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Research Article

Incident Ultraviolet Radiation and Disappearance of the Aquatic Macrophyte *Egeria densa* in a Ramsar Wetlands Site

During mid 2004, abrupt environmental changes including a massive die off of the dominant macrophyte *Egeria densa* were observed within the wetlands of Río Cruces, a Ramsar site in southern Chile. One of the hypotheses presented to explain these changes was that increased ultraviolet radiation (UVR) may have been responsible. Since variation in UVR operates at regional scales, it is important to understand if the demise of *E. densa* also occurs at concurrent spatial and temporal scales. The current results demonstrate that monthly and annual variability of UVB was very stable during 1998 to 2006. Furthermore, in situ vertical profiles sampled across the wetlands and nearby rivers showed that UVR penetrates deeper into waters located outside the wetlands, where healthy stands of *E. densa* are commonly seen. The massive die off of *E. densa* within the Río Cruces wetlands cannot be explained by regional variability in UVR, and it is much more likely that the definitive reason is found locally within the wetlands rather than regionally.

Keywords: Ultraviolet radiation; Macrophyte; Ramsar wetlands; Chile

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1 Introduction

Spatial scales of environmental processes are key considerations with respect to the analysis of potential ecological impacts [1]. It is known that processes operating over large geographic scales can be correlated with regional or even local impacts, but the absence of comparable spatial scales emphasizes the need for additional insight and attention to detail [2]. As an example, ultraviolet radiation (UVR) operates on a large spatial scale, often showing wide variation with latitude [3, 4]. Other processes, such as water quality, tide or rainfall, impact watersheds or drainages on relatively smaller spatial scales [1, 5]. The process of relating the two is problematic, and must be undertaken with great care.

During mid-2004, abrupt environmental changes were observed within the wetlands of the Río Cruces [6], a Ramsar site and a nature sanctuary located in southern Chile (ca. 40° S). These changes included: *(i)* a massive die off of a dominant macrophyte, *Egeria densa*, from unknown causes; *(ii)* elevated emigration rates, cessation of reproduction, and increased mortality of the herbivorous waterbird, the black-necked swan (*Cygnus melancoryphus*); and *(iii)* the presence of darkly-stained, brown-colored water throughout the sanctuary during spring and summer.

The macrophyte *E. densa* was the dominant aquatic plant in the area until 2004, and the main food for herbivorous waterfowl, such as the charismatic black-necked swan, *Cygnus melancoryphus*, and the coot, *Fulica armillata* [7]. This area was the largest breeding site of black-necked swans in the Neotropics [8, 9]. Several hypotheses for these environmental changes have been presented [6], most of them involving changes in water quality caused by the effluent waters of a new pulp mill plant located 35 km upstream of the wetlands that initiated operation during February 2004. However, an alternative hypothesis presented by Ramirez et al. [10] proposed that increased UVR, such as that caused by stratospheric ozone reduction, may actually have been responsible.

In this study, the temporal variability of incident visible irradiance and UVR is assessed for the area, including in situ measurements in the waters of the sanctuary and nearby rivers. The main objectives are: *(i)* to compare temporal variation in UVB recorded during 2004 with fluctuations observed for the period 1998–2006; *(ii)* to assess optical properties of water in different locations within the sanctuary and nearby rivers; *(iii)* to assess how patterns of water transparency along the wetlands are affected by estuarine tidal influence, and *(iv)* to discuss the potential role of regional UVR and local scale optical water properties upon the demise of *E. densa* within the Río Cruces wetlands.

2 Materials and Methods

2.1 The Study Area

Designated an internationally important wetlands in 1981 under the terms of the Ramsar Convention, the Carlos Anwandter Nature Sanctuary is a 4877 ha reserve encompassing the shallow wetlands that originated after a major earthquake on May 22, 1960. The Río

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Abbreviations: BSI, Biospherical Instruments Inc.; **PAR**, Photosynthetically Active Radiation; **TSS**, Total Suspended Solids; **UVR**, Ultraviolet Radiation

