Inclusion of an Ultraviolet Radiation Transfer Component in an Urban Forest Effects Model for Predicting Tree Influences on Potential Below-Canopy Exposure to UVB Radiation

Gordon M. Heisler*[a], Richard H. Grant[b], David J. Nowak[a], Wei Gao[c], Daniel E. Crane[a], and Jeffrey T. Walton[a]

[a]USDA Forest Service, 5 Moon Library, c/o SUNY Environmental Science and Forestry, Syracuse, NY, USA 13210; [b]Department of Agronomy, Purdue University, West Lafayette, IN 47907-1150; [c]USDA UV-B Monitoring and Research Program, Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523

ABSTRACT

Evaluating the impact of ultraviolet-B radiation (UVB) on urban populations would be enhanced by improved predictions of the UVB radiation at the level of human activity. This paper reports the status of plans for incorporating a UVB prediction module into an existing Urban Forest Effects (UFORE) model. UFORE currently has modules to quantify urban forest structure, urban tree volatile organic compound emissions, carbon storage and sequestration in urban vegetation, dry deposition of air pollutants on trees, tree influences on energy use for heating and cooling buildings, tree pollen allergenicity index, and replacement cost of trees. These modeled effects are based upon field sampling to characterize land use, vegetation cover, and building features. The field sampling includes recording of tree species, total height, height to base of live crown, and crown width on randomly selected 0.04-ha (0.1 acre) plots. Distance and direction from sampled trees to buildings are also measured. The input for UFORE modeling of effects includes hourly meteorological data and pollution-concentration data. UFORE has already been used in assessing the urban forest function of 13 cities in the United States and 5 cities in other countries. The objective of the present work is to enable UFORE to predict the effect of different urban tree densities on potential average human exposure to UVB. The current version of UFORE is written using the Statistical Analysis System (SAS); a new version will be a user-friendly Windows application and will be available for wide distribution. Progress to date on the UVB module consists primarily of examining available modeling and data collection tools. Two methods are proposed for the UVB module. In Method 1, we will derive predicted UVB irradiance $\langle I_b \rangle$ at person height, that is, below the urban tree and building canopy, using gap fractions (sky view portions) measured from digitized fisheye photos taken from each of the UFORE plot centers during a UFORE field survey. A promising method for analyzing the photos is the use of Gap Light Analyzer (GLA). A human thermal comfort model will be used to determine the times when people would be comfortable outdoors in light attire, and UVB $\langle I_b \rangle$ will be determined for those times. Method 2 will be applied in cases where hemispherical photos cannot be made available, and for making predictions for cities where surveys have already been done. Method 2 will use a 3D canopy UV radiation transfer model to derive $\langle I_b \rangle$ based on tree canopy cover maps from GIS analysis of aerial color IR photographs or Landsat TM images. The UV module addition to UFORE will make it useful in epidemiology of UV-related human disease and assessment of UV benefits, such as in vitamin D production, and it will also facilitate consideration of UV exposure in urban forest management.

Keywords: Computer modeling, human disease, human thermal comfort; urban forest influences, hemispherical photos

1. INTRODUCTION

Human diseases that are linked to UV radiation either as the causative agent or as a factor in susceptibility to disease include the several kinds of skin cancer, several eye diseases, and damage to the immune system. In addition, it is the UV portion, especially the UVB (280 to 320 nm) that is responsible for sunburn and for skin aging and wrinkling[1]. Sunburn itself is a health issue, but more importantly, all forms of skin cancer including cutaneous melanoma (CM) have

* gheisler@fs.fed.us; phone 1 315 448-3214; fax 1 315 448-3216; www.fs.fed.us/ne/syracuse

been found to be related to episodes of sunburn that might have occurred decades before the onset of disease, especially when the sunburn occurred in childhood and early youth[2,3]. One indication of the importance of sun as a causative agent is indicated by the fact that incidence rates of all three skin cancers generally increase with decreasing latitude and with average cumulated UVB irradiance, particularly for basal cell carcinoma (BCC). Incidence of non-melanoma skin cancer in the southern United States is about double that in the north[2].

