Spatially locating threats to the environmental contributions of forest land in the USA

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Abstract. Forest lands in the USA contribute to the economic, ecological, and social well-being of the nation in a myriad of ways including supplying timber, providing habitat to wildlife species, buffering water supplies, and providing recreational opportunities. However, forest lands are increasingly threatened from sources such as urbanization, insects and disease, and pollution. The Forests on the Edge project uses geographical information system techniques to identify the spatial locations of the greatest threats to forest land and to specific forest land contributions. The context for the analyses is the framework of the criteria and indicators of the Montréal Process and the European equivalent, the Ministerial Conference on the Protection of the Forests in Europe. Several general conclusions are drawn from the analyses; (1) the watersheds making the greatest private forest contributions are generally in the eastern USA where watersheds generally have greater percentages of private forest land; (2) watersheds whose contributions are most threatened by urbanization are also generally in the eastern USA; and (3) watersheds most threatened by wildfire are in the East, Pacific Northwest, and central regions of the USA.

Keywords: Montréal Process, geographic information system, forest sustainability,

1. Introduction

The forest lands of the United States of America (USA) contribute in a myriad of ways to the economic, ecological, and social well-being of the nation. Increasingly, however, forest lands are subjected to a variety of threats including urbanization, climate change, invasive flora and fauna, wildfire, pollution, and fragmentation. The increasing emphasis on sustainable forest management requires quantitative and spatial assessments of the impacts of these threats to forest lands and their contributions. The Forests on the Edge (FOTE) project, sponsored jointly by State and Private Forestry and by Research and Development of the U.S. Forest Service, conducts map-based assessments of threats to the nation's forest lands using spatial data layers and geographic information systems. The Montréal process criteria and indicators provide an appropriate context for framing and conducting these assessments (McRoberts et al. 2004). For example, Criterion 2, Maintenance of the productive capacity of forest ecosystems, includes indicators related to forest area and timber production; Criterion 3, Maintenance of forest ecosystem health and vitality, includes indicators related to fire, wind, disease, and insects; and Criterion 4, Conservation and maintenance of soil and water resources, includes indicators related to the contributions of forests to water quality.

The objectives of FOTE are threefold: (1) to construct or obtain nationally consistent data layers depicting the spatial locations of forest lands and their contributions; (2) to construct or obtain similar layers depicting threats to forest land from sources such as urbanization, insects and disease, and pollution; and (3) to identify watersheds whose forest lands simultaneously make the most important contributions and face the greatest threats. Analyses for this report are restricted to private forest lands, including tribal, forest industry, and non-industrial ownerships, in the contiguous 48 states of the USA.

2. Data Layers

All data layers were obtained as or constructed to be nationally consistent and were summarized at the spatial scale of fourth-level watersheds (Steeves and Nebert 1994). Watersheds were selected as the analytical unit because they highlight the important connections between forests and ecological processes. The land area of fourth-level watersheds ranges from 2.28 km^2 (0.88 mi^2) to 22,718.02 km^2 (8795.75 mi^2) with a mean of 3689.54 km^2 (1424.53 mi^2).

2.1 Forest Contributions

2.1.1 Private Forest Land

The primary underlying layer on which all analyses are based is a 100-m x 100-m resolution forest ownership layer constructed by aggregating the classes of the National Land Cover Dataset (NLCD) (Vogelmann et al. 2001) into forest and nonforest classes and using the Protected Areas Database (PAD) (DellaSalla et al. 2001) to distinguish ownership and protection categories. For this study, only watersheds with at least 10-percent forest cover of which at least 50-percent is in private ownership were considered. The 1,025 watersheds satisfying these criteria were ranked with respect to the amount of privately owned forest land as a percentage of total land in the watershed. Thus, a watershed ranked in the 91^{st}-100^{th} percentile category has a higher percentage of private forest land than at least 90% of the qualifying watersheds. A map of the percentile rankings reveals that most qualifying watersheds are in the eastern USA which is to be expected because most forest land in the East is privately owned, while most forest land in the West is in public ownership (Figure 1). Stein et al. (2005a and b) provide detailed information on the forest ownership layer.

