a 2.4 km^2 circular neighborhood with the output stored in a 30 m raster dataset (Fig. 3.5(b)). Forest cover for each cell was similarly computed as the proportion of forested cells within the surrounding 2.4 km^2 circular neighborhood (Fig. 3.5(c)).

Each spatial variable was converted into an index between 0 and 1 using a scaling function. These functions were based on the assumption that areas with a high WUI index (WUI_I) value should contain both high levels of wildland vegetation (predominantly forests in Georgia), and also have high levels of human habitation and utilization. Thus, both the forest index (F_I) and the road index (R_I) increased linearly with increasing densities. The housing index (H_I) increased logarithmically with housing density, based on the assumption that differences in the index at lower housing densities are more important for defining the WUI than differences at higher housing densities.

These input layers were combined using an enhanced version of the favorability function (O'Sullivan and Unwin, 2003). The final WUI index was computed for each 30 m cell as:

$$WUI_I = FI^{0.5} \times HI^{0.25} \times RI^{0.25} \quad (3.1)$$

This function was a weighted geometric mean of the three indices defined previously, with equal weighting assigned to wildland characteristics (the forest index) and to the combined urban characteristics (the housing and road indices). The value of the WUI index was zero whenever one or more of the component indices was zero, and equaled one only when all three of the component indices were equal to one. Thus, the resulting WUI index was lowest at the extremes of

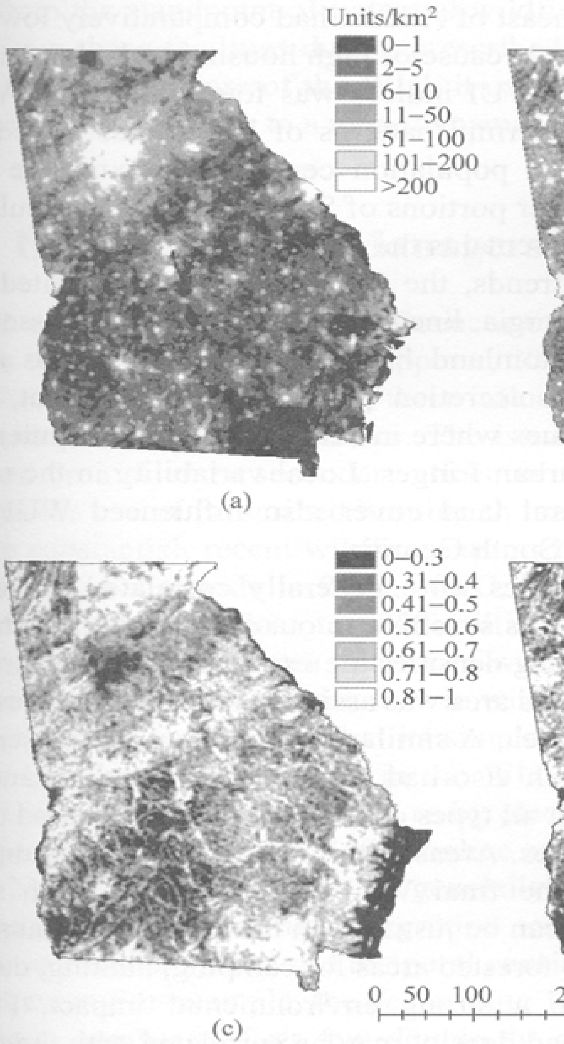

Figure 3.5 Georgia example. (a) Housing density in residential units per square km. (b) Road density in km of road per square km of land area. (c) Forest cover in Georgia as a proportion of total land area. (d) Calculated WUI Index; high index indicates local juxtaposition of housing and natural vegetation, low index value indicates either urban or wildland conditions

the urban-wildland gradient and highest for landscapes falling near the middle of this gradient.

Almost all the areas in Georgia that had high forest cover also had a high WUI index, reflecting the ubiquity of diffuse, low-density development on private lands and extensive road systems (Fig. 3.5(d)). The major exception was the Okefenokee national wildlife refuge, located in the southeastern corner of the state. Another large concentration of the public land in Georgia is in the Chattahoochee national forest, located in the southern Appalachians of Northeast Georgia. However, much of this land was heavily roaded and interspersed with private property, resulting in high WUI indices associated with defined intermix patterns in this portion of the state. The Piedmont region northeast of Atlanta had comparatively low forest cover, but also had high WUI indices because of high housing and road densities. Another large concentration of high WUI indices was found along the Atlantic Coast, resulting from the defined intermix patterns of large areas of industrial timberland juxtaposed with scattered population centers and extensive roads. WUI indices were much lower in other portions of South Georgia, particularly in southwest Georgia where agriculture remains the dominant land use.

