Ceptometer Deployment Method Affects Measurement of Fraction of Intercepted Photosynthetically Active Radiation

Mari-Vaughn V. Johnson,* James R. Kiniry, and Byron L. Burson

ABSTRACT

The fraction of photosynthetically active radiation a canopy intercepts (fiPAR) drives canopy level photosynthesis. There is currently no universal, repeatable fiPAR sensor deployment method. We show variability of fiPAR measurements by three sensor deployment methods, including two 1 by 1 m and one 3 by 1 m method. The deployment method biased measurements ($P = 0.005$) under buffelgrass (*Pennisetum ciliare* L) canopies. These effects were less evident in 'Alamo' switchgrass (*Panicum virgatum* L) and miscanthus (*Miscanthus* × *giganteus*). Canopies of these two species showed deployment method × nutrient addition interaction effects ($P = 0.02$), apparently driven by nutrient effects on leaf area index (LAI). We highlight potential implications of using the different deployment methods via an exercise in the application of Beer's law. As actual LAI increased, effect of deployment method on fiPAR measurements tended to diminish, suggesting in high LAI systems a universal deployment method is not as critical as it is in low LAI systems.

Agronomists, land managers, modelers, and global change biologists wish to determine rates of physiological function driven by a canopy's leaf area index (LAI) and the fraction of photosynthetically active radiation intercepted by the canopy (fiPAR). These include annual aboveground biomass production, evapotranspiration, and photosynthesis. Destructive sampling of stands, while allowing direct measurement of biomass and LAI, is unwieldy, time consuming, and cannot be repeated on the same plants during a season (Asrar et al., 1984; Wilhelm et al., 2000). Further, destructive sampling gives only a static account of the LAI of a given plant community and disrupts the system being sampled, with potentially deleterious ecological and economic effects. Indirect determination of LAI may be accomplished by relating a canopy's fiPAR to its LAI without harvesting. Coupled with LAI, fiPAR data are key parameters in many ecosystem productivity models, as well as related climate, ecological and biogeochemical models (Myneni et al., 1997; Sellers et al., 1997). This experiment addresses the consistency of fiPAR readings by an AccuPAR LP-80 ceptometer (Decagon Devices, Pullman, WA) using three different deployment methods under a variety of grass canopies.

The photosynthetically active portion of the light spectrum absorbed by a canopy drives photosynthesis and results in biomass production. There is a generally linear relationship between plant canopy fiPAR and photosynthesis because rate of biomass production is proportional to fiPAR (Monteith, 1972; Monteith, 1977). A given canopy's fiPAR is driven by the spatial arrangement and orientation of photosynthetic tissues, canopy density, position of the sun, and proportion of diffuse radiation (Barradas et al., 1999).

Leaf area index is a unitless measure of the area of photosynthetic material per unit area of soil surface (Larcher, 1975), which is to say the quantity of leaf–atmosphere interface per unit of soil surface area (Weiss et al., 2004). It is established that LAI is an important factor in determining photosynthesis and subsequent biomass production (Sinclair, 1984). A canopy's fiPAR is also influenced by the canopy light extinction coefficient (k), which is primarily determined by leaf orientation.

A number of models have been developed to describe the interactions between canopy structure and light-interception-driven physiological processes. The classical model put forth by Monsi and Saeki (1953, translated into English in Monsi and Saeki, 2005), is basically Bouguer–Lambert–Beer's law (henceforth referred to as Beer's law; Beer, 1852) adapted to light passing through a plant canopy (Eq. [1]). It relates k, fiPAR, and LAI as follows:

$$\text{fiPAR} = \text{PAR} \times [1 - \exp(k \times \text{LAI})] \qquad [1]$$

where PAR is the incident photosynthetically active radiation, k is the light extinction coefficient, and LAI is the leaf area index for plant biomass above the height at which fiPAR is measured (Thornley, 1976; Monsi and Saeki, 1953, 2005). The k value is presumed to be conservative for a given species at maturity (Monsi and Saeki, 1953, 2005), though there is some controversy over this assumption (Anderson, 1966; Clegg et al., 1974).

