12 Urban Forest Influences on Exposure to UV Radiation and Potential Consequences for Human Health

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Abstract This chapter explores the literature on ultraviolet (UV) irradiance in urban ecosystems with respect to the likely effects on human health. The focus was the question of whether the health effects of UV radiation should be included in the planning of landscape elements such as trees and shading structures, especially for high use pedestrian areas and school play grounds. Ultraviolet radiation can have a strong effect on humans, primarily as a cause or contributing factor for skin cancer and eye cataracts. It is also a probable factor in the development of immune deficiencies. However, UV can also positively affect human health, primarily because it is essential for photosynthesis of vitamin D in human skin. Vitamin D has long been recognized as a requirement for bone health. Recent epidemiological findings attribute vitamin D for the reduction of many types of non-skin cancers. Moreover, there is evidence that it may reduce mortality for those diagnosed with melanoma skin cancer. Alternatively, some public health authorities, particularly those from countries with a large population of northern European descent, strongly recommend that exposure to UV radiation should be minimized to prevent skin cancer. Other agencies, including the World Health Organization, that take a broader world view, differentiate their recommendations according to skin color. They recommend that humans with darker skin, who are likely deficient in vitamin D and also have little access to vitamin D fortified foods, should have moderate UV exposure. Judging from current knowledge of typical spectra of solar radiation in tree shade and the difference between the action spectra (effectiveness versus radiation wavelength) for vitamin D synthesis and that for sunburn in human skin, tree shade has advantages for moderate exposure to solar radiation. Where trees are separated, as is typical in heavily populated urban areas, the shortest wavelengths of UV radiation are scattered from the sky into shady locations with some sky view, and to a small extent, vitamin-D-promoting wavelengths are increased over the radiation spectrum that causes sunburn. The sunburn action spectrum includes longer wavelengths that are less readily scattered into direct beam shade. Global climate change, which is expected to increase temperatures, especially at higher latitudes, may have a variety of effects on UV exposure for human populations. For example, warming could lead to greater exposure as people adapt to increased temperatures by wearing less clothing. However, empirical evidence for a temperature influence on human exposure independent of radiation climate does not seem to exist.

Keywords human health, ozone depletion, skin cancer, urban climate, UV-B radiation, vitamin D

12.1 Introduction

The goal of this review is to summarize recent information on the effect of ultraviolet radiation (UV) on human health in urban areas, and the degree to which urban landscapes might be managed to optimize UV exposure for improved health. Considering both the negative and positive health effects of UV exposure, would urban planning to increase tree cover form an effective public health intervention? Can optimum tree arrangements and species selections be prescribed? More specific questions arise; for example, is it important that shade be provided for school play areas?

To propose answers to these questions, a number of more basic questions must be considered. What are the health impacts of UV on particular populations? What is the relationship between climate and the type of dress, which influences the amount of exposure individuals receive during time spent outdoors? How representative are the UV monitoring networks located within the city? What are the urban atmospheric influences on UV irradiance? Are there trends in UV that may change the importance and effectiveness of proposed shade structures during their term of use? If increased radiation shading is deemed desirable, what types are most effective (e.g., trees or constructed shelters)?

Even though the benefits of UV radiation in photosynthesizing vitamin D and also the consequences of vitamin D for bone health have been known for many years, an increased volume of epidemiological literature published since about 1980 suggests that vitamin D, including that photosynthesized in the body from sunlight, is beneficial for human health (Garland and Garland, 1980; Kimlin, 2004; Engelsen et al., 2005; Turnbull et al., 2005). Relative to recent reviews on urban forest influences on UV radiation (Heisler and Grant, 2000a, b), the apparent beneficial influences of UV radiation in reducing the risk for many cancers through vitamin D production (Garland et al., 2002; Grant, 2002b, c; Grant, 2003; Grant and Garland, 2006) are given greater emphasis in this paper.

Although most urban residents can acquire large doses of UV radiation by spending time in open areas near or within their city, most reports on the subject suggest that vegetation and structures within a city, along with the urban atmosphere, modify UV sufficiently over time to affect human health (Heisler and Grant, 2000a, b; Gies and Mackay, 2004). Tree cover differs from city to city, and can also vary within urban areas. In U.S. residential areas with low building density, trees dominate the environment (Nowak and Crane, 1998; Nowak et al., 2002). Tree cover in urban areas can vary with the climate, culture, local income, city infrastructure, and the tree-management programs carried out by local, state, and federal governments (Miller, 1998).

Other important recent changes that have been published include findings of a reduced downward trend in stratospheric ozone (Newchurch et al., 2003; Malanca et al., 2005; Weatherhead and Andersen, 2006). Most papers written during the last two decades that describe UV effects began with a statement regarding the importance of the research due to probable increases in UV-B (here taken to be radiation between 320 nm and 280 nm, unless specified as the alternate definition of 315 nm to 280 nm) radiation resulting from stratospheric ozone depletion. Although it seems too early to declare a reversal in ozone depletion, recent reports suggest that increased downward trends are unlikely.

The first issue to be considered in regard to the effects of UV radiation on health is the epidemiology of diseases.

12.2 Effects of Solar UV on Human Health and Epidemiology

Human diseases that are linked to UV radiation as either the causative agent or as a factor in susceptibility to disease include several types of skin cancer, eye disease, and damage to the immune system. In addition, it is the UV, primarily UV-B, which is responsible for sunburn and skin aging and wrinkling (Weary, 1996). Sunburn itself is a health issue, but more importantly, some cancers are believed to be related to numerous sunburn episodes.

There are also benefits to UV- radiation exposure, including the production and regulation of vitamin D (Holick, 1999), that claims to reduce the risk for many non-cutaneous cancers (Garland et al., 1985; Gorham et al., 1989; Garland et al., 2002; Grant, 2002a, b, c; Grant, 2003). Table 12.1 lists common cancers with their United States population risk in the order of U.S. mortality.

12.2.1 Sunburn

The action spectra for sunburn and tanning were determined using light skinned volunteers who received narrow bands of constant irradiance on a small area of

Table 12.1 Diseases in the United States that have been associated with UV radiation; in order of U.S. deaths per year (usually for 2001). Incidence and mortality are per annum from recent years. (M) male; (F) female; RI = incidence risk increase; RR = risk reduction; MRR = mortality risk reduction

Disease	Incidence/100,000	U.S. Cases	U.S. Deaths	UV Influence	Vitamin D Influence
Colon cancer	39 (U.S. Centers for Disease Control and Prevention, 2005)		53,000 (Centers for Disease Control and Prevention, 2005)	RR (C.F. Garland and Garland, 1980; C.F. Garland et al., 1999; W.B. Grant, 2003), MRR (C.F. Garland et al., 1999)	RR (C.F. Garland & Garland, 1980), MRR (Moan et al., 2005)
Breast cancer	28 (F)(Centers for Disease Control and Prevention, 2005)		41,800 (Centers for Disease Control and Prevention, 2005)	RR (W.B. Grant, 2002a, 2003), MRR (C.F. Garland et al., 1999)	RR (W.B. Grant, 2003)
Prostate cancer	161 (Centers for Disease Control and Prevention, 2005)		30,700 (Centers for Disease Control and Prevention, 2005)	RR (W.B. Grant, 2003), MRR (C.F. Garland et al., 1999)	
Pancreas	11 (Centers for Disease Control and Prevention, 2005)		29,800 (Centers for Disease Control and Prevention, 2005)	RR (W.B. Grant, 2003)	RR (M) (W.B. Grant, 2003)
Non-Hodgkin lymphoma	18 (Centers for Disease Control and Prevention, 2005)		22,300 (Centers for Disease Control and Prevention, 2005)	RR (W.B. Grant, 2003; Smedby et al., 2005)	
Cancer of ovary	13 (Centers for Disease Control and Prevention, 2005)		14,400 (Centers for Disease Control and Prevention, 2005)	RR (W.B. Grant, 2003), MRR (C.F. Garland et al., 1999)	
Cancer of esophagus	5 (Centers for Disease Control and Prevention, 2005)		12,500 (Centers for Disease Control and Prevention, 2005)	RR (W.B. Grant, 2003)	

(Continued)

Disease	Incidence/100,000	U.S. Cases	U.S. Deaths	UV Influence	Vitamin D Influence
Bladder cancer	21 (Centers for Disease Control and Prevention, 2005)		12,200 (Centers for Disease Control and Prevention, 2005)	RR (W.B. Grant, 2002b)	
Kidney cancer	13 (Centers for Disease Control and Prevention, 2005)		12,100 (Centers for Disease Control and Prevention, 2005)	RR (M) (W.B. Grant, 2003)	
Multiple myeloma	5 (Centers for Disease Control and Prevention, 2005)		10,700 (Centers for Disease Control and Prevention, 2005)	RR (W.B. Grant, 2003)*	
Rectal cancer	14 (Centers for Disease Control and Prevention, 2005)		8,500 (Centers for Disease Control and Prevention, 2005)	RR (W.B. Grant, 2003)	
Melanoma	17 (Saraiya et al., 2004)	55,000 (Saraiya et al., 2004)	7,900 (Centers for Disease Control and Prevention, 2005)	RI (Saraiya et al., 2004), MRR (Berwick et al., 2005)	
Uterus (corpus)	23 (Centers for Disease Control and Prevention, 2005)		3200 (Centers for Disease Control and Prevention, 2005)	RR (W. B. Grant, 2002b)	
Squamous cell carcinoma	107 (Hess et al., 2006)		2,500**	High risk	
Cataract		350,000 (Ocampo and Foster, 2004)	Occurs post surgery	UV among many suspected risk factors	
Basal cell carcinoma	475 (M), 250 (F) (Bader, 2008)	900,000	rare	High risk factor	

* UV exposure did not appear as a significant risk reduction in later studies (Pers. comm., William Grant, August 2005).

