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Continuous Monitoring of Underwater Light in Indian River Lagoon: Comparison of Cosine and Spherical Sensors

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The ecological importance of submerged aquatic vegetation (SAV) in estuaries and coastal zones throughout the world is well established. Water clarity and the availability of light determine seagrass productivity and abundance and the maximal depth to which different seagrass species will grow, or indeed, if they will grow at all. A comparison was made of continuous readings of underwater photosynthetically active radiation (PAR) and light attenuation (k) measured by two types of sensors (spherical and cosine), as part of a study on SAV-PAR interactions in Indian River Lagoon (Florida). The ratio of k calculated from cosine:spherical sensors was fairly constant; over the course of the whole year, cosine sensors provided estimates of k ca. 25% higher than those calculated from spherical sensors. Estimates of k ranged from 0.80-0.92 and 0.64-0.75, respectively, for cosine and spherical sensors. Although cosine sensors provided the same temporal (diel, monthly, and seasonal) patterns of PAR and k as spherical sensors, spherical sensors are recommended over cosine ones for future SAV/PAR monitoring because (1) spherical sensors measure all photons available for photosynthesis by seagrasses and other primary producers and (2) PAR and k are less quickly altered by sensor fouling.

INTRODUCTION

The ecological importance of submerged aquatic vegetation (SAV) in estuaries and coastal zones throughout the world is well established (e.g., Wood et al. 1969, Thayer et al. 1984, Larkum et al. 1989). These highly productive plants provide critical habitat and food for many organisms within coastal and estuarine waters (e.g., Lubbers et al. 1990, Pohle et al. 1991) and are important in nutrient cycling and water movement in the system (e.g., Powell and Schaffner 1991). SAV has major impacts on other biotic resources, including fisheries, with considerable economic significance (e.g., Gilmore 1987, Livingston 1987, Durako et al. 1988). The realization that healthy SAV is required for the ecological functioning and the economical viability of estuarine and coastal ecosystems has triggered significant interest in a better understanding and management of this resource.

Water clarity and the availability of light (measured as photosynthetically active radiation = PAR) determine seagrass productivity and abundance and the maximal depth to which different seagrass species will grow, or indeed, if they will grow at all. Incident light and the attenuation of light within the water column all vary within the course of a day, from day-to-day, and among seasons. Although the general factors contributing to light attenuation in estuaries and lagoons are well know, the specific causes vary from site to site.

A high priority for the management of the Indian River Lagoon (IRL) is attaining and maintaining a functioning macrophyte-based ecosystem (Steward et al. 1992, IRLNEP 1993). The lagoon, located along over 150 miles of the east-central coast of Florida, has the highest biodiversity of any estuarine system in the continental United States (e.g., Gilmore et al. 1983; special issue of *Bulletin of Marine Science*, July 1995). This richness is attributed both to its geographical location, where the warm temperate and tropical flora and fauna overlap, and to its diverse and complex habitats, which include seagrass beds, salt marshes, mangrove forests, and macroalgal communities. SAV is a critical component of the lagoon, playing an important role in biological productivity and species diversity. Within IRL, there are approximately 100,000 acres of seagrasses; all seven species of Florida/Caribbean seagrasses are present (Dawes et al. 1995). The predominant species are *Halodule wrightii* (shoal grass) and *Syringodium filiforme* (manatee grass), with lesser amounts of *Thalassia testudinum* (turtle grass; its northern limit is near Sebastian Inlet), *Ruppia maritima*, and *Halophila* spp.

Since the 1950's, the areal extent of SAV within IRL has been dramatically reduced, with estimated losses as high as 100% in certain areas (Haddad 1985). This decline in SAV coverage has been largely attributed to adverse water quality conditions (i.e., increased nutrients and suspended solids) that result in reduced water clarity, and, thus, less light available for seagrass photosynthesis.

There are few PAR data available for IRL. As part of a study on SAV-PAR interactions in the lagoon, a comparison was made of continuous readings of underwater PAR and light attenuation measured by two types of underwater sensors (spherical and cosine sensors). This communication reports on those comparisons and makes recommendations for future PAR monitoring studies.

METHODS

The data reported in this communication were collected at a site (28° 30.34' N, 80° 35.30' W) located in that part of the Indian River Lagoon system known as Banana River, which, along with the northern region of IRL proper and the southern area of nearby Mosquito Lagoon, are generally considered to be the least impacted, most natural areas of the IRL system. Additional assets of this station were a well-developed seagrass bed consisting of multiple species of seagrass (primarily *Halodule wrightii* and *Syringodium filiforme*, with small quantities of *Halophila englemannii*), existence of historical data and other ongoing environmental monitoring, a well-defined "deep end" of the seagrass bed, and a high degree of security for locating additional sensors for the cosine vs. spherical sensor comparisons.

Arrays of PAR sensors were deployed and maintained at each station over the period of November 30, 1993 to November 30, 1994, with continuous PAR measurements made and recorded as mean values every 15 minutes. There were three types of Li-Cor quantum sensors used:

(1) LI-190SA Quantum Sensors - These flat sensors measure incident vector irradiance (i.e., "cosine" or " 2π" sensors) in the air.
(2) LI-192 SA Underwater Quantum Sensors - These flat, underwater sensors measure sub-surface vector irradiance (i.e., "cosine" or " 2π" sensors). They may also be used in the air, with the appropriate calibration correction.
(3) LI-193 SA Spherical Quantum Sensors - These spherical underwater sensors measure sub-surface scalar irradiance (i.e., "spherical" or "4π" sensors). They may also be used in the air, with the appropriate calibration correction.

All of these sensors measure PAR in the 400 to 700 nm wavelength band, in units of micromoles per square meter per second (μmol m^{-2} s^{-1}). Prior to deployment, all sensors were cross-calibrated to determine the existence of any irregularities and were found to be well within Li-Cor's specifications of $\pm$5% (within one any type of sensor). Data collected by the sensors were stored in Li-Cor LI-1000 DataLoggers.

The PAR array at this station consisted of a datalogger with a deck cosine sensor (labeled "C0"), a deck spherical sensor (using the "air" calibration; labeled "S0"), and six submersed spherical sensors (using the "water" calibration). The underwater cables were enclosed in PVC pipe and securely anchored to the bottom. The datalogger was securely fastened on land. Pairs of sensors (cosine vs. spherical) were deployed at the same locations (i.e., "C1" and "S1" were just above the seagrass canopy and "C2" and "S2" were mid-depth) and also at a site further offshore ("C3" and "S3") at the deep end of the vegetation, which was readily discernible at this station. The differences in depths of the underwater sensors at each station were determined when weather conditions permitted accurate measurements to be made.

