OBJECTIVE INDEX FOR THE RADIAL DISTRIBUTION OF LOW-ORDER LATERAL TREE ROOTS

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ABSTRACT

An objective index describing the radial "evenness" of lateral tree roots has been developed. The index may be applied on the basis of root length or mass or image analysis of root quantity. Unevenness, defined as deviation from a perfectly uniform root distribution, is weighted according to the scale at which it occurs, with unevenness between halves or quarters of the root system receiving more weight than unevenness between sixteenths or thirty-seconds. A sliding frame of reference eliminates the problem of rotational dependence in the initial positioning of the "grid" used to count roots. For practical application the index requires a computer-readable root map, either from a field root-mapping exercise, or from digitised pictures of the exposed root system. Agreement between evenness rankings from visual inspection and from the index is generally excellent.

Keywords: root distribution; morphology; tree architecture.

INTRODUCTION

The evenness of the radial distribution of low-order lateral tree roots is an important characteristic of root system morphology. Plantation trees transplanted as seedlings often have significant unevenness induced by planting technique. This unevenness may make trees more susceptible to windthrow (Bell 1978; Mason 1985), and may be associated with less-efficient use of soil resources. Distortion of the tap root, which may also occur during transplanting, may produce "butt sweep", a bending of the lower part of the tree that reduces its value when felled. To evaluate and compare planting procedures, a measure of root system distortion is required. Several such indices have been reported (Balneaves & De La Mare 1989; Mason 1985) but these are generally subjective, and also tend to be dependent on the rotation of the frame of reference adopted for the measurement. This subjectivity does not mean that these indices are not useful for assessment within an experimental programme where relative values are more important than absolute values, but it does limit their usefulness for more wide-ranging comparisons.

Objective comparisons of root system morphologies are also important for the calibration and validation of computer models of plant root architecture. Difficulties encountered in the validation of such highly stochastic and irregular structures (Brown & Kulasiri 1996) prompted the development of the index described here. The index is well suited to situations where both field observations and simulated root architectures are available in the same computer-readable form (Henderson *et al.* 1983; Brown & Kulasiri 1994).

FORMULATION

As with most radial evenness indices, the root system is divided into segments. The root system is considered to be "evenly" distributed when each segment contains the same amount of some measure of root quantity, perhaps length or root mass. For example, if L m is the total root length of a root system divided into N segments, each segment should contain L/N m of root if the system is distributed evenly. Radial evenness indices intended for application by people in the field commonly use only four or eight segments, typically aligned to a specific compass direction, or to the row of trees being sampled. The low number of segments and arbitrary alignment mean that the same root system can score different evenness values depending on the rotation of the frame dividing it into segments (Fig. 1).

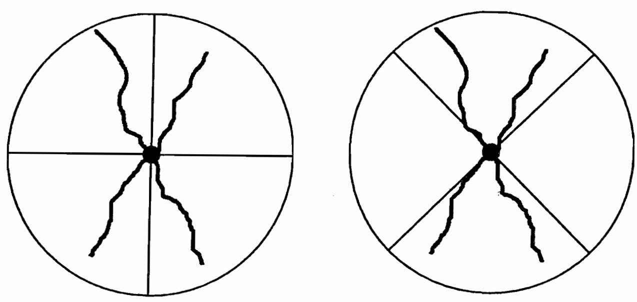
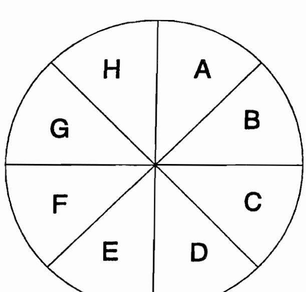


FIG. 1–The same tree could be scored as 1/1/1/1 or 2/0/2/0, depending on frame orientation.

The index presented here avoids any dependence on the rotation of the segments by considering all possible halves, quarters, eighths, and so on by dividing the root system into a high number of segments, say 64, and examining, for example, all 64 sets of 16 contiguous segments which constitute a quarter of the root system. This approach is illustrated in Fig 2, where only eight segments are used for clarity.