2.1.2 Water Quality

Private forest lands provide nearly 60 percent of all water flow from forests in the USA and nearly 30 percent of the water flow originating on land in the lower 48 States[1]. Water flow from forests is generally considered clean relative to water flow from other land uses and, therefore, makes a positive contribution to water quality. The water quality layer depicts the contributions of private forest land to the production of clean water and is based on three underlying assumptions: (1) water bodies near the heads of hydrologic networks are more sensitive to the loss of forest buffers than water bodies near the bases of the networks, (2) the presence or absence of upstream forest buffers influences water quality downstream in the networks, and (3) forest land throughout watersheds, not just those in immediate proximity to water bodies, are important when considering the contributions of forest land to water quality (FitzHugh 2001).

The water quality layer was constructed from two underlying layers, the forest ownership layer and the National Hydrography Dataset (NHD) (USGS 2000) which depicts water bodies in the 48 contiguous states. The layer was constructed in four steps: (1) a 30-m buffer was constructed around all water bodies, (2) the buffers were intersected with the private forest land

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class of the forest ownership layer to quantify the amount of private forest land in close proximity to water bodies, (3) each buffer segment was assigned to one of four categories based on the relative position of the segment to the head of its hydrologic network, and (4) for each watershed, the percentage of forest land in each of the four categories was determined. A water quality index (WQI) was then calculated for each watershed as,

$$WQI=0.6*[A_1 + (A_1*A_2)]+0.4*(0.48*B_1 + 0.24*B_2 + 0.16*B_3 + 0.12*B_4)$$

where A_1=percent of watershed in private forest land, A_2= percent of total forest land in watershed that is privately owned, B_1=percent of private forest land buffer in the first category (nearer head of hydrologic network headwater), B_2=percent of buffer in the second category, B_3=percent of buffer in third category, and B_4=percent of buffer in fourth category (farthest downstream from the head of hydrologic network). Variables A_1 and A_2 represent private forest coverage throughout the watershed, and variables B_1-B_4 represent private forest coverage in the buffers. In WQI, A_1 and A_2 are collectively weighted 0.6, while variables B_1-B_4 are collectively weighted 0.4 to reflect the third assumption above.

2.1.3 Timber Supply

Private forest lands make a substantial contribution to America's timber resources, accounting for 92 percent of all timber harvested in the USA in 2001 (Smith et al. 2004). The timber supply layer depicts the ranking of watersheds relative to an index of the importance of private timberland and is based on data obtained from the Forest Inventory and Analysis (FIA) program of the U.S. Forest Service. The FIA program conducts the national forest inventory of the USA and collects data for an array of more than 375,000 field sample plots distributed across the country with a sampling intensity of one plot per 2400 ha (6,000 ac) (USFS 2005). The private timberland importance index (TI) is based on contributions of the timberland subset of private forest land to the national timber supply. Timberland is defined by the FIA program as forest land that has not been withdrawn from production and that is capable of producing 0.57 m^3/yr (20 ft^3/yr) of industrial wood. For each watershed, three sub-indices are defined: (1) growth index (GI) is the average growing stock volume growth rate on private timberland in a watershed relative to the average across all private timberland in the country, (2) volume index (VI) is the average net growing stock volume per unit area on private timberland in a watershed relative to the average on all private timberland in the country, and (3) area index (AI) is the ratio of private timberland area to total private land area in a watershed relative to the same ratio across all watersheds. TI was calculated for each watershed as,

$$TI = AI*(GI+VI).$$

2.1.4 At-Risk Species

Private forests are crucial for the conservation of many wildlife species; for example, in the Pacific Northwest private forests provide important habitat for the spotted owl (Holthausen et al. 1995). NatureServe and its member Natural Heritage Programs and Conservation Data Centers constructed a geospatial dataset quantifying the number of at-risk species found on private-forest lands in fourth-level watersheds in the contiguous 48 states of the USA. At-risk species are defined as species either federally designated under the Endangered Species Act or designated as imperiled, critically imperiled, or vulnerable based on the NatureServe Conservation Status Ranking system (NatureServe 2007). For plant and animal species, the NatureServe ranks represent an estimate of the risk of extinction. The ranks are based on factors such as abundance, distribution, population trends, and threats. Status is assessed at global, national, and state/province levels and is based on current or past observations by authoritative sources in areas where the species is or was previously present.

