

Managing *for* Healthy Ecosystems

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Modeling Assessment of the Biological and Economic Impact of Increased UV Radiation on Loblolly Pine in the Middle Atlantic States

John J. Streicher and Keith Endres

INTRODUCTION

Consideration of the economic impact of environmental degradation provides additional justification for stewardship that imposes regulation and operational costs to aid remediation measures. The assessment of the economic impact of an ecological stressor within a geographic region requires knowledge of the distribution of vulnerable receptors within the region, determination of appropriate spatial and temporal resolution of the stressor, and information about the exposure and effect relationship. The increases in the surface flux of solar ultraviolet (UV) radiation due to decreasing stratospheric ozone are a stressor for numerous plant species, including the commercially important loblolly pine (*Pinus taeda*). The extent of species range and biomass of loblolly pine can be estimated for the Middle Atlantic area from U.S. Forest Service Forest Inventory and Analysis (FIA) data. An empirical exposure and effect function may then be applied to approximate biomass reduction and economic impact in a single-stressor perturbation scenario.

Problem Statement

Terrestrial flux of solar ultraviolet-B radiation (UV-B) is a naturally occurring plant stressor. Internal repair and protection mechanisms at the cellular level have evolved to cope with preindustrial levels of UV-B. The intensity of UV-B radiation reaching the earth's surface is mediated by atmospheric gases and aerosols, with ozone being the predominant mediator. With anthropogenic releases of ozone-depleting substances, increases in surface fluxes of UV have been predicted and observed. Loblolly pine is perhaps the most vulnerable of all conifers found near sea level. Typically, the loblolly pine receives relatively less UV-B than high-elevation conifers and adapts less effectively to increased UV-B than conifers indigenous to higher elevations.

Historical Perspective

The Montreal Protocol (1987) and subsequent amendments and adjustments have restricted the atmospheric release of ozone-depleting substances. The abundances of several chlorofluorocarbons (CFCs) have been monitored since 1978. Recent data suggest that tropospheric concentrations of

some CFCs are now decreasing. However, a 3- to 5-year lag in transport to the stratosphere implies that stratospheric ozone will continue to decline, with total column ozone decreasing to a minimum near 2010. Biological stress responses to increasing UV-B may be expected during this time (Caldwell et al., 1994). Nearly one half of species evaluated have exhibited physiological or morphological sensitivity to UV-B (Sullivan, 1997).

Definitions

Incident solar radiation is measured as a spectral flux with units of watts-per-square-meter-per-nanometer wavelength, or $W/m^2/nm$. Biologically effective exposure, or explicitly, area-normalized biologically effective exposure, is measured as biologically weighted flux, or W/m^2_{be} . Biologically effective dose, or explicitly area-normalized biologically effective dose, is the time-accumulated biologically effective exposure, and is measured as biologically weighted energy density, with units of biologically weighted joules per square meter, or J/m^2_{be} .

Risk Assessment

Surface fluxes of UV-B at specific locations are determined by geodesic as well as atmospheric variables. Latitude and elevation, in addition to aerosol loading, total column ozone, and cloud cover, all affect the exposure and cumulative dose received by plants. The radiation microclimate of a specific plant is further determined by slope and aspect of the local terrain, and by shading from adjacent plants and geologic structures. The actual UV-B dose received by individual conifer needles will vary greatly within an individual tree. The risk assessment approach taken here is at a spatial resolution of four-digit hydrologic unit code (HUC) watershed, and at a temporal resolution of 3 years. In meteorological terminology, this assessment falls between mesoscale and synoptic scale. This assessment approach makes no statements with respect to effects on finer than a spatial mesoscale, or a 3-year temporal scale.

This study examines the possible effect of increases in UV-B on the loblolly pine within the Middle Atlantic states area. As an economically valuable species, potential economic loss was examined as well. Current atmospheric total column ozone for the latitude and longitude of the watershed centroid were estimated using a regional regression model based on satellite and ground-based ozone measurements. Backcast and forecast estimates of changes in total column ozone derived from the NASA Goddard Institute for Space Studies (GISS) Global Circulation Model (GCM) were used to calculate average daily biologically effective doses for the months of April and July, in the years 1979 and 2010. Average daily biologically effective doses were calculated by month for each watershed in the Middle Atlantic having measurable biomass of loblolly pine. Dose-response relationships developed by Sullivan et al. (1992) were applied to loblolly growth rates for two cases of ozone loss: reasonable worst-case ozone loss and effect-threshold ozone loss.

MODELING METHODS

Overview

The assessment of risk to loblolly pine due to anthropogenically driven increases in surface fluxes of solar UV-B radiation must consider the temporal and spatial profile of the stressor, the spatial distribution of the receptor, the spectral specificity of effects, and the time-dependence of the cause-effect relationship (i.e., the dose metric). Dose-response function then relates a hypothetical exposure scenario to a biological quantity, such as annual growth rate deficit. The economic aspect of the analysis must assign a dollar value to the growth rate deficit, and scale the calculation from a normalized per unit cost, up to a regional economy scale (e.g., the Middle Atlantic states region).

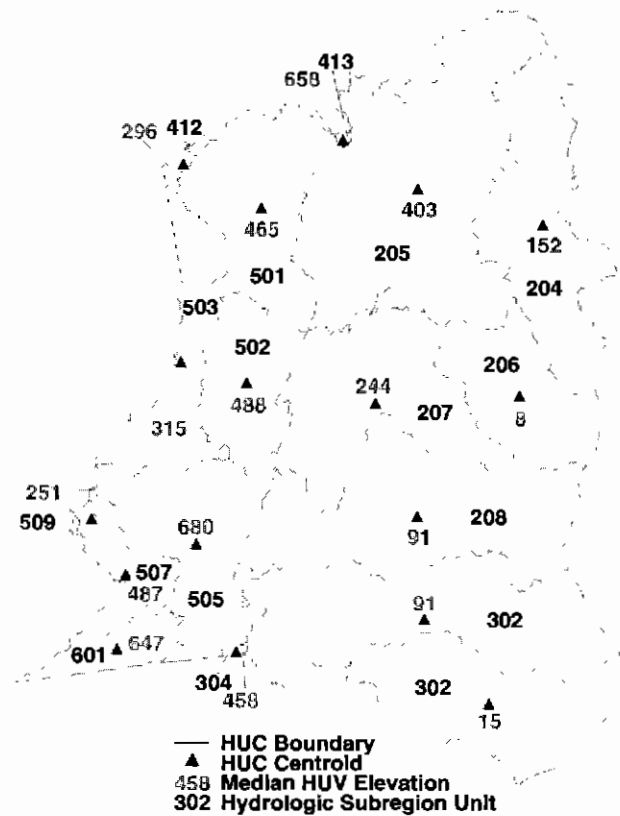


Figure 54.1 Middle Atlantic Integrated Assessment (MAIA) region, showing HUC centroid location and HUC median elevation in meters.