PAR measurements were made continuously and recorded at 15-minute intervals for all sensors during the entire photoperiod for 12 months. All dataloggers were synchronized to Eastern Standard Time. Use of an additional datalogger permitted a system of switching out the deployed datalogger each week as well as downloading data, checking/replacing batteries, and maintaining the dataloggers under more environmentally friendly laboratory conditions. Batteries were changed as needed (low battery warnings provided adequate lead time for changing batteries, given the frequency of downloading). Because of the rapid fouling of sensors, all submersed sensors were manually cleaned twice weekly, a frequency initially based on previous experience in the lagoon (M.D. Hanisak, unpublished).

Data sets were assembled by combining the individual weekly data files. Any lines of data with missing values for any of the underwater sensors were omitted (i.e., if one of those sensors did not have a valid reading, than k could not be calculated). Typically, such missing values occurred near the beginning and end of the photoperiod, or as a result of negative readings due to terminal block problems. Corrections for sensor drift were applied to the raw data by assuming a linear drift during the period of deployment (Li-Cor, personal communication). Vertical attenuation coefficients were calculated from the standard equation (e.g., Kenworthy and Haunert 1991):

$$\mathbf{k = -ln\,(I_z/I_o)\,/\,z}$$

where k = vertical attenuation coefficient
I_z = PAR at the deeper sensor ($\mu mol \cdot m^{-2} \cdot s^{-1}$)
I_o = PAR at the shallower sensor ($\mu mol \cdot m^{-2} \cdot s^{-1}$)
z = difference between the depths of the two sensors (meters)

Data that were recorded during periods of station maintenance (e.g., changing out of dataloggers or sensors, cleaning of sensors) were not included in the statistical analyses. Also removed from analyses were k values that were either obviously too low ($k \leq 0$) or too high ($k > 5$). These extreme values were caused by a number of problems including differential or heavy fouling of the sensors, drift algal accumulations obstructing sensors, and, often, the first and last readings during the photoperiod when sun angle is extreme and relatively rapid changes in PAR are occurring. Preliminary data analyses resulted in only using data collected during the first 48 hours following each cleaning of the sensors to eliminate the effect of fouling organisms on reducing the measured PAR values. Additional data reduction occurred after considering diel patterns (see Results).

In addition to presenting some of the raw data graphically, data are presented as mean ± standard error (SE). Statistical analyses were performed with SAS statistical software (SAS Institute 1988). Statistical significance among means was tested with analysis of variance (ANOVA). When ANOVA indicated the existence of significant differences, the Tukey-Kramer test determined which means were significantly different ($P < 0.05$).

RESULTS

Even with cleaning the sensors twice a week, there were times when the amount of fouling significantly reduced the amount of underwater PAR measured by the sensors (Fig.1). The effect of fouling on the calculation of underwater light attenuation (k) was greater for the cosine sensors than on the spherical sensors (Fig. 2). There was no significant (paired t-test: $P > 0.05$) change in k estimates before and after cleaning of spherical sensors, but there was a significant change for cosine sensors (paired t-test: $P = 0.005$). Deployment of sensors (the C3 and S3 sensors) at a greater depth substantially reduced the variability of the k estimates.

Comparison of all data collected at 12:00 hour (noon) throughout the year for the two sensor types indicated similar patterns, but different absolute values, for both PAR (Fig. 3) and k (Fig. 4). As noted above, considerable reduction in variability was achieved when one of the sensors (C3 and S3 sensors) was deployed in deeper water (Fig. 4).

