1.7 BIOLOGICALLY-EFFECTIVE UV-B EXPOSURES IN UNDERSTORIES OF FOREST CANOPIES: POTENTIAL IMPACTS OF CLIMATE CHANGE

Richard H. Grant[1]*, Kent Apostol[1] and Wei Gao[2]

[1]Purdue University, West Lafayette, Indiana and [2]USDA UVB Monitoring and Research Network, Ft. Collins, Colorado

1. INTRODUCTION

Currently the northern temperate regions have lost stratospheric ozone at 4% to 7% per decade (Madronich et al., 1998). For latitudes associated with the northern deciduous forest in Indiana this corresponds to 10 to 20 DU (Dobson units). This decreased stratospheric ozone corresponds to increased solar ultraviolet (UV) radiation at the top of forest canopies. Furthermore under climate warming scenarios, we would expect more frequent penetration of tropical air masses with associated low stratospheric ozone levels into mid-latitudes thereby increasing the variability in surface solar UV radiation. Changes in the onset of warmer conditions will likely shifts the time of leaf-out of temperate forests (Kramer et al., 2000).

The impact of these climate changes on UVB exposure of plant species in the herbaceous layer of the temperate deciduous forest is unknown since changes in UV exposure associated with changes in phenology may shift competitive advantage to different species (Gold and Caldwell, 1983; Kramer et al., 2000). In this study, we explored the variability in UVB exposure of the herbaceous layer. During the leafing-out period in mid-latitudes there are many changes in ozone column and cloud cover associated with weather systems resulting in a highly variable solar radiation period (Fig. 1).

The herbaceous layer of deciduous canopies consists of many plant species that develop prior to the leafing out of the overstory. Most of the solar UV exposure of the understory herbaceous layer is received during the over-canopy leaf-out. The penetration of UVB radiation into the understory of a deciduous forest canopy diminishes as the canopy develops overhead.

Few measurements of the UV environment at pedestrian level have been made. Below-canopy broadband irradiance measurements of the UV environment have been made under forest canopies by Brown et al. (1994), Yang et al. (1993), and Lee and Downum (1991), and Grant et al. (2001). None of these measurements were able to partition the diffuse and direct beam components to the global irradiance.

The ability to measure the penetration of UV radiation depends in part on the sensitivity of the measuring instrument. Measurements of the UV irradiance under a tropical forest canopy by Lee and Downum (1991) showed no detectable radiation.

The penetration of radiation varies with wavelength given differences in the diffuse component of the global irradiance and the optical properties of the canopy elements. In measurements made in a variety of forests in temperate and tropical regions the attenuation of UVB and photosynthetically active radiation (PAR) varied, with some measurements showing UV-B attenuation less than PAR in relatively low density canopies and gaps and PAR attenuation less than UV-B in fully-leaved temperate deciduous forest canopies (Brown et al. 1994). Measurements over the course of two days of the radiation environment under an oak canopy of LAI (leaf area index) 1.7 showed UV-B to be attenuated to a greater extent than the PAR (Yang et al. 1993).

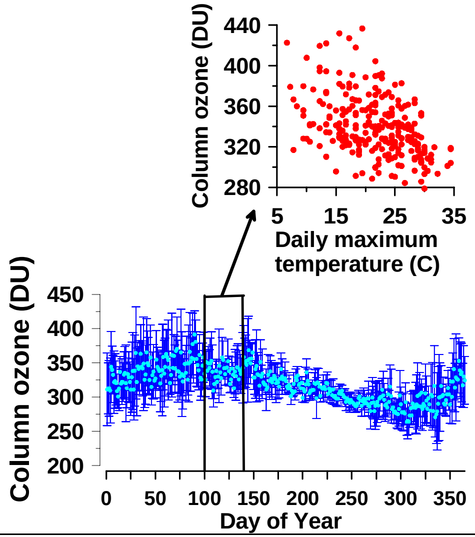

Figure 1 – Column ozone relative to time of year and daily air temperature (2000-2004). The error bars represent one standard deviation. (Cooperative Weather Station air temperature measurements at W. Lafayette, IN, USA at http://shadow.agry.purdue.edu and Earthprobe OMS satellite-base column ozone measurements for Urban, IL, USA at http://toms.gsfc.nasa.gov/ozone/ozone.html).