This assessment was completed with spatial subdivision by watershed at the four-digit HUC resolution. This resolution of the Middle Atlantic states region resulted in approximately 20 subregions (watersheds). The UV-B dose profile varies continuously in space across the region. Assignment of a single-dose profile to a subregion required choosing a representative point within the subregion for model calculations. Calculations estimating dose profile were determined for the latitude and longitude of the watershed centroid at the median watershed elevation, as shown in Figure 54.1.

The temporal resolution used in the development of the dose profile varied considerably with model component. A broadband radiative transfer model used to determine solar zenith angle iterated in 1-min time steps. The ozone model iterated in 1-day time steps. A linear dose metric computed a daily biologically effective dose. Daily average biologically effective doses are reported by month, however. Projections of future midlatitude ozone depletion were with 1-year precision. The temporal resolution of the dose–response function, however, was 3 years, and was clearly the limiting factor in the temporal resolution of the assessment. Consequently, dose profiles at 1-month resolution were considered adequate. July is presented as the month of peak biologically effective dose. April is presented as an early growing season month during which emergent growth structures are initially exposed to sunlight.

Model Suite: Description and Usage

No single model existed to perform the entire assessment. Consequently, a series of models and modeling approaches were used in succession to calculate ozone, UV-B surface flux, exposure, dose, growth rate reduction, and cost. A brief description of models/approaches follows.

A regional total column ozone regression model was developed from composite satellite and ground-based ozone measurements. This model was used to calculate current (1999) ozone as a function of Julian day, latitude, and longitude within the Middle Atlantic states region.

A discrete-ordinate spectral radiative transfer model (LibRadtran, version 0.13) was used to calculate the spectral flux $W/m^2/nm$ for selected solar zenith angles, total column ozone levels, and elevations above sea level. Spectral flux was calculated at a resolution of 0.05 nm. Global (beam plus diffuse) radiation was used for subsequent exposure calculation.

The biologically effective exposure W/m^2_{be} was then calculated by convolution of the Caldwell generalized plant spectral weighting function with the spectral flux (Caldwell et al., 1986). Spectral weighting functions, or action spectra, quantify the relative effectiveness by wavelength of incident light. The Caldwell function was normalized at 300 nm in this analysis, following the convention established in previous photobiological work.

Calculation of the biologically effective exposure for several solar zenith angles, ozone levels, and elevations enabled the development of a simple regression model of biologically effective exposure as a function of these input variables. This simple regression model was then incorporated into a sun-tracking model with a 1-min time resolution to calculate a daily biologically effective dose J/m^2_{be} using an assumed linear dose metric.

Ultraviolet radiation dose and response data for loblolly pine (Sullivan et al., 1992) were used to estimate growth rate reductions. Laboratory and field experiments approximated diurnal and seasonal variation of UV with supplemental UV corresponding to various hypothetical ozone depletion scenarios (Sullivan et al., 1988; 1989). A dose-response regression function was developed from the data and used to investigate possible growth rate reductions corresponding to two ozone depletion scenarios.

Data from the FIA were queried by four-digit HUC watershed. Total loblolly biomass by HUC was reported for three size classes, as well as annual loblolly biomass growth rate. Annual growth rate by HUC was determined, and future growth rate was estimated by applying the regressed dose-response function for projected ozone reductions.

The economic assessment of growth rate reduction considered fixed stumpage price by tree size. (The stumpage price refers to unprocessed raw wood; value-added wood products would command a substantial price premium.) While lumber prices fluctuate with market demand and supply, and regional pricing variations can and do exist, the prices used in this assessment were recent fixed quotes for Virginia stumpage, published in *Timber Mart-South*. Tree size categories were saw timber (diameter > 8.9 in.); pole timber (8.9 in. > diameter > 5 in.); and sapling/seedling (5 in. > diameter). The dollar values associated with each size category were as follows: saw timber at \$24.16, pole timber at \$19.12, sapling and seedling at \$8.06. Annual biomass production was similarly assigned a dollar value within each watershed, and projected annual growth deficit due to UV-B stress was then evaluated in dollars.

RESULTS

Dose calculations were completed only for watersheds having recorded loblolly pine biomass. Figure 54.2 presents the total aboveground biomass by hydrologic subregion. Loblolly pine trees are found throughout most of the Middle Atlantic states region, but predominantly in the southernmost areas, and nearer the low elevation coastline than the interior highlands. The Chowan-Roanoke (HUC 0301), Neuse-Pamlico (HUC 0302), Lower Chesapeake (HUC 0208), and Upper Chesapeake (HUC 0206) watersheds account for more than 95% of loblolly biomass within the Middle Atlantic states region.