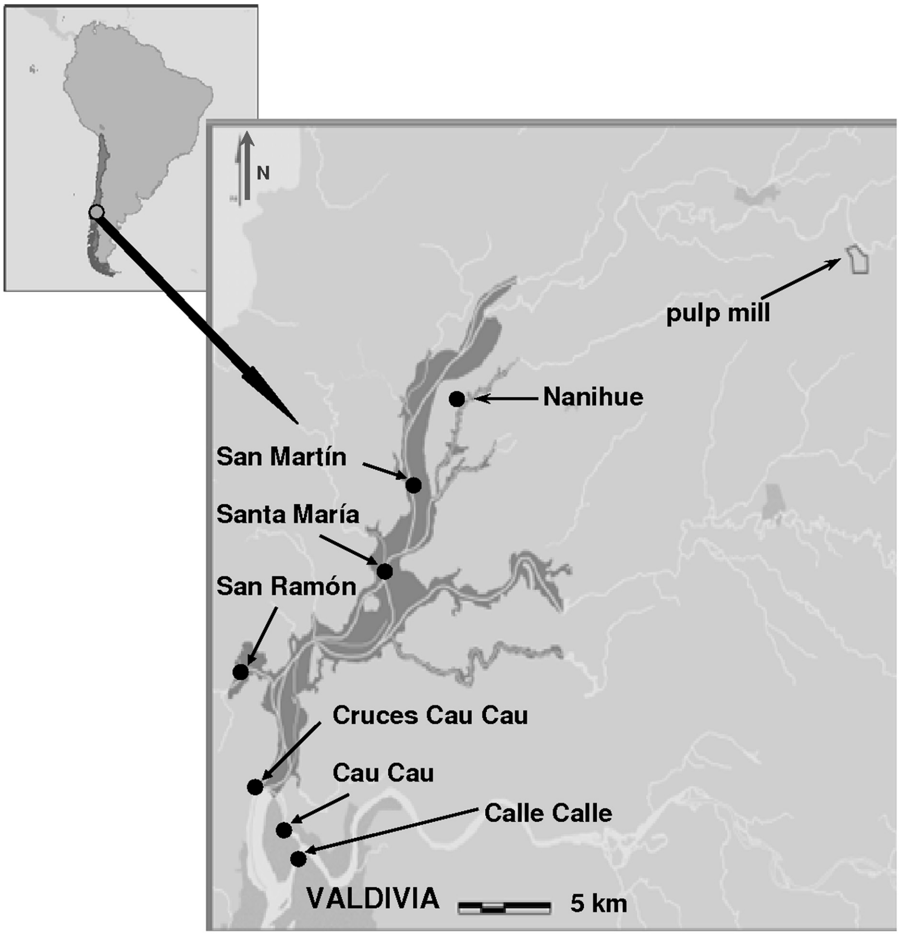

Figure 1. Location of the wetlands of Río Cruces or the sanctuary, north of Valdivia, southern Chile, and water sampling stations (see text). The darker areas around the Río Cruces and tributary rivers are shallow water zones primarily represented by swamps and marsh vegetation. The approximate location of the pulp mill, which started to operate during February 2004, is indicated at the upper right corner.

Calle Calle flows around the city of Valdivia, and the Río Cruces flows from north to south through the watershed, see Fig. 1. The sanctuary is an estuarine system, and its proximity to the Pacific Ocean ensures that flow rates are influenced daily by tides.

2.2 Incident Solar Irradiance

Regional measurements of incident solar irradiance (UVR and PAR) were acquired using a high-resolution scanning spectroradiometer (model SUV-100, Biospherical Instruments Inc, San Diego, CA, USA) located on the roof of the building of the Faculty of Sciences of Universidad Austral de Chile in Valdivia. Since 1998, daily scans between 280 and 600 nm were performed at 15 min intervals whenever the solar zenith angle was less than 93°. The system was fully automated and required operator attention only for periodic manual calibrations and operational checks. The SUV forms the heart of the United States National Science Foundation's UV Spectroradiometer Monitoring Network and general information on the SUV including specifications can be found in the work of Booth et al. [11].

The temporal variability of both the maximum as well as integrated UVB radiation, i.e., 290 to 315 nm, was analyzed for the period 1998 to 2006. Monthly averages were calculated for each year and used to calculate the historic mean, Q1, the median, Q3, and the coefficient of variation for the period. The differences between months in maximum and integrated UVB were examined through an ANOVA with Tukey's a posteriori comparisons. Pearson correlation analyzes were used to determine if the mean variation in maximum and integrated UVB radiation observed during the months of 2004 was similar to the observed variation in the same months of the other years. Due to the absence of data for the period January–June, the data for 1998 was excluded from these analyzes. The variability of maximum and integrated UVB between 2004 and other years was examined using a t-test of paired differences, where the difference (Δ) for the variable maximum UVB radiation (as well as for integrated UVB) is defined as:

$$\Delta_{\mathrm{UVBmax}} = \mathrm{UVB\ max}_{2004} - \mathrm{UVB\ max}_{\mathrm{year\ (t)}}$$

with the null hypothesis: $\Delta_{\mathrm{UVBmax}} = 0$. E_d (λ) [nm] is the downward irradiance for waveband λ and K_d [−] the downward attenuation coefficient. Due to the multiple use of the data from 2004, the significance was evaluated after a Bonferroni correction with values of $p' = 0.006$.