More complicated models utilize fiPAR coupled with LAI and other variables to describe global biogeochemical cycles as well as physiological functions such as photosynthesis, evapotranspiration, and conductance (Myneni et al., 1997; Sellers et al., 1997). Though Knyazikhin et al. (1998) suggest Beer's law does not adequately capture variability in canopy architecture when

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Abbreviations: fiPAR, fraction of photosynthetically active radiation intercepted by the canopy; LAI, leaf area index; PAR, photosynthetically active radiation.

modeling below the landscape scale, Vargas et al. (2002) suggest that Beer's law effectively represents the relationship between LAI, fiPAR, and *k* until the onset of leaf senescence. In this study, we included Beer's law as a demonstration of one application of how fiPAR measurements can be used. Other applications of fiPAR include those described by Sellers et al. (1992).

Using Beer's law, modelers can calculate values for any of the variables (PAR being an input) in the law if they know or can reasonably estimate the remaining two variables (Kiniry et al., 1992). The AccuPAR LP-80 ceptometer can be programmed to calculate LAI based on fiPAR and PAR measurements in the field and a user estimated *k* value (Decagon Devices, 2004). If, however, one of the variables, such as fiPAR, is biased by the method of ceptometer deployment, the predicted LAI or *k* will also be biased. A central problem with these calculations and meta-analyses of published results is the assumption that ceptometer deployment is equivocal. In addition to being affected by factors such as soil albedo, canopy heterogeneity, row spacing, and plant clumping (Andrade et al., 2002; Nouvellon et al., 2000; Clegg et al., 1974) *measured* fiPAR is potentially biased by the means of ceptometer deployment. Here we explore deployment method as a potential source of bias, using destructive samples to determine LAI and Beer's law to calculate *k*.

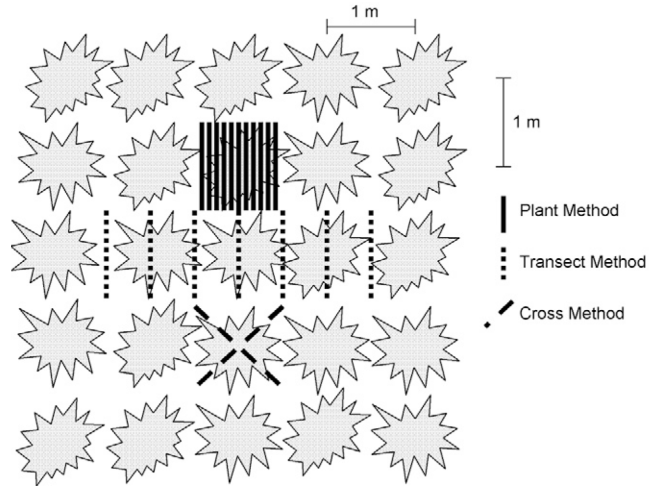

Fig. 1. Depiction of the three ceptometer deployment methods for sampling the fraction of photosynthetically active radiation intercepted by the canopy (fiPAR) with the AccuPAR LP-80 sensor. Although this shows the method being used on three separate rows of plants, during the experiment, the methods were all applied to the same row, such that the same central 1 by 1 m area was sampled by all three methods. This is the same area subsequently destructively harvested to directly determine actual leaf area index (LAI).

MATERIALS AND METHODS

Field Sites

Measurements were conducted in two separate experiments at two different field sites. In Experiment 1, four buffelgrass cultivars (Common, Frio, Llano, and Nueces) were measured at the Texas A&M University Farm near College Station, TX (30°32′39.25″ N, 96°25′46.56″ W). Soils were Westwood silt loam (fine-silty, mixed superactive, thermic Udifluventic Haplustepts). Plots were established from seedlings in 2003 with 1 m between plants and 1-m row spacing. The three replications were nested in a larger area planted with buffelgrass. Plots were burned and cultivated in the spring of each year.