** From an estimate that appeared in the Squamous Cell Carcinoma website of eMedicine (Hess et al., 2006) before 2006.

exposed skin over different times to create a variance in doses (Parrish et al., 1982; McKinlay and Diffey, 1987). The average time to administer a tanning dose in the UV-B varied from 0.36 min to 7.15 min, depending on the wavelength. Parrish et al. (1982) did not report whether there would be reciprocity between time and irradiance in administering the dose. At some wavelengths, subjects were exposed for considerable lengths of time, up to nearly five hours for longer wavelengths in the UV-A (400 nm − 320 nm). The reciprocity issue may be important in evaluating the effectiveness of shade structures, because presumably there is some level of irradiance below which no damage would occur, even if the subject spent a long time undergoing that irradiance. For more on the reciprocity issue, see the Section 2.10 'Calculation of optimal times for exposure to sunlight' in Chapter 2 (McKenzie and Liley, 2009) of this volume.

12.2.2 Skin Types

The effect of skin color on absorption of light, including the UV, was recently investigated by Nielsen et al. (2004). Skin absorption is largely a function of reflection and absorption by melanosomes. In the visible wavelengths, reflection is greater in light skin, but below the range of 300 nm to 330 nm, reflection is greater in dark skin; a non-intuitive finding with implications for health of dark-skinned populations.

12.2.3 Immune Function

Although UV-B is strongly absorbed in the skin and in the outer layers of the eye and does not penetrate any deeper into the human body, it can affect the human immune system, because part of the immune system is in the outer layers of skin, and the cells of the skin produce mediators that modulate immune responses both locally and throughout the body (De Gruijl, 1995; Longstreth et al., 1998). De Fabo (1994) and Chapman (1995) suggested that UV-B is the probable cause of infectious diseases and cancer, due to its affect on immune systems. Another concern is that excess UV radiation may reduce the effectiveness of immunizations against infectious diseases (Chapman, 1995). De Gruijl (1995) reported that excess UV-B exposure can suppress immune functions even in people with dark skin.

12.2.4 Skin Cancers

It is believed that exposure to UV leads to skin cancers because the UV forms DNA photolesions that induce gene mutations (Pfeifer, 1997). Cutaneous melanoma (CM) and basal cell carcinoma (BCC) seem to be associated with intense intermittent exposure, whereas squamous cell carcinoma (SCC) seems to be related to cumulative exposure (Melville et al., 1991; Weinstock, 1993; Saraiya et al., 2004).

The importance of urban environmental design and configurations in influencing skin cancers depends on the epidemiology of these diseases. Gathering epidemiological data on non-melanoma skin cancers is difficult, in part because these diseases are not always included in cancer reporting registries (Weinstock, 1993). 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 UV-B irradiance, particularly for BCC (Leffell and Brash, 1996). Incidence of non-melanoma skin cancer in the southern U.S. is about double that in the north (Weinstock, 1993).

12.2.4.1 Non-Melanoma Skin Cancers

Non-melanoma skin cancers (SCC and BCC) are the most frequently diagnosed (Table 12.1) and are the most rapidly rising forms of cancer in white populations (International Agency for Research on Cancer, 1992). Estimates are that in recent years in the U.S., there have been 800,000 cases diagnosed each year, about twice as often in men as in women (Long et al., 1996; Saraiya et al., 2004). In 2004 there were an estimated 2,300 deaths from non-melanoma skin cancers, primarily from SCC (Saraiya et al., 2004). However, the cancer characterized as the most common world-wide is BCC (Chuang et al., 1990; Gailani et al., 1996). Both BCC and SCC are concentrated on the skin surfaces that are most exposed to the sun (Weinstock, 1993).

The estimated lifetime risk of BCC in the white population of the U.S. is 33% to 39% for men and 23% to 28% for women (Bader, 2008). BCC is rarely found in people under 40. Like SCC, BCC skin cancer incidence is a function of average UV-B irradiance in a geographic area, though the relationship is even stronger for BCC (Leffell and Brash, 1996; Heisler and Grant, 2000a).

We might expect average temperature to also be related to skin cancer incidence, because in warmer temperatures, people might wear less clothing to keep cool while outdoors. This could explain the fact that the relatively cool temperatures present in San Francisco result in lower incidence of BCC and SCC than predicted by the average July UV-B dose. However, in a simple regression analysis for the relationship between BCC and SCC incidence, with July UV-B dose and average temperature as predictor variables, temperature did not significantly add to the prediction of cancer incidence after UV-B dose was included (Heisler and Grant, 2000a). The relationship between the dress of pedestrians (skin exposure) and type of climate seems worthy of study. Human thermal comfort models are available that could be used in such studies (Heisler and Wang, 2002).

12.2.4.2 Melanoma

Cutaneous malignant melanoma (CM) is much more life threatening than BCC or SCC. The CM rate increased in the U.S. from 6.8/100,000 in 1973 to 17.4/100,000 in 1999 (Saraiya et al., 2004), and to an average of 19.4/100,000 from 2001 to 2005 (National Cancer Institute, http://seer.cancer.gov/statfacts/html/melan.html). It has been noted for many years that melanoma rates tend to be higher at lower latitudes, following the trend toward a higher incidence of solar radiation with decreasing latitude (Whiteman and Green, 1999).

It has been estimated that 65% to 90% of melanoma cases have been caused by exposure to the sun (Saraiya et al., 2004) with a higher estimated percentage of 95% occurring in Australia (Australian and New Zealand Bone and Mineral Society et al., 2005). One of the remarkable recent findings is that solar elastosis, a histologic indicator of cutaneous sun damage, has been positively associated with melanoma survival (Berwick et al., 2005), suggesting that people with melanoma who have had the most sun exposure have higher survival rates than those with less sun exposure. These observations raise the possibility that high amounts of vitamin D that result from high sun exposure may also increase melanoma survival. However, Berwick et al. (2005) state that other factors could be attributed to the increased survival rate among people with the highest sun exposure; for example, the association between sun exposure and early detection of melanoma.

Some reports suggest that CM is related to intermittent extreme sun exposure (Melville et al., 1991; Weinstock, 1993) rather than to cumulative exposure over long time periods. This is consistent with the fact that melanoma incidence tends to be higher of indoor workers than of outdoor workers (Koh and Lew, 1994), though it could also be consistent with indoor workers having low amounts of vitamin D. People diagnosed with melanoma often do have low vitamin D levels (Egan et al., 2005). Additionally, high exposure to the sun during childhood and early youth seems to positively correlate with CM incidence (Weinstock, 1993), particularly for those who suffered blistering sunburns. If sunburn is the primary cause of melanoma, then higher rates would be expected in mid-latitude U.S. regions where sunburn rates are highest among Caucasians (Saraiya et al., 2002).

An early study suggested that UV-A may be important in CM (Setlow, 1974). If so, there are a number of consequences. Some investigators hypothesize that the risk of melanoma may have increased because until recently, sunscreens blocked only UV-B and not UV-A. The suggestion is that blocking only UV-B is detrimental in part because UV-B causes the body to produce vitamin D, which may protect against melanoma (Garland et al., 1992). If the majority of solar-induced melanomas are caused by UV-A, then malignant melanoma will not be affected to any major extent by stratospheric ozone loss. Additionally, shade would be more important for melanoma prevention, because UV-A penetration is less than UV-B penetration into shaded areas (Grant and Heisler, 2001).

Higher incidence of CM has been assumed to be a result of increased UV due to ozone depletion (Madronich and De Gruiji, 1993). A 1996 examination of the effect of the Montreal Protocol and its amendments (Slaper et al., 1996) concluded that although UV-B would peak near the year 2000, skin cancer rates will continue to increase into the middle of the present century; approximately 10% higher than in 1976. By 2100, the Slaper study concluded that CM incidence rates would return to the 1976 levels.