UVB affects on the human immune system have been suggested as precursors to infectious diseases and cancer[4,5]. Another concern is that excess UV radiation may reduce the effectiveness of immunizations against infectious diseases[5]. Excess UVB exposure can suppress immune functions even in people with dark skin[6]. The diseases, their relationship to UV radiation and the possible influences of urban forests on disease incidence have been reviewed by Heisler and Grant[7,8].

Despite the long list of negative effects of UVB exposure, the epidemiological implications are complex. Reports from a decade or more ago[2,9], as well as a recent study[3] indicate that while CM is related to intermittent extreme sun exposure, the risk may be reduced by moderate cumulative exposure over a lifetime. This is consistent with the fact that melanoma incidence tends to be higher in indoor workers than in outdoor workers[10]. This suggests that low levels of cumulative exposure, such as might be experienced in urban settings with ample tree cover, may be beneficial for melanoma. Features such as tree shade for children's play areas, which could reduce UVB sufficiently to prevent sunburn, may be very important. In contrast to CM, risks for the less-lethal squamous cell and basal-cell carcinomas were increased with increased lifetime exposure.

There has also been for some years a theory consistently expounded in the literature that too little exposure to UVB is associated with increased risk of non-cutaneous cancers[11-15]. One proposed mechanism for increased non-cutaneous cancers is the reduced vitamin-D production with lower UVB, such as in northern climates or as a result of air pollution over cities. A cited example is the decided trend of increased incidence of breast cancer from south to north in the United States[12,16] that has been interpreted as being caused by decreased vitamin D production with the lower UVB exposure in the north[17]. In this case, it seems that most of the geographic variation in breast cancer can be explained by demographic patterns, primarily the lower age at birth of first child in the south. Breast cancer mortality is lower among women who give birth at a young age[16]. There are experimental laboratory findings that suggest vitamin D inhibits proliferation of cancer cells, but any association between vitamin D and cancers is evidently small, because it does not appear clearly in epidemiological studies[18].

Humans do benefit from UV radiation in the production of vitamin D. Exposure to UVB is involved in both synthesis and breakdown of vitamin D by a complex series of photochemical reactions[18] that regulate the production of vitamin D so that toxic levels are not reached[19]. Only low levels of UVB exposure are needed in the synthesis process[19]. This suggests that tree shade in urban areas would not greatly limit vitamin D production, or that tree shade might not limit it at all. Vitamin D deficiency is not presently a general problem in North America, partly because of fortification of foods[20], though it is reported to be a problem in places such as Mexico City, where UV radiation is greatly reduced by pollution[21].

Because of the complexity of human diseases related to UVB radiation and the apparent benefits of moderate UVB exposure, knowledge of below-canopy UVB irradiance will contribute to studies of human disease epidemiology. Though much of peoples' UV exposure is voluntary, for example they can voluntarily visit a beach and acquire a blistering sunburn, there is an involuntary, unintentional aspect to exposure in routine outdoor life in urban areas, especially in residential neighborhoods. This occurs because of the invisibility of UVB irradiance and because of the difference between UVB shade patterns and visible light shade patterns. Because of the high diffuse sky radiance in the UVB, for points on the ground near trees but in sunlight, relative irradiance (I_r, irradiance below canopy/irradiance above canopy) in the UVB may be reduced significantly, whereas visible I_r may be almost not reduced at all. In the shade of a single tree, I_r in UVB is 20 to 60% that in the open, with minimum values directly under the tree, where visible I_r may be not more than 10 to 15% of visible in the open[8,22]. Average UVB irradiance exposure in urban areas in absolute terms will depend in part on local climate along with tree cover amounts and tree types.

Knowledge of tree influences on UVB radiation across a city will also be of benefit in managing urban trees. The medical literature suggests that generally reductions of UVB will be health enhancing, though there may be situations in which enhanced UVB will be a benefit. Governments can plant and maintain public trees in parks, along streets, and in schoolyards to enhance or reduce shade. For example, urban foresters can select trees for planting that will grow to have large dense crowns or smaller crowns, and they can prune trees slightly or more heavily to reduce shade[23]. Also, governments and non-governmental groups can encourage planting of trees to increase or reduce shade on private property.