Experiment 2 was conducted on a dairy farm near Gustine, TX (31°54′37.10″N, 98°23′0.57″ W), where the effects of nutrient and water addition on aboveground biomass (and LAI) production in Alamo switchgrass and miscanthus were being assayed in a separate experiment. Soil at the sites is Pedernales loamy fine sand (mixed superactive, thermic Typic Paleustalf). In April 2007, 5 by 5 m plots were established from seedlings, with one plant per m^2. There were five replications of the two species in two treatments. The treatment was the addition of water and nutrients (effluent application) while the control was natural precipitation and no additional nutrient inputs.

Species Assayed

In each of the experiments, two plant architectures were represented: a bunchgrass and a rhizomatous grass. The buffelgrass in Experiment 1 is an east African C_4 grass introduced to Texas in the 1940s and has successfully established in semiarid regions of North and South America, Australia, Africa, India, and various island systems (De Lisle, 1963; Cox et al., 1988; Burgess et al., 1991). Buffelgrass spreads aggressively in both disturbed and undisturbed areas, currently dominating millions of hectares in North America (Búrquez-Montijo et al., 2002; Arriaga et al., 2004). The Common and Frio varieties maintain a bunchgrass-type growth form. Frio was released in 1999 for its cold tolerance (Hussey and Burson, 2005). The Nueces and Llano varieties do not form dense bunches, but spread by rhizomes and tiller to fill in the space between plants within a row. Nueces and Llano were developed and released in 1977 for their cold tolerance and rhizomatous growth form (Bashaw, 1980).

The two species in Experiment 2 are candidate biofuel species. Switchgrass is a perennial warm season bunchgrass native to much of the United States (Stubbendieck et al., 1992). The Alamo switchgrass accession was selected from lowland plants found along the Frio River in south central Texas. Miscanthus is a naturally occurring sterile hybrid introduced from Japan to Denmark in 1930 (Lewandowski et al., 2003). Miscanthus is being investigated for biofuel production potential across much of Europe and, more recently, the United States (Heaton et al., 2004). Switchgrass maintains a bunchgrass growth form, whereas miscanthus is rhizomatous.

Sampling Methods

The tool used to sample fiPAR was a linear LP-80 AccuPAR ceptometer, which measures light in the 400-700nm (PAR) waveband (Decagon Devices, Pullman, WA). Experiments 1 and 2 were sampled at six evenly spaced dates between 30 April and 7 July 2008, and 24 April and 8 July 2008, respectively. Three ceptometer deployment methods were used (Fig. 1). The AccuPAR LP-80 operator's manual suggests when measuring row crops, one should strive to represent the PAR intercepted both within the rows and between the rows. Therefore, in each deployment method, we used the LP-80 linear ceptometer (Decagon Devices, Pullman, WA) to measure from the middle of a furrow (the midpoint between rows) to the middle of an adjacent furrow to capture the row and inter-row canopy effects. The ceptometer was leveled before each measurement and care was taken not to shade any of the ceptometer or external sensor with the researcher's shadow. The same researcher took all measurements to minimize sampling error caused by potential differences in researcher sampling technique. In all methods, edge rows were not measured and all measurements were taken at least 1 m from the end of an interior row. All measurements were taken within 2 h of solar noon.

In all deployment methods, an external quantum sensor was placed on a leveled tripod in a location with an unobstructed view of the sky. The external sensor measured unobstructed PAR above the canopy concomitant to measurements of PAR taken by the ceptometer below the canopy. Before taking each below-canopy measurement with the ceptometer, a calibration factor (*cf*) was determined for the sensor–ceptometer measurements (the mean ratio of 10 rapidly taken unobstructed ceptometer measurements to 10 simultaneous unobstructed external sensor measurements). This calibration value was used to correct fiPAR values (Eq. [2]) for each replicate so that fiPAR would be actual fraction of photosynthetically active radiation intercepted by the canopy (PAR_b) without bias from any subtle differences in calibration of the external sensor or ceptometer, as PAR above the canopy (PAR_a) would be used to calibrate the measurement:

$$\mathrm{fiPAR} = \mathrm{PAR_b}/cf\,\mathrm{PAR_a} \qquad [2]$$

The same calibration correction factor was used for the calculation of fiPAR by each of the three deployment methods in the same replication, as they were taken in rapid succession.

