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A comparison and correction of light intensity loggers to photosynthetically active radiation sensors

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Abstract

Accurate light measurements are important in the analysis of photosynthetic systems. Many commercial instruments are available to determine light; however, the comparison of light estimates between studies is difficult due to the differences in sensor types and their calibrations. The measurement of underwater irradiance is also complicated by the scattering and attenuation of light due to interactions with particulates, molecules, and the bottom. Here, three sensor types are compared to evaluate the calibration of light intensity loggers to estimate photosynthetically active radiation (PAR). We present a simple calibration of light intensity loggers that agree within 3.8% to factory-calibrated scalar PAR sensors under a wide range of environmental conditions. Under the same range of conditions, two identical factory-calibrated PAR sensors showed a similar difference of 3.7%. The light intensity loggers were calibrated to a high-quality PAR sensor using an exponential fit ($r^2 = 0.983$) that accounts for differences in sensor types with respect to the angle of incoming light, scattering, and attenuation. The light loggers are small, robust, and simple to operate and install, and thus well-suited for typical subsurface research. They are also useful for small-scale measurements, when broad spatial coverage is needed, or in research requiring multiple sensors. Many studies have used these simple light intensity sensors to estimate PAR, yet their limitations and advantages in mimicking PAR have not been well defined previously. We present these small and user-friendly loggers as an excellent alternative to more sophisticated scalar PAR sensors.

The measurement of photosynthetically active radiation (PAR) has received much attention in the literature as it is one of the main variables controlling primary production. PAR is defined as the rate of electromagnetic radiation received on a surface with wavelengths from 400 to 700 nm, which corresponds to light energy absorbed by photosensitive pigments with units of µmol photons m^{-2} s^{-1} (Brooks 1964; Federer and Tanner 1966; Booth 1976). The measurement of PAR under water presents a number of challenges, such as light scattering and attenuation with depth, as well as differences among the spectral responses of different sensor types. The scattering of light causes it to deviate from a straight path through the water column due to reflection off particulates in the water or the sediment surface, as well as interactions with water molecules and density stratifications. Spectral attenuation causes specific wavelengths of light to be increasingly absorbed by the water molecules with depth, and therefore, the spectral response and calibration of sensor types becomes important when measuring at different depths. Due to sensor designs, no PAR sensor can absorb light from all angles, and therefore variations in the response to different light angles exist between manufacturers and sensor types. In general, the spectral and angular responses of different sensor types is a problem for comparing PAR measurements obtained with different sensors, a topic that has been reviewed extensively (Jerlov 1968, 1976; Jewson et al. 1984; Kirk 1994; Meyercordt et al. 1999).

The intercalibration of different light sensor types that may have dissimilar responses under variable light conditions has been suggested as a way to obtain comparable light measurements (Booth 1976; Jewson et al. 1984; Meyercordt et al. 1999). The comparison of sensor types is complicated by differences in light-collecting properties that may vary with environmental conditions such as depth, turbidity, and intense light-scattering (Jewson et al. 1984; Arst et al. 2000). Sensors may also differ in their spectral response, defined as the sensitivity to the specific wavelengths that they measure.

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The angle of incoming light may also affect measurements due to the sensor type or shading caused by sensor design. This may be further complicated by variances of up to 35% between light sensors from the same manufacturer (Jewson et al. 1984) and by deviations of up to 50% between sensors of the same model (Forster 1998). A study by Meyercordt et al. (1999) compared instruments from three manufacturers of high-quality PAR sensors and found a deviation of up to 188%, which was attributed to the collecting properties of each sensor. In many cases, the differences in sensor-collecting properties, spectral response, and the ability to measure diffuse radiation requires an individual calibration in order to determine accurate and comparable PAR measurements (Meyercordt et al. 1999).

There are two main types of sensors commonly used to measure underwater PAR, planar, and scalar sensors. Planar sensors have a flat light collecting surface that responds to light that impinges on their surface from downward directions. Planar sensors tend to underestimate PAR because the collecting surface does not absorb upwelling radiation or light that reflects off of particles in the water and the sediment surface (Booth 1976; Arst et al. 2008). Scalar PAR sensors have a hemispherical or spherical collecting surface that functions to absorb light from 2π to 4π steradians, respectively. They are believed to record more accurate measurements of total underwater PAR, as they absorb diffuse radiation from most directions (Booth 1976). For these reasons, it has been suggested that planar sensors are insufficient for studies requiring accurate scalar PAR measurements (Arst et al. 2008), for example those involving phytoplankton residing within the water column where diffuse radiation may be a significant form of available light. Most commercially available planar PAR sensors are also cosine corrected, which consists of a block of light diffusing material that is designed to reduce errors associated with light impinging on the sensor surface from low incident angles. A cosine-corrected planar sensor will produce more accurate measurements of PAR than a planar sensor without cosine correction under light conditions that are not ideal, such as during sunset and sunrise where the angles of incoming light are small.