2.3 In Situ Downward Irradiance and Water Transparency

Field sampling in seven stations included in situ vertical profiles of downward spectral UV irradiance, water transparency with a Secchi disk, and determinations of suspended solids. Four stations were located on the Río Cruces, i.e., San Martin, Santa Maria, San Ramón and Cruces-Cau Cau, one station in a tributary river, i. e., Nanihue, and two outside of the wetlands, i. e., Cau Cau and Río Calle Calle, see Fig. 1. All stations were sampled during the spring low tides of September 17th 2006, November 18th 2006 and February 23rd 2007, while San Ramón, Cruces-Cau Cau, Cau Cau and Calle Calle were sampled during the spring high and low tides of October 5th 2006 and January 24th 2007.

In situ vertical profiles of downward irradiance and incident surface irradiance were collected with a PUV-2500 (BSI, San Diego, CA, USA) profiling UV radiometer. The PUV measures the flux at discrete wavebands using high-performance filter photodetectors at 305, 320, 340, 380, 395 nm and with a 400 to 700 nm broadband PAR detector at a rate of 15 complete frames of data per s [12, 13].

Water transparency in the visible region was also determined with a standard black and white Secchi disk. The Secchi depth was recorded as the depth of disappearance of the disk, and was conducted by the same individual throughout the entire study.

Measurements of downward irradiance were used to calculate the spectral diffuse attenuation coefficient, k_d (λ,*z*), as a metric for transparency in the UV. This attenuation coefficient is rate of change of irradiance with depth and is defined by Eq. (1):

$$k_d(\lambda, z) = \frac{-1}{E_d(z,\lambda)}\left[\frac{dE_d(z,\lambda)}{dz}\right] \quad (1)$$

where k_d (λ,*z*) is the spectral attenuation coefficient for the wavelength, λ, as a function of the depth *z*, and E_d (λ,*z*) is the downward irradiance for λ at depth *z*.

2.4 Suspended Solids

Discrete samples of water were taken for analysis of suspended solids, and filtered through Millipore 0.45 μm GF/F filters following standard procedures [14].

3 Results and Discussion

During the spring-summer period, turbid, brown-colored waters were present from San Martín to Cruces-Cau Cau including Nanihue. Similar water type was observed only during low tides at the Cau Cau tidal channel, but never at the Río Calle Calle.

In general, the highest values of both maximum and integrated UVB radiation were recorded in the austral summer during December–January, and the lowest during April–September, see Fig. 2. The highest monthly variations were observed during May and the lowest during September–March, CV in Fig. 2. Monthly maximum and integrated UVB recorded during 2004 showed significant positive correlations with monthly variation recorded during other years of the study period, i. e., *r*-Pearson > 0.98, $P < 0.05$, $n = 12$. Paired comparisons between years showed that integral UVB radiation measured during the year 2004 was significantly lower only with respect to 1998 and 1999, i. e., 1998 vs. 2004: $n = 182$, $t = -2.81$, $p = 0.005$, and 1999 vs. 2004: $n = 364$, $t = -388$, $p < 0.001$. These results reaffirm that monthly and annual variability of UVR during the year 2004 was similar to that for 1998 to 2006 [6], and regional patterns of UVB observed during 2004 cannot explain the demise of *E. densa* within the local wetlands of the Río Cruces.

Vertical profiles of downward irradiance show that there are significant differences in the optical properties of the water between stations, and that these differences may influence the flux of UVR in