The index is the weighted sum of deviation from the expected $^1/_8$ of total in eight segments A, B, C, D, … H, plus deviation from $^1/_4$ of total in eight overlapping "quarters" AB, BC, CD, DE, … HA, plus deviation from $^1/_2$ of total eight overlapping "halves" ABCD, BCDE, CDEF, … HABC. Finally, the index is divided by the maximum possible value of the above summation, which for eight segments is 70.

FIG. 2–Overlapping alignment.

The index is the weighted sum of deviations at each scale, from ½ down to $1/N$, where N is the number of segments used. In general N will be a power of 2. If segments are labelled $1 \ldots N$, and O_i denotes the proportion of total root length (or mass, etc.) observed in segment i, then the value of the index is increased by $|O_i - 1/N|$ for each segment (where $1/N$ is the proportion expected in each segment of an even system and $|x|$ denotes the absolute value of x). Simlarly, every two contiguous segments should contain $2/N^{\text{ths}}$ of the root system. As the scale increases from $1/N$ up to ½ of the root system, deviation from the expected fraction of total root length becomes more significant, in terms of its impact on tree stability and root evenness. But the number of segments comprising successively larger fractions of the root system also increases, thereby weighting deviations from even distribution at larger scales more heavily.

If a value c is defined such that $c = \log_2 N$ (i.e., $2^c = N$), the index is the total of three layers of summation, each of c levels of scale contains 2^c (or N) sets of $2^c - i$ segments, where i is the scale level from 1 (half the root system) to c (one segment). The index should be divided by its maximum value, M, to give a value ranging from 0 (perfectly even distribution) to 1 (all roots in one segment). The first author can be contacted for source code or assistance with implementation of the index. The complete index is given in Equation 1.

$$\text{Index} \quad = \sum_{i=1}^{c} \sum_{j=1}^{2^c} \left| \sum_{k=1}^{2^{c-i}} O_{j+k-1} - \frac{1}{2^i} \right| \times M^{-1} \qquad (1)$$

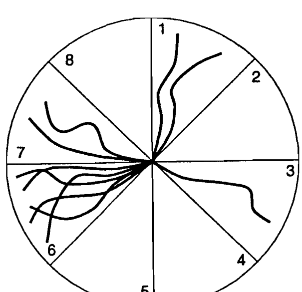
where O_x = the proportion of root mass or length occurring in segment x if $x > 2^c$, subtract 2^c from x

M = the maximum of the summation (all roots in one segment).

$$\sum_{i=1}^{c} (2^{c+1-i} - 2^{c+1-2i})$$

EXAMPLES

Given the system pictured, with 10 roots of equal length, the index is calculated as follows (note that eight segments are too few to avoid the influence of rotation described above—in reality, 64 is probably an ideal number):



Segment	Root length	O_i
1	2	0.2
2	0	0.0
3	1	0.1
4	0	0.0
5	0	0.0
6	5	0.5
7	2	0.2
8	0	0.0

$$A = \left| \sum_{k=1}^{2^{c-i}} O_{j+k-1} - \frac{1}{2^i} \right|$$

	Halves $i = 1$		Quarters $i = 2$		Segments $i = 3$	
j	k	A	k	A	k	A
1	1,2,3,4	$\boxed{0.200}$	1,2	0.050	1	0.075
2	2,3,4,5	0.400	2,3	0.150	2	0.125
3	3,4,5,6	0.100	3,4	0.150	3	0.025
4	4,5,6,7	0.200	4,5	0.250	4	0.125
5	5,6,7,8	0.200	5,6	0.250	5	0.125
6	6,7,8,1	0.400	6,7	0.450	6	$\boxed{0.375}$
7	7,8,1,2	0.100	7,8	0.050	7	0.075
8	8,1,2,3	0.200	8,1	0.050	8	0.125
		1.8		1.4		1.05 total

Normalised evenness index (divide by M) 4.25/8.75 = 0.486. The boxed 0.200 value occurs because the half represented by segments 1–4 should contain 0.5 ($^4/_8$) of the total root system, but in fact contains only 0.3. Similarly, the boxed 0.375 occurs because segment 6 should contain only 0.125 ($^1/_8$) of the total root system, but in fact contains 0.5 ($^5/_{10}$), 0.375 = 0.5 – 0.125.