12.2.5 Eye Diseases

The most common association between UV radiation and eye disease is the possibility that UV can cause senile cataracts, a clouding of the eye lens. Cataracts are the most common and severe chronic eye disease considered to be the cause for approximately 53% of the cases of blindness across the world (Long et al., 1996). Cataracts are treatable only by surgery in which the natural eye lens is removed and replaced by a plastic lens; the most common surgery in medicine (Belkin, 1994). The use of hats and eyeglasses can greatly reduce eye exposure to UV (Rosenthal et al., 1991), and it is evident that tree shade in urban areas would also reduce exposure. Parisi et al. (2001a) point out that the diffuse component of UV radiation is usually responsible for most eye damage because of the natural aversion people have to looking at the sun. They also measured UV-B and UV-A diffuse fraction in open areas as well as beneath trees (see Section 12.4.3). The epidemiology of cataractogenesis is complicated by the possibility that cataracts increase with higher air temperature (Sliney, 1986)

12.2.6 Sunscreen Effectiveness

The effectiveness of sunscreens is pertinent to the role of UV in urban areas because sunscreens provide an alternative to seeking shade. Sunscreens can clearly provide a high degree of protection against sunburn, dependent on the effectiveness number or sun protection factor (SPF). However, some studies have found a high incidence of sunburn even when there is a high rate of sunscreen use (Davis et al., 2002). There is uncertainty as to whether sunscreens that prevent sunburn can also prevent immunosuppression effects and tumors (Garland et al., 1992; International Agency for Research on Cancer, 1992; Gorman, 1993; Garland et al., 1994; Bestak and Halliday, 1996). Given the uncertainty about sunscreen effectiveness, there is a general concern that those who rely too heavily on sunscreen protection abandon other protective measures (Wright, 1994). Other possible measures of protection could include seeking shade at mid-day and wearing protective clothing.

12.2.7 Positive Impacts

It has long been recognized that some diseases are alleviated by moderate UV-B exposure (van der Leun and de Gruijl, 1993), though the benefits of vitamin D from sun exposure were generally not emphasized.

12.2.7.1 Vitamin D

Although more literature is now available regarding the benefits of UV in the production of vitamin D and the consequent reductions in non-cutaneous cancers, sorting out the risks and benefits of UV exposure is not a simple task. Humans benefit from UV radiation by the production of vitamin-D (e.g., Diffey, 1991; Webb, 1993; Harvard Women's Health Watch, 2004; Webb, 2006). Exposure to UV-B is involved in both synthesis and the breakdown of vitamin D by a complex series of photochemical reactions. These reactions regulate the production of vitamin D so that toxic levels are not reached (Webb, 1993; Webb, 2006).

Balancing the negative influences of exposure to UV radiation against possible benefits from vitamin D production has been termed a conundrum (Webb and Engelsen, 2005), and is indeed considered as such by many in the medical research community. However, some believe there is no conundrum. Their recommendation would be to avoid sun exposure and acquire vitamin D from a proper diet and supplements (Gilchrest, 2007). Others recommend that humans allow for moderate sun exposure, sufficient to photosynthesize adequate vitamin D, yet not to the point where skin damage occurs (Webb, 1993; Garland et al., 2002; Holick and Jenkins, 2003; Dowd and Stafford, 2008). Taking the opinion that a balance of exposure is best, McKenzie and Liley (Chapter 2 this volume) examine the time required to achieve balance in a range of climates. The balance is possible because only low levels of UV-B exposure, far less than one Minimal Erythermal Dose (MED) for the initiation of sunburn in light-skinned individuals, defined as 200 Jm^{-2}, is needed in the vitamin D synthesis process (Webb, 1993), although the time needed for adequate vitamin D varies widely depending on the levels of irradiance and spectrum, skin type, and clothing (Webb and Engelsen, 2005; McKenzie and Liley, Chapter 2, this volume).

Many articles suggest that vitamin D deficiency is currently not a common problem in North America, partly because of fortification of foods (Simard et al., 1991). However, a panel of experts convened by the U.S. Centers for Disease Control and Prevention (U.S. CDC) in 2001 indicated concern about recent rickets cases (Scanlon, 2001). Even though vitamin D supplements have apparently been a general public health benefit, irregular application of the supplements has been noted. Survey results have shown that many samples contained either much less or much more vitamin D than stated on the label (Chen, 1999). During the 1940s in Europe, foods fortified with excess amounts of vitamin D caused intoxication in infants, leading to hypercalcemia and irreversible brain damage (Chen, 1999). A 1995 study reported rickets to be a problem in Mexico City, because UV radiation was greatly reduced by pollution (Galindo et al., 1995). Low vitamin D is much more prevalent in dark-skinned populations in the U.S. In one study, hypovitaminosis D occurred in 40.4% of black women compared to 4.4% among white women (Giovannucci, 2005). Low levels of vitamin D are also common among women in religious groups that require most of the body to be covered (Gannagé-Yared et al., 2000; Glerup et al., 2000). Low vitamin D can also be a serious problem for those who have medical conditions that require avoidance of sun exposure, such as organ-transplant recipients, those with xeroderma pigmentosum, or people who must take medications that increase sensitivity to UV radiation (Reichrath, 2007).

The 2002 United Nations assessment of the effects of ozone depletion devoted a single paragraph to UV effects on vitamin D. While noting some evidence for high UV exposure or high levels of vitamin D in reducing the risk of some non-cutaneous cancers, it asserted that there is "no simple direct relationship between the vitamin D hormone and UV exposure because of the many regulatory feedback mechanisms," (De Gruijl et al., 2002). The 2006 United Nations assessment (Norval et al., 2007) has a more detailed treatment with about 50 citations dealing with vitamin D benefits for the immune system, internal cancers, autoimmune diseases, and possible infectious diseases.

The action spectrum for the formation of pre-vitamin D by sun exposure in human skin is based on a single study published in Science by MacLaughlin et al. (1982), but there are somewhat differing interpretations of this graphically represented spectrum. The spectrum has an approximate bell-shaped curve with a maximum near 295 nm and tails that approach 0 near 255 nm and between 315 nm and 320 nm. The original spectrum published in Science and republished at a larger size by Chen (1999) is plotted with a linear scale of response over one order of magnitude. It is not clear from the figure that the longer-wavelength end of the response actually reaches an absolute value of 0 by 315 nm, as has been assumed by some users (Webb et al., 1988; Webb, 1993; Kimlin, 2004; Engelsen et al., 2005), or whether it extends to longer wavelengths. A close perusal of the action spectrum curve suggests it approaches 0 in the vicinity of 320 nm asymptotically, and may extend beyond 320 nm. Michael Holick (pers. comm., July 22, 2005), one of the original authors of the Science article, expressed his belief "that the limit of 315 nm is correct." Even a small response at 320 nm could be significant under natural solar radiation because irradiance is typically three orders of magnitude larger at 320 nm than at 295 nm or 296 nm where the vitamin D response apparently peaks. Webb and Engelsen (2005) extrapolated the MacLaughlin relative vitamin D action spectrum to 0.001 at 320 nm, which would somewhat affect the action spectrum convoluted with a solar irradiance spectrum. Figure 2.1 shows the relative action spectrum for vitamin D interpreted from the figure in Chen (1999), with the exception that the Webb and Engelsen (2005) extrapolation to 320 nm is used. The convolution of the action spectrum with a typical solar irradiance spectrum in Fig. 2.1 shows the wavelength most important for vitamin-D to be about 310 nm. A 2006 report by the International Commission on Illumination (CIE) (Bouillon et al., 2006) tabulated a re-interpretation of the vitamin D action spectrum from MacLaughlin et al. (1982) and extrapolated the tail to a value of 0.000,078 at 330 nm. The new interpretation of the vitamin D action spectrum is contrasted to the CIE erythema action spectrum in Fig. 2.5 of McKenzie and Liley (Chapter 2, this volume).

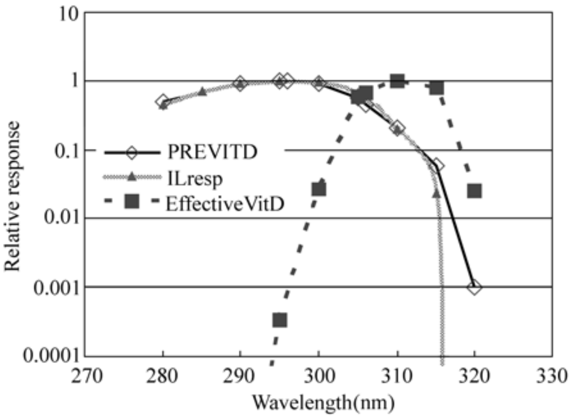

Figure 12.1 Action spectrum of pre-vitamin D_3 formation in human epidermis (PREVITD) from Webb et al. (1988), typical response of International Light UV-B radiometer SED240/UV-B/W (ILresp), and relative effectiveness of typical solar irradiance spectrum in formation of pre-vitamin D_3 (adapted from Heisler, 2005)

Figure 12.1 also shows the typical manufacturer-provided response function of an International Light SED240/UV-B/W filtered vacuum photodiode UV-B sensor (IL)[1]. The response was shown by the manufacturer only for every 5 nm, with a finite response at 315 nm and zero response at 320 nm. Up to 315 nm, the relative IL response is nearly identical to the MacLaughlin et al. (1982) vitamin D action spectrum, and depending upon the interpretation of that action spectrum, the similarity may be even closer between 315 nm and 320 nm than Fig. 12.1 suggests. The IL sensors were used in a series of measurements of tree influences on UV-B irradiance at Purdue University (Grant and Heisler, 1996; Grant, 1997; Grant and Heisler, 2001; Heisler et al., 2003a). Thus, the results of those measurements should relate closely to vitamin D synthesis.