This paper reviews progress toward development of a method to assess the spatial and temporal averages of below-canopy UVB irradiance in urban areas as influenced by trees and buildings. Urban structure for 13 cities in the United States and also cities in Canada, Spain, Puerto Rico, and China has been or is being assessed by an urban forest effects model (UFORE) that continues to be developed[24-26]. Our objective is to adapt the collection of urban structural information for UFORE and to add to the data processing in UFORE to make predictions of relative UVB irradiance across a city. Accomplishments to date are primarily in assessing potential methods for modeling relative irradiance and for validating the predictions.

2. APPROACHES AND TOOLS

2.1 Urban Forest Effects model

The Urban Forest Effects model, UFORE, currently has modules to quantify urban tree volatile organic compound emissions, carbon storage and sequestration in urban vegetation, dry deposition of air pollutants on trees, tree influences on energy use for heating and cooling buildings, tree pollen allergenicity, and replacement cost of trees. These modeled effects are based upon field sampling to characterize land use, vegetation cover, and building features. The field sampling includes recording of tree species, total height, height to base of live crown, and crown width on randomly selected 0.04-ha plots. Distance and direction from sampled trees to buildings are also measured. In a recent UFORE assessment for Syracuse, NY, a city with an area of 65 km^2 ha and about 150,000 residents, the sample was based on 200 plots. Plot density depends in part upon resources available and accuracy desired; for the City of Baltimore, which is much larger than Syracuse, there were 202 plots in a recent UFORE field sample. In some cities, assessments have been repeated to determine trends.

The analysis of sample data to estimate effects of urban structure on air quality requires input of hourly meteorological data and pollution-concentration data from the U.S. Environmental Protection Agency's Aerometric Information Retrieval System (AIRS). To date, the meteorological data for actual representative years have been used, rather than climatological averages or typical data, such as Typical Meteorological Year (TMY) data.

2.2 UV module by Method 1

We propose two different approaches for a UVB prediction module in UFORE. The first makes use of hemispherical photos to be taken from each plot center in a UFORE field survey (Step 1 in Figure 1). A portion of the randomly located UFORE plots fall on buildings or other places where people would not ordinarily walk. These will not be included in the UV predictions. In the recent Syracuse survey, only 14% of the plots in

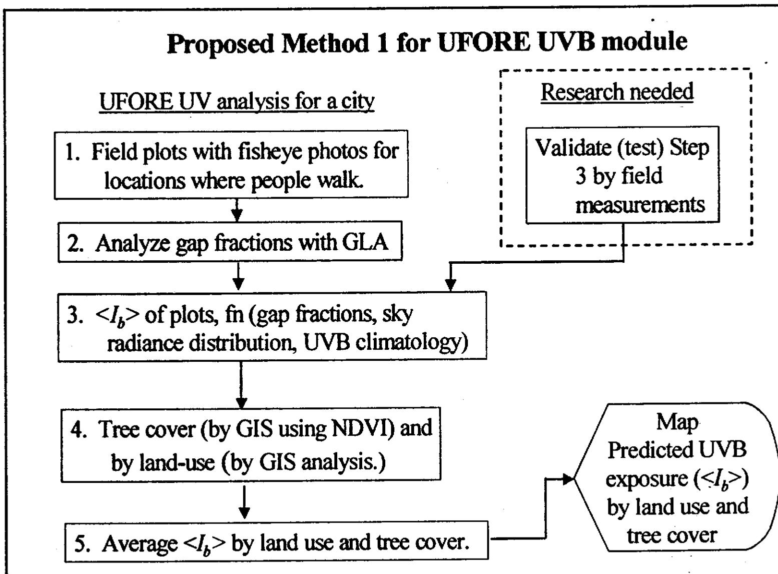

Figure 1. Proposed method for implementing a UFORE UVB module using hemispherical photos to model below-canopy irradiance, I_b.

residential land uses were not walkable. The photos could be taken with an available Canon 7.5-mm-focal-length hemispherical lens and a film camera with color film, or with a digital camera and a lens such as the Nikon FC-E8 fisheye lens with a digital camera. There have been some differences in results noted between film and digital cameras however, with film being considered the more reliable[27]. Previously, when using fisheye photos for evaluating tree density, placing the camera on a sturdy tripod at a height of 1 m has worked well, though the photographer was required to crouch low while the exposure was made. Bracketing the exposure assured an optimal exposure for processing.