The 1999 estimated UV-B dose profile by watershed for April and July is shown in Figure 54.3. The April biologically effective doses ranged from 3.2 KJ/m^2 in the Delaware watershed (HUC 0204), to 4.0 KJ/m^2 in the Monongahela (HUC 0502), Chowan-Roanoke, and the Neuse-Pamlico

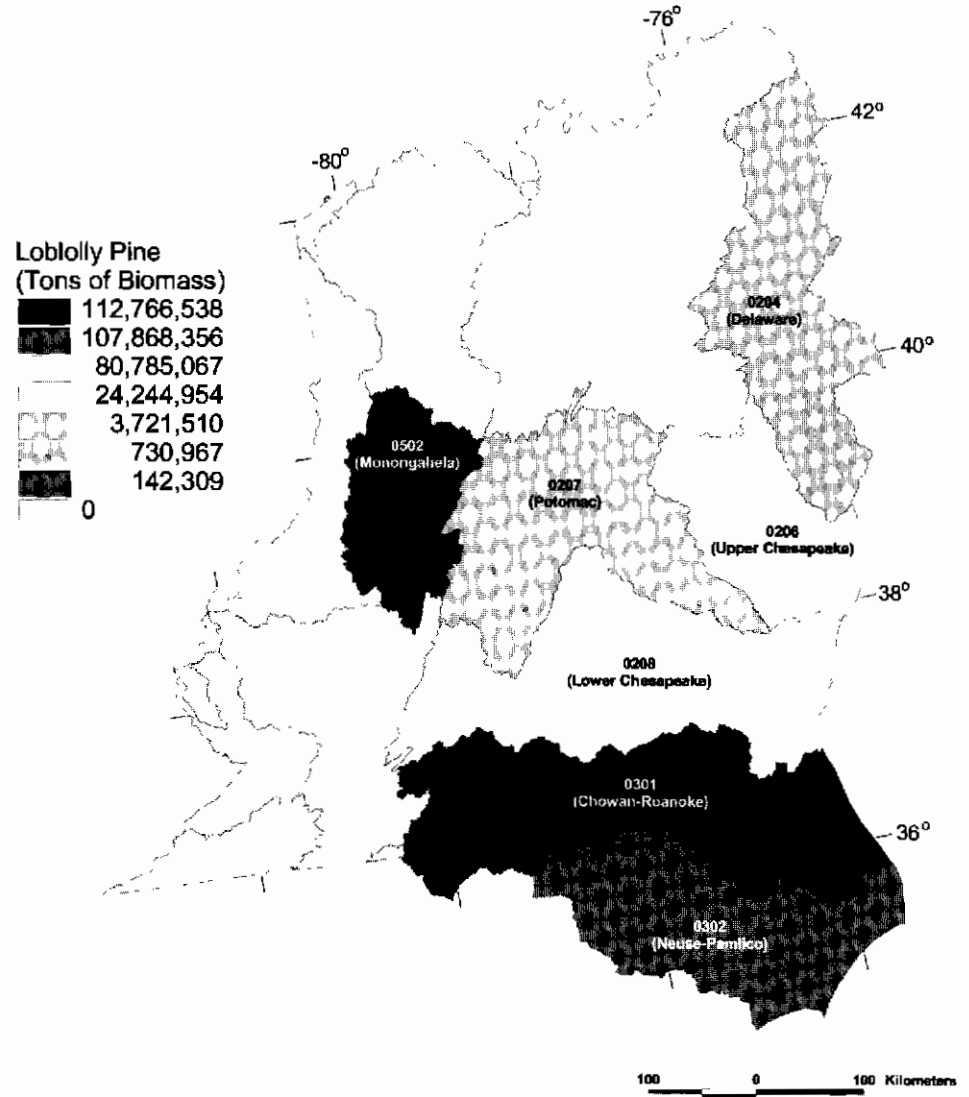


Figure 54.2 Loblolly pine total aboveground biomass (tons) by watershed.

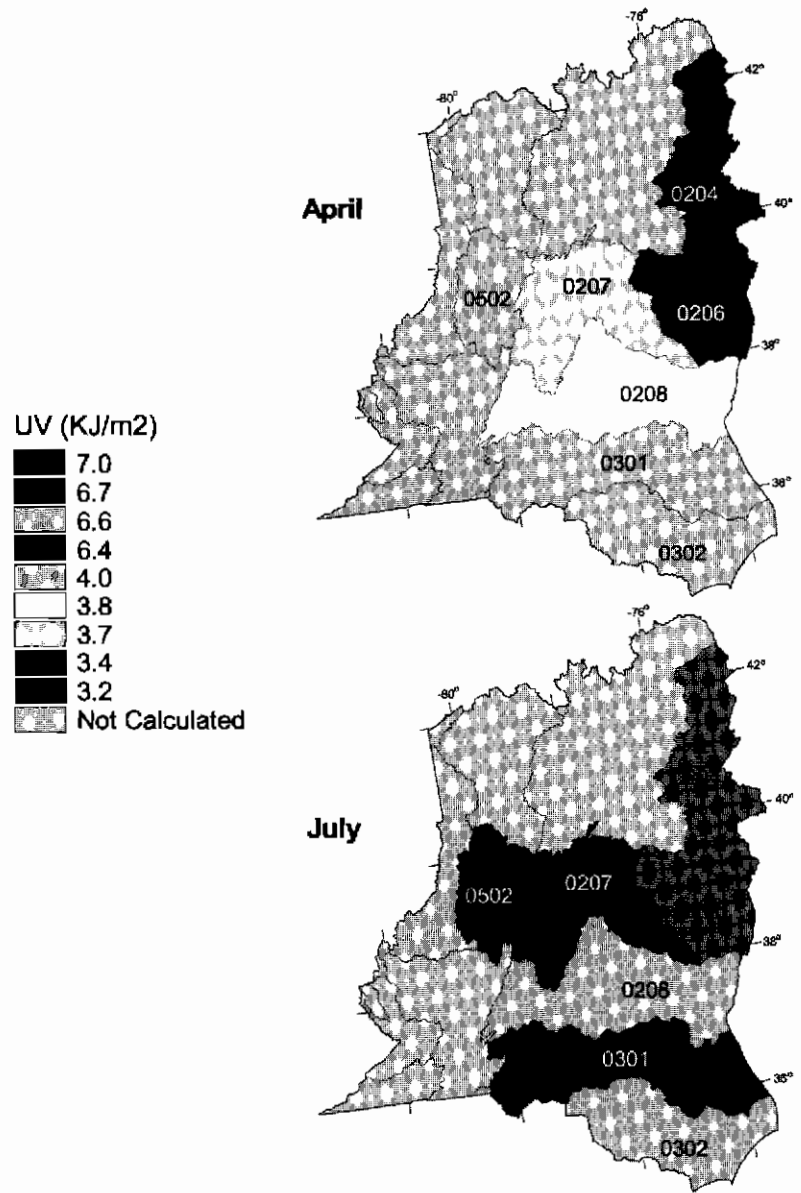


Figure 54.3 Estimated biologically effective UV-B dose profile by watershed for the months of April and July 1990.

watersheds. The July doses ranged from 6.4 KJ/m² in the Delaware and Upper Chesapeake watersheds, to 7.0 KJ/m² in the Monongahela watershed.