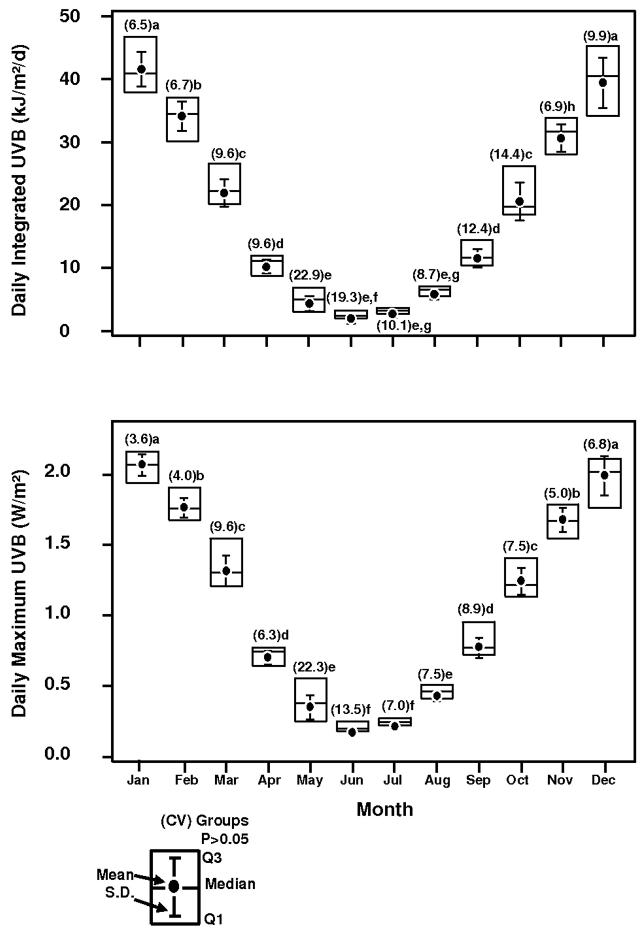

Figure 2. Mean (SD) and boxplot (Q1, Median, Q3) of daily dose rate of integrated and maximum values of UVB (290–315 nm) for the period 1998 to 2006. The number in parentheses indicates the monthly coefficient of variation (CV) among years. The results of ANOVA for integrated and maximum UVB are: F (11,90) = 412.61, $p < 0.0001$ and F(11,90) = 662.82, $p < 0.0001$, respectively. Similar letters represent similar mean groups at $p > 0.05$ (Tukey post hoc test).

the water column. As an example, UV transparency is significantly higher outside the wetlands (Calle Calle) than inside (San Ramón) during summer time when river flow is reduced and isothermal throughout the water column, see Fig. 3. The 10% light level for 320 nm is 74 cm for the Río Calle Calle, but only 2.3 cm at San Ramón.

In general, spectral attenuations increase with decreasing wavelength in aquatic systems, but there were large seasonal differences observed in the attenuations for UVR and PAR, see Fig. 4. In summer, the average attenuation coefficients of four stations located in the main channel of Río Cruces showed maximum values of 12.4 ± 1.7 m^{-1} for 305 nm decreasing to 5.2 ± 0.8 m^{-1} for 395 nm. K_d(PAR) diminishes to 1.6 ± 0.5 m^{-1}. As expected, the same pattern was observed for the early- and mid-spring; UVR was attenuated less in spring, possibly related to the reduced sediment load transported by the river as compared to summer when resuspension results in higher sediment loads, see Fig. 5.

Within the wetlands, the highest transparency for 305 nm was measured during early spring at San Martin station with K_d (305 nm) = 7.8 m^{-1}. An extreme low transparency was also measured in this same station during summer, i. e., K_d (305nm) = 14.8 m^{-1}. K_d

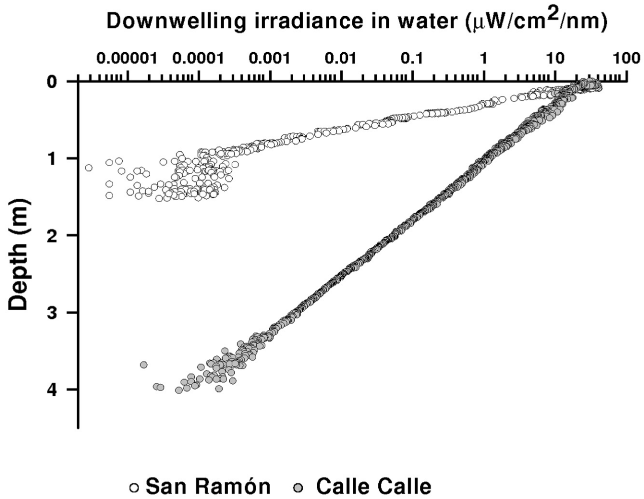

Figure 3. Vertical profiles of downwelling UVB radiation at 320 nm for two selected stations in the study area: San Ramón within the Sanctuary and Calle Calle outside of the wetlands (see Fig. 1).