The transition from the polar air mass domination of the mid-latitude winter to the tropical air mass domination of the summer occurs during the spring- primarily during May and early June in the region of the

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Corresponding author address: Richard H. Grant, Purdue University, Department of Agronomy, 915 W. State St., W. Lafayette, IN 47907-2054; email: rgrant@purdue.edu.

Figure 2 – Hemispherical view of the canopy on April 29, 2004. The calculated path of the solar disk is indicated in yellow.

temperate deciduous forest. This corresponds with the leaf-out of the forest. Associated with this period of leaf out and transition in dominant air masses is a shift in the column ozone (Fig. 1). In general increasing air temperatures correspond with decreasing column ozone and decreasing solar declination resulting in increasing UV irradiance. As the canopy leaf area fills in, the canopy transmittance will decrease—mitigating increases in UV irradiance for the herbaceous vegetation at the base of the canopy.

The goal of this experiment was to determine the temporal variation in UV canopy transmittance during leaf-out and estimate the UV exposure of the herbaceous layer under the deciduous forest canopy.

2. EXPERIMENTAL DESIGN

The solar UV radiation in the understory of a deciduous upland forest near West Lafayette, Indiana (Martell Forest, Department of Forestry and Natural Resources, Purdue University; 40.47 N, 86.99 W) was studied between 15 April and 1 June of 2004. The overstory of the forest consisted primarily of red oak (*Quercus borealis*), white oak (*Quercus alba*), sugar maple (*Acer saccharum*) , basswood (*Tilia americana*), shagbark hickory (*Carya ovata*), and bitternut hickory (*Carya cordiformis*). Canopy view factors throughout the study period were determined from hemispherical photographs (Fig. 2) using *GLA 2.0*® assuming a uniform sky radiance distribution (Lertzman et al., 1999). Leaf area index (LAI) was determined from the hemispherical photographs. Repeated estimation of the threshold for sky in the images resulted in an estimated LAI error of +/- 0.2.

The solar UV radiation was measured using a portable ultraviolet multi-filter rotating shadow band radiometer (UV-MFRSR). The UV-MFRSR measures the diffuse and global solar irradiance in seven narrow (2 nm nominal FWHM bandwidth) wavebands at nominal center wavelengths of 300-, 305-, 311-, 317-, 325-, 332-, and 368- nm. Direct beam irradiance is calculated by subtraction of diffuse from the global irradiance. Irradiance measurements in the understory were recorded for periods of approximately 8 hours centered on solar noon (when the solar zenith angle was less than 60^o) on various days during the leafing out of the deciduous forest.

Measurements were compared to the UV-MFRSR at the West Lafayette UV-B Climate Monitoring Station (distance 5 km) to determine the canopy transmittance of UV-B. PAR was also measured at both locations using LiCOR quantum sensors and the canopy transmittance of PAR was calculated as for the UV wavelengths. Canopy transmittance was calculated from the synchronous reference measurements and under-canopy measurements for direct beam, diffuse, and global irradiance in all wavebands.

Scattering in the canopy was evaluated by spectral variation in canopy transmittance with respect to sky condition and canopy (trunk/branch and leaf) view factors. The spectral reflectance of bark and dead leaves were evaluated on air-dried samples using a Perkin Elmer Lambda 19 spectrophotometer following the procedures described in Grant et al. (2003).

The measured canopy transmittance was compared to the transmittance predicted from a three-dimensional canopy radiation transport model (Grant et al., 2002) that accounted for solar zenith angle, cloud cover and canopy density. The model assumed a uniform array of spherical tree crowns with a full-canopy view factor corresponding to the view for the canopy after complete leaf-out and LAI values corresponding to the indirect measure of LAI from the hemispherical photographs. Canopy transmittance of diffuse, direct beam and the global irradiance was estimated for solar zenith angles between 15^o and 60^o and sky conditions from cloud-free to overcast.