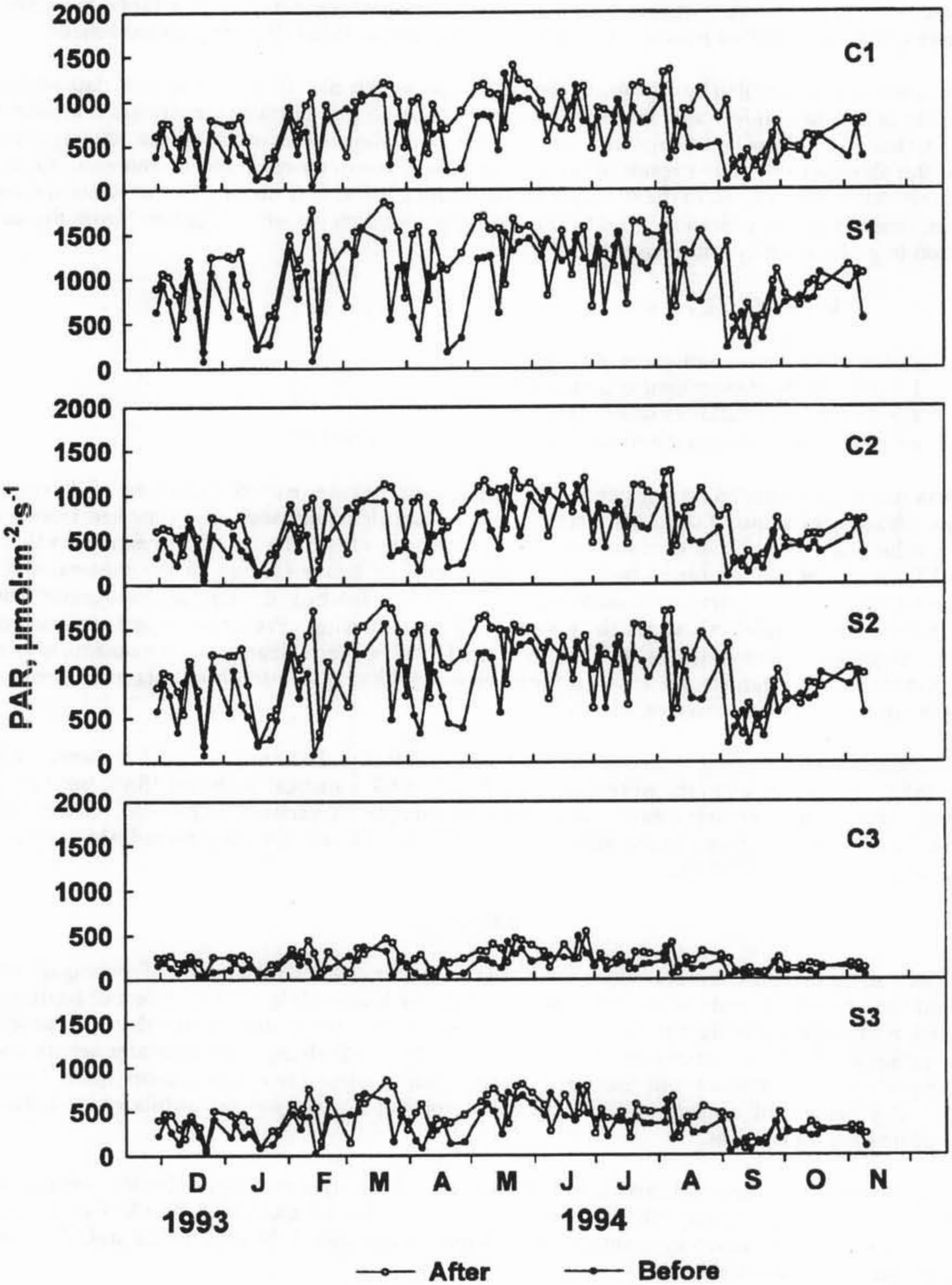

Figure 1. PAR (µmol•m $^{-2}$ •s $^{-1}$) measured by the C1, S1, C2, S2, C3, and S3 sensors, before and after sensors were cleaned, from November 30, 1993 to November 30, 1994.

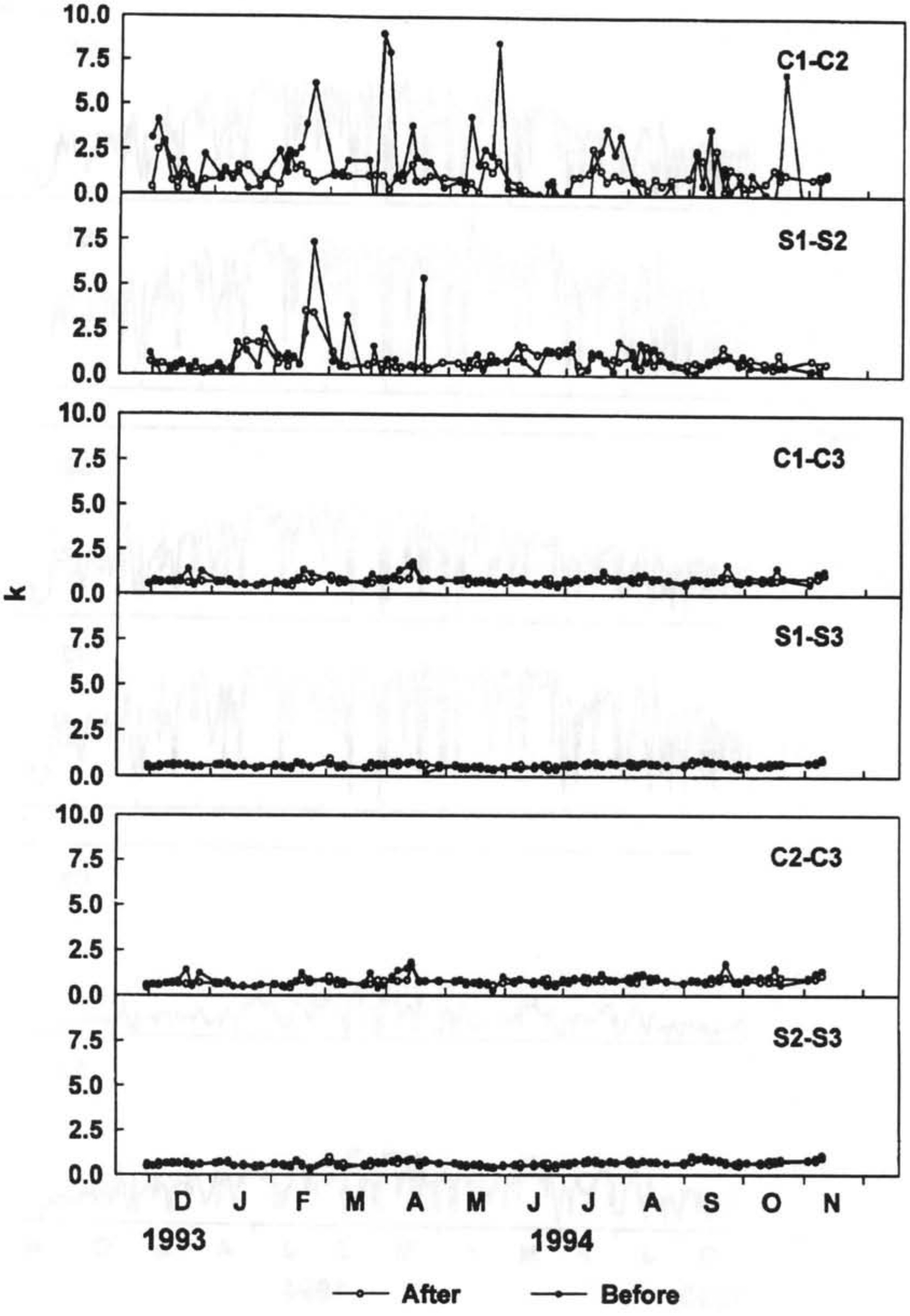

Figure 2. Vertical attenuation coefficients (k), before and after sensors were cleaned, from November 30, 1993 to November 30, 1994, calculated from various cosine (C) and spherical (S) sensors.