For comparison, a 1979 backcast dose profile is shown in Figure 54.4. Total column ozone has decreased by approximately 5% since 1979, and therefore biologically effective dose would have been less in 1979. Figure 54.3 presents 1979 doses relative to base year 1999, expressed as a percentage of base year doses. April UV-B doses have increased significantly more than July doses in the last 20 years. April 1979 doses were 14 to 17% less than those of April 1999, with the Delaware watershed having experienced the greatest increase in the last 20 years. The April relative increases follow a latitudinal ordination, with the more northerly latitudes showing the greatest increase relative to the lower absolute dose that is expected in the north. The July dose changes ranged from 10 to 11%, with latitude being a less significant factor.

Two hypothetical future cases of midlatitude ozone depletion were examined. A reasonable worst-case scenario of 10% total column ozone decrease from current levels by 2010 is shown in Figure 54.5. April and July dose changes are shown relative to current (1999) doses. Note that the April dose is forecast to increase very significantly relative to 1999. As was seen in the backcast, the greatest relative changes are expected to occur in the northernmost watersheds of the region. The Delaware watershed would experience an April increase of 34% relative to April 1999. Overall, April biologically effective dose would increase by 29 to 34% under an additional 10% total column ozone decrease. The July increases would range from 20 to 22%.

A second hypothetical scenario was examined: an effect threshold scenario with 15% ozone depletion from current levels. This is not a forecast of midlatitude ozone depletion; rather, it is an economic exercise to estimate the magnitude of the cost of lost productivity if UV-B radiation were to exceed the threshold known to cause diminished biomass productivity. Figure 54.6 shows the loblolly average annual growth as biomass accumulation. The ordination of growth rate mirrors the biomass tonnage shown in Figure 54.2, with the ranking from greatest to least being: Chowan–Roanoke, Neuse–Pamlico, Lower Chesapeake, Upper Chesapeake, and Potomac (HUC 0207) watersheds. The FIA database recorded insignificant biomass growth in the Delaware and Monongahela watersheds. Figure 54.7 displays loblolly growth rate reduction for the 15% ozone depletion scenario. Percentage reduction biomass accumulation for a 3-year period is indicated in the legend. The Monongahela and Potomac watersheds would experience a 2% reduction in biomass accumulation; the Neuse–Pamlico, Chowan–Roanoke, Lower Chesapeake, and Delaware watersheds would experience a 1% reduction in biomass accumulation; and the Upper Chesapeake would be unaffected. The growth reduction gradients follow physiography more than latitude, with higher elevation experiencing the greatest potential loss of productivity.

A query of the FIA database by tree size class, and by watershed, is presented as a bar chart in Figure 54.8. The Monongahela and Delaware watersheds (HUC 0502 and 0204, respectively) have virtually no loblolly. The Chowan–Roanoke and Lower Chesapeake watersheds (HUC 0301 and 0208, respectively) have substantial loblolly stands, with the sapling and seedling class predominating. The value of loblolly is a function of size. Figure 54.9 presents a bar chart of the dollar value of loblolly stands by tree size class and by watershed. Since larger trees have greater economic value, this economic weighting scheme gives the pole timber class the greatest value in six of seven watersheds.

Figure 54.10 shows the estimated stumpage dollar value for loblolly stands by watershed. The ordination of these watersheds exactly mirrors their ranking by biomass. Figure 54.11 presents the estimated 3-year economic loss due to growth rate reduction under a 15% additional ozone depletion scenario. The losses are concentrated in the southernmost watersheds, with Chowan–Roanoke experiencing the greatest economic loss. The 3-year loss for the entire Middle Atlantic states region is estimated to be approximately \$7.3 million in raw loblolly timber.