For this study, NatureServe selected animal populations that occur only on private forest lands by comparing the locations of at-risk populations with locations of protected and non-protected private forest lands from the forest ownership layer. Data gaps include lack of at-risk species data for Arizona, Massachusetts, and the District of Columbia; lack of at-risk fish data for Idaho; and incomplete at-risk animal data for Washington.

2.1.5 Interior Forest

Wear et al. (2004) note that wildlife conservation activities must focus on not only the availability of habitat but also on the structural integrity of that habitat. They further identify habitat contiguity, a measure of the isolation of forest patches, as a natural index of the structural integrity of forests. In this context, a measure of habitat contiguity is the proportion of forest land that is functionally distinct from forest edge. A value may be determined for this measure as the proportion of forest observation or measurement units cells in a spatial area that are surrounded by other forest units. For this study, the interior forest layer was constructed in three steps. First, forest observation or measurement units were defined to be the 100-m x 100-m pixels of the forest ownership layer described in Section 2.1.1, and for each watershed, the forested units or pixels were identified. Second, forested pixels were labeled interior forest if 90% of the pixels in a surrounding 8 x 8 pixel window (65 ha, 158 ac) were also forested. Third, the proportions of interior forest pixels for all watersheds were determined, and all watersheds were assigned a percentile ranking based on these proportions. Note that a watershed could have very little forest land but a high proportion of interior forest.

2.2 Threats to Private Forest Lands

2.2.1 Urbanization

The urbanization layer depicts predicted threats to private rural forest lands resulting from conversion to urban or exurban uses. The layer is based on estimates of current population and housing density data obtained from the 2000 Census of the USA and predictions of housing density increases. A spatially explicit model was used to predict the full urban-to-rural spectrum of housing densities (Theobald 2005). The model uses a supply-demand-allocation approach and is based on the assumption that future growth patterns will be similar to those observed in the past decade. Future patterns are forecast on a decadal basis in four steps: (1) the number of new housing units in the next decade is forced to meet the demands of the predicted populations, (2) a location-specific average population growth rate from the previous to the current time step was computed for each of four density classes: urban, suburban, exurban, and rural, (3) the spatial distribution of predicted new housing units was adjusted with respect to accessibility to the nearest urban core area, and (4) predicted new housing density was added to the current housing density under the assumption that housing densities do not decline over time. For these analyses, predicted new housing was not permitted to occur on public or protected private land as indicated by the forest ownership layer. The spatially explicit housing density predictions were combined with the forest ownership layer to identify watersheds with the greatest predicted conversion of private rural forest land to urban and exurban uses. Stein et al. (2005b) provide detailed information on this layer.

2.2.2 Wildfire

Although wildfire is one of the most compelling threats to forest land, particularly in the western USA, predicting the threat of wildfire incidence is extremely complex and relies on a variety of regional variables and models. Further, even if the models could be readily implemented to construct a national layer, the geographic consistency of the layer would be questionable. Therefore, as a surrogate for wildfire risk, FOTE used the 1-km x 1-km resolution current fire condition class (CFCC) data which depict deviations of fire incidence from historic natural fire regimes and estimated efforts necessary to restore stands to historic regimes (Schmidt et al. 2002). These data reflect the assignment of forest lands to one of three CFCC classes: (1) $CFCC_1$, forest lands with fire regimes that are within or near historical ranges and that can be maintained by treatments such as prescribed fire or fire use; (2) $CFCC_2$, forest lands with fire regimes that have been moderately altered from historical ranges and that may require moderate levels of prescribed fire, fire use, hand or mechanical treatment, or a combination to be restore the historical fire regime; and (3) $CFCC_3$, forest lands with fire regimes that have been substantially altered form historical ranges and that may need high levels of hand or mechanical treatment before fire is used to restore historical fire regimes. Among these classes, wildfire risk is assumed to be greater in $CCFC_1$ than in $CCFC_2$ and greater in $CCFC_2$ than in $CCFC_3$. The appeal of the CFCC classes is that they are objective, nationally consistent, and are assumed to correlate well with the threat of wildfire incidence.