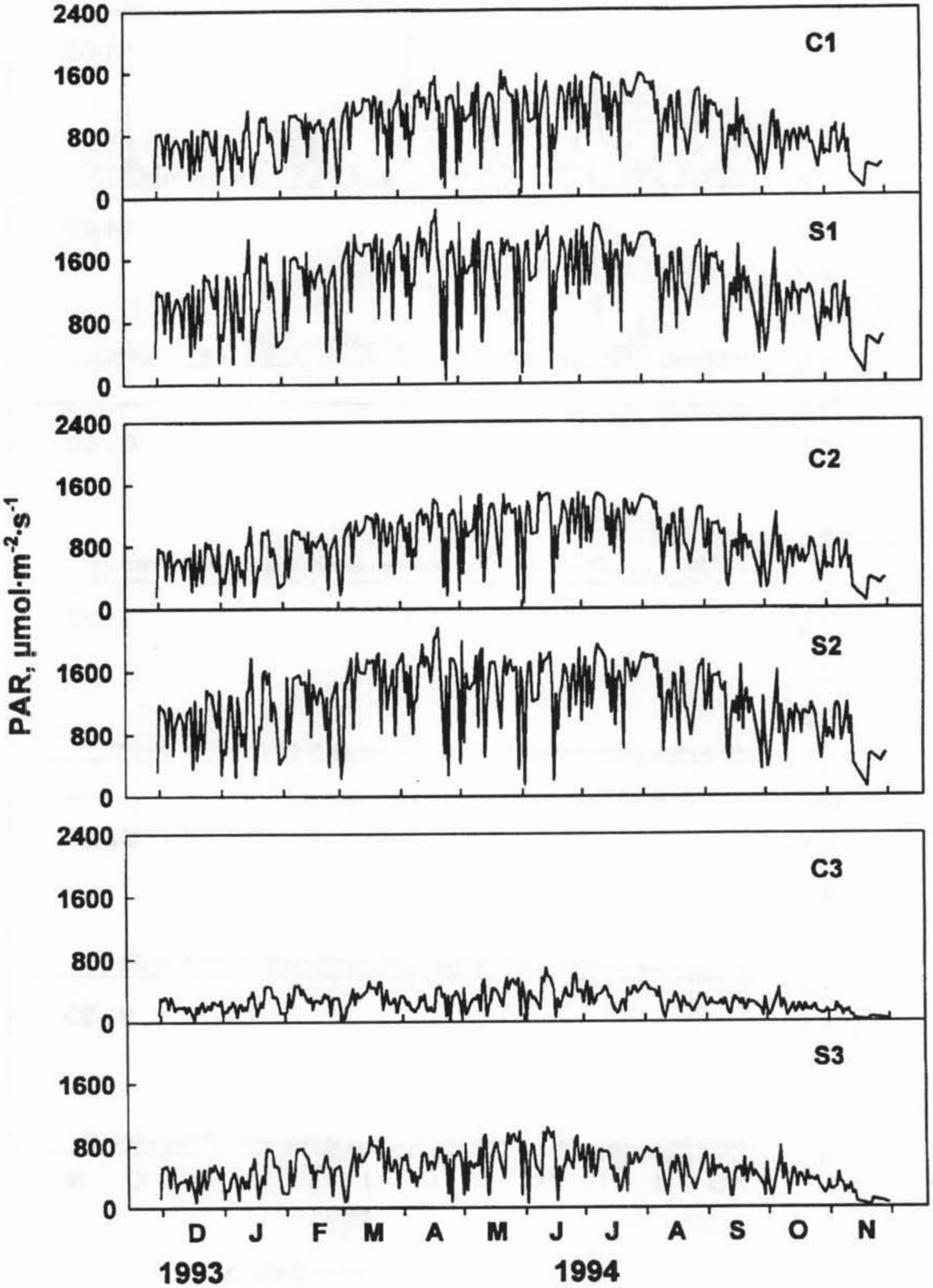

Figure 3. PAR (µmol•m $^{-2}$•s $^{-1}$) measured by the C1, S1, C2, S2, C3, and S3 sensors, at 1200 (noon), from November 30, 1993 to November 30, 1994.

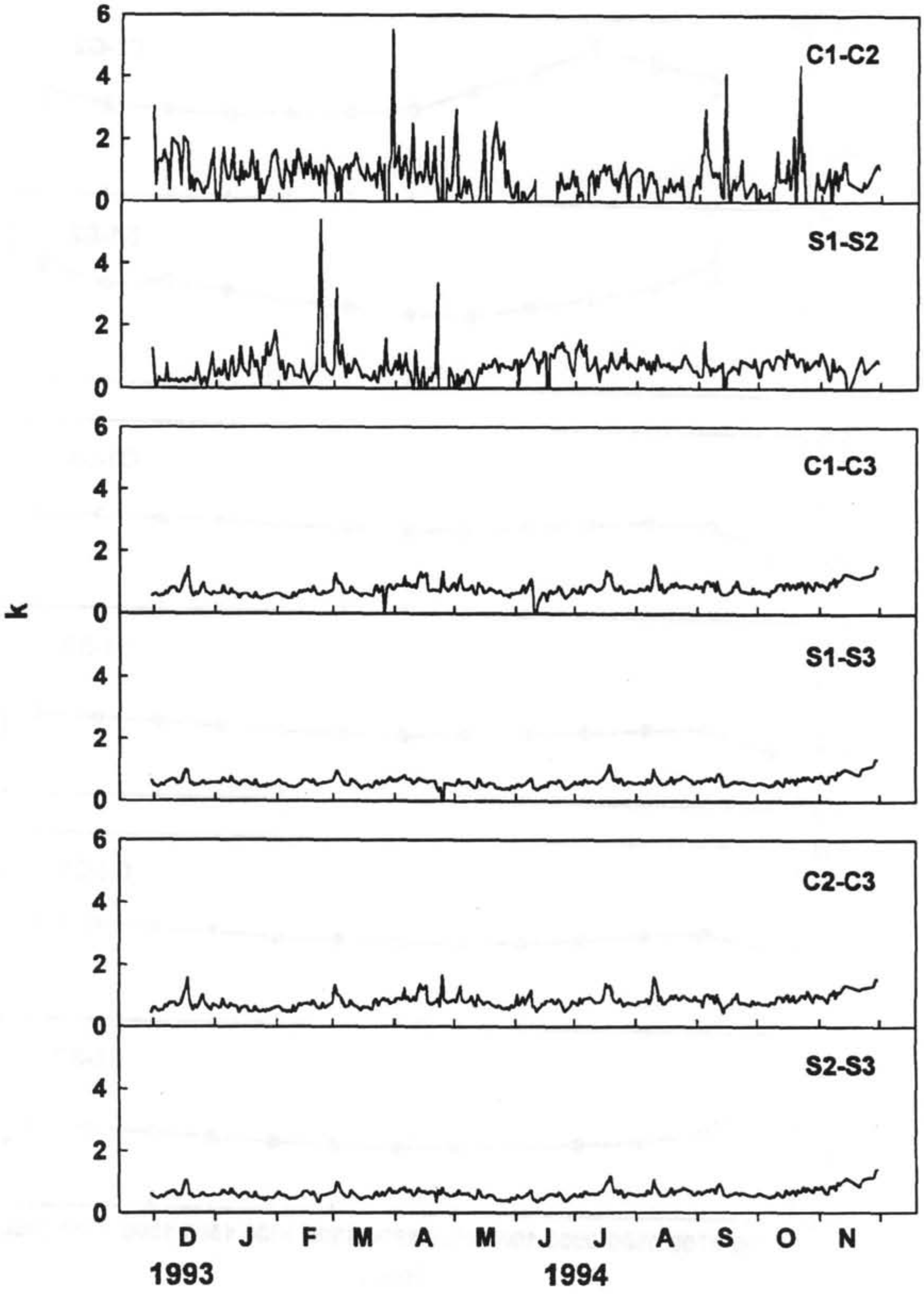

Figure 4. Vertical attenuation coefficients (k), at 1200 (noon), from November 30, 1993 to November 30, 1994, calculated from various cosine (C) and spherical (S) sensors.