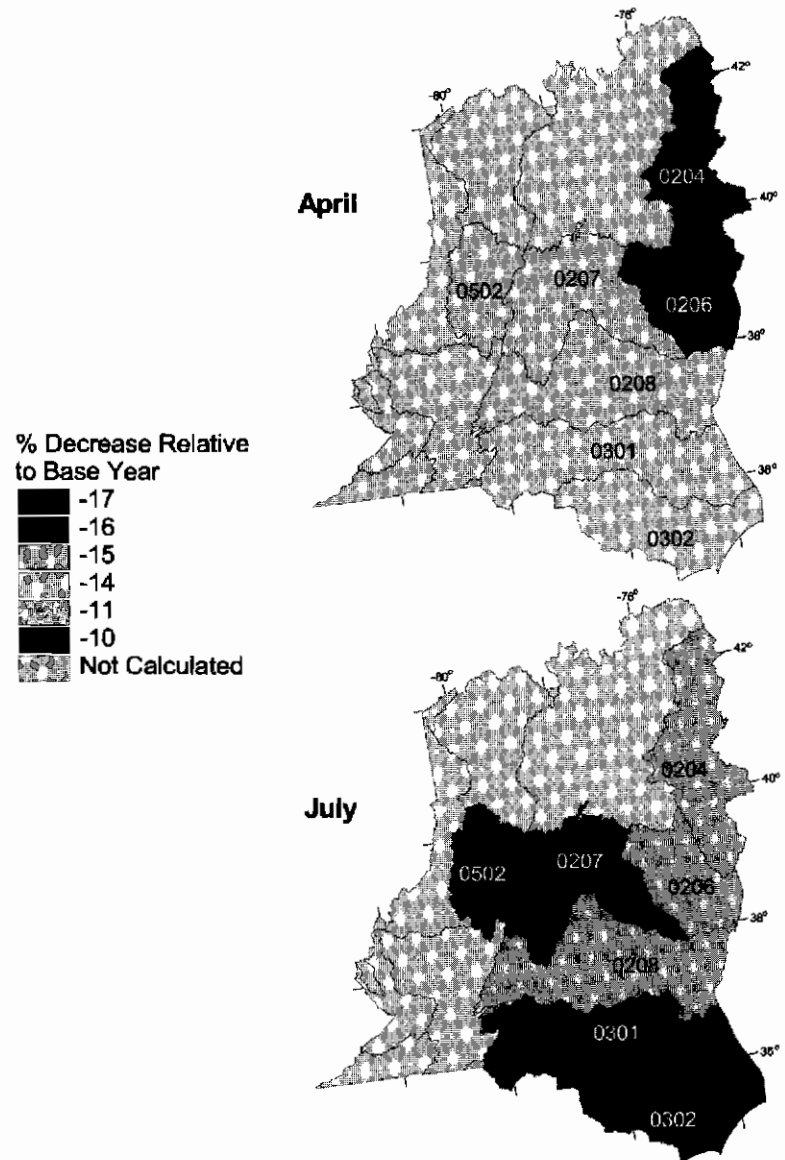


Figure 54.4 Backcast (year 1979) estimated biologically effective UV-B dose profile by watershed for the months of April and July. April 1979 doses are estimated to be 14 to 17% less than April 1999; July 1979 doses are estimated to be 10 to 11% less than July 1999.

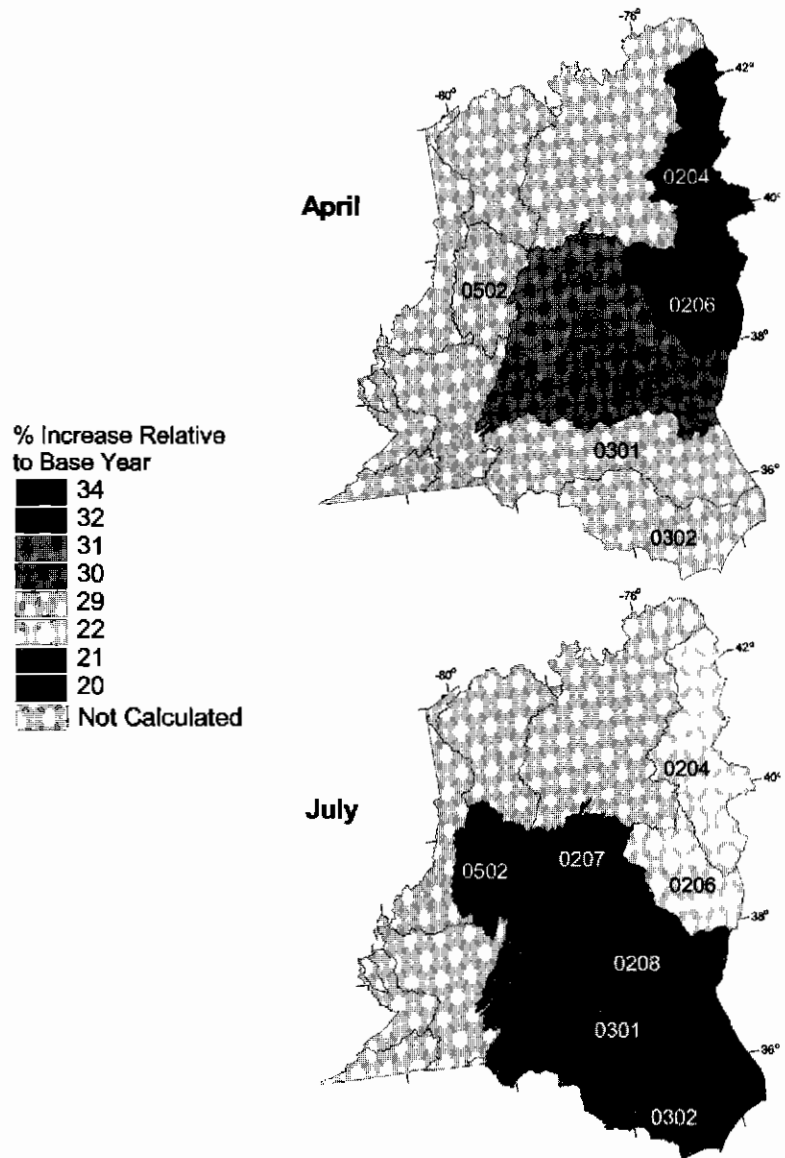


Figure 54.5 Forecast (year 2010) estimated biologically effective UV-B dose profile by watershed for the months of April and July.

