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Vertical point quadrat sampling and an extinction factor to calculate leaf area index

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The appropriateness of a correction factor to derive leaf area index (LAI) from contact frequency using vertically-inserted point quadrat sampling was investigated. Point quadrat data were collected in a grid pattern over 72 individual shrubs and grass plots comprising eight common Great Basin scrub species of widely divergent ecology and canopy form. Destructive sampling and intercept measurements were used to determine LAI values. Extinction coefficients were then calculated from paired LAI and contact frequency. For all eight species, this extinction coefficient was statistically equivalent to 0·5 as a result of spherical leaf angle distribution, permitting LAI estimation simply by multiplying contact frequency by 2.

Keywords: leaf area index; point quadrat; leaf angle; canopy extinction factor

Introduction

LAI is a dimensionless expression of the one-sided area of leaves per unit area of ground which is useful for comparing ecologically-important leaf-based vegetation processes. Direct measurement of LAI poses a challenge for the researcher and, of the methods available, few are well suited to the vegetation of arid and semi-arid scrublands. The purpose of this paper is to revisit an archival data set to test the use of an established correction factor to estimate LAI from vertical point quadrat-derived contact frequencies. This fresh look at the point quadrat method (Levy & Madden, 1933) was prompted by recent advances in the literature that relate canopy architecture to leaf distribution functions (Campbell, 1986; Campbell & Norman, 1989; Norman & Campbell, 1989). The ultimate application for a simplified point-quadrat estimation of LAI is the short, often discontinuous vegetation canopies of arid and semi-arid land. This vegetation often contains significant, though variable, quantities of standing dead stems which, in addition to stature and spacing, presents poor conditions for estimation of LAI by light meter with inversion of Beer-Bouger's Law (for example, Pierce & Running, 1988).

The original data set was prompted by necessity: repetitive LAI measurements were needed in Great Basin shrub-steppe vegetation for ecological study of plant water use

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and drought response (Groeneveld *et al.*, 1985). The physiognomy of this vegetation prescribed the approach needed for estimating LAI. At that time, I rejected an existing application of the point quadrat method that employs pins inclined at some angle (Warren Wilson, 1963). I found that the angled-pin point quadrat method was poorly adaptable to field conditions because the required pin length for measuring canopies that occasionally attained 2 m height caused the supporting equipment to be highly unstable (up to 3-m long pins cantilevered at angles of 32·5° or 13° and 52° from the horizon; Warren Wilson, 1963). Thus, for an intended application to provide repeatable estimates of scrub vegetation LAI, I chose to adapt the point quadrat method for vertical pin alignment. Initially these data were used to calculate species-wise linear relationships of total numbers of pin–leaf contacts for estimation of LAI.

Whether with angled or vertical pin insertion, the point quadrat technique provides an estimate of leaf cover from measurement of the contact frequency of points (considered dimensionless; Goodall, 1952) that are lowered through the canopy. Contact frequency is expressed as the number of contacts divided by the number of pins employed (Goodall, 1952). According to Norman & Campbell (1989), contact frequency, 'N_i', is related to canopy LAI, 'LAI_i', through the canopy extinction coefficient, K_i, such that:

$$N_i = LAI_i K_i \qquad \text{(Eqn 1)}$$

Although the arrangement of leaves within plant canopies is highly complex, fortunately for the sake of simplicity, the average alignment and orientation of the population of leaves can be accurately described statistically (Goel & Strebel, 1984; Campbell, 1986; Wang & Jarvis, 1988; Campbell & Norman, 1989). One such leaf-angle distribution function is spherical, where leaf angles are approximated by lines normal to the tangent of a sphere. Thus, I hypothesized that if K_i for a given species were known in advance, it would provide a correction factor to derive LAI from vertical-point-frame-measured N_i.

Study area, species and methods

The data set was developed during 1983 at several locations on the 1200 m floor of the Owens Valley, California which is located at the western edge of the Great Basin. The Owens Valley has an arid climate (10–15 cm annual precipitation) with hot summers and cool winters. The eight species studied are common perennial plants of sunny, open habitats on the floors and bajadas of broad open valleys in much of the Great Basin. The Owens Valley floor contains large areas of land influenced by shallow ground-water which offered the opportunity to include species inhabiting these relatively wet zones and also species inhabiting nearby xeric sites. The test species, described in Table 1, cover a wide range of ecological niches and canopy and leaf morphologies. Individual shrubs were chosen to represent a gradation in size to test the method. In a similar manner, the fixed-size grass plots were selected to provide a range of cover. Numbers of samples differ among the study species with an emphasis placed upon the principal shallow ground-water species analysed in the water-relations study.