Analysis of the photos will yield the gap fractions of 10° solar zenith angle and azimuth angle regions over the hemisphere above (Step 2). Software called Gap Light Analyzer © (GLA) for analysis of hemispherical photos is available from Simon Fraser University or the Institute of Ecosystem Studies[27] for free download by the Internet. Our preliminary evaluation of this software indicates it is easy and fast to use and provides good accuracy in determining gap fractions. An important feature is that it has a drawing tool that can be used to easily darken buildings that have a color that could be confused for sky, and it is usually not confused by highlights that appear on some photos when the sun is in the picture.

In Step 3 (Figure 1) UVB I_b for each of the plot centers will be predicted as the sum of the sky radiance and direct beam contributions for a representative UVB climatology. The GLA program can assist with direct beam irradiance component. Other information needed for prediction of below-canopy irradiance is the diffuse fraction of total irradiance and a way to model the sky radiance distribution. For cities with a USDA UVB Monitoring station nearby, the diffuse fraction will be available from the UV-MFRSR observations as a first approximation, though caution will be needed because most of the USDA sites are intentionally sited to be little influenced by urban atmospheres. Sky radiance distributions in the UV have been modeled by Grant et al.[28-30].

The source of data to develop the UVB climatology will vary from city to city. In Baltimore, Maryland, which will be the location of a UFORE resurvey in 2004, development of the climatology will be aided by UVB irradiance measurements being made near the center of the city with a broadband sensor. These measurements began in May 2001 as part of the Baltimore Ecosystem Study, a Long Term Ecological Research Site[31]. Measurements from the USDA UVB Monitoring Program site at Beltsville, Maryland will also be useful.

Further study is necessary to derive specifications for an optimum UVB climatology for comparison of different cities. An objective will be to represent the below-canopy erythemally weighted UVB irradiance during periods when people are likely to be most sensitive to UVB irradiance, that is, when they will be comfortable outdoors in light attire. These periods will be based in part on modeling human comfort using algorithms from a program called OUTCOMES (available at http://www.fs.fed.us/ne/syracuse) that predicts human comfort of a person based on a full set of weather variables, activity of the person, and the clothing ensemble. An accessory program that was used in a sensitivity analysis of OUTCOMES (Sensitivity) can input hourly Typical Meteorological Year data and calculate a comfort index for all hours of the year[32]. Below-canopy UVB irradiance for a city in a UFORE survey will be compared on the basis of total monthly above-canopy irradiance and area-averaged below-canopy UVB irradiance with different land uses during the periods when people are most likely to be sensitive by virtue of their attire. These periods will generally correspond approximately with times when deciduous trees are in leaf. The use of OUTCOMES will fit in well with plans to incorporate the program into a UFORE module to evaluate tree influences on human health.

We have some experience in modeling I_b near and under tree cover[22,33-35]. However, the modeling of I_b in Step 3 will require verification by short-term measurements at some of the plot centers in some cities. This will be a research activity separate from the operational UFORE surveys. Spectra in the ultraviolet have seldom been measured below tree canopies[36]. Though broadband UVB sensors can be used to measure the erythemally weighted irradiance, an improved physical understanding will be attained if spectral or at least multi-band measurements can be made, such as with a UV-multifilter-shadowbanded radiometer.

In Step 4, the fraction of land covered by trees is required so that the modeled below-canopy UVB irradiance at the plot centers may be extrapolated to other parts of the city by using the assumption that other locations in the same land use category and with the same tree cover classes will have identical average below-canopy irradiance. The Multi-Resolution Land Characteristics (MRLC) consortium is currently mapping tree cover for the entire United States on a 30-×-30-m grid using circa 2000 Landsat TM spectral images[37]. Greater resolution can be achieved using high-resolution IR aerial photo images[38] for Normalized Difference Vegetation Indices (NDVI) techniques. Though the technology for use of high-resolution images to obtain tree cover is still emerging, accuracy of 86% in identifying tree cover has been obtained[38].