Many authors have reported using simple light-intensity loggers, designed to measure relative differences in total available radiation, to estimate underwater PAR values through calibration (Glud et al. 2002; Boese et al. 2005; Piniak and Brown 2008; Liu et al. 2009; Fanta et al. 2010; Tait and Schiel 2010; Hulatt and Thomas 2011; Pedersen et al. 2011; Wall et al. 2011; Koch at al. 2012). However, little information on these calibrations has been provided, and the differences between simple light-intensity loggers and scalar PAR sensors have not been considered. This article compares three different light sensor types that were used to estimate PAR. We list the strengths and weaknesses of each type, as well as the quality and accuracy of their PAR estimates. We also show that light intensity loggers can be used to estimate PAR as accurately and reliably as scalar PAR sensors.

Materials and procedures

Evaluated sensor types

Eleven Onset light and temperature dataloggers (UA-002-64 HOBO Waterproof Temperature/Light Pendant Data Logger), one Odyssey Integrating PAR Sensor (Dataflow Systems PTY Limited), and two LI-1000 LICOR dataloggers with LICOR Spherical Quantum PAR Sensors (LI-193SA calibrated May 2009) were compared. The HOBO pendant temperature and light logger (HOBO) is a small (6 × 3 × 2 cm), self-contained, planar sensor designed for measurement of light intensity (150-1200 nm). The Odyssey Integrating PAR sensor (ODY) is a self-contained cylindrical (4 cm diameter × 16 cm long) PAR logger (400-700 nm) with a planar cosine-corrected sensor. The LICOR Spherical Quantum Sensor (LICOR) is a 4π scalar PAR sensor that must be connected to a nonwaterproof data logger, and is a standard instrument for PAR measurement. The LICOR has a reported angular response of $< \pm 4\%$ error up to ± 90° from the normal axis. Whereas the LICOR receives light from all angles, its angular response is reduced at 180° from the normal axis due to shading from the sensor housing.

Controlled growth chamber experiment:

To compare differences between HOBO and the two PAR sensors, the sensors were placed in a growth chamber (Conviron 4030, Controlled Environments Limited) set to produce different PAR levels. The 11 HOBOs (referred to as letters B through O) used were mounted on a rotating circular plate to expose them to identical light conditions and the two PAR loggers were mounted to stands at the same height. The HOBOs were set to log light every 5 s; the ODY and LICOR were set to integrate over 0.25 h intervals. The growth chamber was set to have variable light intensities at 35, 165, 380, and 605 μmol photons m^{-2} s^{-1}. Data were recorded over 76 h.

Field experiments

Three HOBOs (loggers H, K, and L), an ODY, and a LICOR were deployed through 10 d on a permanently submerged sand flat in outer West Falmouth Harbor, Massachusetts, USA (41° 36.22 min N, 70° 38.42 min W) during August 2009. The same logging parameters were used as in the light chamber experiment. Three HOBOs were used to reduce the variability of measurements by subsequent averaging and to provide a check for the other sensors if one was fouled. The HOBOs were mounted at the same height as the two PAR sensors on the top of PVC poles 10 cm above the sediment surface. The depth of the light meters varied from 0.4 m to 2.0 m, depending on tidal stage. The light sensors were faced upward and separated to prevent shading. The data logger for the LICOR was mounted in a dry box on a float. Every 24 h, data were downloaded from the HOBOs whereas the ODY and LICOR were capable of logging the full duration of the experiment.

Six HOBOs (B, H, I, K, L, and M) and the ODY were also compared with two LICORs near Key Largo, Florida at two sites: a reef (25° 06.59 min N, 80° 18.12 min W) and a seagrass bed (25° 06.58 min N, 80° 18.14 min W) in July 2010.

The reef site is in Grecian Rocks Sanctuary Protection Area and can be characterized as a shallow, algal-dominated fringe reef. The seagrass site is located just inshore of the reef with a homogenous coverage of the seagrass *Thallassia testudinum*. The two LICORs, ODY, and six HOBOs were deployed 1.1 m from the bottom at the reef with water depths varying between 1.7 to 2.4 m. The two LICORs, ODY, and HOBOs B, M, and I were deployed at 0.45 m above the bottom in the seagrass bed with water depths varying between 3.5 to 4.2 m. Data were retrieved in the same manner as the experiment above.

Data analysis

Data from each HOBO in all experiments were averaged over 0.25 h intervals. The HOBO data were plotted against each other to determine if any sensors were fouled. Data from the field experiments were discarded if silt deposits, algae cover, etc. were observed on the loggers. The HOBO and ODY data were calibrated to the LICOR data using an exponential decay fit:

$$\mathrm{PAR}_{\mathrm{LICOR}} = \mathrm{A}_1\mathrm{e}^{(-\mathrm{HOBO}/\mathrm{t1})} + \mathrm{y}_0 \qquad (1)$$

where PAR_{LICOR} is the PAR data from the LICOR (µmol photons m^{-2} s^{-1}), *HOBO* is the HOBO or ODY raw output data (lumens m^{-2} or µmol photons m^{-2} s^{-1}, respectively) and A_1, $t1$, and y_0 are fitting constants. The calibration was done for a 48 h period and then applied to other time periods for validation. The HOBO data were compared with the LICOR data using first an individual fit for each HOBO logger, and then one fit for all HOBO data. Data were then compared using regression analysis, standard statistical parameters, and ANOVAs to compare the output for each logger type.