The canopy transmittance was empirically modeled as a function of time, cloud cover, and solar zenith angle. The modeled canopy transmittance in combination with estimated above-canopy irradiance were then used to predict the irradiance received by understory vegetation of a canopy leafing out in the spring under the measured conditions. Changes in penetration of UV-B radiation at mid-latitudes due to changes in ozone column depth were then evaluated to determine what the relative impact of ozone column changes on herbaceous layer UV-B exposure.

3. RESULTS

The forest canopy had an initial stem area index (SAI) of 0.5. By 25 days into the leaf-out, the canopy was reaching full leaf-out with an LAI of 3.3. This estimated LAI at 25 days is comparable to the Oak forest studied by Yang et al. (1993). The view of the sky began at 0.55 at day 0 and approached a constant of approximately 0.05 by day 41.

The penetration of diffuse radiation was equal to that of the global radiation in the UV wavelengths (Fig. 3). Consequently it appears that the areal averaged canopy gap fraction was equal to the gap fraction along the diurnal transect of the sun across the canopy during the course of the day.

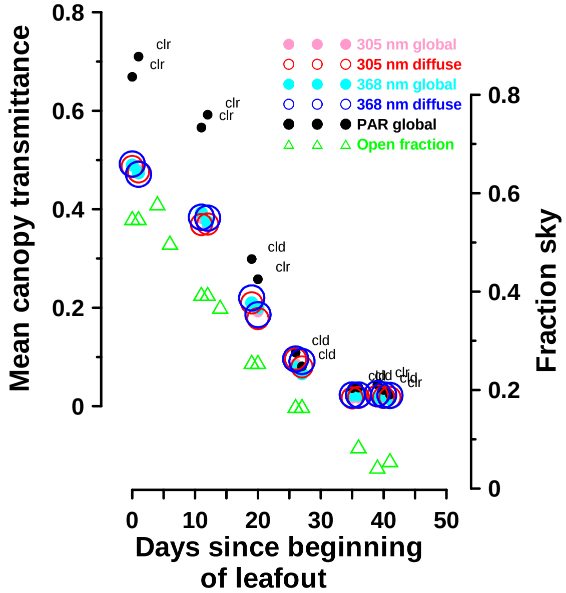

Figure 3- Temporal variation in canopy transmittance and sky view. Day 0 corresponds to April 15 (DOY 106)

Mean canopy transmittance was not sensitive to sky conditions (Fig. 3). This was likely due to the uniformity of the canopy causing the frequency of sunflecks across the sensor as the day progressed (for instance following path indicated in Figure 1) to equal the fraction of sky visible across the entire hemisphere (Fig. 2).

The rate of decrease in UV transmittance (305 or 368 nm) corresponded with the rate of decrease in sky view (Fig 3). This suggests that the canopy transmittance between 305 and 368 nm can be used to approximate sky view. The linear regression between the 305 nm global transmittance and sky view had a slope of 0.92 and a coefficient of determination (r^2) of 0.98. The corresponding regression for 368 nm transmittance had a slope of 0.92 and an r^2 of 0.92.

The mean canopy transmittance in the PAR always exceeded that in the UV-A or UV-B (1.4:1). Mean canopy transmittance in the UV-A wavelengths was negligibly greater than that in the UV-B wavelengths.

The higher mean PAR transmittance was clearly evident in the early part of the leaf-out, but by the time the leaves in the upper canopy had fully expanded the transmittance of PAR was effectively equal to that of the UV-A or UV-B by day 25 (Fig. 3). This corresponded to a computed LAI of 1.5. Higher PAR than UV-B transmittance was found by Yang et al., (1993) for a 1.7 LAI oak forest. Brown et al. (1994) found PAR transmittance was greater than UV-B in several fully-leaved temperate deciduous forest canopies.

The low transmittance of UV-B radiation in the fully-leaved forest may result in irradiance levels too low for some sensors. This is the probable cause for the statement of Lee and Downham (1991). In addition, relatively insensitive sensors may not be able to detect the small differences in PAR versus UV penetration under the full-leafed canopy.