The final product of the UFORE UV module will be maps that portray spatially averaged UVB exposure across the city, as well as tabulated below-canopy average irradiance by land-use groups. These will be presented in absolute irradiance terms (I_b) and as relative irradiance (I_r) compared to the above-canopy irradiance.

2.3 Method 2, using a 3D UVB Radiation Transfer (UVRT) model

Our initial plan for predicting UVB I_b was to use UFORE plot data directly for assessing transfer of UVB through urban trees by means of a 3D model[39]. The UVRT model predicts radiation transfer on a point-by-point basis through a modeled vegetation canopy that consists of plant crowns that are assumed to be ellipsoidal. The x and y axes of the ellipsoids may be equal or unequal. Upon examining data from recent UFORE plots it became apparent that large trees just off the plot could have a large effect on I_b. Therefore, the 3D UVRT model could not be used directly with UFORE plot data to derive $\langle I_b \rangle$.

For cases where fisheye photos are not available, Steps 1 and 2 in Figure 2 will first be used for determining tree cover and land use according to normal UFORE procedures. In Step 3, the 3D UVRT model will be used to develop predicted spatially averaged irradiances by the tree cover classes and land use categories, both relatively and absolutely, using the assumptions of Grant and Heisler[35]. They assumed that buildings were not important in determining average $\langle I_r \rangle$ and that trees were uniformly distributed on a grid spaced so that the modeled tree density equaled the tree density as measured by remote-sensing techniques. The spatially averaged predictions were based on running the 3D UVRT model for a large number of points below the grid of model trees.

Some research will be needed to adapt the 3D UVRT model to the Method 2 UFORE module and to verify the results. One needed adaptation is the inclusion of buildings within the model along with trees. Models of the effects of buildings on solar radiation are present in the literature[40,41]. Considering the building influences on UVB along with the tree influences will provide a categorization of essentially the entire urban structure on UVB, because, in the absence of snow cover, little UVB is usually reflected from ground surfaces. (This could be untrue if surfaces are intentionally whitened[7]). In an actual city environment, trees are not spaced equally, so model experiments will need to be conducted to examine the effect of clustering on average and maximum irradiances. Another item for research is the effect of tree crown density on transmission of UVB radiation. Tree crowns vary in leaf desity by species and also by tree size[42]. The 3D UVRT model includes a factor for leaf density within the crowns of trees. Validation of Method 2 will also be carried out by comparison to results using Method 1 in one or more cities where both methods are possible.

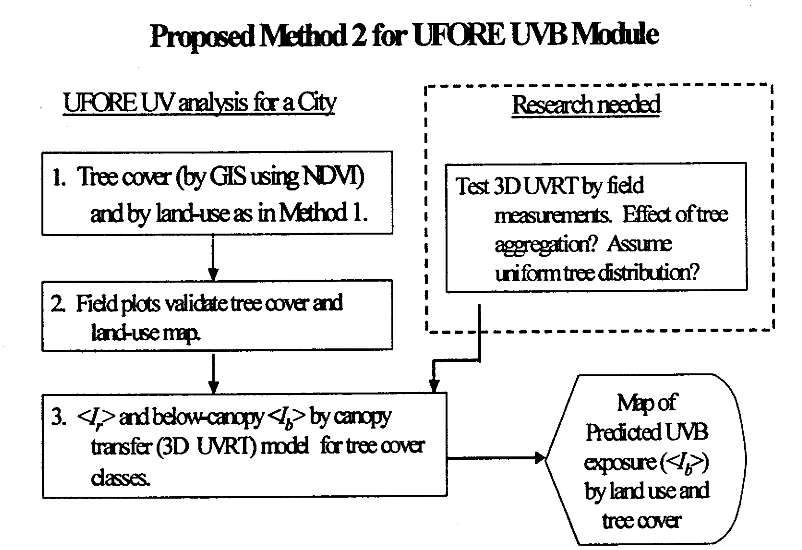

Figure 2. Proposed method for implementing a UFORE UVB module using hemispherical photos to model below-canopy irradiance, I_b.