In additional to these statewide trends, the WUI index also exhibited finer-grained local variability. In South Georgia, linear patterns reflected the association between forested wetlands and bottomland habitats. Circular patterns around numerous small cities reflected the accretion pattern of development, which created rings of high WUI index values where increasing forest cover intersected suburban housing densities on the urban fringes. Local variability in the relative dominance of forest and agricultural land cover also influenced WUI index patterns across much of Central and South Georgia.

Although road and housing densities were generally correlated, there were several areas where the WUI index was sensitive to our specification of the road index. West of the Okefenokee, housing densities are extremely low but rural road densities were very high. Therefore, this area was assigned high WUI indices rather than being identified as a wildland area. A similar phenomenon was observed at the Fort Stewart military base, which also had low housing densities and high road densities. Our decision to weight all types of roads equally in the road density calculations influenced these outcomes. Areas with high densities of unimproved roads had a similar influence on the final WUI index as areas with similar densities of highways. This decision can be justified on the contention that smaller roads provide direct human access to forested areas for camping, hunting, dumping, and other activities that can have a strong environmental impact. For the standpoint of fire risk assessment, road density may be correlated with the density of ignitions from human sources (Cardille et al., 2001; Zhai et al., 2003).

This example demonstrates that the results of this type of deductive modeling exercise are highly sensitive to the assumptions that underlie the variable selection, scaling, and weighting. However, this sensitivity is advantageous in that it allows the WUI index to be "tuned" to specific objectives. Consider a WUI index intended to identify areas where human infrastructure is likely to limit the applicability of prescribed fire as a fuel management treatment. Potential liability for traffic accidents caused by smoke is a major concern in this regard. Because the potential for such an accident would increase with traffic volume and speed, it would make sense to develop a weighted road density function based on road size.

Additional sources of spatial data can also be readily incorporated into a WUI model. In particular, more detailed information on historical fires, fuels and potential ignitions sources would help to identify forested areas where uncontrolled wildfire is most likely to occur. Detailed information on the locations, of hospitals, schools, utilities, and other infrastructure would be also useful for evaluating the

WUI from the standpoint of potential wildfire risks, as well as managing smoke away from these facilities during prescribed burns. Although our current model presents a static picture of the WUI, it could be enhanced to investigate patterns of development, leading to a more dynamic view of the interface.

3.4 Implications for Managers

Growth of the WUI has many influences on forests and their management (e.g., Duryea and Hermansen, 2002; Zipperer, 2002). Tourism, recreation, and amenity migration are prime examples of these influences. Here we will concentrate on the relationships with fire and smoke. The issues can be generalized into a primary effect on fire risk and a secondary effect on traditional forest management, which includes the use of prescribed burning to manage hazardous fuels. The values at risk are substantial: recent wildfire seasons have seen high costs for suppression ($1.5 billion nationwide in 2002, NIFC, 2001) and damage (the 1998 wildfires in Florida alone cost close to $800 million in damage, Butry et al., 2001). The growing WUI increases both the risk of wildfire occurring and the cost of wildfire by placing higher values at risk than in wildland areas.

Fire behavior is understood at its simplest as the interaction of fuels, weather, and an ignition source. People in the WUI can affect fire behavior by altering natural plant communities as well as by placing artificial fuels (i.e., structures) in the landscape Doolittle, 1978; Donoghue and Main, 1985; Prestemon and Butry, 2005). Natural ignition sources are generally lightning but humans introduce arson, accidents, and transportation as ignition sources. Estimating actual wildfire risk introduces broader spatial and temporal considerations than are used for predicting fire behavior. For example, the devastating 1998 fire season in Florida was below average in number of fires, but double the average number occurred during the summer (Butry et al., 2001). Anomalous weather patterns associated with El Niño-Southern Oscillation (ENSO) caused a build-up in fuels during the preceding year and there was an unusually sharp transition to the dry La Niña phase (Brenner, 1991; Butry et al., 2001). Broad scale modeling of the 1998 Florida fires validated that temporal dynamics are important to effectively estimating wildfire risk (Prestemon et al., 2002) and including socioeconomic conditions of communities improves the understanding of underlying causes of wildfires (Mercer and Prestemon, 2005). At the rural end of the WUI, at least in Florida, there were fewer wildfire ignitions and lower aggregate area burned, probably because forest management was active and prescribed burning frequent. In more densely populated areas with higher property values, prescribed burning was rare and ignitions and the area burned were higher (Mercer and Prestemon, 2005).