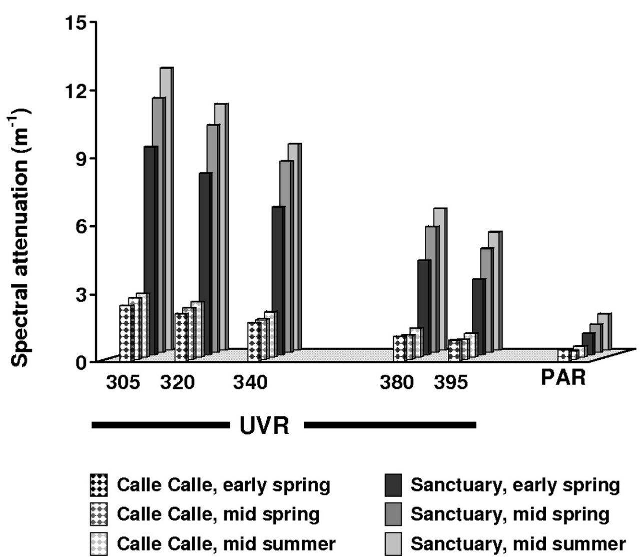

Figure 4. Average spectral downward diffuse attenuation coefficient, k_d (λ), at high tide for three seasonal periods throughout the wetlands compared to the reference station, Calle Calle. Times: Early Spring, Sept 17th 2006; Mid Spring, Nov 18th 2006; Mid Summer, Feb 23rd 2007. The spectral diffuse attenuation coefficients throughout the wetlands were obtained as the average of the $k_d(\lambda)$ coefficients from the four stations located at the sanctuaries: San Martín, Santa María, San Ramón and Cruces Cau Cau.

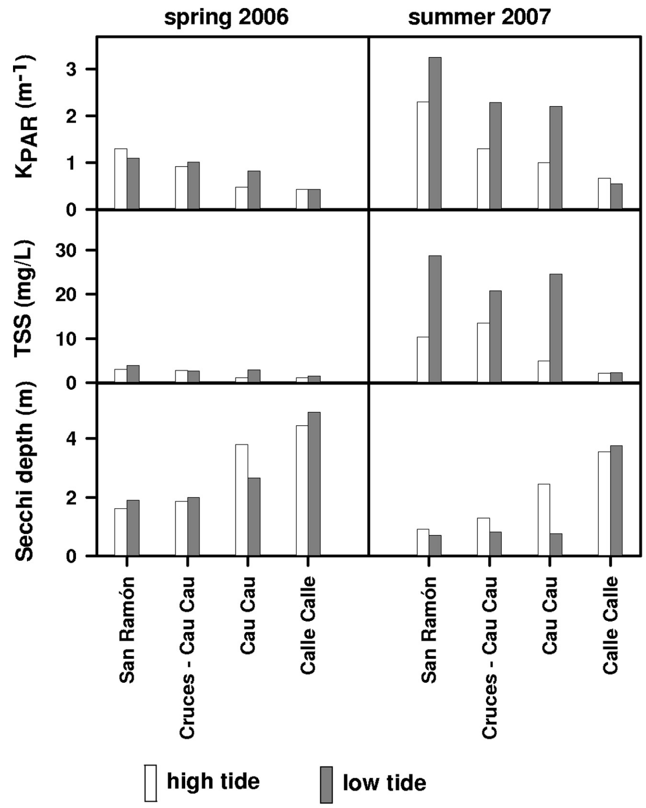

Figure 5. Seasonal and tidal variability in downward attenuation coefficient of PAR (K_d (PAR)), total suspended solids (TSS) and Secchi depth at four sampling stations ordered from the southern limit of the sanctuaries (San Ramón and Cruces-Cau Cau) to Río Calle Calle, outside of the wetlands (see Fig. 1).

(PAR) measurements show that the euphotic depth varied between 5.8 m in San Martin (early spring) and 2.3 m in Cruces-Cau Cau and San Ramón (summer). Stations located further south in the Sanctuary had lower transparencies because of higher total suspended solids, see Fig. 5. In general, attenuation coefficients increased from early winter to summer as a function of the decrease in flow rates for the Río Cruces. It is worthwhile to mention that studies carried out within the Sanctuary during March 2003 (Stefan Woelfl, personal communication) using a LI-COR quantum sensor LI 190SA and an underwater quantum sensor LI-192SA, revealed average K_d(PAR) values of ca. 1.0 m^{-1}, which is more than 50% lower than those measured during the summer samplings of the current study (Stefan Woelfl, personal communication). This result suggests that the optical properties of waters within the sanctuary changed significantly after 2003 [15].