3. CONCLUSIONS

The UFORE model provides a method for estimating a wide range of urban forest effects, several of which are important to human health. The addition of a UV module will be of benefit for epidemiological purposes. At present, given the lack of knowledge of average tree effects on UV irradiance, some remaining uncertainty about the role of UVB irradiance on human health within the medical community, along with the difficulty of characterizing human behavior with respect to outdoor life, the role of trees in effecting human disease by providing UVB shade is difficult to quantify. If we can quantify the effects of trees on UVB irradiance, epidemiologists will be able to add a factor for routine UVB exposure in urban areas to their equations. The range of tree influences on UVB irradiances that are determined will also have a use in health education. At present, people are told to seek shade in mid-day; with the additional information on UVB relative irradiances, it will be possible to better indicate in a coherent way that all shade is not equal.

The information on UVB exposure will also have a use in operational urban forestry, landscape architecture, and the move to shade schoolyards in the United States. From existing knowledge of tree influences on UVB irradiance along with study of the medical literature, the best guess on tree management is that tree shade should be maximized where possible. The modeling, particularly in Method 1, will illustrate patterns that yield low exposure to UVB irradiance.

ACKNOWLEDGMENTS

Dr. Cheryl Bawhey and Dr. Yadong Qi provided helpful review comments on an earlier version of this paper. Jack Stevens and Bob Hoehn assisted with use of UFORE sample data. Measurements of solar radiation and climate in Baltimore, MD are partially supported by the National Science Foundation through the Institute of Ecosystem Studies, Millbrook, NY, which administers the Baltimore Ecosystem Study, a NSF Long Term Ecological Research site.

REFERENCES

1. P. Weary, "An undeclared epidemic of skin cancer," in *Symposium on Environmental Applications*, p. 96, American Meteorological Society, Boston, 1996.
2. M. A. Weinstock, "Ultraviolet radiation and skin cancer: Epidemiological data from the United States and Canada," in *Environmental UV Photobiology*, A. R. Young, L. O. Bjorn, J. Moan, and W. Nultsch eds., pp. 295-343, Plenum Press, New York, 1993.
3. C. Kennedy, C. D. Bajdik, R. Willemze, F. R. De Gruijl, and J. N. Bouwes Bavinck, "The influence of painful sunburns and lifetime sun exposure on the risk of actinic keratoses, seborrheic warts, melanocytic nevi, atypical nevi, and skin cancer," *Journal of Investigative Dermatology* **120,** no. 6, pp. 1087-1093, 2003.
4. E. C. DeFabo, "Effects of UV-B radiation on human and animal health," in *Stratospheric Ozone Depletion/UV-B Radiation in the Biosphere*, R. H. Biggs and M. E. B. Joyner eds., pp. 197-198, Springer-Verlag, Berlin, 1993.
5. R. S. Chapman, "Effect of solar UV radiation on the risk of infectious disease in humans: epidemiologic considerations," *Photochemistry and Photobiology* **61,** no. 3, pp. 243-246, 1995.
6. F. R. de Gruijl, "Impacts of a projected depletion of the ozone layer," *Consequences* **1,** no. 2, pp. 1-10, 1995.
7. G. M. Heisler and R. H. Grant, "Ultraviolet Radiation, Human Health, and the Urban Forest," Forest Service Gen. Tech. Rep. NE-268, 35 pp., U.S. Department of Agriculture, Newtown Square, PA, 2000.
8. G. M. Heisler and R. H. Grant, "Ultraviolet radiation in urban ecosystems with consideration of effects on human health," *Urban Ecosystems* **4,** pp. 193-229, 2000.
9. S. K. Melville, F. S. Rosenthal, R. Luckmann, and R. A. Lew, "Quantitative ultraviolet skin exposure in children during selected outdoor activities," *Photodermatology, Photoimmunology, Photomedicine* **8,** pp. 99-104, 1991.
10. H. K. Koh and R. A. Lew, "Sunscreens and melanoma: implications for prevention," *Journal of the National Cancer Institute* **86,** no. 2, pp. 78-79, 1994.
11. C. F. Garland and F. C. Garland, "Do sunlight and vitamin D reduce the likelihood of colon cancer," *International Journal of Epidemiology* **9,** no. 3, pp. 227-231, 1980.
12. G. Cowley, "Can sunshine save your life?," *Newsweek*, p. 56, December 30, 1991.
13. E. S. Lefkowitz and C. F. Garland, "Sunlight, vitamin D, and ovarian cancer mortality rates in US women," *International Journal of Epidemiology* **23,** no. 6, pp. 1133-1136, 1994.
14. C. Garland, F. C. Garland, E. D. Gorham, M. Lipkin, H. Newmark, M. F. Holick, and J. V. Raffa, "Ultraviolet B, vitamin D, and their mechanisms in cancer prevention," in *Ultraviolet Ground- and Space-based Measurements, Models, and Effects*, J. R. Slusser, J. R. Herman, and W. Gao eds., pp. 313-323, The International Society for Optical Engineering, SPIE, Bellingham, WA, 2002.