Managing hazardous fuel loads in the WUI will be critical for reducing the risk of catastrophic wildfires. Even though land ownership changes and land use is converted from forestry to housing development, the land cover often remains in forest, albeit a less dense forest cover than if managed for timber. In the South, especially in the rapidly urbanizing areas along the coasts, long growing seasons and usually abundant moisture cause those potentially hazardous fuels re-grow within a few years of burning (Brose and Wade, 2002). Prescribed burning remains the most effective treatment of potentially hazardous fuels in southern forests (Haines et al., 2001) and there are many guidelines for conducting prescribed burns in wildland areas (Wade et al., 1989). Land managers use prescribed burning to treat 6 million – 8 million acres of forest and agricultural land annually in the South. Use of prescribed burning in the WUI is still practical but calls for an even higher level of planning and preparedness, safe conduct, and communication to neighboring landowners and local officials (Miller and Wade, 2003; Wade and Mobley 2007).

Even when continued forest management is feasible, there will be further constraints on use of prescribed burning in the WUI due to smoke. In fact, smoke is probably the key issue in suitability of prescribed burning as a way to manage fuel loads in the interface. Concerns with smoke are several: local and regional air quality (Achtemeier 2001 and 2003), visibility on roads (Mobley, 1989), health impacts especially on sensitive segments of the population with respiratory problems (Sorenson et al., 1999), and nuisance effects (Monroe, 2002). Problem smoke is not confined to the South and reduced visibility from smoke on highways has caused fatalities in Western states such as Oregon, as well as in the South (Achtemeier et al., 1998; Achtemeier, 2002). Nevertheless, smoke from prescribed burning is a critical issue in the South due to a combination of physical (meteorology, climate, topography), biological (fire-affected vegetation and hazardous fuels), and social (population density, road network) factors. While smoke can be a problem at any time during a wildland fire, the worst conditions are in valley bottoms and drainages during the night (Achtemeier, 2002) and smoke can combine with moist air masses to produce exceptionally dense "superfog" that reduces visibility to fractions of a meter (Achtemeier, 2003).

Managing hazardous fuel loads across the wildland to urban gradient is a complex problem of many facets without obvious solution. The location within the WUI, time since last fire, stand density, and the quality of woody material affects the range of treatment options available. Not all ecosystems within the WUI are susceptible to ignition, except under extreme drought conditions. If fuels have accumulated by fire exclusion (lack of prescribed burning or suppression of wildfires), overly dense forest stands will have developed that require mechanical reduction of overstory and midstory woody stems before understory woody and herbaceous material can be treated. If the stand to be treated is in the wildland, conventional timber harvesting equipment may be used, and the operation may be economically feasible if there is sufficient timber value. If the operation is conducted in the intermix zones, mechanical reductions (i.e., thinning) may be feasible as a one-time treatment to bring fuel loads into balance. Forest operations selected for WUI applications must be appropriately matched to the terrain and stand conditions, the unique constraints of operating in the WUI, the product specifications of any extracted materials, and the prescription requirements of the treatment. Conventional mechanical reduction equipment is designed to operate effectively on large areas so high speed and maximum cutting width are common design goals. Operations for the WUI, on the other hand, should be lightweight to minimize soil impacts and road transportation problems. Cutting width and speed may not be as important as minimizing thrown debris and operating in tight quarters near structures and the public.

Suitability of an area for continued forest management is affected by exurbanization due to parcelization of the forest estate, reduction of tract size, and diseconomies of scale. Conventional forest operations face significantly increasing costs as tract size drops below 25 acres (Greene et al., 1997). This is primarily due to the increasing overhead of move-in costs and delay time associated with large capital-intensive equipment. In the diffuse boundary intermix zone where individual ownerships are small or in the distinct boundary zone where forest land is becoming parcelized into smaller ownerships, conventional economics may not apply (Wear and Newman, 2004). In the WUI, operations that involve a single machine performing multiple functions will have lower move-in costs (Wilhoit and Rummer, 1999). A small forwarder with a harvester head on the crane (a harwarder) would be a unique multi-function machine for WUI extraction needs. Smaller equipment where multiple machines can be moved on a single transport trailer may also be advantageous. Harvesting equipment mounted on all-terrain vehicles (ATV) can be easily transported from site to site. In dense, overstocked stands resulting from fire suppression, individual stems may be too small for conventional products and biomass thinning for energy wood may be appropriate. In such cases, combining a small chipper with cut-to-length harvesting systems may be feasible (Bolding and Lanford, 2001). Biomass material that has no product value may have to mulched and left in the stand to minimize costs. New technology to collect and bundle small material in the woods for transport to processing facilities and the development of bioenergy conversion technologies may provide additional options in the future. A complete fuel reduction treatment in the WUI will thus require an integrated system of several machines to achieve stand management goals while minimizing costs and maximizing fiber recovery and utilization.