Early evidence that UV-B exposure in mid and high latitudes during winter was limiting for vitamin D photosynthesis was provided by high incidence of rickets in winter (Chen, 1999). A model recently available online (http://zardoz.nilu.no/%7Eolaeng/fastrt/VitD.html) (Engelsen et al., 2005) provides easily obtained estimates of the length of time during a day that UV-B irradiance would be sufficient to photosynthesize pre-vitamin D from 7DHC, which is one of the important roles of UV-B radiation in regulating vitamin D (Holick, 1999).

A CIE standards committee issued a report with a slightly revised interpretation of the MacLaughlin et al. (1982) vitamin D action spectrum (Bouillon et al., 2006). This spectrum is used by McKenzie and Liley (Chapter 2, this volume) to explore diurnal, seasonal, and latitudinal differences between erythemally weighted and pre-vitamin D-weighted irradiances. McKenzie and Liley point out

1 Company names are provided for the convenience of the reader and do not constitute an endorsement of a product by the USDA or the Forest Service.

that because pre-vitamin-D weighting depends more strongly on the shorter UV wavelengths, it is more dependent on ozone and solar zenith angle (SZA) than erythemal weighting.

12.2.7.2 Apparent Anti-Cancer Benefits of UV

Among the vast array of literature recently published on the possible benefits of UV exposure for preventing or reducing the progression of a multitude of cancers are two reviews of special note written by Giovannucci (2005) and Grant and Holick (2005) on the effects of vitamin D, and a report stating that greater exposure actually increases survival among melanoma victims (Berwick et al., 2005; Egan et al., 2005). It has been observed that malignant melanoma is often accompanied by low 1,25-dihydroxyvitamin D_3 (the active form of vitamin D) serum levels (Egan et al., 2005). A study by Smedby et al. (2005) found reduced risk of non-Hodgkin lymphoma in individuals with high exposure to sun.

Although the benefits of sun exposure for cancer reduction were mentioned in Apperly (1941) and Peller and Stephenson (1937), the school of thought that low exposure to UV-B is associated with an increased risk of non-cutaneous cancers apparently began in earnest with Garland and Garland (1980), who suggested that vitamin D reduces the risk of colon cancer. Papers that suggest sunlight reduces the risk for breast cancer are Gorham et al. (1989), Garland et al. (1990), Gorham et al. (1990), and Grant (2002a); papers indicating a reduced risk for other non-cutaneous cancers were written by Grant (2002b, c; 2003) and Lefkowitz and Garland (1994). Grant (2002b, 2003) found inverse associations between regional summer UV-B irradiance and cancer risk for 14 kinds of cancer. Table 12.1 lists current findings and associated references on the effects of UV-B exposure and vitamin D, and the risks of acquiring, and mortality rates for, 15 different cancers. A few studies made direct associations between vitamin D levels of individuals and the risk of cancer, some of which are shown in the last column. These reports are increasingly noted in the popular press, e.g., Newsweek (Cowley, 1991; Raymond and Adler, 2005) and Reader's Digest (Dranov, 2006).

A difficulty in the epidemiology is that there are many possible confounding effects relating to cancer incidence, and the total list of these influences can usually not be included in an analysis. For example, there is a decided trend of increased incidence of breast cancer from south to north in the US (Garland et al., 1990; Sturgeon et al., 1995). This trend has been interpreted as being caused by decreased vitamin D production with the lower UV-B exposure in the north (Garland et al., 1990). However, according to Sturgeon et al. (1995), most of the geographic variations in breast cancer can be explained by demographic patterns. For example, women residing in the southern areas of the U.S. typically give birth to their first child at a younger age, and their breast cancer mortality rate is lower. However, the study by Sturgeon et al. (1995) did not examine environmental factors such as UV exposure. Giovannucci (2005) cited examples that suggest an inverse relationship between sun exposure and breast cancer, but did not mention incidence of first childbirth at a younger age in the south nor the 1995 Sturgeon et al. paper. Until recently, the potential effect of vitamin D on cancer was often, perhaps usually, not included in cancer epidemiological studies (Giovannucci, 2005).

Although an apparent vitamin D effect in reducing cancer risk and virulence has been deduced for a large range of cancers, individual cancers differ in their response to vitamin D. For example, the relationship between vitamin D and prostate cancer is mixed (Giovannucci, 2005), though there does appear to be a positive relationship between very low 1,25(OH)2 D (the active form of vitamin D) and a higher risk and greater progression of prostate cancer (Giovannucci, 2005).

12.3 UV Climatology

12.3.1 Ozone Trends

Most research reports on UV radiation effects assume continued depletion of ozone, (e.g., Ono et al., 2005). As recently as 2004, a report from the CDC alluded to prospects for additional increases in UV-B as a result of ozone depletion (Saraiya et al., 2004), although, in doing so, they cited Diffey (1991) and Koh et al. (1993), rather than more recent work on stratospheric ozone trends.

Ground level measurements of total column ozone (TOC, includes ozone in the lower atmosphere, the troposphere, and the stratosphere—the major part of total column ozone) are made at about 30 locations In the U.S., with UltraViolet MultiFilter Rotating-Shadowband Radiometer (UV-MFRSR) instruments (Slusser et al., 1999; Gao et al., 2001), which have the advantage of automatically measuring total column ozone under most cloud conditions. Some of these measurements were recorded over the course of a decade, which is sufficient for predicting ozone trends. An examination of operational ozone measurements by UV-MFRSRs at Beltsville and Queenstown, MD since 1999 (data from the USDA UV-B Monitoring and Research Program, http://uvb.nrel.colostate.edu/UVB/index.jsf) indicates that there are cycles of $\pm 10\%$ in the differences in TOC (depth of all ozone in the atmosphere if it could be brought together in a layer, measured in Dobson Units (DU) = 0.001 cm) measured at the two UV-MFRSR sites, but that long-term averages between the ozone records are similar. The ratio of the Beltsville UV-MFRSR ozone to Brewer (Brewer Spectrophotometer, an instrument to measure TOC, SO_2, and UV spectra) measurements of ozone at the National Atmospheric and Space Administration, Goddard Space Flight Center (NASA/GSFC) at nearby Greenbelt, MD (data from Alexander Cede and Gordon Labow) is 0.996 over about four years.

A cursory examination of the TOC records from the Earth Probe Total Ozone Mapping Spectrometer (EPTOMS) satellite for Washington, DC, the UV-MFRSR sensors at Beltsville and Queenstown, MD, the Brewer sensor at GSFC, and the recent Ozone Monitoring Instrument (OMI, which continues the TOMS satellite ozone measurements) ozone measurements (data from Gordon Labow) suggests that ozone in this locale tended to level off between 2000 and 2005. This conclusion is reached even after making allowance for the observed error in TOMS ozone since 2002 (Gordon Labow, pers. comm.), the cycles in the UV-MFRSR measurements, and the preliminary nature of the OMI measurements. One impression from examining TOC records over a period of years is that variability is large over short periods, and that there is a great need for continued ozone and UV monitoring, improvement of monitoring instrumentation and systems, and characterization of extreme ozone and UV events. Grant and Slusser (2005) point out the importance of extreme ozone events for crops research; the same no doubt applies to human health.

The 1998 United Nations Environment Programme assessment of ozone depletion estimated that since the 1970s, the northern temperate regions have experienced increases in erythemal UV radiation of approximately 4% in summer and fall, and 7% in winter and spring (Madronich et al., 1998). In the Southern hemisphere, the corresponding increase was about 6% year-round. The 1998 assessment indicated that international agreements to limit emissions of ozone depleting substances were showing evidence of success in reducing most, but not all, types of the depleting chemicals, and it suggested that a turnaround in ozone depletion and high levels of UV-B radiation might begin about 2000. By 2003, there was some evidence that the trend of ozone reductions was at least slowing (Newchurch et al., 2003; Malanca et al., 2005). While these studies show a slowing trend in ozone reductions, they do not show ozone increases. The return to the ozone and UV-B conditions that existed prior to the 1980s is apparently still decades away (Weatherhead et al., 2000; McKenzie et al., 2003; World Meteorological Organization (WMO), 2003; Weatherhead and Andersen, 2006). The 2006 WMO assessment estimates that global (60°S – 60°N) ozone will return to pre-1980 levels around the middle of the 21st century, at or before the time when stratospheric abundances of ozone-depleting gases return to pre-1980 levels (WMO, 2007).

The possible effect of greenhouse gases and global temperature change on stratospheric ozone causes additional uncertainty in the recovery process; greenhouse gases may speed ozone recovery because the gases lead to cooling of the stratosphere, which reduces the efficiency of the catalytic ozone destruction processes (WMO, 2007; Dyominov and Zadorozhny, 2008). However, periods of unusually low stratospheric ozone at mid-latitudes correspond with the intrusion of sub-tropical air masses (Bojkov and Balis, 2001; Siani et al., 2002), which further underscores the need for continued monitoring. Climate change will also influence surface UV radiation through changes in cloud formations and the ability of the earth's surface to reflect light (WMO, 2007).