The first deployment method was the Plant Method (Fig. 1). A 1 by 1 m area was designated, which, due to plant spacing, was typically the equivalent of sampling a single plant. The ceptometer was inserted 10 cm above ground level into the plant canopy at 10-cm intervals for the horizontal distance of 1 m. For each measurement, the ceptometer was inserted into the row at a 90° angle to the row orientation. The ceptometer's measuring surface is 80 cm long, so at every point two measurements were taken, one with the base of the ceptometer in the center of the furrow on one side of the row and the second pushed through the row, with the tip of the ceptometer at the center of the furrow on the other side of the row. The resultant 22 measurements were averaged (by the ceptometer) to provide the mean measured fiPAR for the Plant Method.

The second deployment method was the Transect Method. In this method, the 1 by 1 m of row used in the Plant Method was used as a reference point. A length of 1 m added to both ends of the Plant Method's meter was incorporated into the transect to be measured, such that the transect was 3 by 1 m, with the middle meter being the same meter used in the other two methods. Measurements were made 10 cm above ground level and at 50-cm increments along the transect. For each measurement, the ceptometer was inserted at a 90° angle to the row; the two measurements for each insertion point were taken as discussed for the Plant Method, so the full meter from furrow center to adjacent furrow center was represented. The resultant 14 measurements were averaged (by the ceptometer) to provide a mean measured fiPAR for the Transect Method.

The third deployment method was the Cross Method. This method is the least time consuming of the three methods. The same 1 by 1 m of row sampled in the Plant Method was assayed with the Cross Method. The ceptometer was inserted from the endpoints of the meter at a 45° angle from the row orientation, such that the base of the ceptometer was anchored in the middle of the furrow and the tip pointed into the row. After a measurement was taken, the ceptometer was pushed 20 cm through the canopy until its tip reached the center of the adjacent furrow at the opposite end of the meter being measured. These two measurements were then repeated starting at the other end of the meter, so that an "X" shape was formed across the meter of the row being measured. The resultant four measurements were averaged (by the ceptometer) to provide a mean fiPAR measurement for this method.

After all three deployment methods were used to collect fiPAR data, the aboveground biomass located in the meter common to all three methods was harvested. Tissues were transported to the laboratory in coolers to prevent leaf distortion. Representative grab subsamples were randomly selected from each sample. Photosynthetic tissues were run through the LI-3100 leaf area meter (LiCor Inc., Lincoln, NE). To minimize error associated with the leaf area meter measurements, we calibrated the machine at the beginning of each sampling date measurement with the calibration disk included with the machine. Further, we cleaned the belts with alcohol and vacuumed the machine between sample runs to assure that measurement errors were nominal. With these frequent checks on machine accuracy, LAI variation among samples measured on the LI-3100 can be attributed to actual sample variation rather than measurement error.

The LAI was then calculated from measured leaf area, the ground area sampled, and the ratio of subsample fresh weight to total sample fresh weight. Using Beer's law (Eq. [1]), the *k* values were calculated for each method using the mean fiPAR for that method and mean LAI values for the shared 1 by 1 m area of aboveground biomass.

Statistical Methods

The mean measured fiPAR values and Beer's law were used to calculate the mean *k* value for each deployment method, averaged across sampling dates (Table 1). For each experiment, variation in fiPAR was assessed by analysis of variance (ANOVA) using a mixed model with repeated measures (PROC MIXED, SAS version 9.1, Cary, NC). Interactions were explored with Bonferroni adjustment to Fisher's least squares means. All means reported in figures and tables were derived from raw data rather than from least squares means data.