Although these classes reflect the widely varying state-level commitments to wildfire mitigation efforts, they do not reflect ease of access to forest lands experiencing wildfire or the availability of resources to combat wildfires.

For each watershed, all private forest lands were assigned to one of the three CFCC classes, and a watershed-level index was calculated as,

$$CC = CC_1 + 2 * CC_2 + 4 * CC_3,$$

where CC_i is the is the area of private forest land in class $CFCC_i$. As the formula for the index indicates, the weight assigned to each CFCC class is twice as great as the weight of the class with the next lower wildfire risk. Each watershed was assigned a percentile ranking based on its CC index value.

2.2.3 Ozone

Ozone affects forest ecosystems by causing foliar lesions and rapid leaf aging, altering species compositions, and weakening pest resistance (Chappelka et al. 1997, Miller 1996). It is the only gaseous air pollutant that has been measured at known phytogoxic levels at both remote and urbanized forest locations (US EPA 1996). The ozone layer depicts private forest land threatened by ground level ozone and was based on late summer observations by FIA field crews of ozone damage to bioindicator species known to be sensitive to ground level ozone. Data for more than 2,500 FHM plots nationwide were available for the study. Each plot was assigned a biosite value based on a subjective assessment by trained observers of the quantity and severity of damages (Coulston et al. 2003, Smith et al. 2003). Inverse distance weighted interpolation was used to create a map of ozone damage. This map was then combined with the forest ownership layer to identify private forest land with elevated levels of ozone damage. For each watershed, the percentage of private forest land in moderate or high damage categories was calculated.

2.2.3 Nitrate and Sulfate Deposition

Acidic deposition, the transfer of strong acids and acid-forming substances from the atmosphere to the earth, has become a critical stress affecting forested landscapes across the USA. Effects can include increased sulfate and nitrate levels in soils and waters which, in turn can alter soil and water chemistry and affect trees and other living organisms (Driscoll et al. 2001). The nitrate and sulfate layers were created from National Atmospheric Deposition Program data (NADP 2007). The data were used to interpolate yearly wet sulfate and wet nitrate deposition maps using gradient plus inverse distance interpolation (Nalder and Wein 1998). This technique adjusts for elevational, longitudinal, latitudinal gradients when present in the data based on local regression of the 20 nearest neighbors. The wet sulfate deposition maps (2000-2004) were then averaged to produce a map of average annual deposition 2000-2004 (kg/ha/yr). The same was done for wet nitrate deposition. Cross-validation (Issaks and Srivastava 1989) was performed to estimate the bias and precision of the yearly map.

2.2.5 Insect Pests and Disease

The Forest Health Monitoring (FHM) program of the U.S. Forest Service is a national program charged to estimate the status, changes, and trends in indicators of forest health. The FHM program bases its assessments on data obtained from ground plots, ground and aerial surveys, and other sources covering all forested lands. Using data from Landsat satellite imagery, the STATSGO (USDA 2007a) and SSURGO (USDA 2007b) soil databases, and the FIA and FHM programs, the FHM program led development of the National Insect and Disease Risk Map (NIDRM) (FHTET 2007). The NIDRM is a 1-km x 1-km resolution strategic product intended to provide broad overviews of forest risk. The primary methodology was the GIS-based multi-criteria framework for modeling risk (Eastman et al. 1997).

A five-step multicriteria process was used to construct the NIDRM (Krist et al. 2006). First, lists of forest pests (risk agents) and their target host species were compiled at the regional level using models constrained to specific geographic areas. Second, criteria (factors and constraints) that determine the susceptibility and vulnerability to each risk agent were identified, ranked, and weighted. Third, risk agent criteria values were standardized, and the resultant criteria maps were combined using a series of weighted overlays to produce a final risk assessment. Fourth, for each risk agent/forest host species pair, modeled values of potential risk of mortality for each pest were used to predict basal area loss over a 15-year period. Fifth, the resultant values from Step 4 were compiled, and the 1-km x 1-km grid cells of the national base map that are at risk of encountering a 25 percent or greater loss of total basal area in the next 15 years were identified.