Some other possible arrangements and their scores are illustrated in Fig. 3 for comparison. The failure to distinguish between the two examples which score 0.51 in Fig. 3 is a side effect

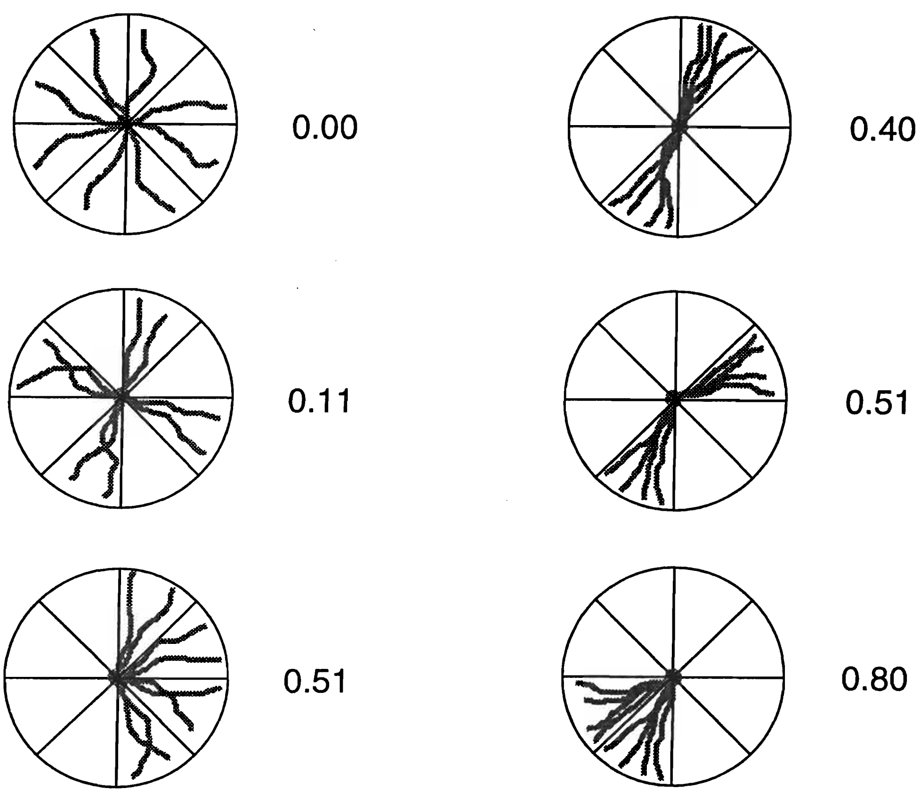


FIG. 3–Examples of (un)evenness index scores.

of using only eight segments; the index is intended for computerised application to precise root maps or image data, where a larger number of segments would be used. Index values for root maps derived from data (Table 1) generously made available by Alex Watson (Watson & O'Loughlin 1990) are given in Fig. 4. Note that the index measures distribution around the centre of the root system, i.e., the base of the stem, and so a root collar off-centre in an otherwise relatively even root system will score highly. Where shown, grids are 1 × 1 m spacing.

DISCUSSION

The index may require some fine tuning for specific applications, although its general form is probably sufficient for most uses. Roots of different orders could be weighted to differing degrees, or examined separately, if the root map being used was sufficiently sophisticated and the behaviour of different orders warranted the distinction. Root number is probably not the ideal measure of root quantity, as one root may curve and pass through many segments, particularly when the segments are narrow as happens when a high number of segments are used.

Digitised images of root systems may also be used as computer-readable input for the index. After the stem has been removed, careful excavation will allow a root system to be exposed *in situ* without displacement. A photograph or video recording of the exposed system taken from directly above the root collar may be digitised (Brown 1994). Minor image processing can produce a binary (two-colour) image of the root system against a blank background. The roots may be spray-painted with fluorescent paint to increase contrast if necessary. Given the location of the centre of the root system within the image, a simple pixel to segment mapping can be used to provide an index of the amount of "material" in each segment—the O_i input to the index.