Assessment

Light logger specifications

The pros and cons of each light logger type are outlined in Table 1. The HOBOs are inexpensive, easy to use, record temperature, and allow for small-scale measurements; however, they require calibration and have limited factory specifications. The ODY is relatively inexpensive, simple to use, and has a more advanced sensor, but it is not factory calibrated and also has limited manufacturer specifications. The LICOR is expensive, difficult to use, and is complicated to deploy in the field; however, it comes with extensive factory specifications and is a standard instrument used for PAR measurements underwater.

Light chamber experiment

The standard deviation between the 11 individual HOBO's raw data (lumens m^{-2}) at each preset light level varied between 1.3% and 2.3% of the mean (data not shown). When calibrated to the LICOR PAR data using a single exponential fit for all HOBO loggers (Fig. 1A), the deviations were between 2.2% and 3.6% at each light level (Fig. 1B). The fitting function (Eq. 1) for the single exponential fit for all 11 HOBOs had average constants of $A_1 = -8165.9$, $t1 = 1776.4$, and $y_0 = 8398.2$ and an average $r^2 = 0.998$. Using this single exponential fit for all HOBOs, the calculated PAR values were significantly different from each other at each light level (at $P < 0.01$, $F_{10} = 0.76$, $F_{10} = 0.95$, $F_{10} = 0.33$, and $F_{10} = 0.12$ for PAR levels of 35, 165, 380, and 605 µmol photons m^{-2} s^{-1}, respectively). However, when each logger was calibrated using individual fitting functions (Fig. 1C), the variation was reduced to between 0.1% and 0.7% at each light level (Fig. 1D). Using individual exponential fits for each HOBO, the calculated

Table 1. A comparison of the pros and cons of the three light logger types.

	Pros	Cons
HOBO pendant logger	Inexpensive ($42 each, $110 reader/software)	Data requires heavy post-processing
	Simple field deployment	Limited data logging period (at 5-s intervals = 72 h)
	Temperature sensor	Light intensity sensor
	Use multiple loggers, reduces data loss	Records at user-specified intervals (no integration)
	Small, easy to handle, and mount	Requires calibration
	Can be used for microscale measurements	No stability or accuracy reported by manufacturer
	Average out variations with multiple loggers	Housing scratches and degrades easily, shading sensor
Odyssey integrating PAR sensor	Fairly inexpensive ($195 each, $15 cable)	Difficult to download/open if using often
	Simple field deployment	Needs to be calibrated
	Cosine-corrected photosynthetic irradiance sensor	Difficult battery replacement
	User-specified integration periods	No stability or accuracy reported by manufacturer
	Small, easy to handle, and mount	No temperature sensor
LICOR LI-193SA	Guaranteed factory calibration (±5%)	Expensive (~$3,000 depending on cable length)
	Spherical 4π scalar sensor	Difficult operation
	User-specified integration periods	Difficult field deployment and mounting
	Excellent angular response, stability, sensitivity	Bulky, nonwaterproof, long cables
		No temperature sensor