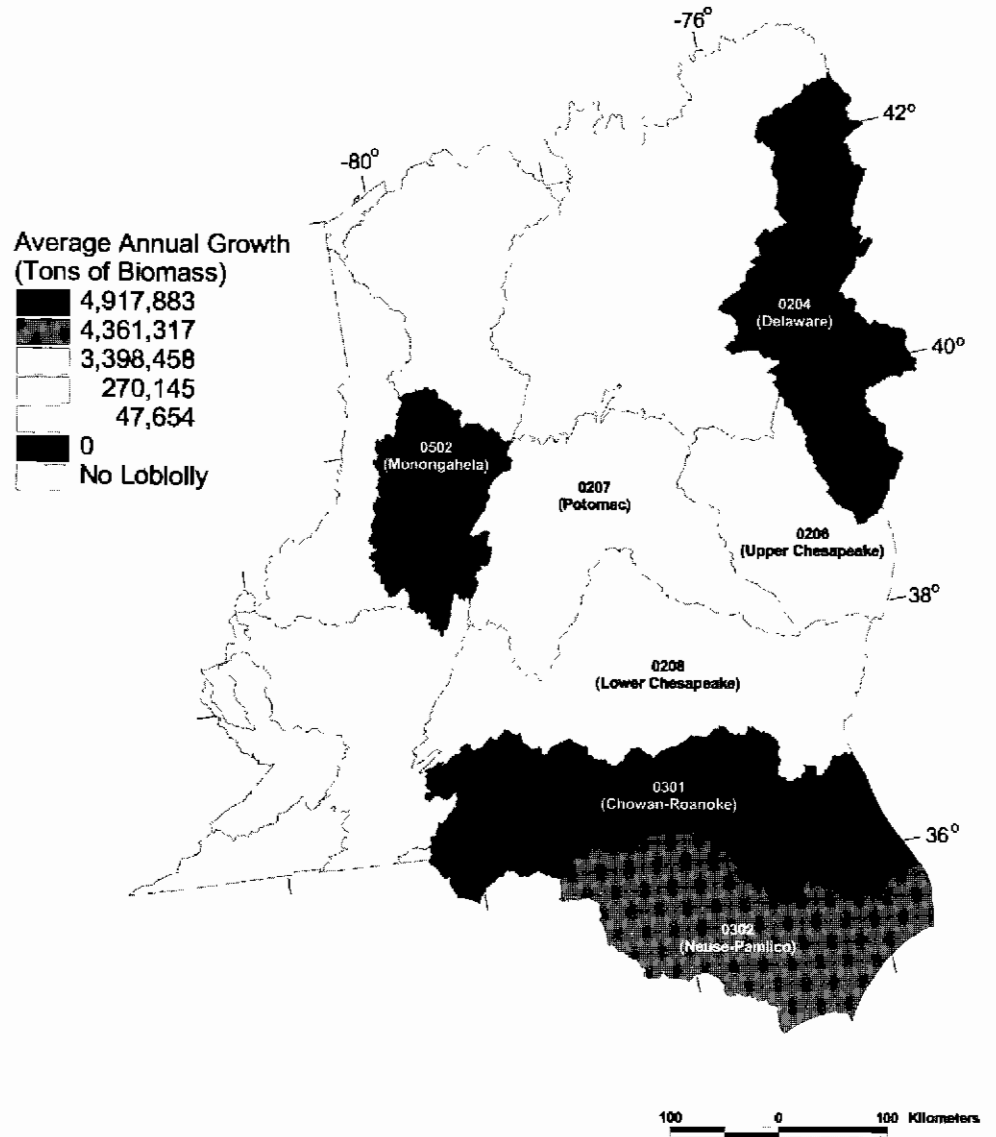


Figure 54.6 Loblolly average annual growth as tons of biomass.

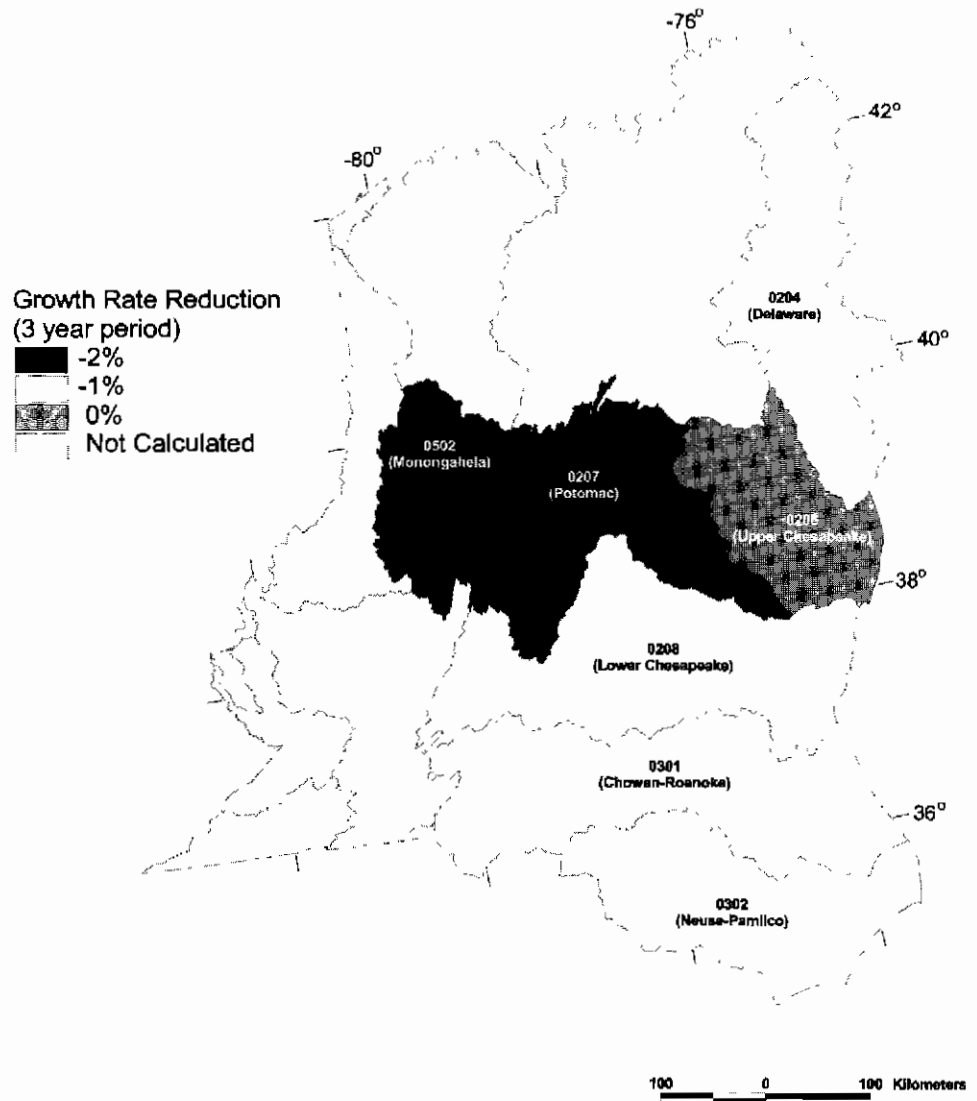


Figure 54.7 Loblolly growth rate reduction for a hypothetical 15% ozone depletion scenario. Percentage reduction in biomass accumulation is indicated in the legend.