12.4 Urban Structural Influences

The overall impression left by medical literature is that UV radiation in urban areas does have important consequences for human health, but that because little is known about the influence of urban structure on UV exposure, the epidemiological effects of UV radiation in urban areas are not being fully evaluated. Thus, knowledge and methods to predict spatial and temporal distribution of UV would be very beneficial to epidemiology. Such knowledge could also benefit public education and urban planning.

There can be significant differences between reductions of the visible portion of the solar spectrum (that is, the shade pattern we see) and reductions of UV by trees and other structures in urban areas. Large differences may occur in relative irradiance (below/above urban canopy) between the visible and thermal radiation that people see and feel and the ultraviolet spectrum. The differences occur partly because visible and UV radiation differ in the diffuse fraction of total irradiance (Grant and Gao, 2003), in the distribution of sky radiance (Grant, 1985; Grant and Heisler, 1997; Grant et al., 1997a, b) in reflectivity of urban structural surfaces (Heisler and Grant, 2000a), and in optical properties of leaves at different wavelengths (Grant et al., 2003).

12.4.1 Sky Radiance and Diffuse Fraction

It is well known that the atmosphere scatters shorter wavelengths of solar energy much more than longer wavelengths, and that the scattering increases with SZA (Iqbal, 1983). Usually, more than half of the UV-B irradiance arriving on earth is from diffuse radiation from the sky. The greater fraction of radiance from the sky has profound implications for the amount of UV-B irradiance in urban ecosystems.

Not only the sky radiance fraction, but also the distribution of sky radiance, is important in determining irradiance in urban ecosystems where often much of the sky is in view. Models of radiance distributions have been developed for use in predictions of tree and building effects on irradiance (Grant and Heisler, 1996; Grant et al., 1997a, b). The distribution for photosynthetically active radiation (PAR, essentially visible radiation) has a large gradient in radiance in the sun half of the sky and a decided dark portion opposite the sun in the other half of the sky (Grant et al., 1996; Grant and Heisler, 1997). The pattern for UV-A is similar to the pattern for the PAR, though the gradient is smaller. The UV-B distribution has a generally smaller gradient, that is, the irradiance is relatively equal from all parts of the sky, owing to the greater scattering of the energy in this waveband (Grant and Heisler, 1997; Grant et al., 1997a).

12.4.2 UV Reflectivity

The radiation environment in urban areas depends, to a large extent, on the reflectivity of the building materials, paving surfaces, and vegetation. Reflectivities in the UV for many surfaces have been tabulated (Sliney, 1986; Blumthaler and Ambach, 1988; Feister and Grewe, 1995; Heisler and Grant, 2000a). However, reflectivity differences for particular materials within a type (i.e., variances in: (1) color and kind of paint, (2) concretes, (3) building siding, and (4) specialty glass) seldomly seem to be available for the UV, although albedo for total solar radiation is more likely to be available. Almost all surfaces, except snow surface (albedo may be greater than 90%), have UV reflectivities of less than 25%; and only a few materials have UV albedo over 10%. Water and glass have low UV reflectivity at near normal incidence, but may reflect most UV radiation at nearly glazing incidence (Koller, 1965). This means that with high incidence angles, reflection from glass-walled buildings could nearly double the UV-B irradiance on a person standing near the building (Heisler and Grant, 2000a).

A suggestion for making buildings more energy efficient and cities cooler is to increase the albedo of sidewalks, streets, and building surfaces (Akbari et al., 1990; Levinson and Akbari, 2001). Whitening wall or paving surfaces may significantly increase UV-B irradiance on pedestrians and may also increase UV-B loads on vegetation. Heisler and Grant (2000a) estimated that if roof or pavement surfaces were whitened in a sufficient portion of a city so as to increase the general reflectivity of the landscape by 35 percentage points, probably the maximum possible, UV-B reflectivity might be increased up to 20%, again probably the maximum possible, and downward UV radiation at ground level might be increased by about 3%. While some programs have recently been successful for stimulating the lightening of building roof surfaces, the whitening of paving has been limited (http://www.epa.gov/heatisland/strategies/coolpavement.html).

Because the transmission of UV radiation through leaves is negligible for almost all tree species (Yang et al., 1995; Gao et al., 1996; Qi et al., 2002; Grant et al., 2003; Qi et al., 2003a, b; Qi et al., Chapter 18, this volume), leaf optical properties are essentially a matter of reflectivity from the leaf surface. Ultraviolet reflectivity is generally less than 10%; this value is low compared to PAR reflectivity, which is generally in the range of 10% to 30%.

12.4.3 Tree and Building Influences on UV

12.4.3.1 Measurements

Along with protective clothing and sunscreen use, seeking shade is a primary means recommended by public health agencies to avoid excess exposure to UV radiation (Environmental Protection Agency, 1995; Parisi and Kimlin, 1999; Saraiya et al., 2004). However, tree effects on UV may differ significantly depending on the view of the sky and to some extent, the trees species. Ultraviolet shadows generally differ substantially from the shadows of visible light (Heisler et al., 2003a); with UV shadows being more "fuzzy" and much less sharp edged than visible shadows. Most research on shading structures and trees has been carried out under the premise that minimizing UV exposure at all times is most beneficial to people (Grant, 1997; Moise and Aynsley, 1999; Gies and Mackay, 2004); however, this view may change with increased value placed on the solar production of vitamin D.

The distribution of radiance across the sky for different wavelengths is important for irradiance in urban areas. With distributions such as the PAR, where most of the sky radiance emanates from regions close to the sun, shadows are distinct, and irradiance at points within a shadow is minimally enhanced by radiance from regions of the sky farther from the sun (Grant et al., 1996; Grant and Heisler, 1997). For the UV-A, and more so for the UV-B (Grant and Heisler, 1997; Grant et al., 1997a, b), the radiance is more evenly distributed across the sky, so that in shadows, irradiance may be considerably augmented by sky radiance if large areas of the sky are in view. This effect is enhanced by the greater proportion of total irradiance in the open that comes from the sky in the UV bands (Grant and Gao, 2003).

One effect of shade is the increase in the diffuse fraction (ratio of diffuse to direct-beam radiation). Parisi et al. (1999) found the average full-sun diffuse fraction for UV-B radiation in the open was 0.39, 0.26, and 0.46 during the morning, noon, and afternoon, respectively. In tree shade, the diffuse fractions were increased so that they averaged 0.60 to 0.61 for any of the time periods.

Available information on tree influences on UV irradiance is largely derived from essentially anecdotal measurements under a few trees with broadband sensors (e.g., Grant and Heisler, 1996; Moise and Aynsley, 1999). Spectral measurements at tree and in open have been taken simultaneously because of the limited availability of only one spectroradiometer (Parisi et al., 2001b). Part of the reason for the scarcity of data is the surprising difficulty in finding individual trees located where irradiance near or under the tree is not influenced by buildings or other nearby trees. The possibility for replications of measurements for full-sized trees of the same species is especially unlikely.

Results from a survey of tree influences on UV radiation (shown in Table 12.2) (Grant and Heisler, 1996; Heisler et al., 2003a), illustrate the effect of mature deciduous street trees, typically found in older suburban neighborhoods, on the PAR and UV-B irradiance at points of pedestrian height with significant sky views. Irradiances measured with UV-B and PAR sensors close together on one tripod were averaged over half-hour time periods at a mid-western US location (latitude 40.5°N). The sensor that measured the UV-B (an International Light SED240/UV-B/W) had a response from 280 nm to 320 nm, cutting off sharply before 320 nm, unlike erythemal sensors that extend into the UV-A (Fig. 12.1). Skies were clear for all measurements. Comparable irradiances measured at a rural field provided an open-condition reference. Upward-facing, hemispherical-view photos from each measurement point (Fig. 12.2) showed that the percent of effective sky view varied from 34% to 60%. The examples include configurations where the shade was provided by trees only (Fig. 12.2(a), (b), (c)), and also by trees and buildings (Fig. 12.2(g)).

In the examples shown in Table 12.2, for in-leaf trees in the shade, PAR was as low as 15% of irradiance in the open (Point b), and UV-B was 44% of open. Conversely, at locations near in-leaf trees, but out of their visible shadow, PAR was not appreciably reduced, while UV-B measured at Point e was only about 59% of that in the open. Trees with only bare branches and twigs can cause substantial reductions in irradiance (Heisler, 1985). Table 12.2 also shows that the 44% of UV-B in the shade of leafless trees was only 7 percentage points more than the relative irradiance in the shade of in-leaf trees. The difference in relative irradiance in the UV-B was much less between shade and sunlit points (averaging 24 percentage points for in-leaf trees vs. 16 percentage points for leafless trees) than in the PAR (averaging 81 percentage points for in-leaf trees vs. 67 percentage points for leafless trees).