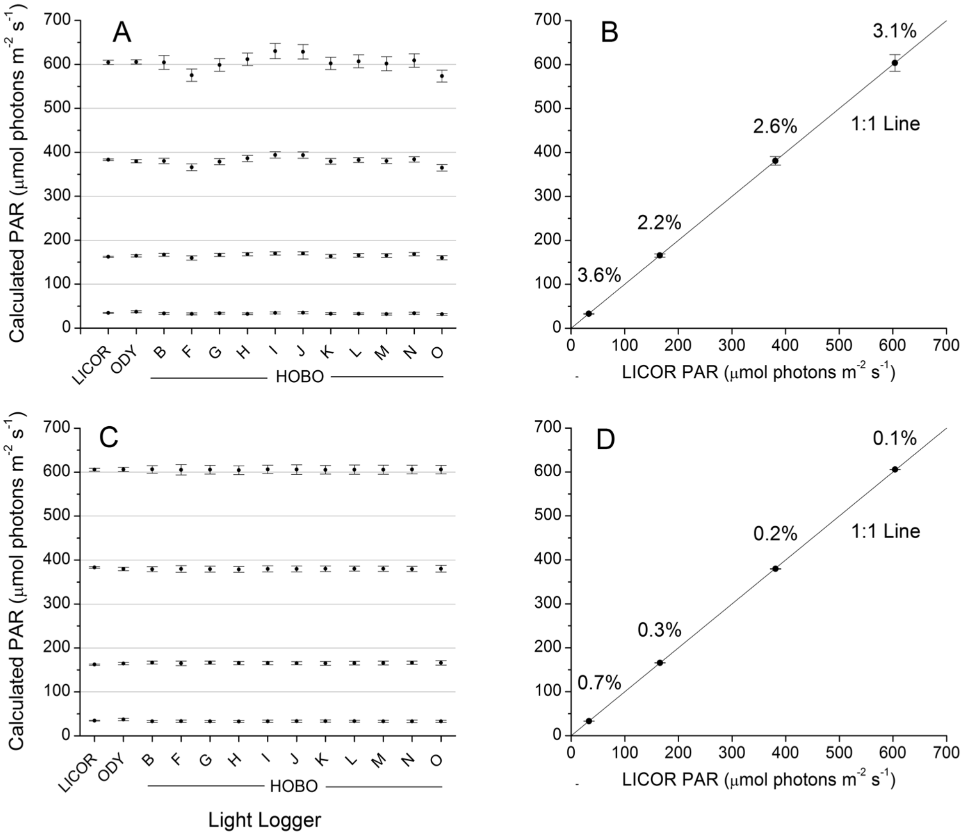

Fig. 1. Fig. A and B show the LICOR, ODY, and calculated HOBO data calculated using a single exponential fit for all HOBOs. Fig. C and D show the LICOR, ODY, and calculated HOBO data calculated using an individual exponential fit for each HOBO. The four rows of data points in A and C represent the four light chamber settings and error bars represent standard deviations for all figures. Figs. B and D show the calculated PAR values averaged across 11 HOBOs with the numbers above points representing the standard deviation as a percent variation from the mean with n = 90, 54, 47, and 48 (0.25 h intervals). There were no significant differences between HOBOs calibrated using individual fits for each HOBO at $P = 0.01$. However, significant differences were found between the HOBO loggers using a single calibration on all loggers at $P < 0.01$.

PAR values were not significantly different from each other at any for light level (at $P = 0.01$, $F_{10} = 25.40$, $F_{10} = 42.58$, $F_{10} = 127.60$, and $F_{10} = 78.87$ for PAR levels of 35, 165, 380, and 605 μmol photons m^{-2} s^{-1}, respectively).

Field experiments

Fifteen minute averages of the HOBOs H, K, and L data used above the Massachusetts sand flat (sand) were correlated to the LICOR 15 min integrations using exponential fits (Eq. 1, Fig. 2A, B, and C) as in the lab experiment. The ODY data were similarly correlated to the LICOR data (Fig. 2D). The fitting function (Eq. 1) had average constants of $A_1 = -22022.5 \pm 49.7$, $t1 = 26855.2 \pm 1680.0$, and $y_0 = 2037.8 \pm 50.7$ (± SE) and an average $r^2 = 0.983$ for the three HOBOs. The ODY software requests a single point for calibration; however, our results show an exponential fit with constants of $A_1 = -4924.7$, $t1 = 20992.9$, and $y_0 = 4929.0$ with an $r^2 = 0.991$, which improved the fit to the data and increased the r^2 (linear fit $r^2 = 0.956$). Integrating all the data for the sand over the 10 d period, the cumulated HOBO- and the ODY-derived PAR values differed from the LICOR by 0.8% and 1.7%, respectively. A 24-h integration of HOBO and ODY data above the sand on a sunny day varied from the LICOR data by 0.1% and 0.2%, respectively.

Similar results were observed for the Florida seagrass bed (seagrass) and reef (reef). An exponential fit was used for each loggers' data (to the LICOR data) at each site with an average $r^2 = 0.981$ for HOBOs B, M, and I above the seagrass, an average $r^2 = 0.989$ for HOBOs H, K, and L above the reef and an average $r^2 = 0.971$ for HOBOs B, M, and I above the reef. The similar fit for the ODY had $r^2 = 0.979$ for the seagrass and $r^2 = 0.988$ for the reef. The average fits for the HOBO data for the sand, reef, and seagrass are shown in Fig. 3.

Fig. 4 shows a 24-h time series of LICOR PAR values and calibrated HOBO and ODY PAR values for the sand (Fig. 4A), the reef (Fig. 4C), and seagrass (Fig. 4E) sites. When integrated over the 24-h period, the HOBO and ODY data were 3.8% and 4.5% larger than the LICOR data for the sand site, 2.7% and 4.5% larger for the reef site, and 1.9% and 1.0% larger for the seagrass site, respectively (Fig. 4B, D, and F). The two LICORs over 24 h differed from each other by 3.7% in the seagrass and 1.0% on the reef.