3. Methods

For each contribution and threat layer, the distribution of watershed index values was determined, and a percentile ranking was assigned to each watershed. Threats to particular contributions were evaluated in two steps. First, the averages of the contribution and threat percentile rankings were calculated on a watershed-by-watershed basis. Second, the distribution of the averages was determined and used to assign a new percentile ranking to each watershed. The results are depicted using percentile-based categories similar to those used for individual contributions and threats.

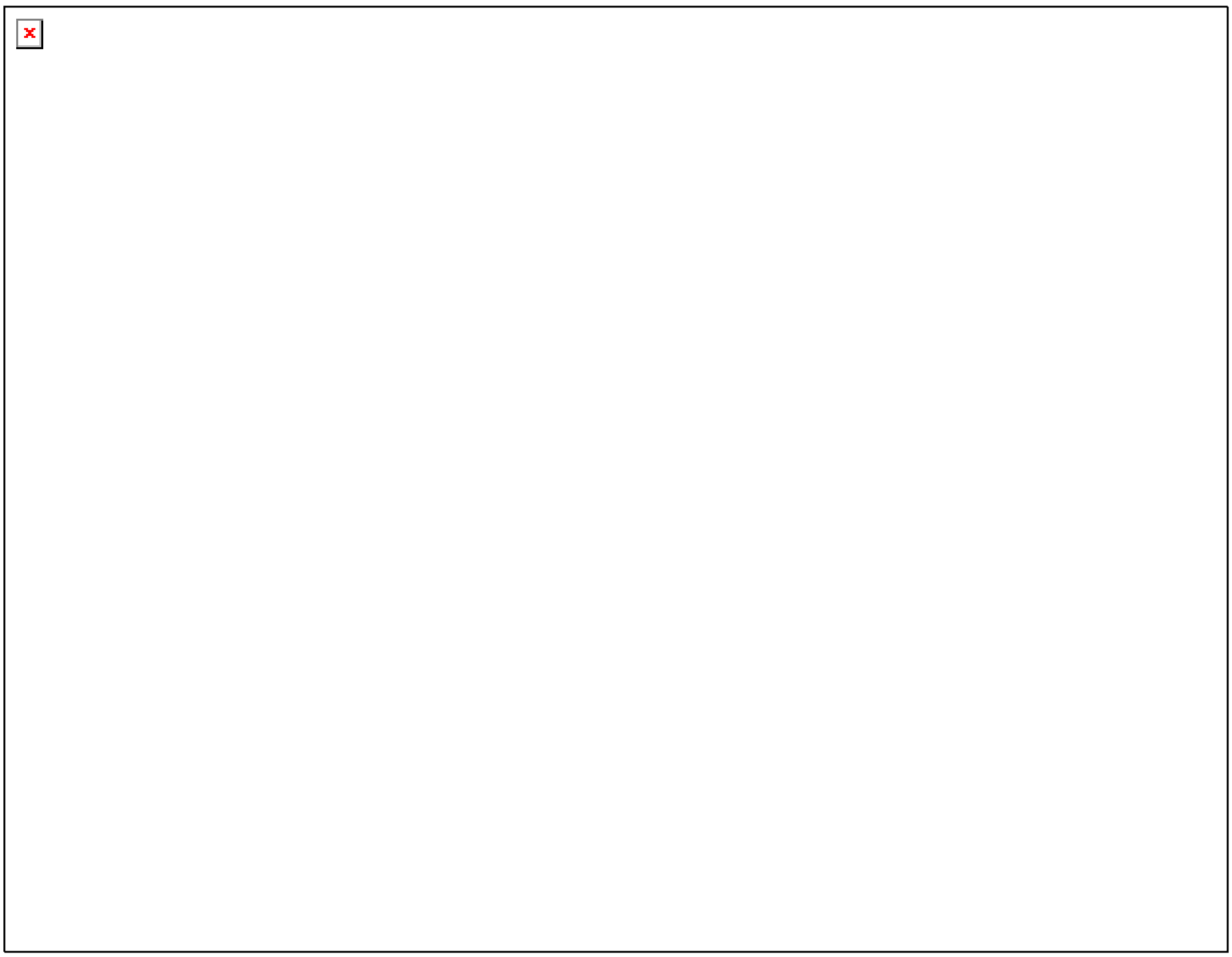
4. Results

4.1 Contributions

Watersheds with the greatest percentages of private forest land are generally in New England, the Southeast, and the Pacific Northwest (Figure 1). The concentration in the East is not surprising, because much of the forest land in the West is in public ownership. Watersheds whose private forests make the greatest contributions to water quality, timber supply, at-risk species habitat, and interior forest align closely with the watersheds with greatest amounts of private forest land.