The UV-B relative irradiances in Table 12.2 are representative of tree effects, though irradiance will differ somewhat with a greater range of SZA and turbidity of the sky. The important contrast is between the relative irradiance in the UV-B

Table 12.2 Average UV-B and PAR irradiance below a street-tree canopy as a percent of irradiance in the open, away from any obstructions (Grant and Heisler, 1996; Heisler et al., 2003a). Column α is solar zenith angle. Sky views are expressed in percent; they would be converted to decimal fractions (0 to 1) in equations

		Percent of irradiance in open		Percent of view				α
Point		UVB	PAR	Buildings	Trees	Sky	Sky_{eff}*	
In-leaf								
Shade	a	21	16	—	32	68	57	57
	b	44	15	—	46	54	47	47
	c	47	18	—	53	47	52	52
Sunlit	d	74	97	—	45	55	45	45
	e	59	96	—	33	67	51	51
Out-of- leaf								
Shade	f	44	27	—	41	59	34	34
	g	30	53	23	17	60	53	53
Sunlit	h	69	96	—	30	70	36	36
	i	56	96	—	43	57	45	45
	j	41	95	31	13	56	60	60

* Sky_{eff} is sky view weighted according to the proportional contribution to irradiance on the horizontal from each 10º zenithal band of the sky.

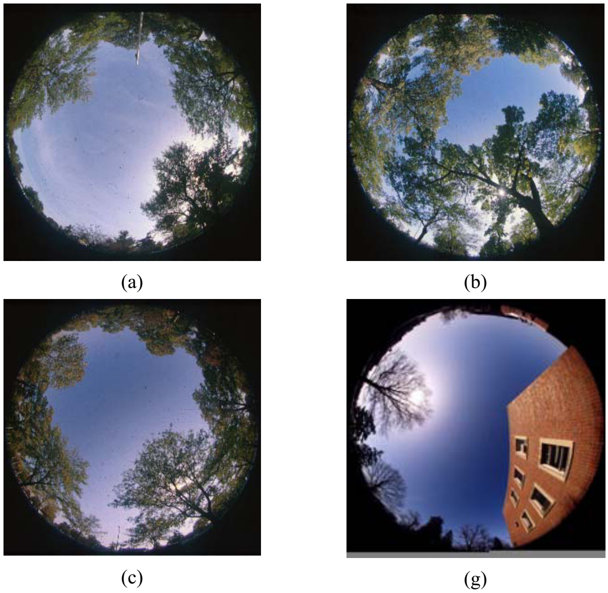

Figure 12.2 Fisheye photos from locations where below-canopy irradiance was measured as listed in Table 12.2. Frames (a), (b), (c), and (g) indicate points listed in the table

and the visible (represented by the PAR band). Most of the in-leaf measurements were made in early September with SZAs ranging from 47° to 57°. Relative irradiances, particularly in the UV-B, would be expected to be smaller because of less scattering with smaller zenith angles and smaller diffuse fractions during mid-day in midsummer.

Differences in sky diffuse fraction are primarily responsible for the differences between UV-B and visible relative irradiance, although differences in reflectance, particularly for sunlit points, can also contribute, especially near building walls. At Point g (Table 12.2 and Fig. 12.2) where a building with a sunlit red brick wall made up 23% of the view, reflection from the wall led to a greater relative irradiance for PAR at a tree-shaded point than when no wall was present. In the UV-B waveband, the wall reduced the relative irradiance because reflection in the UV-B from the brick surface was less than the irradiance that would have come from the sky had the building not been present. Measurements showed that the brick building wall with some windows reflected about 18% of incident visible radiation, whereas according to calculations, it reflected only about 3% of the UV-B.

The effect of reflected radiation from tree crowns on irradiance near the tree is less apparent. As noted in Section 12.4.2, leaf reflectance in the UV-B is about 5% for most species, and PAR reflectivity may be three times larger. Thus, tree crowns contribute little scattered UV-B to adjacent points. However, reflection from trees would be significant in the PAR, and this could partly explain the small reduction of 3% for PAR in sunlit points near trees (Table 12.2).

Other studies have shown results comparable to those in Table 12.2. Where the sun is only obscured by a small tree crown leaving a large portion of the sky in view, the contrast between reductions in the visible and UV wavelengths is even more pronounced. For example, with a tree blocking only 20% of the sky view, UV-B relative irradiance was 63% compared to a visible relative irradiance of about 10% (Grant, 1997).

The potential effect of differences in tree species on UV-B irradiance below their crowns has not been well quantified (Heisler et al., 2003a). This is due to such factors as: (1) the importance of diffuse sky radiation in determining irradiance below tree crowns; (2) the difference in crown density with tree size and pruning regimes, and (3) the considerable difficulty of sampling irradiance effects of individual tree crowns when no other nearby trees and buildings have any influence. These tree and building influences are especially important in the UV-B.

Reductions in UV-B can almost be complete where trees obscure most of the sky. In tropical Australia, UV-B irradiance with clear sky conditions and a range of SZAs was reduced to an average of only 3% by the "dense foliage" of a fig tree, though sky view was not specified (Moise and Aynsley, 1999). This was a greater reduction than provided in seven other urban shade structures that ranged from a school grandstand to a concrete walkway cover. There are also large reductions of UV-B under dense forest canopies. Where the sky is nearly completely obscured and UV-B irradiance is reduced to essentially negligible levels, relative PAR penetration will be greater than UV-B penetration (Lee and Downum, 1991; Brown et al., 1994). This might be expected due to the low transmittance of UV radiation through leaves (Grant et al., 2003). Even in forest canopies with thin but horizontally uniform leaf distributions, UV-B is attenuated more than the PAR (Yang et al., 1993).

In order to more precisely evaluate the influence of tree shade on human health, the tree shade influence on various action spectra for health effects, (i.e., pre-vitamin D and erythema) can be modeled if the irradiance spectra are known. Spectroradiometer measurements at Toowoomba, Australia (27.5°S latitude) showed a linear increase in average relative irradiance with decreasing wavelength from 400 nm to 300 nm in the shade of five Australian trees. Relative irradiance at 300 nm was almost double that at 400 nm (Parisi and Kimlin, 1999). Similar measurements were made by Parisi et al. (2001b) for a camphor tree (*Cinnamomum camphora*) with a "medium dense" canopy that was 6.4 m tall and had a 4.2 m-wide canopy that extended to only 0.4 m from the ground. Interpretation of irradiance ratios in shade to irradiance in the open (see Fig. 12.2, Parisi et al., 2001b) yielded the shade ratios as shown in Fig. 12.3 for irradiance in the shade below the edge of the tree crown. A polynomial (shade ratio $= 1.04 \times 10^{-5} \lambda^2 - 0.0105 \lambda + 2.778$, $\lambda =$ wavelength in nm) fit the interpreted points closely ($R^2 = 0.995$) as shown by the curve in Fig. 12.3. The measurements of Parisi et al. (2001b) below the tree crown, but half way from the edge of the crown to the tree trunk, had similar shade ratios. However, at the trunk, essentially all of the sky was blocked from the spectroradiometer's view and the shade ratios varied less by wavelength, ranging from about 0.15 at 305 nm to 0.10 at 395 nm. Figure 12.3 also shows a typical UV spectrum in the open for Lauder, New Zealand at 45°S from Fig. 2.5 in McKenzie and Liley (Chapter 2, this volume) and a predicted spectrum in the tree shade by applying the polynomial curve fit to the Parisi et al. (2001b) shade ratios.

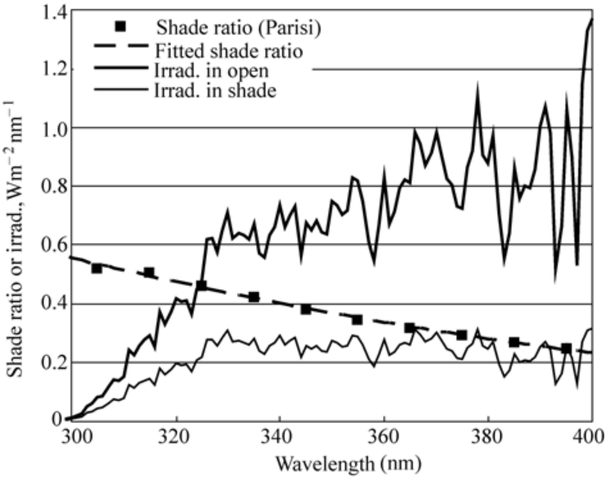

Figure 12.3 Ratio of spectral irradiance on horizontal surfaces in tree shade to irradiance on the horizontal in the open (Parisi et al., 2001b) = square points; polynomial fitted to the shade ratio points = dashed line; spectra of UV irradiance in the open at Lauder, New Zealand on the summer solstice from McKenzie and Liley (Chapter 2, this volume) = heavy black line; and irradiance in tree shade predicted by the Parisi et al. (2001b) shade ratios = thin line

The ratio of vitamin-D-weighted irradiance to erythema-weighted irradiance in tree shade can be higher than in the open. Figure 12.4 shows the irradiances in the open and in the tree shade from Fig. 12.3, but with weighting for erythema (UV_{Ery}) and pre-vitamim D production (UV_{VitD}) using the CIE spectrum for pre-vitamin D (Bouillon et al., 2006). Integrating across wavelength, the ratio of UV_{VitD}/UV_{Ery} is 1.95 in the open and 2.03 in the tree shade. In the example here, the difference is small between UV_{VitD}/UV_{Ery} in the open and in tree shade, and may not be of practical significance, although this ratio will generally be higher in tree shade than in the open. The UV_{VitD}/UV_{Ery} ratio in tree shade would likely be somewhat higher for a location in the shade of a small isolated tree crown, where a large portion of the sky would be in view.