An overall mean *k* for each species/cultivar and deployment method combination was derived with Beer's law as described above. These deployment method–appropriate *k* values were then used in Beer's law with mean fiPAR values for each sampling date for each species/cultivar and method combination to predict LAI. For each species or cultivar, the LAI values calculated with Beer's law (Eq. [1]) and measured fiPAR were regressed against the destructive sample values of LAI for each sampling date. In interpreting the regressions, a given deployment method was considered a better method of quantification based on higher r^2 values, smaller mean square error (MSE), a slope nearer to 1, and an intercept nearer to zero. The regressions for measured LAI compared with predicted LAI (Fig. 2, 3) illustrate the variability of each method by species/cultivar.

RESULTS

The mean empirically measured LAI in these experiments covered a broad range of values, from 1.10 for miscanthus grown without fertilizer to 5.03 for Alamo switchgrass grown under the unlimiting nutrient effects of effluent addition (Table 1). The

Table 1. The mean and maximum leaf area index (LAI) values were measured from destructive sampling. The mean fraction of photosynthetically active radiation intercepted by the plant canopy (fiPAR) measurements were unique to the ceptometer deployment method used. The *k* values for each method were calculated with Beer's law using the empirically measured mean LAI values and the mean fiPAR values particular to that ceptometer deployment method. Frio, Llano, Common, and Nueces are cultivars of buffelgrass. Alamo is a cultivar of switchgrass. Measurements of Alamo and miscanthus were conducted on plants receiving effluent application and on control plants receiving no nutrient and irrigation inputs.

Species/cultivar	Max LAI	Mean LAI	Plant method		Transect method		Cross method	
			fiPAR	*k*	fiPAR	*k*	fiPAR	*k*
Miscanthus control	1.69	1.10	0.58	–0.78	0.59	–0.80	0.72	–1.17
Alamo control	2.10	1.49	0.55	–0.54	0.57	–0.56	0.67	–0.74
Frio	2.28	1.49	0.56	–0.55	0.56	–0.55	0.69	–0.79
Llano	3.14	2.45	0.77	–0.60	0.75	–0.57	0.78	–0.62
Common	5.90	3.14	0.67	–0.35	0.60	–0.29	0.77	–0.47
Nueces	4.87	3.46	0.77	–0.42	0.74	–0.39	0.80	–0.47
Miscanthus effluent	5.56	4.58	0.84	–0.40	0.88	–0.47	0.89	–0.49
Alamo effluent	8.61	5.03	0.91	–0.47	0.91	–0.49	0.93	–0.54

mean empirically measured fiPAR values varied by species/cultivar and by deployment method, with the Plant Method and Transect Method having a comparable range (0.55–0.91 and 0.56–0.91, respectively). The Cross Method did not have as broad a range of fiPAR values (0.67–0.93) as the other two methods and tended to overestimate fiPAR in the lower range. For nearly all species/cultivars there was a common trend of overestimating LAI with all three AccuPAR LP-80 methods when actual LAI was low and underestimating LAI when actual LAI was high compared with destructively measured LAI (Weiss et al., 2004).

In Experiment 1, only main effects were significant. Buffelgrass cultivar mean fiPAR values were significantly different from one another ($F = 21.42$; $P < 0.0001$). Comparing the means among the cultivars showed that fiPAR values measured for the bunchgrass-type cultivar Frio (0.57 ± 0.14) (mean fiPAR ± SD) were more than 20% lower than fiPAR measured for all other cultivars ($P < 0.001$ compared with each other cultivar). There was no difference ($P > 0.05$) between mean measured fiPAR values for Llano (0.72 ± 0.14), Common (0.72 ± 0.15), or Nueces (0.77 ± 0.12). In Experiment 1, the ceptometer deployment method also showed significance ($P = 0.005$). Comparing the ceptometer deployment methods showed the Plant Method and Transect Method were comparable ($P = 0.28$) whereas the Plant Method produced lower ($P = 0.011$) fiPAR values (0.67 ± 0.17) than the Cross Method (0.74 ± 0.13). Similarly, the Transect Method mean fiPAR values (0.65 ± 0.15) were lower ($P = 0.002$) than the Cross Method.