The site-specific calibrations were then applied to data from different sites when each set of loggers (B, M, and I or H,

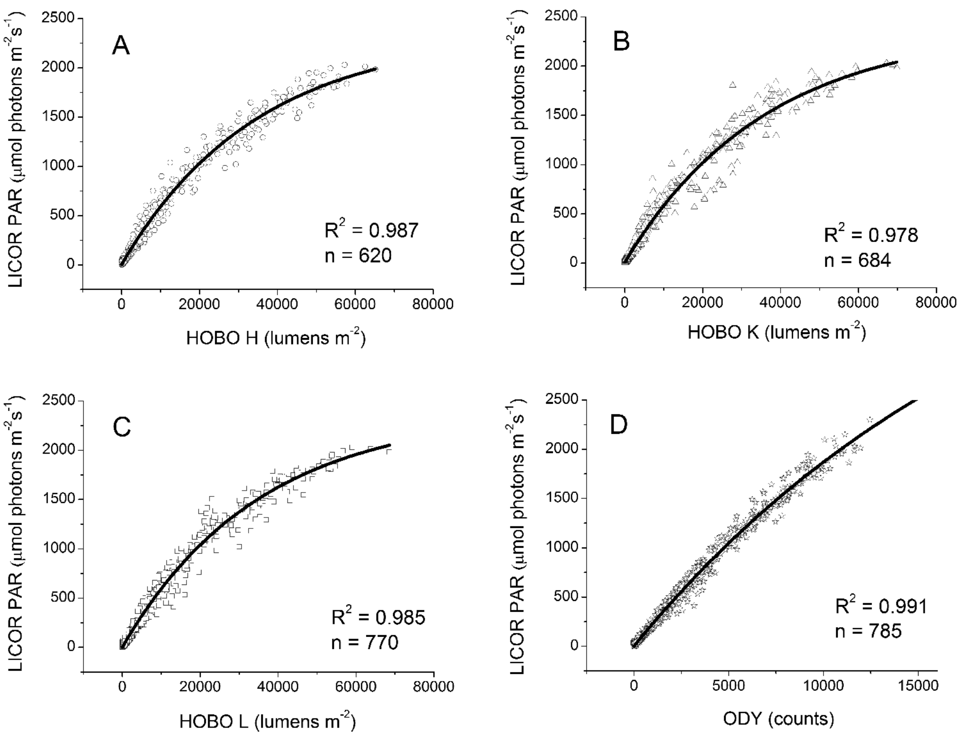

Fig. 2. Examples of correlations between the HOBOs H, K, and L and the LICOR at the sand site are shown in Figs. 3A, B, and C. An exponential function was fitted. The ODY raw data (counts) produced a similar correlation (Fig. 3D).

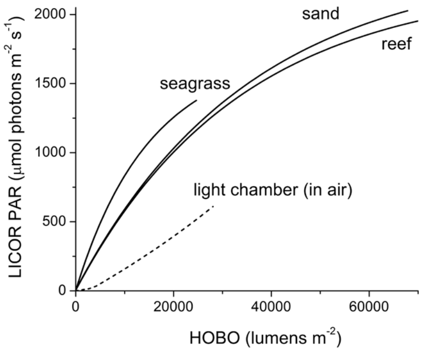

Fig. 3. Average calibration curves for 3 HOBOs at the seagrass, sand, and reef sites showing site-dependent calibrations. The dashed line is that average calibration curve for the 11 HOBOs in the growth chamber and illustrates why calibrations in air cannot be used underwater.

K, and L) were used at more than one site. Specifically, the reef calibration was applied to the seagrass data (Fig. 5A), the seagrass calibration was applied to the reef data (Fig. 5C), and the sand calibration was applied to the reef data (Fig. 5E). The 24-h integrations for the HOBOs and ODY showed differences from the LICOR integrations of –0.7% and 5.8% for the reef calibration on the seagrass data, –10.0% and –7.2% for the seagrass calibration on the reef, and 7.4% and 19.3% for the sand calibration on the reef data, respectively (Fig. 5B, D, and F).

Discussion

The use of HOBOs and ODYs to estimate underwater PAR is a simple approach that has many potential applications. This is underlined by the close agreement obtained here for both user-calibrated ODY and HOBOs relative to the factory calibrated LICOR over a range of conditions (Fig. 4 and 5), despite differences in sensor types and sensor responses. The self-contained HOBO and ODY are especially useful where the LICOR cannot be easily deployed, such as small-scale measurements, remote locations, multiple sampling locations, and measurements inside confined spaces, such as incubation chambers. Errors in PAR measurements reported in the literature for commercially available sensors (35% by Jewson et al. 1984; 50% by Forster 1998; 188% by Meyercordt et al. 1999) suggest that the use of HOBOs and ODYs to estimate PAR, with their close agreement to factory-calibrated PAR sensors, is an excellent alternative.