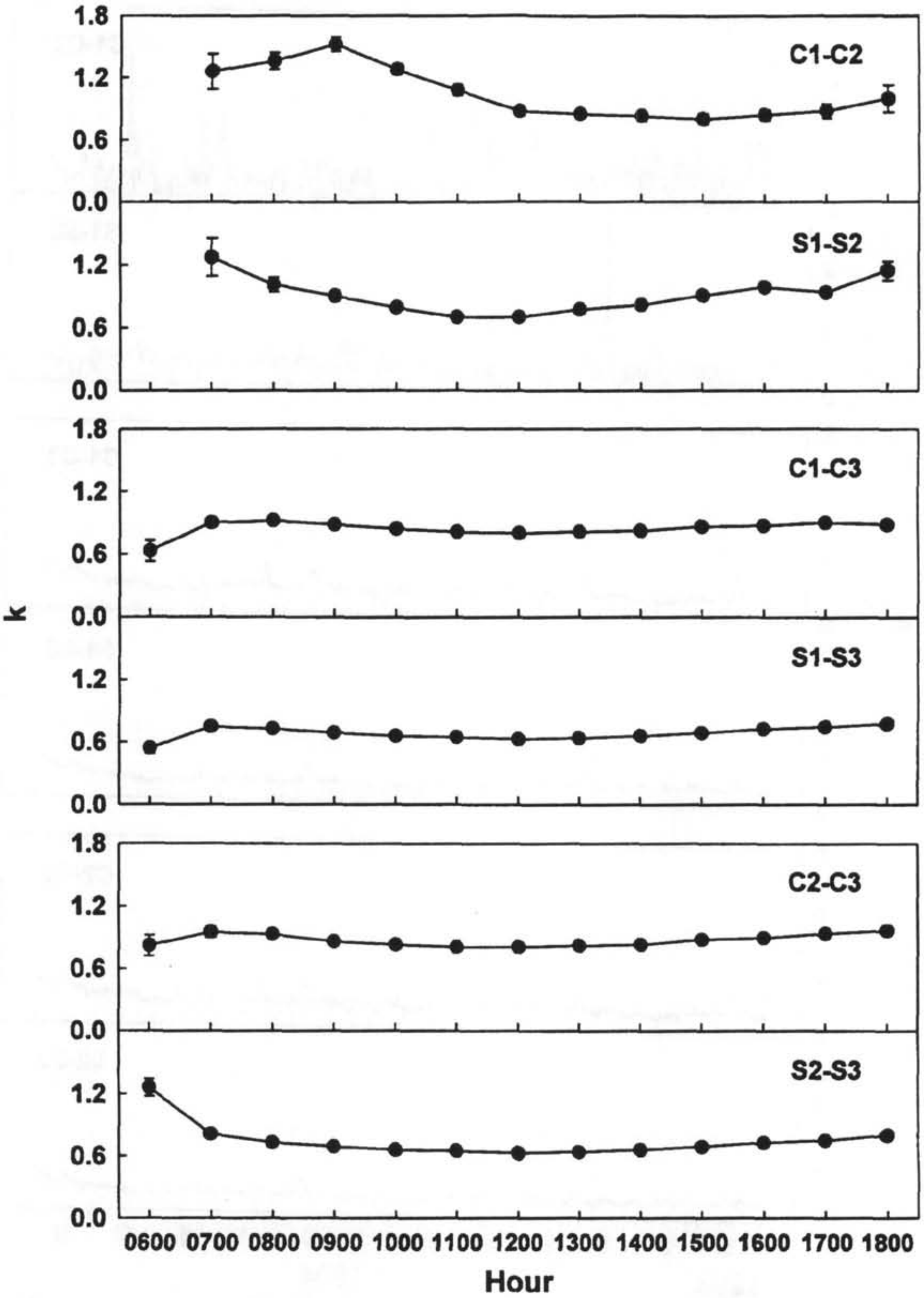

Figure 5. Diel patterns in vertical attenuation coefficients (k), from November 30, 1993 to November 30, 1994, calculated from various cosine (C) and spherical (S) sensors.