In Experiment 2, comparison of ceptometer deployment method effects on quantification of fiPAR and LAI was embedded in a nutrient response effect that was part of a separate ongoing experiment. The repeated measures ANOVA main effects included dairy effluent addition, method and species effects, and their potential interactions. There were main effects for the ceptometer deployment method ($F = 22.20$; $P = 0.0002$), with the Cross Method estimating canopy light interception to be 16% greater (0.81 ± 0.17) than the other methods (Plant: 0.70 ± 0.23; Transect: 0.70 ± 0.22). There were also main effects for the dairy effluent application ($F = 524.58$; $P < 0.0001$), with dairy effluent application causing 43% greater light interception (0.87 ± 0.11) than the control (0.61 ± 0.20). There were also significant interactions: species × effluent ($F = 11.07$; $P = 0.02$) and method × effluent ($F = 6.32$; $P = 0.02$).

In Experiment 2, the interaction effects were explored with Bonferroni adjustment to the Fisher's least squares means ($P = 0.05$). All species × effluent interactions were significant *except*

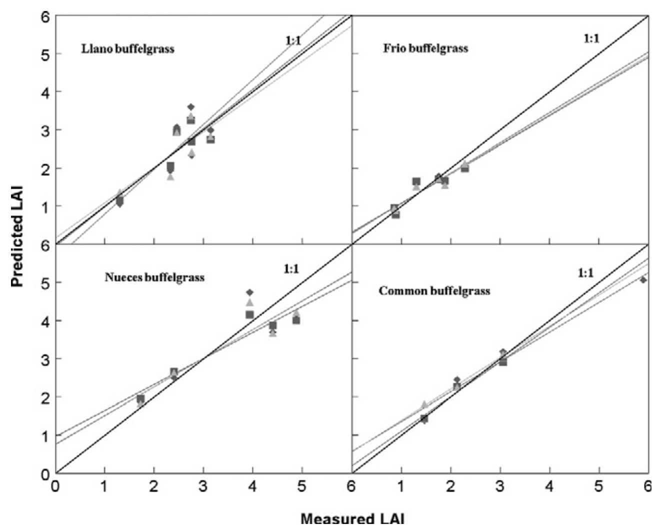

Fig. 2. Regressions of destructively sampled leaf area index (LAI) measurements against LAI estimates based on the fraction of photosynthetically active radiation intercepted by the plant canopy (fiPAR) collected with each of three ceptometer deployment methods using the AccuPAR LP-80 for four cultivars of buffelgrass grown near College Station, TX. Deployment methods include Plant Method (diamond), Transect Method (square), and Cross Method (triangle).

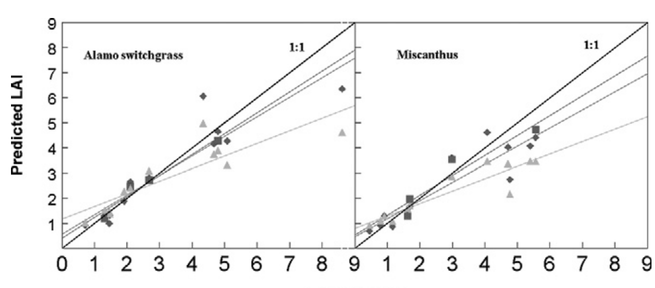

Fig. 3. Regressions of destructively sampled leaf area index (LAI) measurements against LAI estimates based on the fraction of photosynthetically active radiation intercepted by the plant canopy (fiPAR) collected with each of three ceptometer deployment methods using the AccuPAR LP-80 for Alamo switchgrass and miscanthus grown near Gustine, TX. Deployment methods include Plant Method (diamond), Transect Method (square), and Cross Method (triangle).

Table 2. Results for measured leaf area index (LAI) values regressed against LAI values predicted with Beer's law from the fraction of photosynthetically active radiation intercepted by the canopy (fiPAR) measurements collected by each of the three ceptometer deployment methods (Plant, Transect, and Cross Methods).