The variations between PAR sensor data in the literature are mainly due to the differences in sensor design and calibration (Jewson et al. 1984; Meyercordt et al. 1999). Of the sensors we examined, the LICOR is assumed to be the most accurate due to its thorough factory calibration, stability, and light-collecting properties. It is a scalar sensor that receives light from angles of ± 180° from its normal axis, including diffuse light enhanced by turbidity, scattering, and the angle of the sunlight throughout the day (LICOR manual [2006]). The HOBO

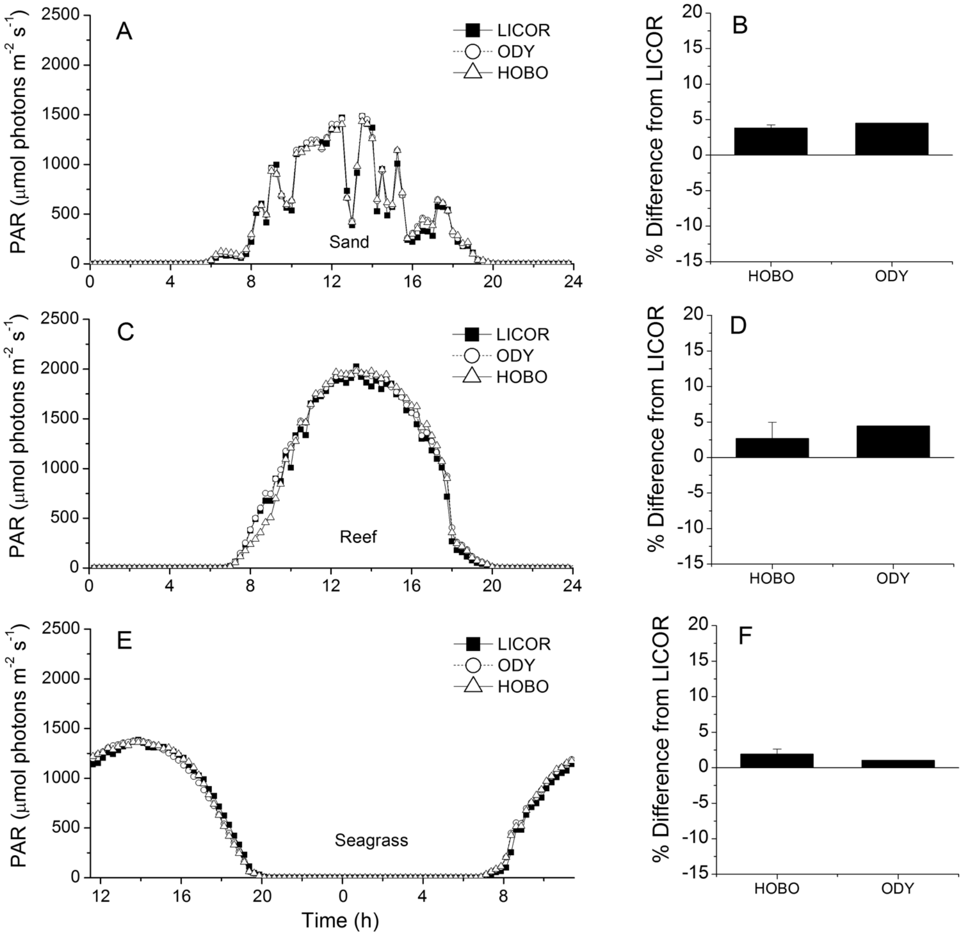

Fig. 4. Calibrated PAR values for the HOBOs and ODY compared with LICOR PAR in the sand (A), reef (C), and seagrass (E). The percent difference from the LICOR PAR values are shown in panels B, D, and F (error bars are SE).

and ODY are planar sensors that have a reduced response at small light angles typically found at dusk and dawn. However, our data show that by using an exponential fit, this reduced response can be effectively corrected for both logger types; otherwise, the sensors would diverge at low light angles and during periods of cloudiness (e.g., Fig. 4A). The similar calibration curves for the ODY and HOBO (both planar sensors) suggest that the exponential fit partially compensates for the differences between the planar and scalar sensor designs. Unlike the ODY, the HOBO is not cosine corrected and thus does not have a diffusing material over its light sensor that partially corrects for the angle of incoming light. This may explain the larger curvature of the fitting function for the HOBOs relative to the ODY (Fig. 2). We expect that if the ODY were fitted against a factory-calibrated, cosine-corrected, planar PAR sensor such as the LI-192 (LICOR), the fit would be linear due to the similar light-collecting properties and sensor design. With respect to the HOBOs, we also found a substantial improvement when calibrating each logger individually (Fig. 1). Overall, our data demonstrate that simple light intensity loggers can be used as a reliable substitute for more sophisticated PAR sensors (Fig. 4).