Once woody fuels have been reduced, there remains the need to establish and maintain a low-risk herbaceous understory and prevent development of higher-stature woody fuels. In the South, the need for re-treatment can be as frequent as every 2 – 5 years in some fuel types (e.g., coastal flatwoods; Brose and Wade, 2002). Alternatives to use of fire to manage understory fuel loads over large areas are few, due to higher cost of mechanical and chemical alternatives and the required frequency of application. In localized areas protecting high-value structures or resources, alternatives to prescribed burning may involve mechanical reduction such as mowing or bush-hogging (Windell and Bradshaw, 2000; Rummer et al.,

2002) of current fuel loads and maintenance of low-risk understory through repeated mechanical treatments or herbicides, although such options may not be acceptable to some landowners (Loomis et al., 2000). At the urban end of the WUI gradient and throughout the WUI where individual home sites abut wildland, application of defensible space concepts and use of fire-resistant building and landscaping materials are critical to minimizing losses due to wildfires (Monroe, 2002; Long et al., 2005). In some states, local regulations are beginning to reflect these needs (Haines et al., 2005).

3.5 Conclusion

The rapid expansion of the US population since World War Ⅱ into formerly rural areas has caused significant shifts in land use and land cover that present the natural resource manager not only with constraints on traditional land management but also a new class of resource and people management problems in the interface zone where urban and wildland uses must co-exist. This rapidly expanding and changing WUI is more than a boundary or discrete class of land use, and can best be understood as a set of complex social, physical, and biologic gradients. Where the WUI mixes people with fire-affected forest vegetation, particular problems arise. Fire risk problems in the WUI are greater than in wildland because there is a higher risk of catastrophic wildfire; ignitions by humans increase and fuel loads generally are greater because of lack of on-going management. By placing higher values at risk (i.e., structures built within fire-affected forests), the potential costs of wildfires are greater. The cost of wildfires goes well beyond damage to structures, as scenic viewscapes can remain damaged for years and affect tourism-based economies (Butry et al., 2001).

The Southern US exemplifies the problems of mixing urbanized land uses with fire-affected natural vegetation. Because of an extensive road system, the entire South must be regarded as a WUI, at least in terms of managing smoke from prescribed burning. Even highly urbanized areas such as Atlanta, Georgia have been affected by smoke from wildfires and prescribed burning. Urbanization constrains traditional forest management and use of prescribed burning even at the wildland end of the WUI gradient because of concerns for liability from escaped fire, transportation safety, and regional air quality. Moving toward the urban end of the gradient, these concerns greatly increase and pose the dilemma of the lack of fuel management increasing the risk of occurrence and severity of inevitable wildfire.

Managers need additional tools to define the current WUI and affordable methods for monitoring land use change and updating the WUI. Such tools will provide managers with improved ability to estimate wildfire risk at a scale that permits them to plan appropriately to attack wildfire when it occurs to minimize property losses and insure firefighter safety. Individuals living in the WUI need to be educated as to their risk and their responsibility for reducing that risk. Remote sensing (RS) and geographic information systems, along with spatial information at appropriate scale, will play a critical role in providing managers with monitoring capability that can also be used to educate the public about the WUI: nothing says it like a map.

Acknowledgements

Discussions with many people helped shape the ideas presented here. Special mention goes to Scott Goodrick, Gary Achtemeier, and Yongqiang Liu for broadening our understanding of the issues surrounding smoke management. We also profited from discussions with Joe O'Brien, Tom Waldrop, Ken Outcalt, Dale Wade, and Yangjian Zhang. Helpful reviews were provided by Ken Cordell, Jeff Prestemon, Wayne Zipperer, and two anonymous reviewers.