CONCLUSION

As it is often not feasible to find a simple set of practical measurements which adequately define complex, variable, biological entities such as root systems, indirect comparisons with their real-world counterparts may be useful. The index presented here ranks root systems according to "evenness", a very widely applicable characteristic often used subjectively for both identification and comparison. The index's specification in a form suitable for objective repeatable use with computer-readable root maps allows it to be used for inter-trial comparisons, and for model calibration applications.

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TABLE 1–Data (image pixel counts) for trees in Fig. 4. In that Figure the trees are ordered 3, 4, 5, 2, 1 and 2, 1, 5, 4, 3 for 8- and 16-year groups respectively.

Eight-year-old trees										Sixteen-year-old trees									
1		2		3		4		5		1		2		3		4		5	
642	656	204	213	246	257	261	395	541	312	611	381	931	1200	77	72	204	51	143	224
2170	1137	709	776	162	146	105	228	747	758	638	1207	1257	1180	69	203	29	559	239	405
869	718	403	327	245	341	221	613	66	73	1132	1241	1130	995	193	400	816	1113	303	193
344	302	199	117	228	246	713	395	189	109	1216	1444	1176	1060	784	1079	698	1168	184	301
271	163	125	97	387	643	145	243	167	496	1746	2423	371	1632	1077	1613	845	428	618	1137
78	8	85	80	519	212	256	1088	200	388	1296	1092	973	521	986	1299	279	360	946	926
8	12	78	82	217	149	806	773	371	904	1194	1790	1746	779	1742	1385	241	665	801	356
18	21	97	104	147	152	943	739	1166	717	943	549	683	797	1176	537	666	1101	464	342
12	20	132	269	106	120	1466	885	365	923	582	578	1177	865	496	479	1056	551	176	301
18	22	296	291	111	175	370	254	379	394	1631	1509	704	570	574	388	1362	680	381	396
26	29	367	322	256	487	210	121	464	574	863	925	1267	944	478	1109	753	448	303	260
33	188	234	111	178	230	98	51	732	220	624	660	1226	757	1927	1039	657	749	527	465
207	140	311	104	303	323	41	351	109	111	739	888	652	497	612	421	1008	1090	422	838
111	88	134	101	216	227	683	322	79	48	689	828	519	404	784	1539	1299	1594	1623	884
221	308	278	318	269	1130	678	2175	63	83	625	472	459	535	1107	354	1033	405	1031	1019
324	740	378	503	842	771	730	1227	101	143	289	342	530	851	1199	481	636	736	578	487
696	601	442	316	557	932	739	214	142	144	387	251	1140	1011	303	331	1351	1096	561	543
1281	330	381	112	292	284	109	290	122	214	626	1155	815	816	335	361	952	398	645	739
400	227	141	261	587	359	177	218	717	435	724	527	1208	904	504	474	404	177	637	609
538	262	173	272	284	302	404	356	459	567	1104	878	1694	433	331	643	11	13	845	1102
94	77	326	330	376	602	394	235	789	1054	388	316	845	1284	309	230	188	394	1028	743
151	472	122	125	401	843	190	173	960	531	466	501	1100	556	231	230	1151	1479	1121	1376
610	297	29	25	480	234	299	365	726	736	182	155	1093	1231	449	589	806	1175	1007	556
198	274	20	94	94	67	596	1252	943	1037	811	912	1022	506	914	837	1771	884	464	412
538	256	307	313	80	103	586	306	1056	1278	1222	2402	258	477	405	431	305	231	444	1125
460	221	275	376	564	443	320	233	911	640	2326	987	469	337	1161	693	162	293	1466	1339
255	695	513	453	754	657	187	127	505	521	806	1183	321	479	550	951	178	68	795	1092
923	1400	399	449	336	99	76	73	267	148	742	1324	758	786	229	166	184	229	837	1040
1106	966	266	519	76	126	55	168	110	236	874	834	1951	1828	105	230	272	628	1087	1102
1025	1489	849	827	235	245	229	367	172	162	1192	1044	585	1461	291	242	428	397	932	562
1143	946	299	806	298	609	501	403	99	93	893	657	1852	1544	195	99	321	607	851	558
432	631	1000	249	438	574	359	432	113	209	420	414	2012	4125	90	76	319	245	1104	218