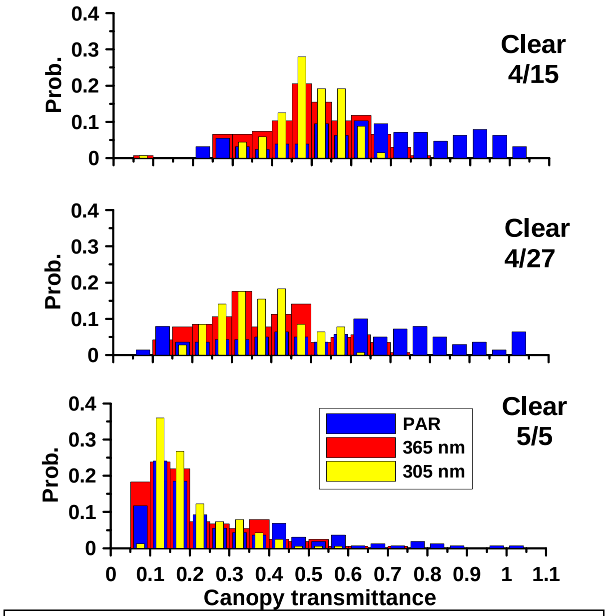

Figure 4 – Variability in global transmittance at 305 nm, 368 nm, and PAR during the greatest changes in leaf-out.

Variability in PAR transmittance due to the transiting of the solar beam across the canopy hemisphere was greater than that of UV-A and UV-B wavelengths (Fig. 4). This was expected since the diffuse fraction in the PAR is much smaller than that in the UV resulting in more distinct differences in the transmittance in and out of sunflecks (Fig. 4).

Before the leaves began to emerge (4/15/2004), the canopy transmission in the UV wavelengths were nearly normally distributed about the 0.5 mean transmittance (Fig. 4). During this same period, the PAR transmittance was nearly uniformly distributed (Fig. 4)—a result of the greater direct beam component of PAR global irradiance. As the leaf-out progressed and the periods of sun-fleck decreased in frequency, the distribution of instantaneous canopy transmittances became more positively skewed.

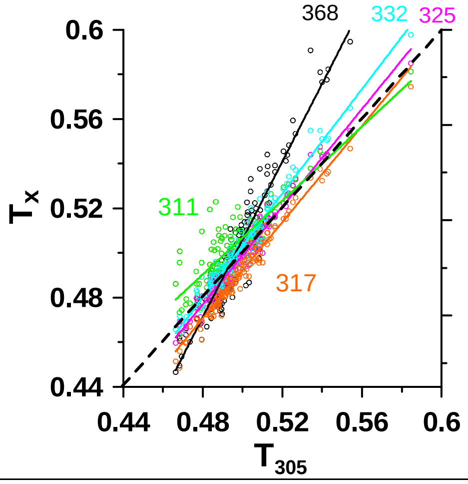

Figure 5 – Relative penetration of UV radiation on April 15, 2004. x refers to the wavelength of solar radiation (311 nm to 368 nm) indicated within the figure.

3.1 Wavelength dependence of diffuse penetration

The penetration of diffuse radiation in the UV wavelengths was greater for longer wavelengths than shorter wavelengths within the UV wavelength range (Fig. 5; Table 1). Consequently, UV-A radiation (325, 332, and 368 nm) had slightly greater penetration than UV-B (305, 311, 317 nm).

The wavelength dependence in diffuse radiation penetration was evident under cloud-free or high cirrus sky conditions but not under cloudy conditions. The weak wavelength dependence was also only apparent under conditions of relatively high transmittance near solar noon but not generally throughout the day. The transmittance during cloud-free skies at 311 was typically equal to or less than that at 305 nm (Table 1). The ratio of transmittance during cloud-free skies at 317 and 325 nm to that at 305 nm was on average 1.10. The ratio of transmittance during cloud-free skies increased with increasing wavelength (Table 1).