A point quadrat frame with 10 cm spacing between pins was deployed sequentially to obtain a grid of vertically sampled points through individual crowns of shrubs and on 0·5 m × 0·5 m homogeneous monoculture plots of the two grass species (Figs 1 and 2). During point frame/canopy intercept measurements, metal stakes were emplaced to guide location of the point frame. For development of contact frequency, N_i, only those pins which penetrated each canopy were counted (yielding Σ_{pins}). For shrubs, this population consisted of those pins that penetrated the vertically-projected area of canopy cover; for the homogeneous cover in each grass plot, a constant number of pins was used for sampling each square plot. All contacts of the sharpened pin tips with leafy material were tallied and summed for each shrub crown and grass plot ($\Sigma_{contacts}$). The ratio $\Sigma_{contacts}/\Sigma_{pins}$ yielded canopy total values for N_i.

Projected shrub canopy area, 'A_{canopy}', was calculated for individual shrubs by (1) measuring intercept lengths (m) across the canopy along each grid line for two opposing axes, (2) calculating an arithmetic average intercept for each axis, and (3) multiplying the two axes together to yield m^2 of projected area. Canopy intercept measurements were conducted at each grid location with the point frame in position to serve as a guideline.

Following the measurement of crown intercept dimensions and tallying all pin point/leaf contacts, fresh leaves were harvested from each shrub by hand stripping and from each grass plot by clipping to ground level. Non-green leaves were discarded from these samples, and the remaining green leaf tissue was placed in plastic bags and stored

Table 1. *Species evaluated for this study: morphologic descriptions from Hickman (1993); ecologic amplitude generated by the author (unpublished data)*

Family and species	Morphology and ecological amplitude
Asteraceae	
Artemisia tridentata Nutt. ssp. *tridentata* [big sagebrush]	< 3 m woody, monoecious evergreen shrub with 3-toothed, wedge-shaped densely pubescent leaves (12–40 mm); coarse, well-drained soils; alluvial fans
Chrysothamnus nauseosus (Pallas) Briton ssp. *consimilis* (E. Greene) H. M. Hall & Clem. [salt rabbitbrush]	0·5–2·5 m suffrutescent, monoecious, deciduous shrub with threadlike leaves (2–6 mm); sodic soils; shallow ground-water; valley floors
Chenopodiaceae	
Atriplex canescens (Pursh) Nutt. [four-wing saltbush]	< 2 m woody, dioecious, evergreen shrub with scurfy coating of trichomes on linear leaves (8–50 mm); well-drained soil; alluvial fan margins
Atriplex confertifolia (Torr. & Frém.) S. Watson [shadscale]	< 1 m, woody, dioecieous, evergreen shrub, ovate leaves (8–24 mm) with scurfy coating of trichomes; coarse to fine-textured, often sodic soil; valley floors
Atriplex lentiformis (Torr.) S. Watson subsp. *torreyi* Hall & Clem. [Torrey saltbush]	0·8–3 m, woody, dioecious, evergreen shrub, hastate leaves (7–50 mm) with scurfy coating of trichomes; shallow ground-water; fine-textured sodic soils; valley floors
Sarcobatus vermiculatus (Hook.) Torr. [greasewood]	5–3 m, woody, monoecious, deciduous shrub with succulent, glabrous needle-like leaves (5–28 mm); shallow ground-water; fine-textured sodic soil; valley floors
Poaceae	
Distichlis spicata (L.) E. Greene [saltgrass]	rhizomatous grass with stiff, ascending 2-ranked glabrous leaves (20–100 × 1–4 mm); shallow ground-water; sodic soil; valley floors
Sporobolus airoides (Torr.) Torr. [alkali sacaton]	tufted bunch grass with drooping glabrous leaves (120–400 × 2–6 mm); shallow ground-water; fine-textured sodic soil; valley floors