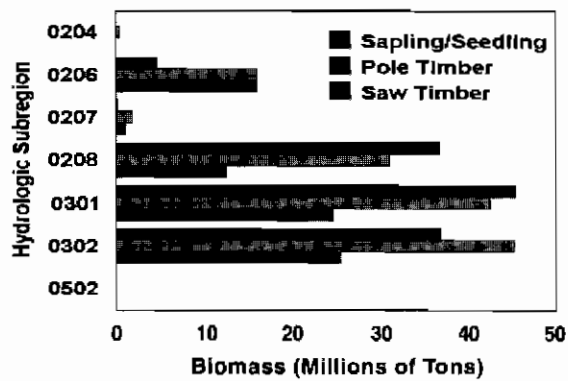


Figure 54.8 Biomass by tree size class.

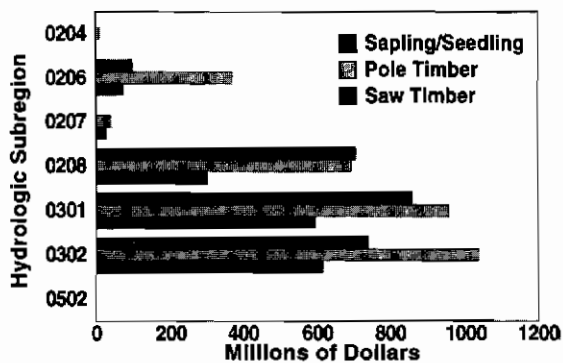


Figure 54.9 Dollar value of loblolly stands by tree size class and by watershed.

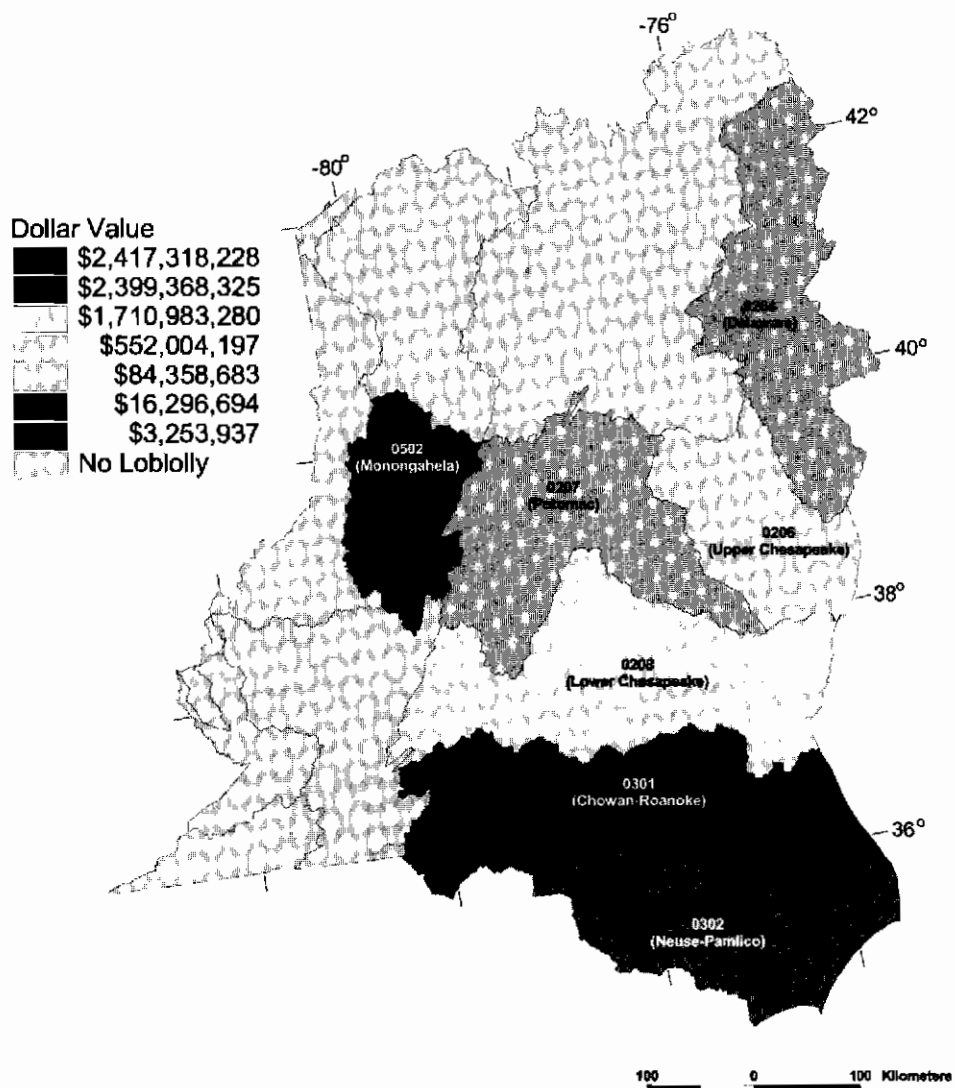


Figure 54.10 Estimated stumpage dollar value for loblolly stands by watershed.