References

Achtemeier GL, (2001), Simulating nocturnal smoke movement. *Fire Management Today*, **61**: 28 – 33

Achtemeier GL, (2002), Problem smoke. In: Hardy C, Ottmar RD, Peterson JL, et al. (eds) Smoke management guide for prescribed wildland fire. Boise, ID: National Wildfire Coordinating Group

Achtemeier GL, (2003), On the origins of "Superfog"—a combination of smoke and water vapor that produces zero visibility over roadways. In: Proc. 2nd Intl. Wildland Fire Ecology and Fire Management Congress and 5th Symposium on Fire and Forest Meteorology, held 16 – 20 November 2003, Orlando, FL; American Meteorological Society, Boston, MA; J8.9, 4

Achtemeier GL, Jackson W, Hawkins B, Wade DD, McMahon C, (1998), The smoke dilemma: A head-on collision! In: Wadsworth KG (ed), Transactions of the 63rd North American Wildlife and Natural Resources Conference, held 20 – 24 March 1998, Orlando, FL. Wildlife Management Institute, Washington, DC: 415 – 421

Alig RJ, Kline JD, Lichtenstein M, (2004), Urbanization on the US landscape: looking ahead in the 21st century. *Landscape and Urban Planning*, **69**: 219 – 234

Bliss JC, Nepal SK, Brooks RT, Larsen MD, (1997), In the mainstream: environmental attitudes of mid-South landowners. *Southern Journal of Applied Forestry*, **21**(1): 37 – 43

Bolding MC, Lanford BL, (2001), Forest fuel reduction through energy wood production using a small chipper/CTL harvesting system. Proceedings of 24th Annual Meeting Council on Forest Engineering, 15 – 19 July 2001, Snowshoe, West Virginia. Council on Forest Engineering, Corvallis, OR; CD-ROM

Brenner J, (1991), Southern oscillation anomalies and their relation to Florida wildfires. *Fire Management Notes*, **52**(1): 28 – 32

Brose P, Wade DD, (2002), Potential fire behavior in pine flatwood forests following three different fuel reduction techniques. *Forest Ecology and Management*, **163**: 71 – 84

Butry DT, Mercer DE, Prestemon JP, Pye JM, Holmes TP, (2001), What is the price of catastrophic wildfire? *Journal of Forestry*: 9 – 17

Butry DT, Prestemon JP, (2005), Spatio-temporal wildland arson crime functions. Paper presented at the Annual Meeting of the American Agricultural Economics Association, 26 – 29 July 2005, Providence, Rhode Island. Published on the Internet at http://agecon.lib.umn.edu/cgi-bin/pdf_view.pl?paperid=16442&ftype=.pdf (last accessed 9 October 2007)

Cardille JA, Ventura SJ, Turner MG, (2001), Environmental and social factors influencing wildfires in the upper Midwest, United States. *Ecological Applications*, **11**: 111 – 127

Caulfield JP, (1998), A fund-based timberland investment performance measure and implications for asset allocation. *Southern Journal of Applied Forestry*, **22**(3): 143 – 147

Cohen JD, (2000), Preventing disaster: Home ignitability in the wildland-urban interface. *Journal of Forestry*, **98**(3): 15 – 21

Cordell HK, Bergstrom JC, Betz CJ, Green GT, (2004), Socioeconomic forces shaping the future of the United States. In: Manfredo MJ, Vaske JJ, Bruyere BL, Field DR, Brown PJ (eds). Society and natural resources: A summary of knowledge. Jefferson, MO: Modern Litho. 361

Cordell HK, Bliss JC, Johnson CY, Fly M, (1998), Voices from Southern forests. In Wadsworth, K.G., editor, Transactions of the 63rd North American Wildlife and Natural Resources Conference, held 20 – 24 March 1998, Orlando, FL. Wildlife Management Institute, Washington, DC: 332 – 347

Cordell HK, Macie EA, (2002), Population and demographic trends. In: Macie EA, Hermansen LA (eds) 2002. Human influences on forest ecosystems—the Southern wildland-urban interface assessment. USDA Forest Service Southern Research Station General Technical Report SRS-55. Asheville, NC: 11 – 35

Clutter M, Mendell B, Newman D, Wear D, Greis J, (2005), Strategic factors driving timberland ownership changes in the U.S. South. Report to the Southern Group of State Foresters, November 2005. Retrieved January 7, 2006 from http://www.srs.fs.usda.gov/econ/pubs/southernmarkets/strategic-factors-and-ownership-v1.pdf