For comparison purposes, underwater UVR and PAR at the river Calle Calle station outside of the sanctuary was largely unaffected by the seasonal changes within the study period, see Fig. 4. K_d values for all the UVR channels increased only slightly from spring to summer and at least 10% of the surface incident PAR was available throughout the water column.

Damaging UV does not always penetrate to the bottom even in shallow stations where *E. densa* are absent. Nanihue, a tributary of the Río Cruces, showed turbidity extremes during mid-spring and mid-summer with K_d (305nm) $\approx$ 32 m^{-1}, i.e., the 10% light level is 7 cm. The shallowness of this river (no more than 1.5 m during summer) probably contributes to this high turbidity, which is likely due to sediment resuspension from small waves induced by wind and tides.

The highest values of K_d(PAR), i.e., 2.3 to 3.3 m^{-1} and TSS, i.e., 20.8 to 28.7 mg/L, were found during the low tide of summer in the waters within the sanctuary (San Ramón and Cruces-Cau Cau) and close to the wetlands (Cau Cau) with large differences observed between tides, see Fig. 5. At high tides, attenuation coefficients were reduced by ca. 50%. Routine measurements of water transparency using a Secchi disc corroborate higher transparencies during low and high tides during spring; from 1.6 to 2 m in the stations from the wetlands (San Ramón and Cruces-Cau Cau), to almost 5 m at station Calle Calle and large differences between tides in summer, see Fig. 5.

These results confirm that tidal variability and seasonality impact water transparency and total suspended solids in the study area. Higher loads of TSS during the low tides of the summer season result in elevated attenuation coefficients of PAR and reduced Secchi depths. The higher loads of TSS during the summer season are related to washover and resuspension of sediments during low tides from the shallow areas of the sanctuary because of reduced river flow during the dry season, i. e., 20 m^3/s compared to 175 m^3/s in winter [16].

The values of K_d(PAR) and TSS were significantly and positively correlated (K_d(PAR) = 0.586 + 0.084 · TSS, R^2 = 0.834, $p < 0.0001$). The Secchi depth and TSS were significantly and negatively correlated (Secchi depth = 4.027 −1.119 · TSS, R^2 = 0.747, p < 0001). Secchi depths were also significantly correlated with K_d(PAR) (Secchi depth = 2.11 · K_d (PAR)$^{-1}$, R^2 = 0.95, $p < 0.001$). This high correlation was likely to be obtained since the water column was always well mixed and measurements were performed by the same person throughout the study.

Although Huovinen et al. [17] showed the midday summer levels of UVB in the region of Valdivia were high enough to produce damage and stress in intertidal marine macroalgae for 1998 to 2003, the effect of these high UVR levels in summer would be more harmful for the *E. densa* located in more transparent waters outside the sanctuary, e. g., station Calle Calle where this macrophyte survived. The current measurements show UVR is not elevated during the study period and that it is strongly attenuated in situ in the upper water layers of the wetlands, protecting the growing benthic plants against potentially harmful UVB radiation. The disappearance of this macrophyte occurred during mid-2004, i. e., in winter time, when radiation levels were lowest and showed no significant differences in 2004 compared to the preceding or following years.

4 Concluding Remarks

(*i*) The monthly and annual variability in the flux of incident UVB during the year 2004 was similar to the values recorded during the period 1998 to 2006.

(*ii*) Vertical profiles of downward irradiance show that there are significant differences in the flux of UVR. Sites located within the sanctuary and affected by brown-colored waters had higher attenuation coefficients than waters located outside the wetlands and not affected by the stain.

(*iii*) The attenuation coefficients of downward irradiance increased from early spring to summer within the sanctuary. In contrast, underwater UVR and PAR at the station of Río Calle Calle, i. e., outside of the sanctuary, is largely unaffected by seasonal changes.

(*iv*) Tidal variability and season affect water transparency and total suspended solids contents in the study area. Higher loads of TSS during the low tides of the summer season result in higher downward attenuation coefficients of PAR and lower Secchi depths.

(*v*) It can be reasonably concluded that the massive die off of *E. densa* is unrelated to increased exposure to UVR since: *(i)* 2004 did not show significant differences in incident UV flux compared with other years; *(ii)* the disappearance of this macrophyte occurred during mid-2004 when the radiation levels are at a seasonal minima; and *(iii)* UVR penetrates deeper into the waters of Río Calle Calle, where healthy stands of *E. densa* are commonly seen.

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