We have evaluated the HOBO and ODY calibrations for a number of sites with different depths, albedos, and water clarities, which all produced reliable data that matched the standard factory calibrated LICOR data within 3.8% and 4.5%, respectively (Fig. 4). However, if the HOBOs are calibrated in deep water and then deployed in shallower water, precision may decrease due to the attenuation of PAR with depth (Kirk 1994; Jewson et al. 1984; Arst et al. 2000) especially considering the wide spectral response of the HOBOs. This is evident in Fig. 5C where the seagrass calibration (~4 m depth) is used on the reef data (~1 m depth), which leads to a 10.0% underestimation of PAR for the HOBO. A similar effect is expected for very turbid or cloudy conditions, where increased scattering may cause a deviation from the calibration (Jewson et al. 1984). For example, we suspect that the relatively large differences found between sensors when using the sand calibration on the reef may be due to differences in turbidity between subtropical Florida and the temperate Massachusetts coastal estu-

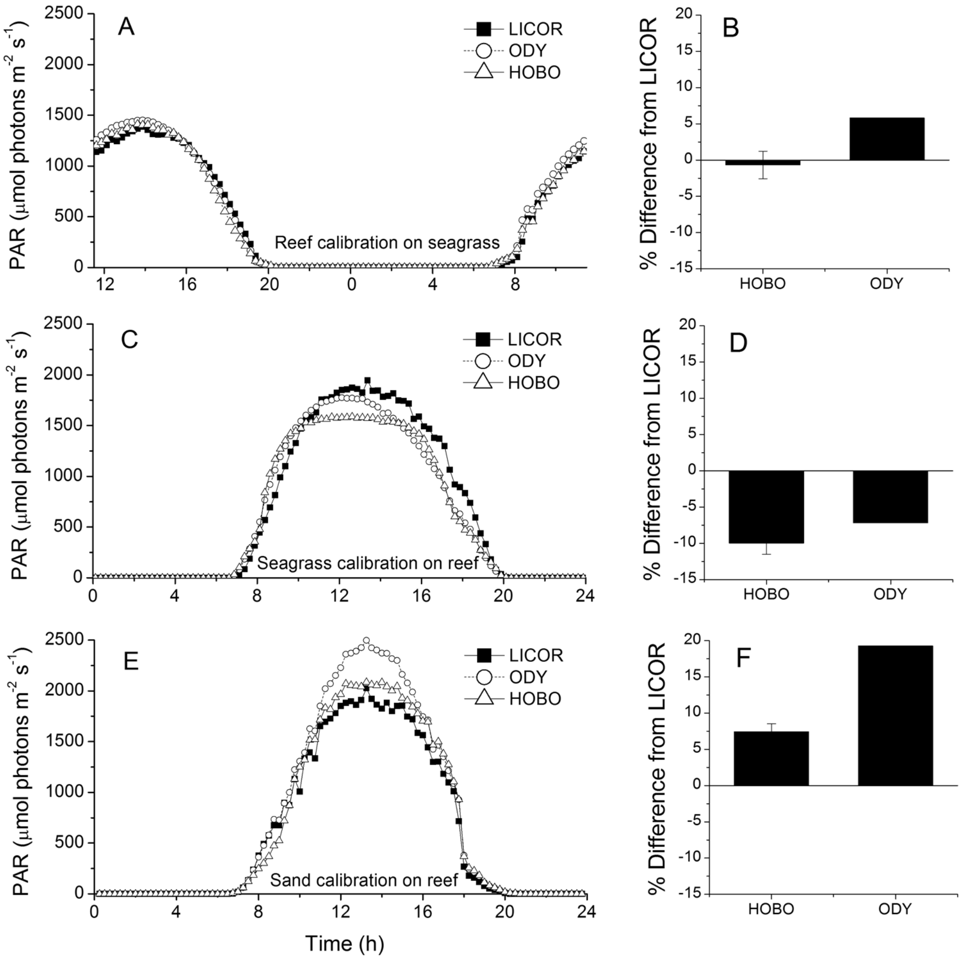

Fig. 5. Application of calibrations to different sites. The reef calibration was applied to the deeper seagrass data (A), the deeper seagrass calibration is used on the reef data (C) and the sand calibration is applied to the reef data (E). The percent difference from the LICOR PAR values are shown in panels B, D, and F (error bars are SE).

ary, leading to an overestimation of PAR on the reef (Fig. 5E).

We also conducted measurements at sites with different albedos (seagrass and sand), where the sand was expected to have a much greater error due to upwelling radiation reflected from the sand surface (Fig. 4B, F). However, we did not observe large deviations for the high albedo sand site (0.1% difference on a sunny day over the sand); this suggests that the exponential fit may help alleviate errors due to upwelling radiation or that upwelling radiation is negligible, even at high albedo sites. Also, a range of sunny and cloudy conditions were present at these sites but the diffuse radiation under cloudy conditions did not produce any notable differences between the sensors (e.g., Fig. 4A). This suggests that if calibrated as described above the HOBOs can be applied successfully over a range of environmental conditions found at a particular site.