Duryea ML, Hermansen LA, (2002), Challenges to forest resource management. In: Macie EA, Hermansen LA (eds) 2002. Human influences on forest ecosystems—the Southern wildland-urban interface assessment. USDA Forest Service Southern Research Station General Technical Report SRS-55. Asheville, NC: 93 – 113

Donoghue LR, Main, WA, (1985), Some factors influencing wildfire occurrence and measurement of fire prevention effectiveness. *Journal of Environmental Management*, **20**: 87 – 96

Doolittle ML, (1978), Analyzing wildfire occurrence data for prevention planning. *Fire Management Notes*, **39**(2): 5 – 7

Forman RTT, (2002), Road Ecology. Island Press, Washington, D.C

Greene WD, Harris TG, DeForest CE, Wang J, (1997), Harvesting cost implications of changes in the size of timber sales in Georgia. *Southern Journal of Applied Forestry*, **21**(4): 193 – 198

Hagen JM, Irland LC, Whitman AA, (2005), Changing timberland ownership in the Northern Forest and implications for biodiversity. Manomet Center for Conservation Sciences, Report #MCCS-FCP-2005-1, Brunswick, Maine, 25

Haight RG, Cleland DT, Hammer RB, Volker CR, Rupp TS, (2004), Assessing fire risk in the wildland-urban interface. *Journal of Forestry*, **102**(7): 41 – 48

Haines TK, Busby RL, Cleaves DA, (2001), Prescribed burning in the South: Trends, purpose, and barriers. *Southern Journal of Applied Forestry*, **25**(4): 149 – 153

Haines T, Renner C, Reams M, Granskog J, (2005), The national database of wildfire mitigation programs: state, county and local efforts reduce wildfire risk. p 1 – 7 in Proceedings of the joint meeting of the Society of American Foresters and Canadian Institute of Foresters "One Forest Under Two Flags", held Edmonton, Alberta, Canada: Society of American Foresters, Bethesda, MD

Hammer RB, Stewart SI, Winkler RL, Radeloff VC, Voss PR, (2004), Characterizing dynamic spatial and temporal residential density patterns from 1940 – 1990 across the North Central United States. *Urban and Landscape Planning*, **69**: 183 – 199

Hirschhorn JS, (2000), Growing pains: Quality of life in the new economy. National Governors' Association, Washington, DC

Hobbs F, Stoops N, (2002), Demographic trends in the 20th Century. Census 2000 Special Reports, CENSR-4. US Census Bureau, Washington, DC

Hull RB, Stewart SI, (2002), Social consequences of change. In: Macie EA, Hermansen LA (eds) 2002. Human influences on forest ecosystems—the Southern wildland-urban interface assessment. USDA Forest Service Southern Research Station General Technical Report SRS-55. Asheville, NC: 115 – 129

Jacobson SK, Monroe MC, Marynowski S, (2001), Fire at the wildland interface: the influence of experience and mass media on public knowledge, attitudes, and behavioral intentions. *Wildlife Society Bulletin*, **29**(3): 929 – 937

Kramer EA, Conroy MJ, Elliott MJ, Anderson EA, Bumback WR, Epstein. J, (2003), A Gap Analysis of Georgia. U.S. Geological Survey, Reston, VA

Long AJ, Wade DD, Beall FC, (2005), Managing for fire in the interface: Challenges and opportunities. Chapter 13 in Vince SW, Duryea, ML, Macie EA, Hermansen LA. Forests at the Wildland-Urban Interface. CRC Press, Boca Raton. 201 – 223

Loomis JB, Bair LS, Omi PN, Rideout DB, González-Cabán A, (2000), A survey of Florida residents regarding three alternative fuel treatment programs. Report to the Joint Fire Science Program, July 26, 2000. 88

Loomis JB, Bair LS, González-Cabán A, (2001), Prescribed fire and public support: knowledge gained, attitudes changed in Florida. *Journal of Forestry*, **99**(11): 18 – 22

Macie EA, Hermansen LA (eds), (2002), Human influences on forest ecosystems—the Southern wildland-urban interface assessment. USDA Forest Service Southern Research Station General Technical Report SRS-55. Asheville, NC: 160

Mackun PJ, Wilson SR, (2000), Population trends in metropolitan areas and central cities, 1990 to 1998. Retrieved January 7, 2006 from http://www.census.gov/prod/2000pubs/p25-1133.pdf

Mercer DE, Prestemon JP, (2005), Comparing production function models for wildfire risk analysis in the wildland-urban interface. *Forest Policy and Economics*, **7**: 782 – 795