Table 1 – Forest optical properties

Wavelength x (nm)	Bark reflectance ratio (x/305 nm)	Canopy diffuse transmittance ratio (x/305 nm)
311	1.04 ± 0.02^{+}	0.95 ± 0.17
317	1.07 ± 0.04	1.10 ± 0.08
325	1.11 ± 0.09	1.04 ± 0.08
331	1.15 ± 0.11	1.14 ± 0.08
368	1.37 ± 0.11	1.79 ± 0.21

$^{+}$Mean ± standard deviation

The observation that spectral differentiation of canopy transmittance occurred only under skies with small reductions in direct beam (cloud-free or thin cirroform) and not under cloudy skies would be expected if the enhanced diffuse penetration was a result of scattering off the bark of direct beam radiation (commonly termed complementary radiation).

Could the bark account for the enhanced diffuse radiation at the base of the canopy? The tree trunks of the forest canopy obscured 55% of the sky view at the beginning of leaf-out. These trunks and branches were the only reflecting surface in the canopy at the beginning of the leaf-out. The reflectance of the bark of the dominant tree species were measured. Spectral reflectance measurements showed that, as with dry soils, the spectral reflectance decreases with decreasing wavelength (Fig. 6). White oak had the highest UV reflectance of all species measured. The relative ability of the bark to scatter incident solar radiation was evaluated using reflectance ratios. The

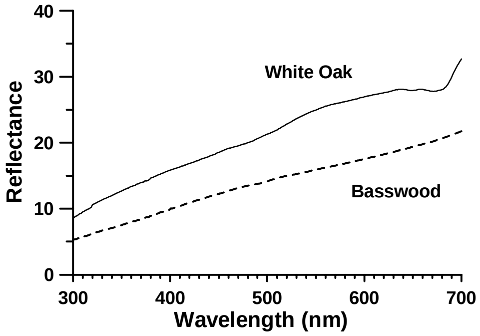

Figure 6 – Spectral reflectance of tree bark.

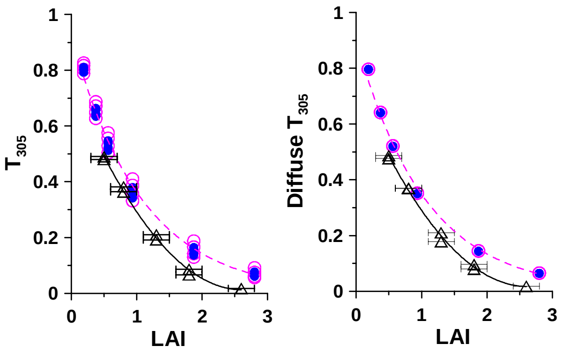

Figure 7 – Mean canopy transmittance at 305 nm. The measured (open triangles-solid line) and modeled 305 nm transmittance for clear skies (open pink circles, dashed line) and broken cloud (closed blue circles) are indicated. Modeled values for 15°, 30°, 45°, and 60° solar zenith angle are illustrated for each LAI.

ratio of PAR reflectance to 305 nm reflectance of an assortment of barks from the forest stand was 2.68 ± 0.42. The ratio of reflectance at 311, 317, 325, 331, and 368 nm to that at 305 shows a general increase with increasing wavelength spread (Table 1). Consequently, the contribution that complementary radiation (that diffuse radiation produced by the diffuse scattering of direct beam radiation and sky radiation, should decrease with decreasing wavelength.

The tendency for greater penetration of longer wavelengths in the UV corresponded with the increased reflectance of the tree bark in the canopy (Table 1). Since the bark is the only selective scattering surface in the leafless canopy, the differences in spectral reflectance of the bark was likely the cause for the preferential transmission of longer wavelength of UV over shorter wavelengths. The correlation between the diffuse transmittance ratios and the bark reflectance ratios for the various wavebands relative to 305 nm was 0.97.

3.2 Modeled canopy transmittance

The early stages of leaf-out were modeled using the three-dimensional (3-D) model of Grant et al. (2002). Modeling conditions were defined given the sky view of the fully-leafed canopy at the end of the study period (defining the canopy crown cover) and estimated crown density based on the LAI and crown dimensions. The irradiance in an array under canopies with LAI ranging from 0.19 to 2.8 were estimated for solar zenith angles of 15°, 30°, 45°, 60° and skies with no clouds, few clouds, scattered clouds, broken clouds, and overcast conditions.