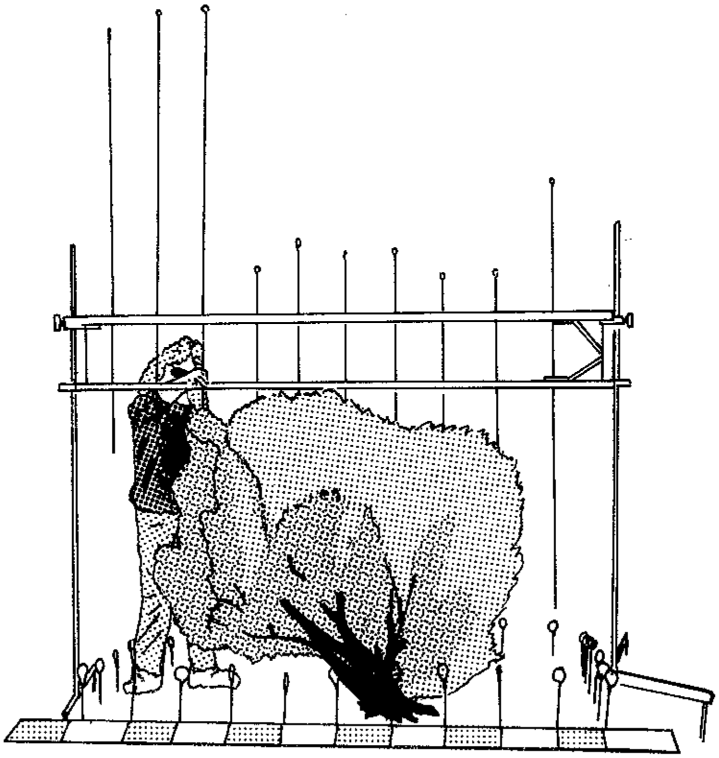

Figure 1. Side view of the point quadrat frame as deployed to obtain leaf/pin contact frequencies in a grid pattern. Chaining pins and a ruled template were used to establish a grid for positioning the point frame. The frame was moved to sample across each grid intercept.

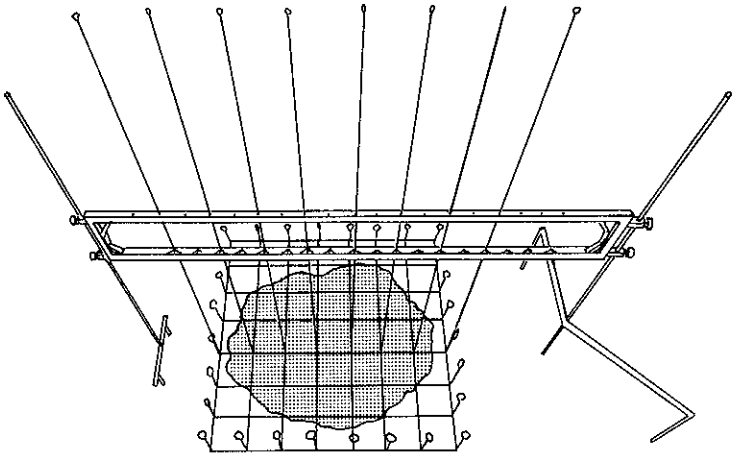

Figure 2. Vertical view of the point quadrat frame in position but with the shrub removed for illustration. The shaded area indicates the projected area of the shrub canopy.

in the shade for protection from desiccation on the way to the laboratory. Total area of leaves within each shrub canopy or grass plot, 'A_{leaf}', was estimated by a method adapted from standard stereologic technique (Weibel, 1979): (1) arranging the freshly harvested leaves as a monolayer on a 1 m^2, decimeter-ruled grid field; (2) estimation of the coverage of each grid cell as a decimal fraction; (3) summing the decimal fraction grid-coverage estimates and; (4) multiplying this sum by 0·01 m^2, the area of each grid cell, to yield m^2 of leaf cover.

For revisiting these data, canopy-total values for LAI_i was calculated from the ratio A_{leaves}/A_{canopy}. Canopy-total values for K_i were then calculated from LAI_i and N_i for each experimental shrub and grass plot.