15. W. B. Grant, "Health benefits of solar UV-B radiation: cancer risk reduction," in *UV Ground- and Space-Based Measurements, Models, and Effects*, J. R. Slusser, J. R. Herman, and W. Gao eds., pp. 324-334, The International Society for Optical Engineering, SPIE, Bellingham, WA, 2002.
16. S. R. Sturgeon, C. Schairer, M. Gail, M. McAdams, L. A. Brinton, and R. N. Hoover, "Geographic variation in mortality from breast cancer among white women in the United States," *Journal of the National Cancer Institute* **87,** no. 24, pp. 1846-1852, 1995.
17. H. G. Ainsleigh, "Beneficial effects of sun exposure on cancer mortality," *Preventive Medicine* **22,** pp. 132-140, 1993.
18. M. E. Martinez, E. L. Giovannucci, G. A. Colditz, M. J. Stampfer, D. J. Hunter, F. E. Speizer, A. Wing, and W. C. Willett, "Calcium, vitamin D, and the occurrence of colorectal cancer among women," *Journal of the National Cancer Institute* **88,** no. 19, pp. 1375-1382, 1996.
19. A. R. Webb, "Vitamin D synthesis under changing UV spectra," in *Environmental UV Photobiology*, A. R. Young, L. O. Bjorn, J. Moan, and W. Nultsch eds., pp. 185-202, Plenum, New York, 1993.
20. A. Simard, J. Vobecky, and J. S. Vobecky, "Vitamin D deficiency and cancer of the breast: an unprovocative ecological hypothesis," *Canadian Journal of Public Health* **82,** pp. 300-303, 1991.
21. I. Galindo, S. Frenk, and H. Bravo, "Ultraviolet Irradiance over Mexico City," *Air & Waste Manage. Assoc.* **45,** pp. 886-892, 1995.
22. R. H. Grant, G. M. Heisler, and W. Gao, "Estimation of pedestrian level UV exposure under trees," *Photochemistry and Photobiology* **75,** no. 4, pp. 369-376, 2002.
23. Q. Xiao and E. G. McPherson, "Rainfall interception by Santa Monica's municipal urban forest," *Urban Ecosystems* Submitted.
24. D. J. Nowak, D. E. Crane, J. C. Stevens, and M. Ibarra, "Brooklyn's Urban Forest," Forest Service General Technical Report NE-290, 107 pp., USDA, Newtown Square, PA, 2002.
25. D. J. Nowak, P. J. McHale, M. Ibarra, D. Crane, J. C. Stevens, and C. J. Luley, "Modeling the effects of urban vegetation on air pollution," in *Air Pollution Modeling and Its Application XII*, S.-E. Gryning and N. Chaumerliac eds., pp. 399-407, Plenum Press, New York, 1998.
26. D. J. Nowak and D. E. Crane, "The urban forest effects (UFORE) model: quantifying urban forest structure and functions," in *Integrated Tools for Natural Resources Inventories in the 21st Century*, M. Hansen and T. Burk eds., General Technical Report NC-212, pp. 714-720, USDA Forest Service, St. Paul, MN, 1998.
27. G. W. Frazer, C. D. Canham, and K. P. Lertzman, "Gap Light Analyzer (GLA), Version 2.0: Imaging software to extract canopy structure and gap light transmission indices from true-colour fisheye photographs, users manual and program documentation," 36 pp.: http://www.rem.sfu.ca/forestry/index.htm or http://www.ecostudies.org/, 1999.
28. R. H. Grant, G. M. Heisler, and W. Gao, "Ultraviolet sky radiance distributions of translucent overcast skies," *Theoretical and Applied climatology* **58,** pp. 129-139, 1997.
29. R. H. Grant and G. M. Heisler, "Obscured overcast sky radiance distributions for the UV and PAR wavebands," *Journal of Applied Meteorology* **56,** no. 10, pp. 1336-1345, 1997.
30. R. H. Grant, G. M. Heisler, and W. Gao, "Clear sky radiance distributions in ultraviolet wavelength bands," *Theoretical and Applied Climatology* **56,** pp. 123-135, 1997.
31. G. M. Heisler, R. H. Grant, W. Gao, J. R. Slusser, and C. Ehrlich, "Solar ultraviolet-B radiation in urban environments: Baltimore, Maryland," in *Ultraviolet Ground- and Space-based Measurements, Models, and Effects*, pp. 62-69, SPIE, The International Society for Optical Engineering, Bellingham, WA, 2003.
32. Y. Wang, "An analysis of an expert system used to predict human thermal comfort in outdoor urban settings," Ph.D Thesis, State University of New York, Syracuse, NY, 2003.
33. R. H. Grant and G. M. Heisler, "Solar ultraviolet-B and photosynthetically active irradiance in the urban sub-canopy: a survey of influences," *International Journal of Biometeorology* **39,** pp. 201-212, 1996.
34. R. H. Grant, G. M. Heisler, W. Gao, and W. King, "Multiple waveband solar irradiance in an open tree canopy: measurement and modeling," in *2nd Urban Envionrment Symposium*, pp. 202-205, American Meteorological Society, Boston, MA, 1998.
35. R. H. Grant and G. M. Heisler, "Modeling UV irradiance in open tree canopies: estimation of pedestrian level exposure," in *Biometeorology and Urban Climatology at the Turn of the Millennium, Selected Papers from the Conference ICB-ICUC'99 (Sydney, 8-12 November 1999)*, R. J. deDear, J. D. Kalma, T. R. Oke, and A. Auliciems eds., WCASP - 50, WMO/TD-No. 1026, pp. 9-14, World Meteorological Organization, Geneva, Switzerland, 2000.