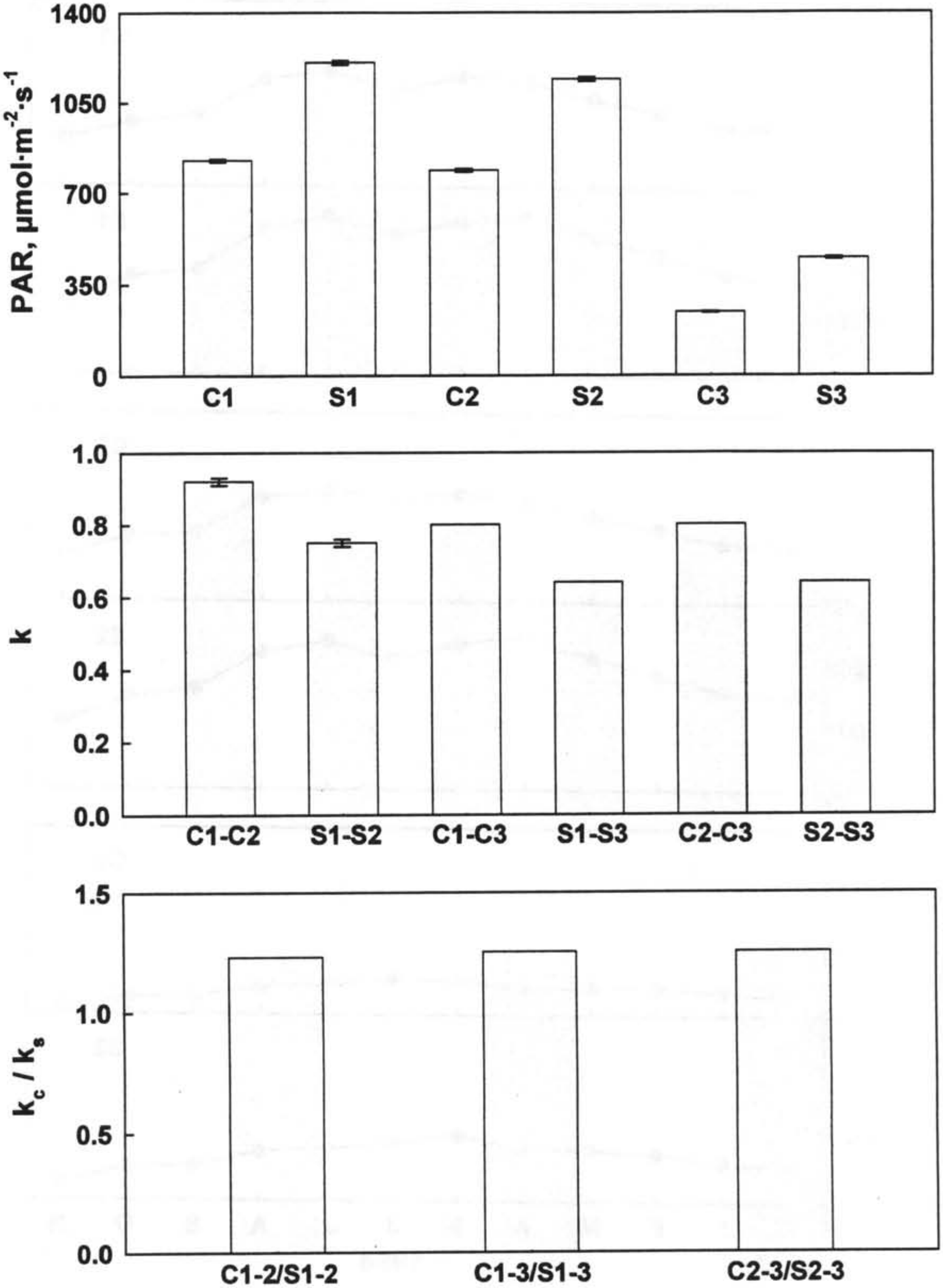

Figure 6. Mean PAR (µmol•m^{-2}•s^{-1}), k, and the ratio of k calculated from cosine sensors vs. spherical sensors, for all data between the hours of 1000-1400, within 48 hours after cleaning of sensors. Data are means (± SE).

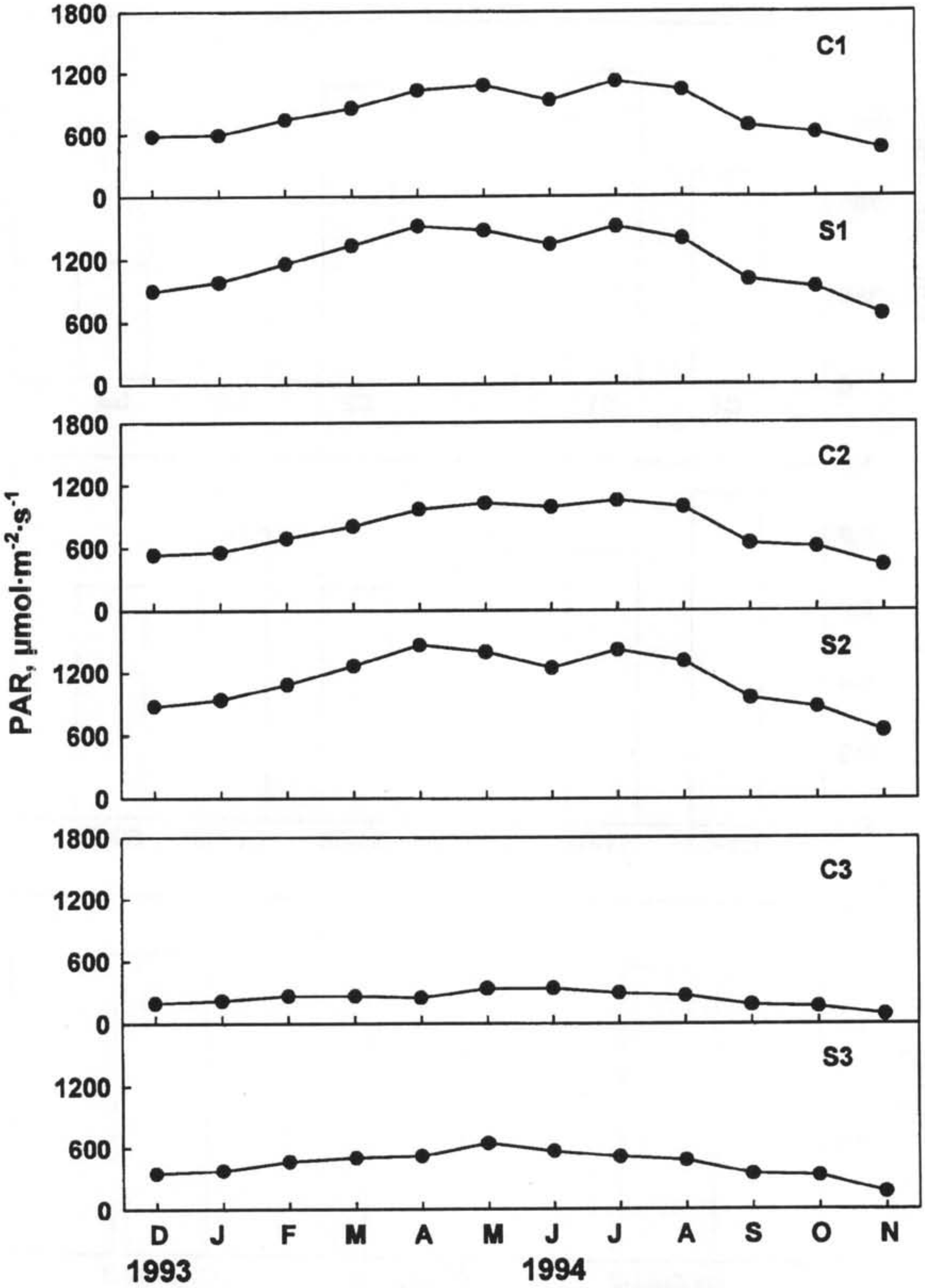

Figure 7. Monthly means (± SE) of PAR (µmol•m^{-2}•s^{-1}) measured by different sensors, for all data between the hours of 1000-1400, within 2 days (48 hours) after cleaning of sensors.