Miller SR, Wade D, (2003), Re-introducing fire at the urban/wild-land interface: planning for success. *Forestry*, **76**: 253 – 260

Mobley HE, (1989), Summary of smoke-related accidents in the South from prescribed fire (1979 – 1988). American Pulpwood Association Technical Release 90-R-11

Monroe M, (2002), Fire. In Macie EA, Hermansen LA (eds) 2002. Human influences on forest ecosystems—the Southern wildland-urban interface assessment. USDA Forest Service Southern Research Station General Technical Report SRS-55. Asheville, NC: 133 – 150

NIFC, (2001), National Fire News, Wildland Fire Season 2000 At A Glance, updated June 14, 2001. National Interagency Fire Center, Boise, ID. Retrieved January 7, 2005 from http://www.nifc.gov/fireinfo/2000/

Nowak DJ, Walton JT, (2005), Projected urban growth (2000 – 2050) and its estimated impact on the US forest resource. *Journal of Forestry*, **103**(8): 383 – 389

Nowak DJ, Walton JT, Dwyer JF, Kaya LG, Myeong S, (2005), The increasing influence of urban environments on US forest management. *Journal of Forestry*, **103**(8): 377 – 382

O'Brien JJ, (1998), The distribution and habitat preferences of rare Galactia species (Fabaceae) and Chamaesyce deltoidea subspecies (Euphorbiaceae) native to southern Florida pine rockland. *Natural Areas Journal*, **18**(3): 208 – 222

O'Sullivan D, Unwin DJ, (2003), Geographic Information Analysis. John Wiley & Sons, Hoboken, NJ

Prestemon JP, Butry DT, (2005), Time to burn: Modeling wildland arson as an autoregressive crime function. *American Journal of Agricultural Economics*, **87**: 756 – 770

Prestemon JP, Pye JM, Butry DT, Holmes TP, Mercer DE, (2002), Understanding broadscale wildfire risks in a human-dominated landscape. *Forest Science*, **48**(4): 685 – 693

Radeloff VC, Hammer RB, Stewart SI, Fried JS, Holcomb SS, McKeefry JF, (2005), The wildland-urban interface in the United States. *Ecological Applications*, **15**: 799 – 805

Ravenel R, Tyrrell M, Mendelsohn R (eds), (2002), Institutional timberland investment. Yale Forest Forum Vol. 5 No. 3. Global Institute of Sustainable Forestry, Yale University, New Haven, CT

Riitters KH, Wickham JD, (2003), How far to the nearest road? *Frontiers in Ecology and Environment*, **1**(3): 125 – 129

Rummer R, Outcalt K, Brockway D, (2002), Mechanical mid-story reduction treatments for forest fuel management. 2002. In: New century: new opportunities: 55th annual Southern Weed Science Society meeting; 28 – 30 January 2002; Atlanta, GA. Champaign, IL: Southern Weed Science Society: 76 [Abstract]

Snyder JR, Herndon A, Robertson WB, (1990), South Florida rockland. 230 – 277 in Myers RL, Ewel JJ (eds), Ecosystems of Florida. University of Central Florida Press, Orlando, FL. 765

Stanturf JA, Kellison RC, Broerman FS, Jones SB, (2003), Productivity of southern pine plantations: where are we and how did we get here? *Journal of Forestry*, **101**(3): 26 – 31

Stein SM, McRoberts RE, Alig RJ, Nelson MD, Theobald DM, Eley M, Dechter M, Carr M, (2005), Forests on the edge: Housing development on America's private forests. General Technical Report PNW-GTR-636. Portland, OR: USDA Forest Service, Pacific Northwest Research Station. 16

Sorenson B, Fuss M, Mulla Z, Bigler W, Wiersma S, Hopkins R, (1999), Surveillance of morbidity during wildfires—central Florida 1998. *Morbidity and Mortality Weekly Report*, **48**(4): 78 – 79

Sullivan WC III, (1994), Perceptions of the rural-urban fringe: citizen preferences for natural and developed settings. *Landscape and urban Planning*, **29**: 85 – 101

Theobald DM, (2001), Land-use dynamics beyond the American urban fringe. *The Geographical Review*, **91**(3): 544 – 564

Theobald DM, (2004), Placing exurban land-use change in a human modification framework. *Frontiers in Ecology and Environment*, **2**(3): 139 – 144

Turner MG, Wear DN, Flamm RO, (1996), Land ownership and land-cover change in the Southern Appalachian Highlands and the Olympic Peninsula. *Ecological Applications*, **6**(4): 1150 – 1172