For the corresponding LAI and sky conditions, the mean canopy transmittance was overestimated by the model by an average of 0.07 (Fig. 7). Model error increased with increasing LAI. The mean canopy diffuse transmittance also overestimated the measured diffuse transmittance by and average of 0.08 with greater error at low LAI (Fig. 7). The approximately 0.2 error in the indirect LAI estimation contributes approximately 0.02 to the modeled transmittance error. Instantaneous 3-min transmittances showed a tendency for the maximum and minimum transmittance over the course of the day to converge with increasing solar zenith angle (Fig. 8). The lower bound of the measured canopy transmittance was well-estimated by the modeled mean transmittance less the modeled mean direct beam transmittance (Fig. 8).

Given the fit of the 3-D model to the measured mean canopy transmittance in the UV, further assessments on the sensitivity of mean canopy transmittance to changes in canopy LAI, solar zenith angle and cloud cover on canopy transmittance were evaluated. As observed in the measurements described above, the predicted mean canopy transmittance was relatively insensitive to cloud cover (Fig. 7) and sensitive to solar zenith angle (Fig. 8) and LAI (Fig. 7). Since the canopy LAI was dependent on time (and presumably

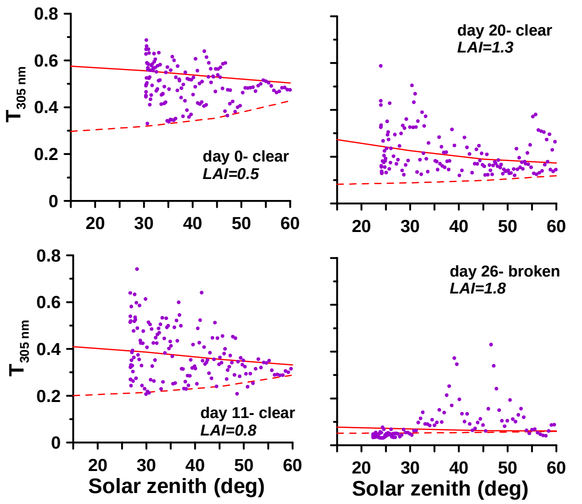

Figure 8 – Comparison of the measured and modeled 305 nm canopy transmittance during leaf-out. Individual values represent the calculated transmittance at 3 min intervals for the indicated days into the study. Cloud cover and estimated LAI are also indicated. The solid line represents the modeled mean transmittance and the dashed line represents the diffuse transmittance.

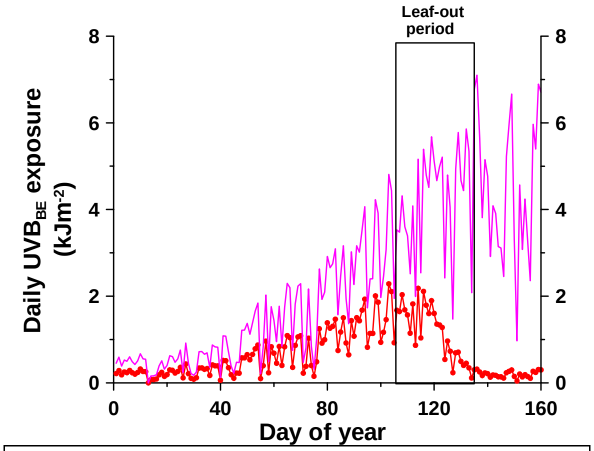

Figure 9—Predicted daily biologically effective UV-B exposure. Daily exposures at the top of the canopy (Purple) and of plants in the forest understory (Red) during the 2001 spring at Bondville, IL are illustrated.

available heat and water; Kramer et al, 2000), an empirical model of the canopy transmittance for the leafing out deciduous forest was developed solely on the measured canopy transmittances.