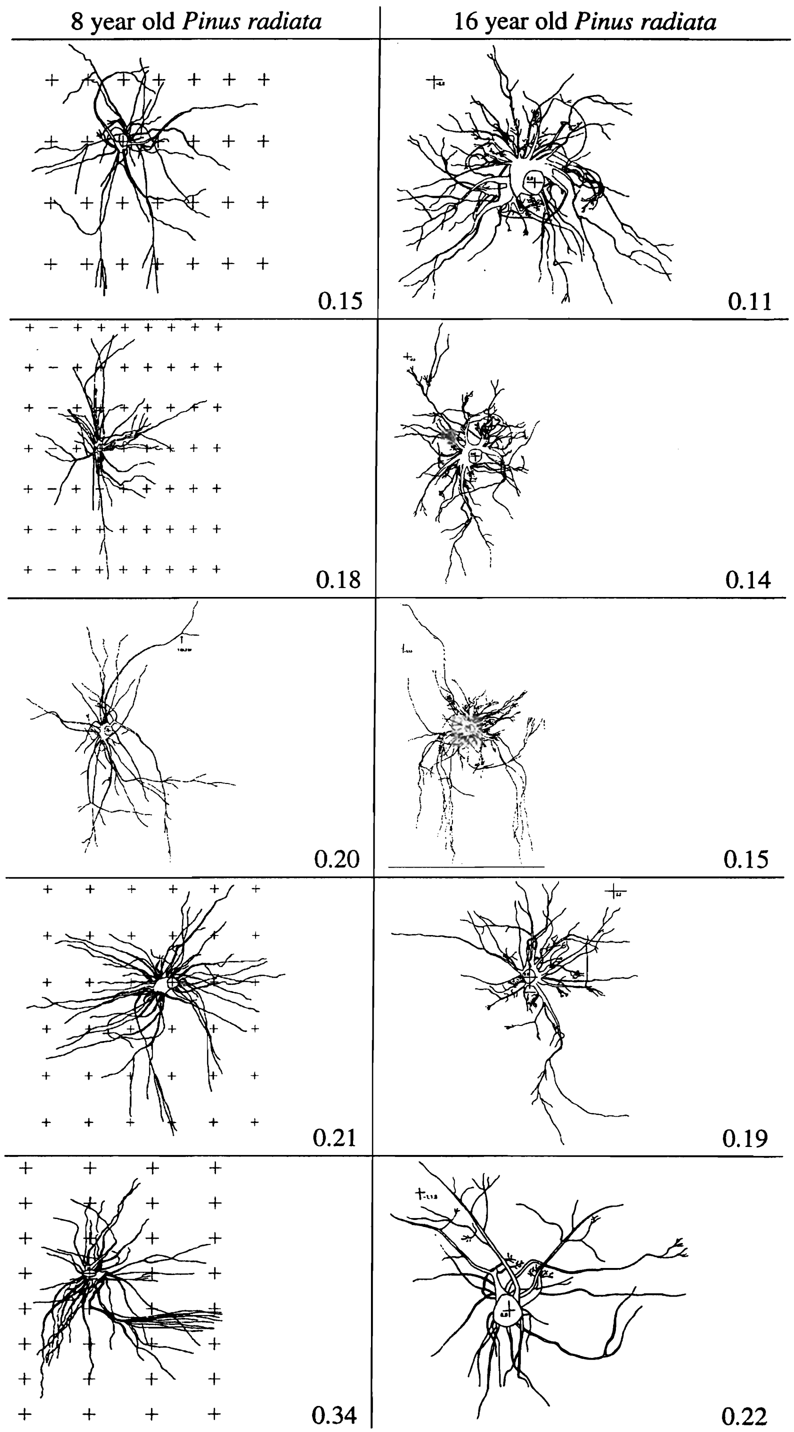

FIG. 4–Index values (64 segments) for 8- and 16-year-old *Pinus radiata* D.Don.

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