A number of studies have used HOBOs in different environments to estimate PAR values; however, the information presented is limited, for example, on how the calibration was performed (Glud et al. 2002; Boese et al. 2005; Piniak and Brown 2008; Liu et al. 2009; Fanta et al. 2010; Tait and Schiel 2010; Hulatt and Thomas 2011; Pedersen et al. 2011; Wall et al. 2011; Koch at al. 2012). Specifically, several studies used HOBOs to evaluate PAR but provided no information on how this was done (Liu et al. 2009; Pedersen et al. 2011; Koch et al. 2012). Tait and Schiel (2010) show the utility of HOBO loggers by using them inside benthic chambers, but did not provide any calibration statistics when compared with a LICOR LI-192 quantum sensor. Glud et al. (2002) calibrated HOBOs to a LICOR LI-192A planar sensor to estimate PAR in an Arctic fjord; however, no calibration curve or statistics were reported. Hulatt and Thomas (2011) compared HOBOs to a LICOR 190SA sensor under a wide range of conditions, but this was done in air and is therefore not directly comparable to our results obtained underwater. Boese et al. (2005) calibrated paired HOBOs to a LICOR spherical PAR sensor in an Oregon estuary and found a linear relationship with an $r^2 = 0.70$ using instantaneous readings. However, these HOBOs were oriented perpendicular to the water surface to capture diffuse radiation, which may explain why their relationship differs from our study. They also reported a deviation from their linear fit at high irradiances, suggesting an exponential dependency may be contained in their data. Fanta et al. (2010) used HOBO loggers calibrated to an underwater quantum sensor using a linear regression with an $r^2 = 0.973$. This study suggests that in shallow, shaded freshwater streams a linear relationship between simple loggers and a PAR sensor may exist, but this is difficult to evaluate further without details of the calibration or how it was performed. Wall et al. (2011) compared daily averaged HOBO readings to that of a LICOR 192 in a mesocosm and found a significant linear relationship, but no information on short-term variations (e.g., peak irradiance or low light levels) was reported. While linear relationships have been found between HOBOs and more sophisticated PAR sensors, it is difficult to evaluate these relationships when the differences between the sensor types were not considered or examined. Piniak and Brown (2008) calibrated HOBOs against a planar LICOR 192SA PAR sensor on a Hawaiian coral reef, which produced an exponential fit. The exponential fit found by Piniak and Brown (2008) agrees with our findings; however, no statistical analysis for their fit was given. ODY loggers have also been used in various studies to evaluate PAR (Roberts et al. 2004; Cooper et al. 2007; Toohey 2007; Nobes et al. 2008), for example to examine microhabitats on coral reefs (Anthony and Hoegh-Guldberg 2003), but used a single point calibration (as recommended by the manufacturer). We found in our direct comparisons that an exponential fit provided a much better correlation for the ODY to the LICOR scalar sensor than when relying on the recommended linear fit.

The maximum difference between the HOBO and the LICOR data were 3.8% when using a same site calibration, which is similar to the maximum 3.7% difference between the two LICORs that were factory-calibrated (both LICORs were calibrated at the same time). The maximum percent difference for the HOBO data was found for the sand site (3.8%; Fig. 4A) and can be attributed to the variability of cloud cover over the day as well as the sand being a high albedo site. However, the largest percent difference between the two LICOR sensors was found in the seagrass (3.7%), which was also the site where the smallest percent difference was found for the HOBOs (1.9%, Fig. 4F). This may be caused by variations in light due to shading by moving seagrass blades; a condition that may be effectively removed by averaging data from multiple HOBOs. The ODY generally had a slightly higher variability than the HOBOs (Fig. 4), which we expect would be smaller (to a similar level of the HOBOs) if multiple ODYs were used. The similar variability of the ODY and the HOBO suggest that both are equally well-suited for estimating PAR.

Comments and recommendations

Trustworthy PAR measurements can only be estimated if a careful sensor calibration is performed; we obtained the best results when all sensor types were deployed parallel in the field under similar conditions where the sensors would subsequently be used. Further, calibration should be done with care to minimize shading and also be done occasionally to account for drift in the sensors. If a user does not require the high accuracy achieved here by using calibrations done at the same site and equivalent to what can be achieved with high quality PAR sensors (here the LICOR), we have shown that calibrations from other sites may be used to produce reliable data. Specifically, in the three examples that were tested here, we found that this increased the deviation from the LICOR PAR measurements from 3.8% to –10.0% for the HOBO and from 4.5% to 19.3% for the ODY. However, we stress that these results cannot be generalized to all sites and anticipate that larger deviations could be found for other sites and field conditions. For example, care must be taken when using a calibration from a deeper site (Fig. 5C), from sites with different albedos (Fig. 5A, C, E) and from sites with different water clarities and light-scattering properties (Fig. 5E).

The ODY and HOBO represent an ideal alternative to more sophisticated PAR sensors, where simplicity and versatility are required. These light intensity loggers can be deployed and retrieved with minimal effort for use in long-term monitoring, large spatial scales, and microhabitats. The use of multiple HOBOs can average out small-scale spatial differences and also ensures that trustworthy data will be recorded even if some sensors fail due to fouling. The deviation of less than 4% from standard PAR sensors is substantially lower than reported for a range of instruments that are factory-calibrated from the manufacturer (up to 188%, Meyercordt et al. 1999) and equivalent to that of two matched and factory-calibrated LICORs. Therefore, the calibration of HOBOs and ODYs to estimate PAR represents an excellent alternative to logistically difficult PAR sensors.

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