Cultivar	Method	*n*	R^2	Slope	*Y* intercept	MSE	Mean LAI	Mean predicted LAI
Common	Plant	4	0.97	0.78	0.57	11.10	3.14	3.02
	Transect	3	0.97	0.91	0.20	1.24	2.22	2.20
	Cross	3	0.99	0.82	0.57	1.27	2.22	2.40
Frio	Plant	6	0.87	0.79	0.28	1.45	1.49	1.46
	Transect	6	0.84	0.76	0.32	1.40	1.49	1.46
	Cross	6	0.91	0.77	0.30	1.51	1.49	1.45
Llano	Plant	6	0.65	1.17	0.38	2.73	2.45	2.49
	Transect	6	0.74	1.03	0.05	2.11	2.45	2.47
	Cross	6	0.60	0.93	0.16	1.71	2.45	2.44
Nueces	Plant	5	0.75	0.75	0.76	5.43	3.47	3.37
	Transect	5	0.90	0.68	0.96	6.50	3.47	3.33
	Cross	5	0.83	0.76	0.75	6.02	3.47	3.37
Alamo	Plant	12	0.84	0.78	0.57	35.00	3.26	3.11
	Transect	4	0.96	0.83	0.40	4.65	2.72	2.67
	Cross	12	0.75	0.50	1.18	14.48	3.26	2.81
Miscanthus	Plant	12	0.84	0.72	0.47	21.91	2.84	2.52
	Transect	4	0.90	0.79	0.53	6.43	2.96	2.88
	Cross	12	0.84	0.49	0.80	10.23	2.84	2.20

control switchgrass (0.59 ± 0.18; mean fiPAR ± SD) compared with control miscanthus (0.62 ± 0.23) and effluent-treated switchgrass (0.89 ± 0.12) compared with effluent-treated miscanthus (0.85 ± 0.11). All but four method × effluent interactions were significant. These included: Plant Method control (0.55 ± 0.21) compared with Transect Method control (0.56 ± 0.21); Plant Method effluent treatment (0.85 ± 0.12) compared with Transect Method effluent treatment (0.84 ± 0.14); Plant Method effluent treatment (0.85 ± 0.12) compared with Cross Method effluent treatment (0.91 ± 0.08); and Transect Method effluent treatment (0.84 ± 0.14) compared with Cross Method effluent treatment (0.91 ± 0.08).

Regression results varied among buffelgrass cultivars (Fig. 2; Table 2). For Llano buffelgrass, the Cross Method had the best MSE, but the Transect Method was best for slope, *y* intercept, and r^2. For Frio, the Cross Method was best for r^2, whereas the Plant Method was best for slope and *y* intercept, and the Transect Method had the lowest MSE. For Nueces, the Plant Method had the lowest MSE, but similar slope and intercept values as the Cross Method, whereas the Transect Method had the greatest r^2 value. For Common, the Plant Method had the best values for slope, *y* intercept, and r^2, but the Cross had nearly as great a value of r^2 and the Transect Method had the lowest MSE.

As in Experiment 1, regression results for Experiment 2 showed a general trend in all methods to overestimate LAI at low LAI values and underestimate at high values (Fig. 3; Table 2). For switchgrass, the r^2 value, *y* intercept, MSE, and slope were all best for the Transect Method. For miscanthus, the MSE, slope, and r^2 value were best for the Transect Method, but the Plant Method had a slightly better *y* intercept.

DISCUSSION

The method of deploying the LP-80 ceptometer affected the measured fiPAR values. This experiment demonstrates the variability that can be produced when using one method of light collection (ceptometer) with three different deployment methodologies on both bunchgrasses and rhizomatous grasses. Unfortunately, we were unable to find a similar comparison of methods for a ceptometer in the literature, as most researchers failed to explain fully their ceptometer deployment methods. Published comparative studies on derivation of fiPAR, LAI, and *k* typically focus on various quantification methodologies by instrumentation, rather than variability with a given instrument (Wilhelm et al., 2000; Vargas et al., 2002; Bréda, 2003; He et al., 2007; Garrigues et al., 2008).