Results

A summary of the experimental data and calculated values for N_i, LAI_i and K_i for each shrub and grass plot are presented in Table 2. The data of Table 2, ranked by decreasing magnitude of LAI values, show that the method used for generating these data is relatively robust. Absence of strong correlation between the ranked LAI values with other data and calculated values in Table 2 show that no large systematic error was induced by the method or calculations and that even very small samples (for example four pins used for a canopy of only 0·04 m^2 leaf area) still fit within the expected bounds defined by much larger samples. The experiment was carried out primarily within a 2-month period, during which no systematic change in K_i across all species was detected. Even though at the lower end of the statistical distribution for K, data for big sagebrush, collected during November, still fit within the range of the other values obtained during mid-summer.

The data of Table 2 are ecologically instructive. Shrub canopy area is highly variable because shrub specimens were chosen to present a range of sizes to test the method while ignoring the LAI that each canopy supported. Despite the variability in A_{canopy}, projected LAI values for shrubs can be compared directly since, in essence, it was derived by normalizing A_{leaf} by A_{canopy}. Large variation in projected shrub LAI_i values demonstrates a high degree of elasticity for the leaf population within each shrub canopy that are controlled by available resources; nutrients and soil water.

Although there is a relatively wide range in values of K_i for individual specimens, K_i values are distributed around a central tendency of approximately 0·5. Figure 3 provides a visual summary of K_i per species and as an overall mean ($N = 72$). With 95% confidence, the true mean K lies between 0·480 and 0·550.

The intent of this study is to evaluate a standard factor to correct vertically-derived contact frequency to yield LAI. Thus, the performance of a standard K value of 0·5 to predict LAI was tested. Figure 4 presents the predicted LAI, using $K = 0·5$, *vs.* measured LAI. The data array well along a line of equivalence. It is important to note that the scatter in this relationship is largely due to the combination of four measured variables, each increasing error multiplicatively. This fact is supported by reduced scatter of the grass data; since the grasses were measured in plots of fixed size, one less source of error was encorporated. When evaluated over the scale of a plant community these errors become negligible as indicated by Monte Carlo analysis conducted to simulate combinations of shrub and grass canopies encountered over the landscape, as would occur during use of vertical point framing along a line transect. One hundred combinations of the 72 K_i values were selected randomly, ten at a time. The resultant mean K values ($N = 10$) yielded an absolute range between 86% and 120% of the overall mean with a coefficient of variation of 2·6% (data not presented).

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One final analysis was prompted by an hypothesis that K_i would tend to decrease as LAI_i increases, advanced by Professor Gaylon Campbell in personal correspondence.

Table 2. *Field data and estimates of LAI and K collected by point quadrat and destructive sampling for each shrub canopy or grass plot. Samples are ranked in decreasing order by LAI (numbers in parentheses are 2 SE of K)*

Big sagebrush (*Artemisia tridentata tridentata*) sampled 11–15–83

$\sum_{pins}$	$\sum_{contacts}$	N	A_{leaf}	A_{canopy}	LAI	K
16	11	0·688	0·333	0·181	1·840	0·374
61	22	0·361	1·183	0·990	1·195	0·302
44	13	0·295	0·543	0·655	0·829	0·356
112	49	0·438	2·105	2·196	0·959	0·456
46	17	0·370	0·437	0·672	0·650	0·568

N = 5; mean K = 0·411 (0·104)

Four-wing saltbush (*Atriplex canescens*) sampled 7–5–83

$\sum_{pins}$	$\sum_{contacts}$	N	A_{leaf}	A_{canopy}	LAI ?	K
22	21	0·955	0·408	0·086	4·744	0·201
78	109	1·397	1·350	0·500	2·700 ○	0·518
41	24	0·585	0·528	0·202	2·614	0·224
30	36	1·200	0·360	0·202	1·782 ○	0·673
23	25	1·087	0·138	0·079	1·747 ○	0·622
34	42	1·235	0·380	0·243	1·564 ○	0·790
49	33	0·673	0·371	0·269	1·379	0·488
29	26	0·897	0·199	0·162	1·228	0·730

N = 8; mean K = 0·531 (0·220)