3.3 UV exposures before and during leaf-out.

The period of significant canopy transmittance during leaf-out occurs between approximately day 105 through day 135. It was assumed that the herbaceous layer greens up starting around 15 March. Virtually the entire UV exposure of these plants occurs from their emergence to the completion of the over-canopy leaf-out. Assuming the same leaf-out period for 2001-2004 provides a means to estimate the impact of the UV radiation on the herbaceous layer.

Variability in the biologically effective UV irradiance (UVB$_{BE}$; Caldwell, 1971) above the canopy during this time ranges from approximately 2 kJm^{-2} to 8 Wm^{-2} (Fig. 9). The corresponding predicted exposure of the herbaceous plants in the understory does not exceed 2.7 kJm^{-2}. The cumulative exposure above the canopy between 15 March (day 74) and 15 May (day 135) was estimated at 204 kJm^{-2} while the exposure in the understory was estimated at 73.8 kJm^{-2} corresponding to an effective canopy transmittance over the entire period of 36%. Peak exposures to the herbaceous layer occur at the beginning of the leaf-out period.

3.4 UV exposures in a changing climate.

Warmer global climates are expected to increase cloud cover. This has been seen in records in several regions of the USA between 1900 and 1987 by Croke et al. (1999) and across the USA in the past 50 years (Sun et al., 2001). The estimated rate of increase in cloud cover over the USA was approximately 5% per 100 years (Sun et al., 2001). Based on the modeling of the mean canopy transmittance at 45^{o} solar zenith (approximate mean solar zenith angle during the study period), a change in cloud cover of 5% will result in a decrease in canopy transmittance of less than 0.01. Assuming a cloud cover effect on the above-canopy UVB$_{BE}$ according to Kuchinke and Nunez (1999) and canopies with LAI between 0.5 and 1.8, a reduction in below canopy daily UV-B exposure of up to1% would be expected due to an increase of cloud cover of 5%. Given the understory exposure of 73.8 kJm^{-2} between 15 March and 15 May, this reduction represents only 7.4 kJm^{-2} (approximately 3 days additional exposure).

As previously stated, studies have shown that there has been a 4% to 7% decreases in total column ozone per decade in northern mid-latitudes (Madronich et al., 1998). This represents a 10 to 20 DU decrease in ozone column depth. The 20 DU ozone column change also approximates the standard deviation of ozone column depths expressed in Figure 1. Prior studies have shown that a 20 DU decrease in column ozone corresponds to a 1.6 kJ m^{-2} increase in UVB$_{BE}$ at the canopy top (Grant and Slusser, 2003). Assuming similar cloud cover conditions (in terms of number of overcast days with low UV irradiance), this 20 DU decrease in column ozone would correspond to approximately 0.6 kJ m^{-2} increase in UV-B exposure for the herbaceous layer of the forest. Given the maximum daily understory exposures for 2001 of approximately 2.7 kJ m^{-2} (Fig. 7), a 0.6 kJ m^{-2} increase represents at least a 22% increase in UV exposure. The impact of such a change in exposure is unknown since little is known about the UV sensitivity of most herbaceous plants. This is an area in need of research.

4. CONCLUSIONS

During the early part of the leaf-out period, the mean canopy transmittance in the PAR exceeded that in the UV-A or UV-B. By 20 days into the leaf-out period, the PAR transmittance was nearly equal to that of the UV. As the leaves in the canopy reached full expansion, the PAR, UV-A and UV-B penetration was essentially equal and small.

Canopy transmittance during leaf-out was not dependent on cloud cover. Greater penetration of solar radiation in longer wavelengths within the UV was probably a result of scattering of direct beam radiation off tree bark in the canopy. The effective canopy transmittance from 15 March through the canopy leaf-out was 36%(based on 2001 measurements). For an expected period of UV exposure for the herbaceous layer of 15 March through 15 May, the herbaceous plants received 74 kJm^{-2} of biologically effective UVB radiation.

Analysis of the herbaceous vegetation exposure impact due to changes in climate indicate that the herbaceous layer vegetation will receive approximately 22% more UVB_{BE} radiation with decreases of 20 DU in stratospheric ozone and approximately 1% less UVB_{BE} radiation with increases of 5% cloud cover.

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