In this study, the Plant and Transect deployment methods results tended to be consistent with one another, whereas the Cross Method tended to overestimate fiPAR, particularly under low LAI conditions. The Transect Method included fewer samples, but sampled more of the canopy than the Plant Method. The Cross Method sampled the same area as the Plant Method, but with fewer samples. Thus, our results suggest that it is possible to get the same fiPAR estimates from either sampling a larger sample area (Transect Method), or by taking more samples within a smaller sampling area (Plant Method) when sampling a fairly homogenous canopy. However, the disparity between the Cross and Plant Method suggest that a critical number of samples must be taken or one runs the risk of overestimating fiPAR, particularly under low LAI conditions.

In Experiment 1, three of the four buffelgrass cultivars had similar fiPAR measurement results. Two of the cultivars were bunchgrass types and two were rhizomatous in growth form (Bashaw, 1980; Hussey and Burson, 2005). The Frio cultivar (bunchgrass type) had lower mean fiPAR and mean LAI values than the other three cultivars, whereas the Common (bunchgrass type) had LAI values that fell between those of the two rhizomatous cultivars and mean fiPAR values statistically equal to those of the rhizomatous cultivars. Results do not suggest that growth form is necessarily responsible for the variation in fiPAR, but it would be interesting to expand this inquiry and include other bunchgrass and rhizomatous grasses. Results suggest that when the species of interest has a low fiPAR, regardless of growth form, the method of ceptometer deployment may lead to a more pronounced effect of fiPAR quantification bias compared with measurements in high fiPAR settings. In this study we did not explore the effect of planting density or row spacing. Low plant density systems tend to have lower LAI and thus, lower fiPAR than do high plant density systems (Darawsheh et al., 2009). The fiPAR ceptometer deployment method used on a species planted at lower density could show more bias than we found in the current study with high planting densities.

Experiment 2 had species × effluent interaction effects, primarily driven by species response to effluent addition, which increased LAI dramatically. Based on destructive measurements there was a 416% increase in miscanthus LAI and a 338% increase in switchgrass LAI under effluent as compared with control. The method × effluent interactions suggest that differences between deployment methods of measurement diminish when LAI is high. In the effluent treatment, there were no differences between the fiPAR measured by each method; however, in the control, where LAI was low, the Cross Method overestimated fiPAR compared with the other two methods. This is in keeping with the cautionary statement in the AccuPAR LP-80 user's manual, which suggests that LAI may be poorly simulated by AccuPAR LP-80 when the canopy is not randomly distributed, such as the case with row crops (Decagon Devices, 2004). Researchers using other fiPAR quantification instruments have also reported that quantifying LAI in low-LAI rather than high-LAI systems may result in measurement bias due to soil albedo, atmospheric conditions, and heterogeneity in plant distribution (Nouvellon et al., 2000). Effluent treatment effect increased LAI, decreasing the heterogeneity or "clumping" effects caused by row-cropping. Under these more homogenous canopy conditions, the fiPAR results of the three deployment methods converged.

CONCLUSIONS

The largest discrepancies observed for various LAI determination methods (Miller's formula method, gap fraction model inversion using an iterative optimization technique, gap fraction measurement interpretation, etc.) are typically most pronounced at large LAI values due to light saturation (Weiss et al., 2004). In our experiment, all three ceptometer methods tended to produce fiPAR values that led to a slight underestimation of actual LAI with Beer's law when effective LAI values were high. Underestimation is common for all indirect methods of estimating LAI (Bréda, 2003). The fiPAR measurements of canopies with larger LAI values de-emphasized ceptometer deployment method differences because they were so dense that over- or under-measuring plants or gaps did not appear to have an effect on fiPAR. Our results suggest that the effect of ceptometer deployment bias is reduced at higher fiPAR and LAI values. When LAI values are low, the Transect or Plant Method should be used to assess fiPAR, but when LAI values are high, all three ceptometer deployment methods described herein may be acceptable for fiPAR assessment. Researchers should more explicitly state the manner in which they deploy such linear PAR sensors.

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