Torrey saltbush (*Atriplex l. torreyi*) sampled 6–23 to 7–18–83

$\sum_{pins}$	$\sum_{contacts}$	N	A_{leaf}	A_{canopy}	LAI	K
36	95	2·639	1·629	0·370	4·403 ○	0·599
95	126	1·326	1·623	0·514	3·158 ○	0·420
31	45	1·452	0·681	0·217	3·138 ○	0·463
172	249	1·448	3·010	1·030	2·922 ○	0·495
61	75	1·230	0·824	0·354	2·328 ○	0·528
140	185	1·321	1·907	0·845	2·257 ○	0·586
69	95	1·377	0·855	0·381	2·244 ○	0·614
115	173	1·504	1·716	0·768	2·234 ○	0·673
60	64	1·067	0·764	2·214	2·214 ○	0·482
293	330	1·126	3·730	1·905	1·958 ○	0·575
7	5	0·714	0·070	0·036	1·944	0·367
231	295	1·277	2·778	1·834	1·834 ○	0·696
4	4	1·000	0·042	0·024	1·750 ○	0·571
83	51	0·614	0·758	0·464	1·634	0·376
204	118	0·578	1·682	1·361	1·236	0·468

N = 15; mean K = 0·528 (0·100)

Saltgrass (*Distichlis spicata*) sampled 7–22–83

$\sum_{pins}$	$\sum_{contacts}$	N	A_{leaf}	A_{canopy}	LAI	K
36	72	2·000	0·995	0·250	3·980	0·503
36	26	0·722	0·520	0·250	2·080	0·347
36	18	0·500	0·213	0·250	0·852	0·587
36	17	0·472	0·169	0·250	0·676	0·699

Table 2. *(continued)*

Saltgrass (*D. spicata*) sampled 7–22–83

Σ_{pins}	$\Sigma_{contacts}$	N	A_{leaf}	A_{canopy}	LAI	K
36	11	0·306	0·162	0·250	0·648	0·472
36	9	0·250	0·085	0·250	0·340	0·735

$N = 6$; mean K = 0·557 (0·146)

Salt rabbitbrush (*Chrysothannus n. consimilis*) sampled 7–13 to 8–16–83

Σ_{pins}	$\Sigma_{contacts}$	N	A_{leaf}	A_{canopy}	LAI	K
66	74	1·121	1·837	0·570	3·223	0·348
113	123	1·088	3·381	1·111	3·043	0·358
81	131	1·617	2·143	0·792	2·706	0·598
140	158	1·129	3·974	1·580	2·515	0·449
111	123	1·108	2·453	1·052	2·332	0·475
28	32	1·143	0·304	0·176	1·727	0·662
55	35	0·636	0·375	0·262	1·431	0·445
112	84	0·750	0·974	0·786	1·239	0·605
58	30	0·517	0·434	0·360	1·206	0·429
14	11	0·786	0·081	0·076	1·066	0·737
60	40	0·667	0·336	0·317	1·060	0·629
16	4	0·250	0·064	0·068	0·941	0·266
161	93	0·578	1·007	1·078	0·934	0·618
67	44	0·657	0·379	0·467	0·812	0·809

$N = 14$; mean K = 0·531 (0·158)

Shadscale (*Atriplex confertifolia*) sampled 7–6 and 7–7–83

Σ_{pins}	$\Sigma_{contacts}$	N	A_{leaf}	A_{canopy}	LAI	K
20	19	0·950	0·286	0·110	2·600	0·365
86	132	1·535	1·520	0·624	2·436	0·630
46	60	1·304	0·551	0·260	2·119	0·615
36	43	1·194	0·378	0·210	1·800	0·664
31	42	1·355	0·479	0·280	1·711	0·792
6	4	0·667	0·041	0·025	1·640	0·407

$N = 6$; mean K = 0·531 (0·220)

Greasewood (*Sarcobatus vermiculatus*) sampled 6–24 to 7–19–83

Σ_{pins}	$\Sigma_{contacts}$	N	A_{leaf}	A_{canopy}	LAI	K
19	25	1·316	0·232	0·069	3·362	0·391
199	180	0·905	3·598	1·191	3·021	0·299
94	67	0·713	1·357	0·486	2·792	0·255
46	58	1·261	0·671	0·292	2·298	0·549
123	90	0·732	1·455	0·673	2·162	0·338
93	70	0·753	1·024	0·525	1·950	0·386
162	105	0·648	1·592	1·106	1·439	0·450
195	226	1·159	1·642	1·255	1·308	0·886
18	13	0·722	0·078	0·073	1·068	0·676

$N = 9$; mean K = 0·470 (0·203)