Turner MG, Pearson SM, Bolstad P, Wear DN, (2003), Effects of land-cover change on spatial pattern of forest communities in the Southern Appalachian Mountains (USA). *Landscape Ecology*, **18**: 449 – 464

USDA and USDI, (2001), Urban wildland interface communities within vicinity of Federal lands that are at high risk from wildfire. *Federal Register*, **66**: 751 – 777

US DOT, (2004), Highway statistics 2003, Public Road Length (Table HM-10). Federal Highway Administration website accessible at http://www.fhwa.dot.gov/policy/ohim/hs03/htm/hm10.htm; last accessed January 24, 2006

Wade DD, Brenner J, (1995), Florida's solution to liability issues. In Weise DR, Martin RE (technical coordinators), Proceedings of the Biswell Symposium: fire issues and solutions in urban interface and wildland ecosystems. USDA Forest Service, Pacific Southwest Research Station General Technical Report PSW-158. Berkeley, CA: 131 – 138

Wade DD, Custer G, Thorsen J, Kaskey P, Kush J, Twomey B, Voltolina D, (1998), Reintroduction of fire into fire-dependent ecosystems: Some southern examples. In Pruden TL, Brennan LA (eds), Fire in ecosystem management: shifting the paradigm from suppression to prescription. Tall Timbers Ecology Conference Proceedings No. 20. Tall Timbers Research Station, Tallahassee, FL: 94 – 98

Wade DD, Lunsford JD, (1989), A guide for prescribed fire in southern forests. Tech. Pub. R8-TP11, USDA Forest Service Southern Region, Atlanta, GA

Wade D, Mobley H, (2007), Managing smoke at the wildland urban interface. General Technical Report SRS-103, USDA Forest Service Southern Research Station, Asheville, NC. 28

Wear DN, (2002), Land use. In: Wear, D.N. and Greis, J.G. eds. Southern forest resource assessment. General Technical Report SRS-53. USDA Forest Service Southern Research Station, Asheville, NC: 153 – 173

Wear DN, Bolstad P, (1998), Land-use changes in Southern Appalachian landscapes: spatial analysis and forecast evaluation. *Ecosystems*, **1**: 575 – 594

Wear DN, Liu R, Foreman JM, Sheffield RM, (1999), The effects of population growth on timber management and inventories in Virginia. *Forest Ecology and Management*, **118**: 107 – 115

Wear DN, Newman DH, (2004), The speculative shadow over timberland values in the U.S. South. *Journal of Forestry*, **102**(8): 25 – 31

Wilhoit J, Rummer B, (1999), Application of small-scale systems: evaluation of alternatives. Presented at the 1999 ASAE/CSAE-SCGR Annual International Meeting, Paper No. 99-5056. ASAE, 2950 Niles Road, St. Joseph, Ml 49085-9659 USA

Wimberly MC, Zhang Y, Stanturf JA, (2005), GIS Application in the wildland-urban interface. Chapter 9 in Shao G, Reynolds K (eds) Computer Applications In Sustainable Forest Management. Springer, Heidelberg. In Press

Windell K, Bradshaw S, (2000), Understory biomass reduction methods and equipment. USDA Forest Service, Technology & Development Program 0051-2828-MTDC. Missoula, MT. [Partial document summarizing the full version, Understory Biomass Reduction Methods and Equipment Catalog 0051-2826-MTDC]

Yin R, Caulfield JP, Aronow ME, Harris TG Jr, (1998), Industrial timberland: current situation, holding rationale, and future development. *Forest Products Journal*, **48**(10): 43 – 48

Zhai YS, Munn IA, Evans DL, (2003), Modeling forest fire probabilities in the South Central United States using FIA data. *Southern Journal of Applied Forestry*, **27**: 11 – 17

Zhang Y, (2004), Identification of the Wildland-Urban Interface at Regional and Landscape Scales. Ph.D. Dissertation. University of Georgia, Athens

Zhang Y, Wimberly MC, (2007), The importance of scale in using hierarchical census data to identify the wildland-urban interface. *Southern Journal of Applied Forestry*, **31**: 138 – 147

Zipperer WC, (2002), Urban influences on forests. In: Macie, E.A. and Hermansen, L.A., editors. 2002. Human influences on forest ecosystems—the Southern wildland-urban interface assessment. USDA Forest Service Southern Research Station General Technical Report SRS-55. Asheville, NC: 73 – 91