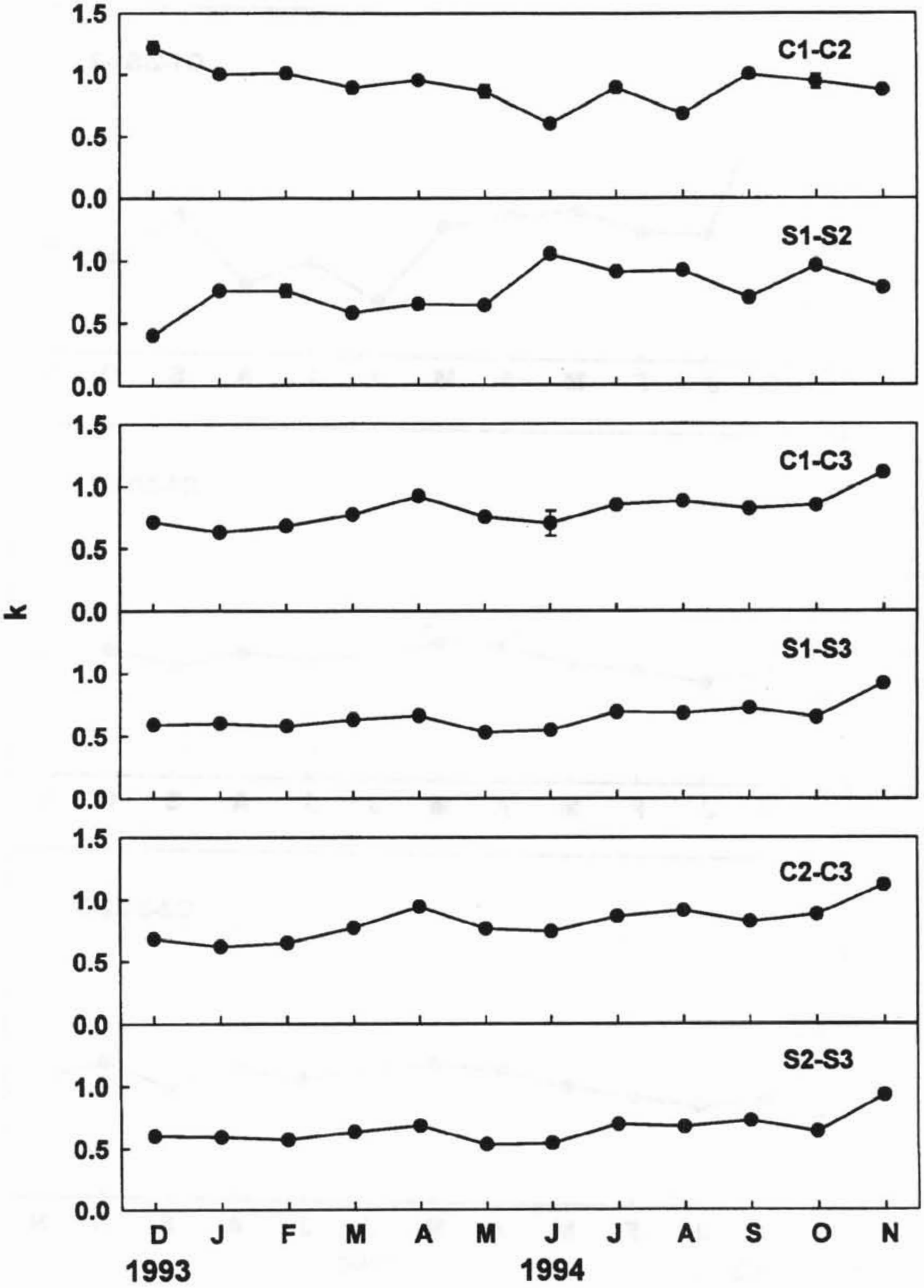

Figure 8. Monthly means (± SE) of the vertical attenuation coefficient (k), for all data between the hours 1000-1400, within 48 hours after cleaning of sensors. Data are means (± SE).