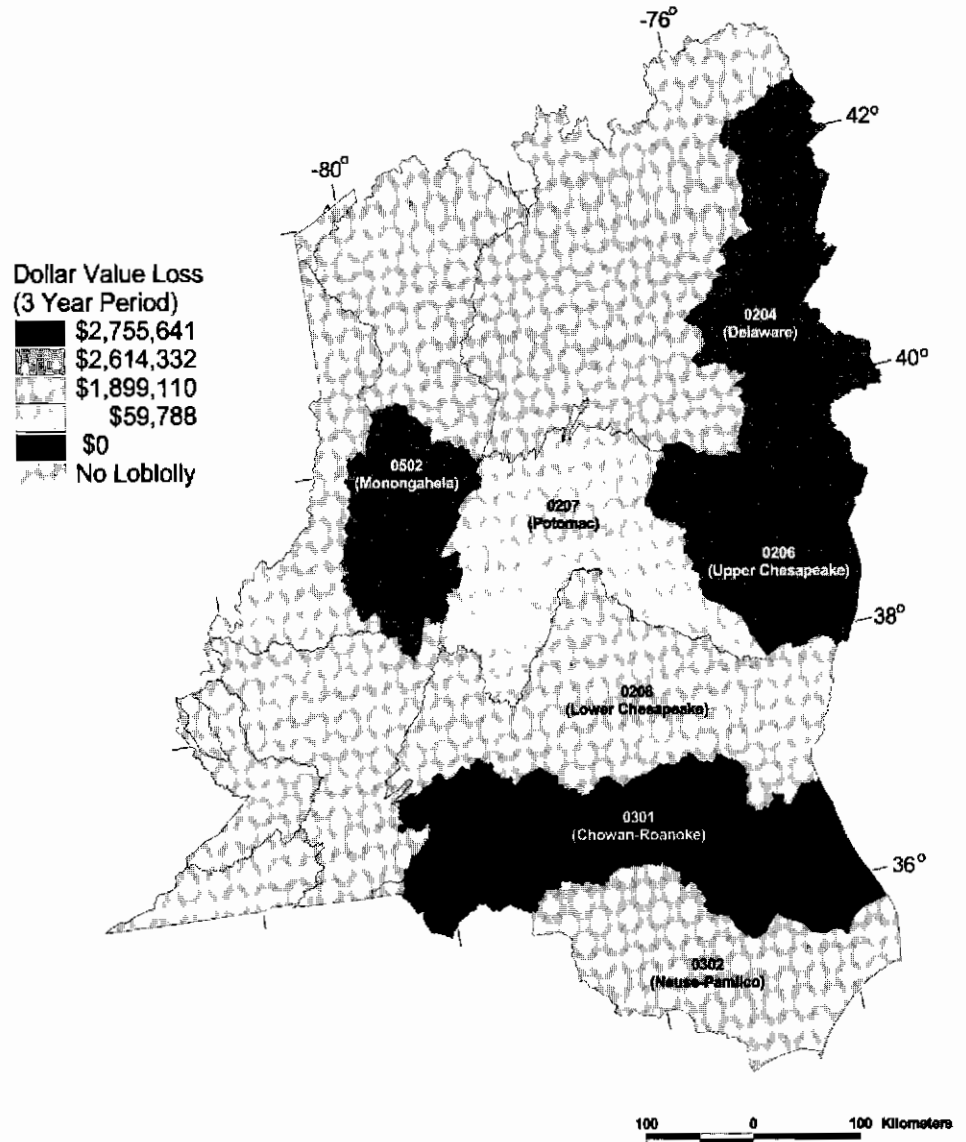


Figure 54.11 Estimated 3-year economic loss due to growth rate reduction under a hypothetical 15% additional ozone depletion scenario (relative to 1999).

DISCUSSION

The sensitivity of the biologically effective dose with ozone, aerosols, and elevation is integral to any consideration of remedial action. The "biological amplification factor," defined here as the biologically effective dose sensitivity to total column ozone, is approximately -2 for ozone (near 300 Dobson units) (i.e., a 1% decrease in total column ozone results in a 2% increase in the biologically effective dose). Background-level aerosols (summer months) decrease the biologically effective dose by approximately 10% (vs. aerosol-free atmosphere). Finally, increasing elevation from sea level to 1000 m will increase the biologically effective dose by approximately 17%.

In field studies conducted on loblolly pine seedlings, ambient light was supplemented with UV-B radiation from lamps (Sullivan et al., 1988, 1989, 1992). The total UV-B radiation applied was intended to replicate clear skies at Beltsville, MD (39°N latitude), as calculated using Green's model. The referenced biologically effective dose for current ozone levels was 8.4 MJ/day_{be} on the summer solstice. This dose was comparable to modeling calculations here only when aerosols were neglected. Monthly average biologically effective doses reported here include background level aerosols that diminish surface doses by about 10%.

The mechanism of UV-B effect on loblolly pine growth reduction is uncertain (Taramura, 1996). Leaf surface reflectance in the UV-B region is generally less than 10%. Absorption of UV-B by chromophores in the cell may disrupt physiological and developmental processes in the needles (Naidu et al., 1993; Staxen et al., 1993). Reduced photosynthetic and evapotranspiration capacity were observed in young needles. Developmentally, a thickening of the epidermis was observed, and needle elongation was reduced (Sullivan et al., 1996). The physiological and developmental deficiencies of young needles maturing under elevated UV-B may begin to explain the overall reduced growth rate of the tree. Production of protective, UV-B-absorbing flavonoid compounds within the cell was not observed in loblolly pine to the extent observed in other conifers (Laakso et al., 1998). A protracted growth deficiency, even after elevated levels of UV-B are removed, may be explained by reduced function of damaged needles for the lifetime of the needles on the tree (Sullivan, 1994; Caldwell et al., 1998).

The threshold of UV-B-induced biomass growth rate reduction appears to be greater than a reasonable worst-case scenario of ozone depletion at midlatitudes. While increases in UV-B are anticipated, the dose-response model used here does not predict loss of biomass production. The relative perturbation in ambient UV-B is expected to be greater in spring than in summer. For the reasonable worst-case scenario, April effective doses will increase by 29 to 34%; July effective doses will increase by 20 to 22%. This substantial increase in spring radiation, coupled with existing increases on the order of 15% relative to 1979, imply a cumulative spring dose increase on the order of 50%, worst case, by 2010. This may have implications for bud structures that emerge in spring.

Economic losses in loblolly pine productivity due to a hypothetical 15% ozone depletion (from 1999 base) would affect the southernmost watersheds of the Middle Atlantic states region. The initial 3-year loss is estimated to be \$7.3 million in raw timber; a substantially greater cost would be estimated if losses in value-added processing and finished products were included. Indications of a prolonged, or cumulative, growth rate deficit due to retention of UV-B-damaged needles have appeared; however, extrapolation beyond an initial 3-year period is not possible due to lack of experimental data.

DISCLAIMER

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