36. A. V. Parisi and M. G. Kimlin, "Comparison of the spectral biologically effective solar ultraviolet in adjacent tree shade and sun," *Physics in Medicine and Biology* **44,** pp. 2071-2080, 1999.
37. C. Huang, L. Yang, B. Wylie, and C. Homer, "A strategy for estimating tree canopy density using Landsat 7 ETM+ and high resolution images over large areas," in *Third International Conference on Geospatial Information in Agriculture and Forestry, CD ROM,* United States Geological Survey, Sioux Falls, SD, 2001.
38. S. Myeong, D. J. Nowak, P. F. Hopkins, and R. H. Brock, "Urban cover mapping using digital, high-spatial resolution aerial imagery," *Urban Ecosystems* **5,** pp. 243-256, 2001.
39. W. Gao, R. H. Grant, G. M. Heisler, and J. R. Slusser, "A geometric ultraviolet-B radiation transfer model applied to vegetation canopies," *Agronomy Journal* **94,** pp. 475-482, 2002.
40. W. H. Terjung and P. A. O'Rourke, "Energy exchanges in urban landscapes selected climatic models," 33(1), 187 p., C.W. Thornthwaite Associates, Elmer, N.J., 1980.
41. M. Bruse, "Assessing thermal comfort in urban environments using an integrated dynamic microscale biometeorological model system," in *Third Symposium on the Urban Environment,* pp. 159-160, American Meteorological Society, Boston, 2000.
42. G. M. Heisler, "Measurements of solar radiation on vertical surfaces in the shade of individual trees," in *The Forest-Atmosphere Interaction: Proceedings of Forest Environmental Measurements Conference*, B. A. Hutchison and B. B. Hicks eds., pp. 319-335, Reidel, Dordrecht, Holland, 1985.