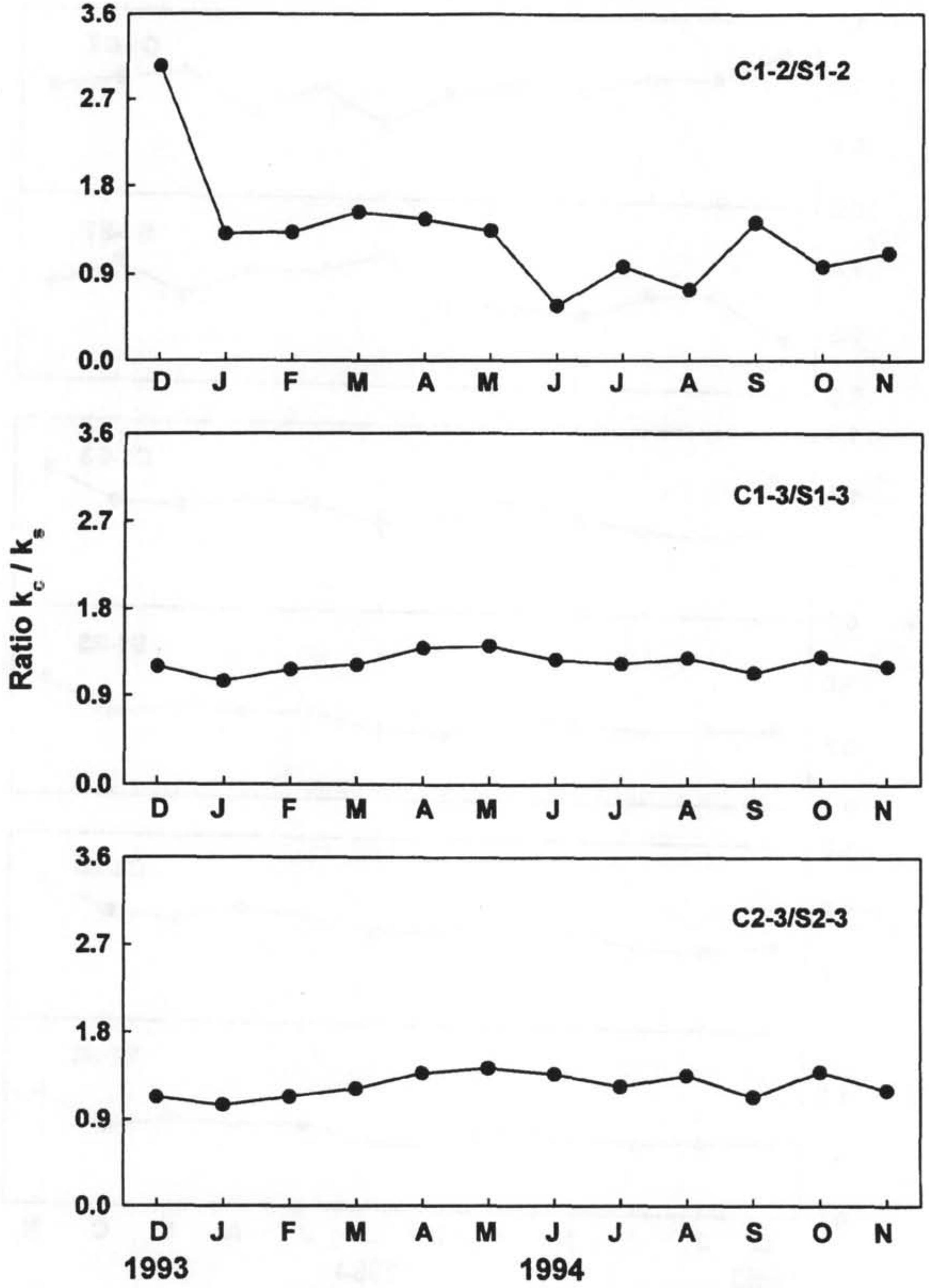

Figure 9. Monthly means (± SE) of the ratio of k calculated from cosine sensors vs. spherical sensors, for all data between the hours 1000-1400, within 48 hours after cleaning of sensors. Data are means (± SE).

Diel patterns were similar for the two types of sensors. Both sensors were usually more variable at the beginning and end of the day (Fig 5). Cosine sensors had a slightly broader window than spherical sensors when k was equivalent to noon readings.

Calculation of the ratio of k from cosine:spherical sensors (Fig. 6) over the course of the whole year indicated that cosine sensors had an estimated k ca. 25% higher than that calculated from spherical sensors. Estimates of k ranged from 0.80 - 0.92 and 0.64 - 0.75, respectively, for cosine and spherical sensors.

While the absolute values of PAR from the two sensors varied, the observed temporal (monthly) patterns were similar (Fig. 7, 8); the ratio of k calculated from cosine:spherical sensors was fairly constant (Fig. 9). These data also show that the relationship of the two sensors is nearly constant when sensors are located at greater depths.

DISCUSSION

Traditionally, underwater PAR has usually been measured with cosine sensors, however the current trend (Morris and Tomasko 1993) is to favor spherical sensors as they better measure the light that is actually available to plants for photosynthesis. At the principal site where the comparison of sensors was made (BR), the cosine sensors routinely measured a k 25% higher than what was obtained with spherical sensors. This value is similar to what others have measured (e.g., Moore and Goodman 1993), and it is highly likely that, at a given site, historical cosine-derived measurements could be reasonably converted to values comparable to what would be obtained with spherical sensors.

A potential drawback to using cosine sensors was that they were more rapidly fouled than spherical sensors. Often the cosine sensors trapped what appeared to be re-suspended sediments, which were less likely to be caught by the spherical sensors. Although cosine sensors did provide the same temporal (diel, monthly, and seasonal) patterns of PAR and k as spherical sensors, the latter are recommended for all future monitoring that focuses on SAV/PAR relationships in the IRL because spherical sensors measure all of the photons available for photosynthesis by seagrass and other primary producers and because PAR and k are less quickly altered as a result of sensor fouling.

There are few readily accessible PAR datasets from the IRL (Kenworthy 1993), and none have employed continuous monitoring of PAR. Highly significant seasonal differences in PAR and k were found. Underwater PAR was maximal in spring followed in order by summer, winter, and fall; this pattern may directly influence seasonal patterns of seagrass biomass and productivity. There was an increase in k during the wet season, suggesting that freshwater impacts on k in the IRL could be an important management issue to address.

Temporal variability also was readily apparent within days (diel variation) and from day to day (daily variation). While the diel curves of PAR were "textbook" in appearance, the relative insensitivity of k to diel fluctuations was surprising. This latter finding suggests that if k, but not PAR, is the parameter of interest, then monitoring of k need not be limited to the traditional "10 to 2" window.

While many factors are involved, much of the short-term variability in measurements of k appears to be due to the shallow deployment of the sensors, which was necessitated because of the shallowness of the "mid-bed" locations. The higher variability of shallower sensors is probably due to wave action. If there is to be any significant continuous monitoring of PAR in the future, it might be appropriate to locate the instrumentation in deeper areas of seagrass beds (e.g., near the "deep edge"), rather than mid-bed.

The concept of continuous PAR monitoring has merit: it is technically feasible to get a rather large dataset at multiple sites, which may be needed to characterize a dynamic, spatially and temporally heterogenous environment such as IRL. Data can be collected year-round, regardless of weather and holidays. Data can be obtained during storm events, major freshwater discharges, phytoplankton blooms, etc. without trying to schedule sampling of such stochastic events in advance. However, continuous monitoring of PAR also has considerable disadvantages, including the need for regular (in IRL: twice weekly) cleaning of sensors and maintenance of data loggers. Other issues such as the uncertain movements of drift algae (a problem relatively localized in time and space in this study) and the potential physical loss/vandalism of monitoring equipment (a problem that was much less than what was anticipated at the start of this study) are also constraints to continuous monitoring. Lastly, it appears that the resulting, enormous data sets (at least using the 15-minute intervals required for this study) are not required to adequately categorize PAR and k; comparison of data collected each day at 1200 (noon) vs. the much larger (17 times) 1000 to 1400 data set indicated that continuous monitoring of underwater PAR was not required to adequately characterize underwater PAR or k in IRL. While use of only a single measurement each day resulted in less precision, there was little, if any, loss of accuracy. It may be better to put limited financial resources into other management needs (e.g., more intensive water quality monitoring) than continuous monitoring of PAR.

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