Table 2. *(continued)*

Alkali section (*Sporobolus airoides*) sampled 7–26 to 7–29–83

Σ_{pins}	Σ_{contacts}	N	A_{leaf}	A_{canopy}	LAI	K
36	68	1·889	1·019	0·250	4·076	0·463
36	64	1·778	0·950	0·250	3·800	0·468
36	30	0·833	0·578	0·250	2·312	0·360
36	24	0·667	0·395	0·250	1·580	0·422
36	26	0·722	0·295	0·250	1·180	0·612
36	24	0·667	0·281	0·250	1·124	0·593
36	13	0·361	0·190	0·250	0·760	0·475
36	15	0·417	0·181	0·250	0·724	0·576
36	6	0·167	0·095	0·250	0·380	0·439

N = 9; mean K = 0·490 (0·085)

As indicated in Fig. 5, this hypothesis was maintained; linear regression showed K_i negatively correlated to LAI_i ($p > 0{\cdot}9975$).

Discussion

Correction of vertical point quadrat-derived frequencies to yield LAI requires division by K. For vegetation comprised of the Great Basin scrub species studied, an acceptable value for K is 0·5 (thus, LAI will be twice N). Indeed, a K value of 0·5 might be expected for many, if not most canopies of perennial plants in open high-light locations since, with random azimuth and spherical or randomly distributed leaf inclination angles (Campbell, 1977):

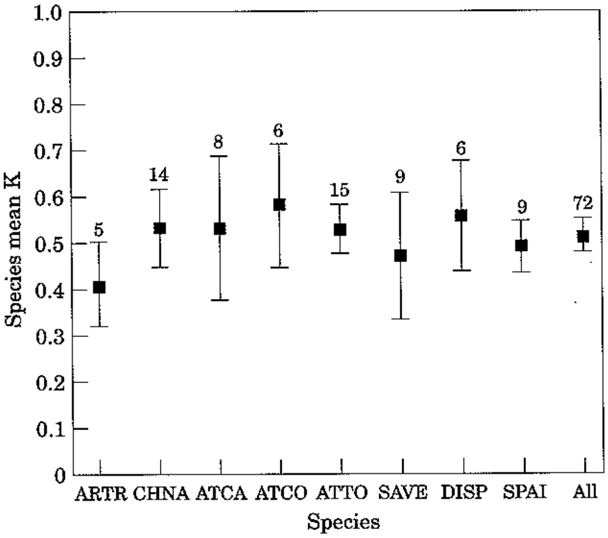

Figure 3. Mean K and error bars representing ± 2 SE (95% confidence interval for the true mean) for each species individually and as an all-species total. Species abbreviations: ARTR = *A. tridentata tridentata*; CHNA = *C. nauseosus consimilis*; ATCA = *A. canescens*; ATCO = *A. confertifolia*; ATTO = *A. lentiformis torreyi*; SAVE = *S. vermiculatus*; DISP = *D. spicata*; SPAI = *S. airoides*.

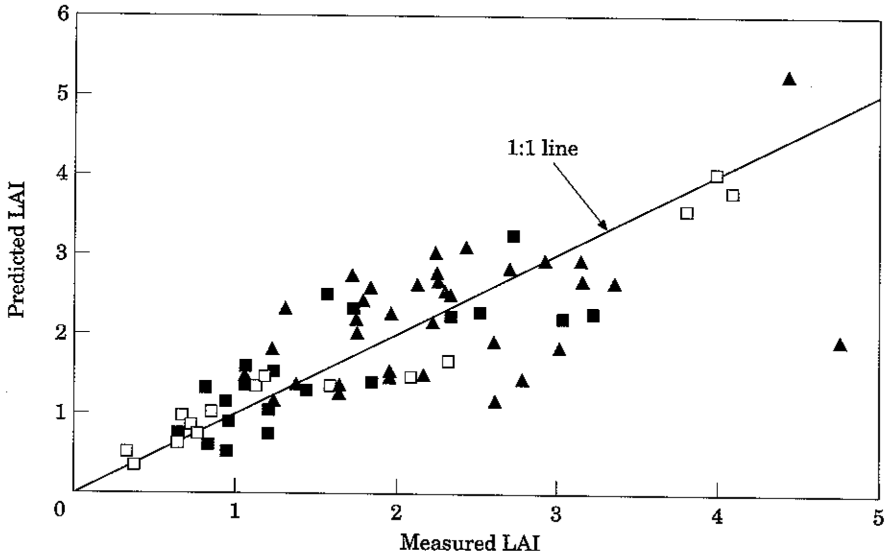

Figure 4. Comparison of measured LAI and LAI predicted using K = 0·5, for Astevaceae (■), Chenopodiaceae (▲) and Poaecea (□).

$$K = \frac{1}{2\sin\theta} \qquad \text{(Eqn 2)}$$

Apparently for these eight species, a spherical leaf angle distribution is appropriate despite the wide latitude of canopy and leaf morphology.