12.4.3.2 Models of Tree Influences on UV-B Irradiance

Traditional methods for modeling solar irradiance below tree canopies have been applied to modeling tree influences on UV. Examples include: (1) use of Beer's law with knowledge of the leaf area index (LAI) for relatively uniform forest

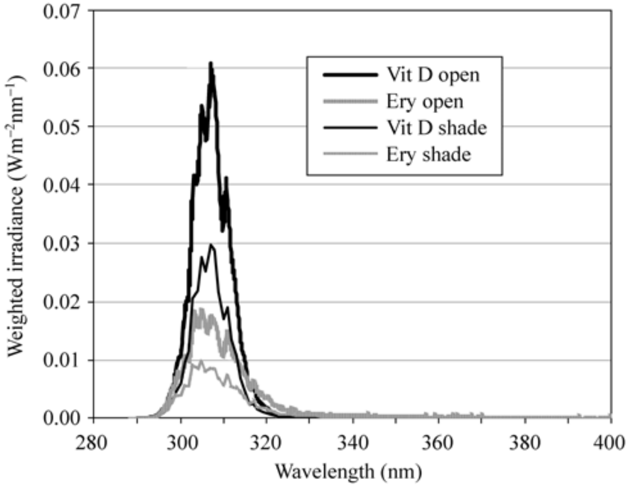

Figure 12.4 The irradiances in Fig. 12.3 for Lauder, New Zealand on the summer solstice from McKenzie and Liley (Chapter 12, this volume) weighted for erythema (grey) and pre-vitamin D production (black) in the open (thick lines) and in tree shade (thin lines) modeled with the shade ratios of Parisi et al. (2001b)

canopies (Yang et al., 1993); (2) models based on fisheye (hemispherical) photos from below the canopy (Grant and Heisler, 1996); and (3) mathematical models that describe the canopy as a series of ellipsoidal shapes of specified porosity (Gao, 1997; Gao et al., 2002).

Beer's law can be used to model the mean UV-B penetration into the forest as a function of LAI for tree influences of a closed uniform forest canopy. Yang et al. (1993) measured the vertical profile of LAI and of broad-band UV-B, PAR, and total global radiation in an oak forest in Pennsylvania. They expressed Beer's law as:

$$t = e^{-k(\text{LAI})} \tag{12.1}$$

where t is the canopy transmission function for a given wavelength band (UV-B, PAR, and total) at a given depth designated by the cumulative LAI downward from the top of the canopy, and k is the corresponding extinction coefficient for the profile. Yang et al. (1993) measured the profile of LAI and irradiance on the horizontal by moving radiation sensors and a canopy analyzer up and down through the canopy on a telescoping tower with a self-leveling platform for the sensors. Average total LAI of the forest was 1.69; measurements were made in late August, after the forest had been partly defoliated by insects earlier in the summer. By regression analyses, Yang et al. (1993) found k values of 0.86, 0.79, and 0.64 for UV-B, PAR, and total solar radiation, respectively. Thus extinction decreased in the order UV-B, PAR, and total global radiation.

To model irradiance on horizontal surfaces, I_{hor}, at locations below non-uniform tree canopies, Grant and Heisler (1996) explored some relatively simple methods based on tree and sky view factors determined from hemispherical photographs (Fig. 12.2). The photographs were analyzed manually to estimate sky view by projecting the images onto a grid with radii and concentric zenith angle circles at 10° intervals beginning at 5° of sky zenith and azimuth, and then counting the number of grid intersections that fell on open sky. Measurement results for these sample locations beneath the street trees are presented in Table 12.2.

The modeling methods included use of a "bulk model" with the assumption that:

$$I_{\text{hor}} = I_{\text{dir}}\delta + f_{\text{sky}} I_{\text{dif}}, \tag{12.2}$$

where I_{dir} was the direct beam irradiance above the canopy, δ was 1 if the point was sunlit and 0 if in shade, f_{sky} was the fraction of the sky visible from the point, and I_{dif} was the diffuse irradiance above the canopy. Implicit in Eq. (12.2) is the assumption that there is no transmission through leaves; no reflection from branches, leaves, or buildings; and that sky radiance is uniform for all sky zenith and azimuth angles. The fraction transmitted to the below-canopy point, T_{canopy}, was modeled as:

$$T_{\text{canopy}} = f_{\text{sky}} F_{\text{diff}} + \delta(1 - F_{\text{diff}}), \tag{12.3}$$

where F_{diff} was the diffuse fraction (0 to 1) of total global radiation.

In the UV-B, F_{diff} varies with atmospheric aerosol content, and though Grant and Heisler (1996) assumed aerosols to be a constant average value in their model, they estimated that over the range of possible aerosol content with clear skies, errors in aerosol content could lead to errors in estimated F_{diff} of about 12% for UV-B and 16% for PAR. The TOC could also affect F_{diff}, though Grant and Heisler (1996) estimated that for a SZA of 40°, and TOC ranging from 250 DU to 450 DU (Dobson units), which is about the maximum range for northern mid-latitudes, F_{diff} would vary by approximately 2%.

Because F_{diff} is typically 0.50 or more, the distribution of I_{diff} across the sky may be important for modeling T_{canopy}. The 'bulk model' of Eq. (12.3) assumed a uniform radiance distribution. A "bulk zonal model" assumed a sky radiance distribution that varied with sky zenith and azimuth, as:

$$T_{\text{canopy}} = \sum[f_{\text{sky},\theta} \Psi_\theta F_{\text{diff}} + \delta(1 - \Psi_\theta F_{\text{diff}})], \tag{12.4}$$

where $f_{\text{sky},\theta}$ was the sky view within each 10° band of sky zenith, Ψ_θ was the normalized sky radiance for the band ($\sum \Psi_\theta$ over the nine bands = 1), and the summation of the right side of Eq. (12.4) is over the nine bands. The term Ψ_θ was derived by applying a previous model of UV-B and PAR sky diffuse radiance distributions for clear sky conditions as functions of zenith and azimuth relative to the sun location (Grant et al., 1996; Grant et al., 1997a). For evaluation of the benefit of including the anisotropic sky radiance, T_{canopy} was also modeled with sky radiance assumed to be uniform across the sky.

Grant and Heisler (1996) also used a "generalized" model that included transmission through tree crowns as sun flecks for generally shaded locations. Over the half-hour sampling periods, transmission to a below-canopy was modeled as:

$$T_{\text{canopy}} = \sum(f_{\text{sky},\theta}\Psi_\theta F_{\text{diff}}(1 - P_{\text{dir}}) + [1 - F_{\text{diff}}(1 + f_{\text{sky},\theta}\Psi_\theta)])P_{\text{dir},} \tag{12.5}$$

where P_{dir} was the sun fleck probability of the crown through which the direct beam penetrated, and again, the summation is over the nine bands. The P_{dir} term was estimated by analysis of hemispherical photographs.

The three different modeling methods showed moderate success in matching measurements. When measured, T_{canopy} was either less than 0.2 or greater than 0.9; the match was within 0.10. The mean bias error was generally low; in the UV-B it was +0.106 for the bulk model, −0.04 for the zonal model with anisotropic sky, and −0.012 for the generalized model. However, in the mid-range of measured T_{canopy}, deviations of modeled values from measured values were as large as 0.24 for the generalized model and even larger, up to 0.31, for the bulk model. Some of the modeling error is most likely caused by the rather course 10º photo analysis. Using the Gap Light Analyzer Program (Frazer et al., 1999) to determine sky view would probably increase modeling accuracy. A study using GLA analysis to estimate UV irradiance in below canopy spaces in Baltimore, MD is currently underway (Heisler et al., 2003b). The study will be based on data from hemispherical photos taken from the centers of urban-forest-inventory plots (Nowak et al., 2004).

By using tree cover from urban tree inventories (Nowak et al., 2004), and assuming that tree cover is uniformly distributed, estimates of average UV-B exposure across urban neighborhoods with differing tree cover can be derived from above-canopy irradiance models (Grant and Heisler, 1999) and from the transmission model of Gao et al. (2002) for UV irradiance below canopies of assumed ellipsoidal shaped crowns. Initial estimates indicate that for a mid-latitude city, average UV-B relative irradiance ranges from 0.33 in single-family residential neighborhoods to about 0.60 in parks and neighborhoods with multiple family dwellings (Grant and Heisler, 1999). This method predicted that in Baltimore neighborhoods consisting of high density residential buildings, with mean tree cover of 20%, there would be an average of 5.0 MED of erythemal radiation over the area between the hours of 10:00 to 14:00 during summer months. In mid- and low-building-density neighborhoods with an average tree cover of 32%, only 3.9 MED of erythemal radiation would be available for exposure to pedestrians during that same time period (Grant et al., 2004; Heisler et al., 2004). Average cloud cover was included in the modeling. According to assumptions of Webb and Engelsen (2005), fair-skinned individuals with one-fourth of their body exposed would require about one hour of exposure to acquire a recommended daily 1000 IU of vitamin D.