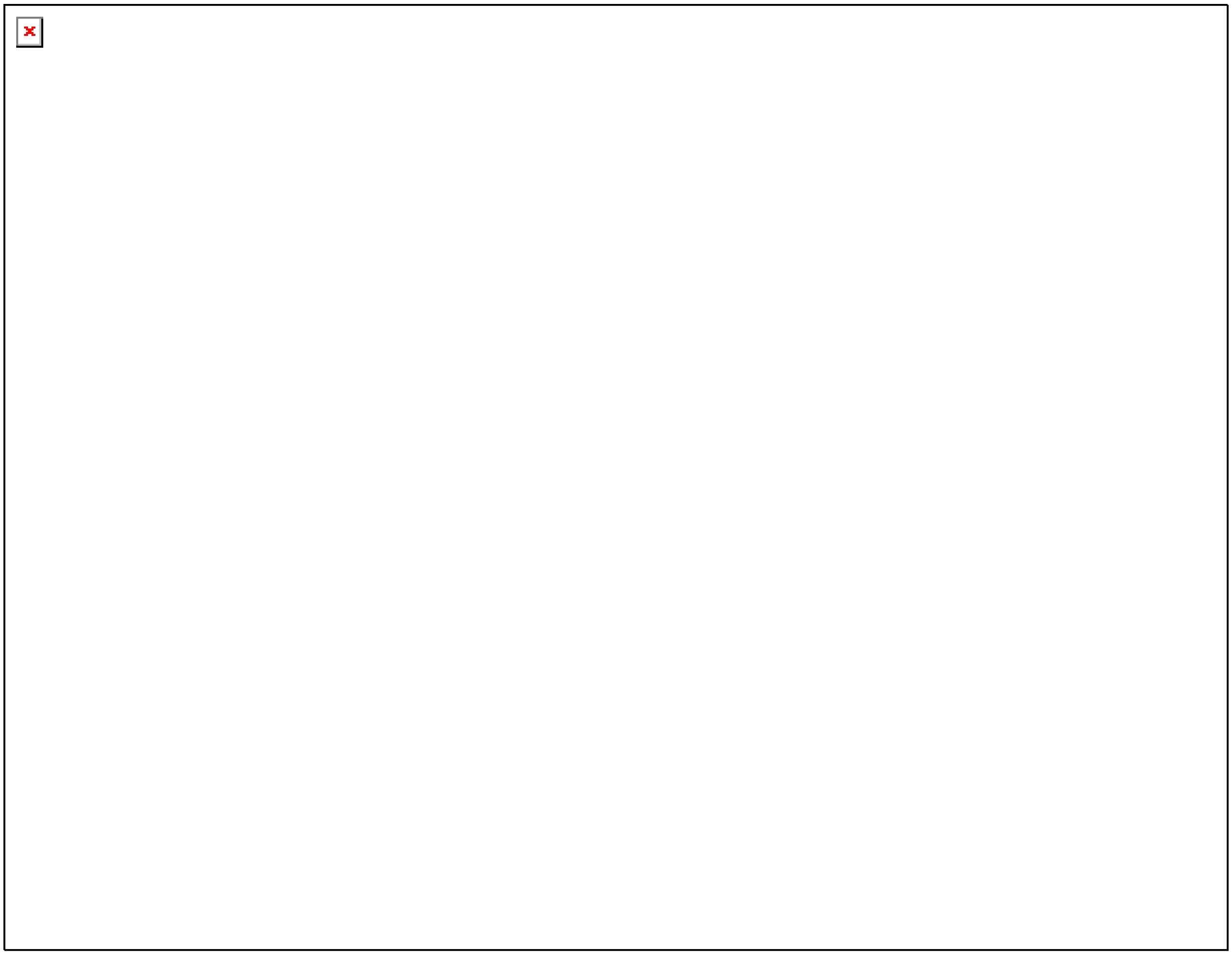
4.2 Threats

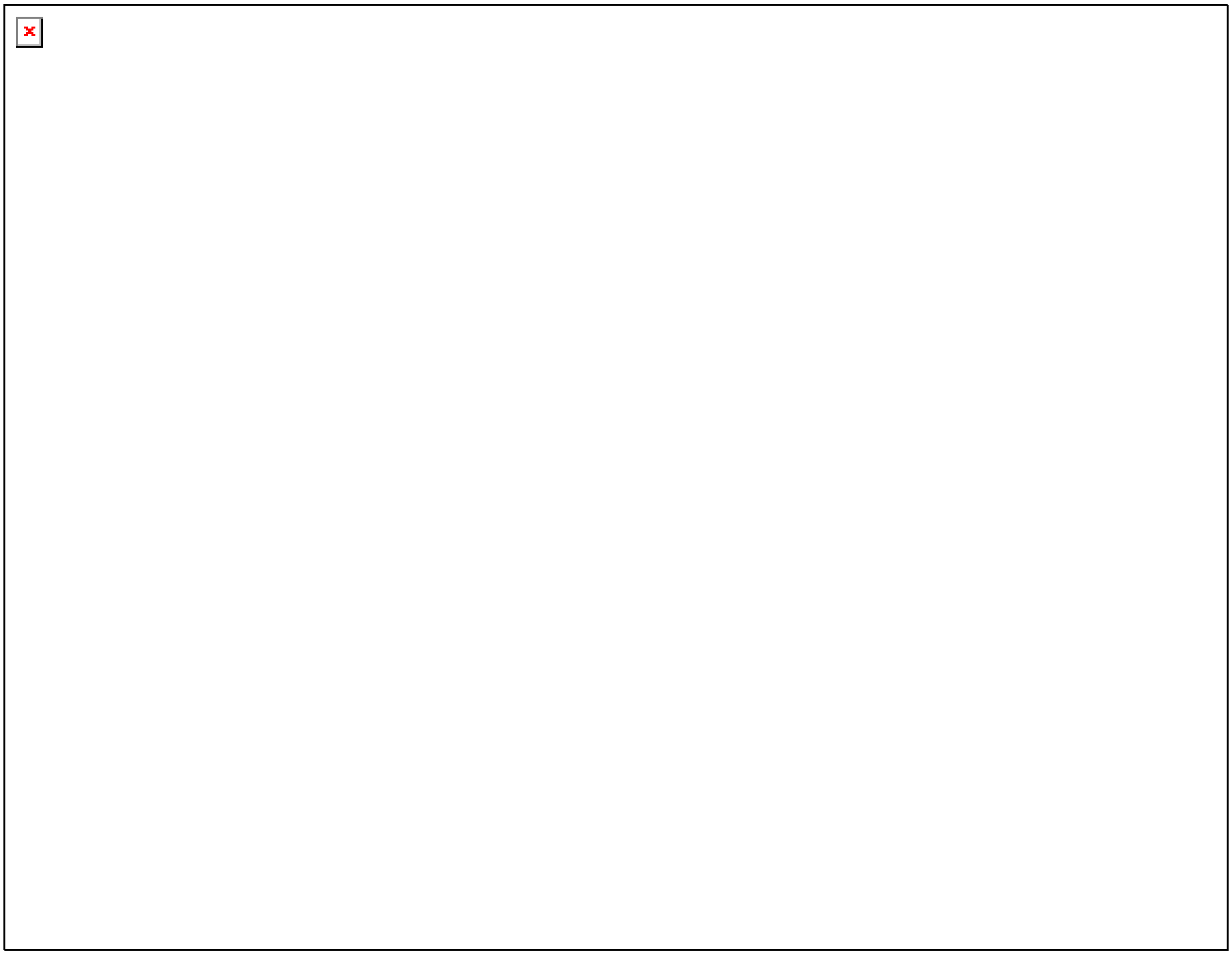
Urbanization threats to private forest land area are concentrated in southern New England and the Southeast, although threatened watersheds are also located in the Pacific Northwest. Wildfire threats to private forest land (as indicated by the surrogate CC layer) are primarily in the northeastern quadrant of the country, although threatened watersheds are also located in the South, Southwest, and Pacific Northwest. Threats to private forests from ozone are found scattered throughout the Eastern USA (Figure 2). Loss of basal area on private forest land from insect pests and diseases is most likely to occur in the East, but also in parts of the Southwest, California, and the Pacific Northwest (Figure 3).