Although, for new species, a good working hypothesis may be K = 0·5, application of a standard correction factor for deriving LAI from vertically-inserted point quadrat contact frequency requires caution: the researcher should have a good working

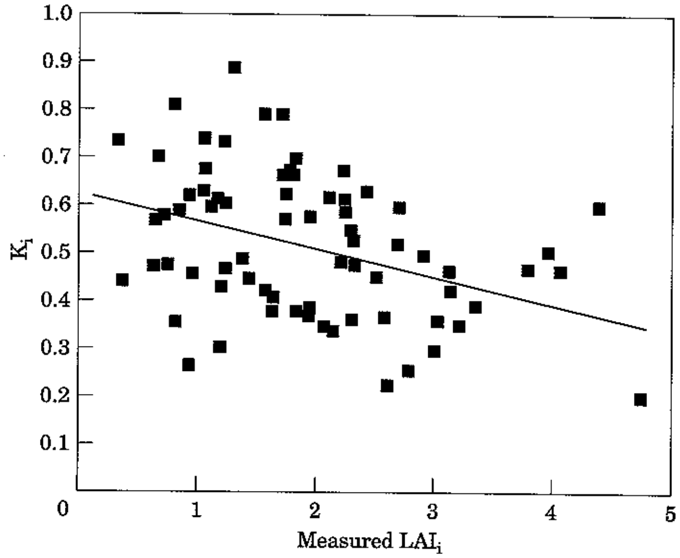

Figure 5. Scattergram of K_i and LAI_i.

knowledge of the species of interest. Perennial species which have marked changes in leaf alignment through the year would be poor candidates for direct application of this method. An example is desert holly (*Atriplex hymenelytra* (Torr.) S. Watson), a Mojave Desert species whose leaves flatten during winter increasing solar gain (Mooney *et al.*, 1974). Likewise, use of vertically-derived contact frequencies and any *a priori*-accepted correction factor would be inappropriate for estimating LAI of plants that show diurnal movement, prevalent in many annual species (Ehleringer & Forseth, 1980, 1989). Finally, if, in advance, the researcher can measure or estimate leaf distribution functions, appropriate functions for K can be selected (Campbell & Norman, 1989).

Another way to think of the K_i values is in terms of a canopy mean angle of leaf alignment. Consider that the probability for a vertically-inserted point quadrat pin to contact a leaf with angled alignment is reduced as a function of the cosine of the angle of alignment measured from the horizon. Thus, for a K value of 0·5, the arc cosine of this value equates to an average angle of leaf alignment of 60°. In the context of leaf angles, decreasing K_i with increasing LAI_i (Fig. 5) leads to an interesting general hypothesis: as canopies become more dense, leaf angles tend to be more vertical which permits light to penetrate farther into the canopy.

Although advances have been made in estimation of LAI using light meters, because of the short stature, discontinuous coverage, and large, but variable, component of dead material in the canopies of arid and semi-arid scrub, the point quadrat system may offer the most accurate data. For short-statured vegetation (generally under 1 m) comprised of the species analysed for this paper, I have found vertically-deployed point quadrat measurements along a transect at regular intervals (line-point; Heady *et al.*, 1959) to be quite rapid. With two researchers, one to lower the pin and another to tally the contacts, 201 readings taken along a 100 m transect (spaced every 0·5 m) can be accomplished within a total of 20 to 60 min, depending on the density and stature of the vegetation, and amount of empty space between shrub canopies. The only equipment necessary for these measurements is a simple frame to guide a single pin, a tape to apportion the position of the measurements along the transect, and stakes to stretch and position the tape. If a set K value can be accepted for the vegetation of interest, the only other consideration for accuracy of the estimate of LAI will depend upon the number of points to be obtained to characterize the vegetation (for example, see discussions in Hofmann & Ries, 1990, 1992; Ortiz & Ames, 1992).

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