12.4.4 Human Exposure

In studies of school children's exposure to UV, boys usually have greater exposure than girls (Melville et al., 1991; Ono et al., 2005). Methods of surveying school children for their exposure were recently described (Ono et al., 2005). One reported trend in U.S. elementary schools is the elimination of outdoor recess (DeGregory, 2005), which would remove the option for significant sun exposure for most children for five days of the week during the school year. Policies for outside time vary widely at different schools, ranging from a school in Arizona where on all days without rain, 1st and 2nd graders had outside recess morning and afternoon, during lunch, plus outside physical education twice a week (Sharon Harlan, pers. comm., July 2005), to some inner city Baltimore schools where outside time is unusual (Janie Gordon, pers. comm., 2007), to some Atlanta, GA schools that are being built without outside playgrounds (DeGregory, 2005). Some public schools insist on students wearing hats or sunscreen for outdoor activities whereas others, even in sunny climates, have no such policy (Sharon Harlan, pers. comm., July 2005)

For those schools that do have outside play areas, another recent development pertinent to UV effects on health is the movement to "green school yards, which will most likely lead to greater tree cover and shading of students. The magnitude of this movement is made evident by a search of the internet using the index words "school yard greening," which receives many hits. This raises the issue of the degree to which UV shading is considered in these programs and the guidance that is available for planning and design for UV modification.

Protection of children during the school day is of special concern in Australia and New Zealand because of the large proportion of fair-skinned individuals in the population and the fact that UV irradiance tends to be higher than in equivalent northern latitudes (Gies and Mackay, 2004; Wright et al., 2007). Though there has been some success with inculcating sun protective behaviors in youth in Australia, the provision of shade structures for school yards has been recommended for additional protection (Moise et al., 1999; Gies and Mackay, 2004). The general suggestion in Australia is that these shade structures should provide a UV protection factor (PF = UV in open/UV transmitted) of 15 for "all-day" protection, although a PF of 4 to 8 would be sufficient over the noon hour (Gies and Mackay, 2004). Many structures that have been built at schools, (i.e., verandahs and pavilions) provided PF of at least a 4 to 8 range (Gies and Mackay, 2004). A higher PF could be obtained by adding trees or vines along the open sides of these structures. For tree shade alone, PF could vary widely, ranging from a value of 1.6 for a small-crowned single tree in the open blocking only 20% of sky view (Grant, 1997) to a value of 46 for tree shade in the school-yard study of Gies and MacKay (2004).

Several epidemiological studies (Garland et al., 1990; Grant, 2003) have found that the relationship between solar radiation in a region and the subsequent risk reductions for non-cutaneous cancers is stronger for rural residents than for urban residents. It has been suggested that this is a function of lifestyle differences

(Garland et al., 1990; Grant, 2003). However, more study seems necessary as an alternative hypothesis states that an urban atmosphere may sufficiently reduce UV-B radiation to reduce the benefit of UV-B radiation for adequate vitamin D production.

12.5 Public Health Information

Over the past several years, medical science seems to be developing a trend toward greater valuation of the benefits of UV-B in vitamin D production, and the value of UV radiation for vitamin D regulation has moderated the prevailing philosophy of major public health agencies around the world that reducing sun exposure as much as possible should be the public health goal. For example, in 2004 the internet site for the Cancer Council of Australia (2004) stated: "Deliberate exposure to sunlight does not provide any health benefits. Australians receive more than sufficient sunlight for vitamin D production from just sitting near a window or by as little as two minutes outside during the day." Because transmission of UV-B through glass is negligible (Turnbull et al., 2005), sitting near a window is probably not a significant source of vitamin D, and the two-minute exposure is generally shorter than needed for vitamin D synthesis (Webb and Engelsen, 2005). In March 2005, many health agencies in Australia issued a joint statement that confirmed the hazards of UV radiation for skin cancer, but they also recognized some of the benefits of moderate exposure for vitamin D production (Australian and New Zealand Bone and Mineral Society et al., 2005), and the internet site for the Cancer Council of Australia (http://www.cancer.org.au/home.htm, updated October 2007) now endorses that view in a page on "The Risks and Benefits of Sun Exposure".

In the U.S., public information generally originates from the U.S. CDC (2005) and the U.S. Environmental Protection Agency (U.S. EPA, 2005). A major study on the effectiveness of educational interventions to reduce skin cancer by reducing exposure to solar radiation was published by the CDC (Saraiya et al., 2004). Seeking shade, including tree shade, was prominently mentioned for UV protection in that study, although the subtleties of different UV exposures possible in "shade" were not discussed. The CDC recently re-evaluated the vitamin D issue (Dr. Mona Saraiya, pers. comm., June 27, 2005). It would seem that many of the findings of the study on intervention effectiveness could be translated to the slightly different messages that would be needed if moderate sun exposure for vitamin D photosynthesis were adopted as a goal.

A question arises as to the appropriate education for non-white populations regarding sun exposure. Recommendations for sun exposure are sometimes given by skin type (Cancer Research UK, 2008), although more often the recommendations are for everyone to avoid the sun as much as possible (U.S. CDC, 2005; U.S.

EPA, 2005) without a differentiation of the message on the basis of skin color. This is despite the high percentage of vitamin D deficiency among African-Americans (Giovannucci, 2005). However, recommendations do differ in other countries from those in the U.S. For example, there are no education programs in Japan on reducing sun exposure, even for school children (Ono et al., 2005); which might be anticipated because of the low incidence of skin cancer among Asians.

12.6 Conclusions

All three of the skin cancers, including the most deadly—melanoma, are related to sun exposure, and although action spectra are not clearly defined, the UV-B band is apparently the most responsible for all three cancers. Though use of sunscreens is widely recommended, there remains an uncertainty about the effectiveness of sunscreens in preventing cancer. The incidence rate of skin cancers has been rising rapidly, even though the use of sunscreens has become widespread. Recent studies muddy the picture about the effect of sun exposure on survival of melanoma victims.

The increasing evidence that adequate levels of vitamin D reduce the incidence of many non-cutaneous cancers suggests a role for tree cover in urban areas for pedestrians and for children's playgrounds as an intervention that reduces sun exposure for the erythemal action spectrum somewhat more than for the vitamin D response spectrum. This difference is caused by the greater scattering of the shortest-wavelength radiation and the apparent limit to the vitamin D action spectrum to wavelengths below 320 nm. Determining if this difference is of practical significance requires further study, especially because the interpretations of the vitamin D action spectrum that are currently in use are based on only one study published in 1982. Additional research on the effective spectra in human skin is underway and seems well-justified.

Methods of modeling UV radiation exposure to pedestrians in different urban neighborhoods are being developed. These methods should be verified by additional UV radiation spectral measurements (Webb, 1991) above and below canopy over extended time periods, and by the use of personal dosimeters with volunteers. The dosimeter studies should include school children and structurally different neighborhoods over a range of building structures and tree densities to evaluate human exposure during everyday activities.

Major modifications to the structure of urban areas, including residential neighborhoods, may be accomplished over time with policies for tree management—including tree species selection for planting. Selection for the eventual size and shape of crowns of planted trees, which is generally known, is more important than considerations of tree-crown leaf density, which is less well known.

Studies on above-canopy UV irradiance in urban versus rural areas are also needed. Such research is especially important because epidemiological studies have shown different disease incidences that may be related to differences in exposure to UV radiation caused by different tropospheric atmospheric constituents.

Below typical street trees at mid-latitudes, where the visible solar irradiance is 10% or 15% of irradiance above trees, UV-B relative irradiance is commonly 30% or 40%. For typical solar radiation spectra during mid-day at mid-latitudes in summer, estimates are that Caucasians with medium-skin color may acquire a daily recommended dose of vitamin D from the sun in one-fourth of the time sunburn would occur. Alternatively, when arms, hands, and face are exposed on sunny days, a standard vitamin D dose could be acquired in just 4 or 5 minutes when in the open, and 12 to 15 minutes when in typical tree shade. Dark-skinned individuals would require about 30 minutes in shade of scattered trees where the view of the sky was substantial. Thus tree shade tends to make possible the recommendations that some researchers make for moderate exposure to UV radiation. An advantage of obtaining UV exposure in tree shade is that the reduction of the longer wavelengths of solar radiation will often produce thermal comfort for people when it would be too hot in direct sun.

Global climate change, which is expected to increase temperatures, especially at higher latitudes, may have a variety of effects on UV exposure for human populations; for example, it might be expected that warming would lead to greater exposure as people adapt to the warmer temperatures by wearing less clothing. However, empirical evidence for the influence of temperature on human exposure, independent of radiation climate, does not seem to exist.

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