4.2.1 Threats to Specific Contributions

Urbanization threats to at-risk species are greatest in the Southeast (Figure 4). Urbanization threats to private interior forest are found throughout the eastern USA and the Great Lakes area but are concentrated in the Southeast and Maine (Figure 5). Urbanization threats to the timber supply and water quality contributions of private forest land are concentrated in southern New England and the Southeast. Wildfire threats to both timber supply and water quality contributions are distributed throughout the East and Southeast, the Lakes States, the Central Hardwoods region, and the Pacific Northwest (Figures 6 and 7).





5. Conclusions

Four primary conclusions may be drawn from this study. First, the FOTE spatial approach to assessing threats to the contributions of forest lands produces useful, visual information that is relatively easy to obtain. The only serious impediment is the difficulty in constructing or obtaining nationally consistent data layers that depict the contributions and threats of interest.

Second, the watersheds making the greatest private forest contributions to timber supply, water quality, at-risk species, and interior forest are generally the watersheds with the greatest percentages of private forest land (i.e. those in the eastern USA, particularly New England and the Southeast, and some watersheds in the Pacific Northwest). Two exceptions are noted. A few watersheds in western California and Florida do not have large amounts of private forest but do have large numbers of at-risk forest-associated species. In addition, a few watersheds in eastern Texas, the Southwest, and Washington State also do not have large amounts of private forest but do have high proportions of private forest classified as interior forest.

Third, watersheds with the greatest urbanization threat to the contributions to timber supply, water quality, at-risk species and interior forest are also generally the watersheds with the greatest percentages of private forest land.

Fourth, the CC surrogate for wildfire depicts the threats to watersheds in the East, although threatened watersheds are also located in the South, Southwest, and Pacific Northwest. Percentile rankings of watersheds based on wildfire threat to the private forest contribution to timber supply and water quality are generally in the Northeast and Pacific Northwest.

An assessment of national forests and grasslands most likely to experience increased pressures from housing development on adjacent private forest lands has also been conducted (Stein et al. 2007).

Future Forests on the Edge work will include assessment of additional contributions and risks intersections and the construction of an Internet-based system that permits users to select particular contribution and threat layers, options for combining them, and options for depicting the results.

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Figure 1. Percentile rankings of watersheds with respect to private forest land as percent of watershed area.

Figure 2. Percentile ranking of watersheds with respect to ozone threat.

Figure 3. Percentile rankings of watersheds with respect to potential loss of basal area on private forest land due to insect pests and diseases.

Figure 4. Percentile rankings of watersheds with respect to urbanization threat to private forest land habitat for at-risk species.

Figure 5. Percentile rankings of watersheds with respect to urbanization threat to interior forest on private forest lands.

Figure 6. Percentile rankings of watersheds with respect to wildfire threat to contribution of private forest land to water quality.

Figure 7. Percentile rankings of watersheds with respect to wildfire threat to timber supply.