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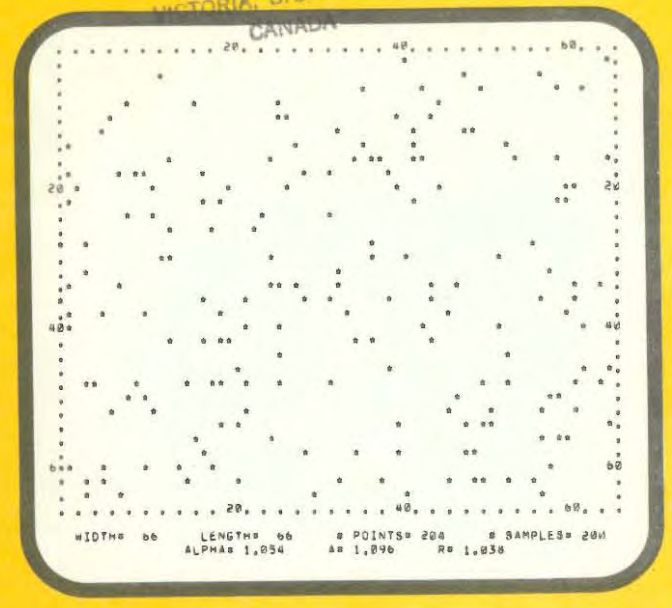

Application of The Indices of Nonrandomness

Of Pielou, Hopkins and Skellam, and Clark and Evans

Howard B. Stauffer
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APPLICATION OF THE INDICES OF NONRANDOMNESS OF PIELOU, HOPKINS AND SKELLAM, AND CLARK AND EVANS

by

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ABSTRACT

This paper describes the application of the indices of nonrandomness of Pielou, Hopkins and Skellam, and Clark and Evans. Details are given of sampling procedure and applicability. Theory and confidence interval tables are included. These three distance sampling methods are useful for measuring the extent of regularity, randomness, or aggregation of objects in space which can be represented by point spatial patterns on a plane.

FORTRAN IV programs are available at the Pacific Forest Research Centre for calculating each of these indices. Listings of these programs are given in the appendices. Examples of some point spatial patterns and their calculated indices are also included.

RÉSUMÉ

L'auteur décrit l'application des indices de points non aléatoires (indices of nonrandomness) de Pielou, et de Hopkins et Skellam, puis de Clark et Evans. Il donne les détails d'echantillonnage et d'applicabilité. Il inclut des tables de théorie et de limites de confiance. Ces trois méthodes d'échantillonnage à distance sont utiles pour mesurer l'importance de la régularité, l'aléatoire, ou l'aggrégation d'objets dans l'espace qui peuvent être représentés sur un plan par des points spatiaux formant un dessin.

Les programmes FORTRAN IV servant à calculer chacun de ces indices sont disponibles au Centre de recherches forestières du Pacifique. Le répertoire de ces programmes se trouve dans les appendices. On y retrouve aussi des exemples de quelques dessins formés de points spatiaux ainsi que leurs indices calculés.

INTRODUCTION

There is an increasing interest in examining the distribution of objects in space which can be represented by point spatial patterns on a plane. Various indices of nonrandomness have been developed in recent years to measure the extent of regularity, randomness, or aggregation (clumping) in point spatial patterns. Of these methods, four quadrat sampling and three distance sampling techniques have gained the most acceptance.

The four quadrat sampling methods involve the procedure of choosing quadrats (randomly spaced or contiguous) and counting the total number of points in each quadrat. The variance over mean radio (V/m) can then be used to calculate indices interrelated as follows. David and Moore (1954) suggested an index of clumping

$$I = V/m - 1.$$

Lloyd (1967) suggested an index of mean crowding

$$\overset{*}{m} = m + I.$$

and an index of patchiness

$$C = 1 + I/m.$$

Morisita (1959) devised an index of dispersion

$$I_\delta = \frac{N}{N-1} \cdot C$$

where N is the total number of points. A frequent disadvantage of these quadrat sampling methods is that the index may or may not be independent of quadrat size (the first two are not, whereas the last two are). But the most serious objection to those methods is that they involve an excessive amount of sampling.

In an attempt to reduce the amount of sampling and calculation, three distance sampling methods have been developed. These methods generally involve the choosing of either random positions (locations given by random X- and Y-coordinates) or random points (representing the objects) and the measurement of the distance or squared distance to the nearest neighboring point. Pielou (1959) suggested a sampling procedure which consists of choosing random positions and measuring the squared distance ω to the nearest point. The average of these squared distances $\bar{\omega}$ and the point density ρ are then used to determine the index of nonrandomness

$$\alpha = \pi\rho\bar{\omega} \ .$$

Hopkins and Skellam (1954) suggested a sampling procedure of first choosing random positions and measuring the squared distance ω_1 to the nearest point, then choosing random points[1/] and measuring the squared distance ω_2 to the nearest neighboring point. These squared distances are then used to determine their index of nonrandomness

$$A = \Sigma\omega_1 / \Sigma\omega_2 \ .$$

Clark and Evans (1954) suggested a sampling procedure of choosing random points and measuring the distance r to the nearest neighboring point. The average of these distances $\bar{r}$ together with the point density ρ are then used to determine their index of nonrandomness

$$R = 2 - 2\sqrt{\rho}\,\bar{r}.$$

Each of these distance sampling methods is a procedure for calculating an index value. This value is within a certain confidence interval of 1, if the point distribution is random.[2/] If the distribution is regular, the value is less than 1, and if the distribution is aggregated, the value is greater than 1. Thus a hypothesis of randomness is acceptable if the index value falls within the confidence interval.

The following sections describe the mathematical basis and application of these three distance sampling techniques.

PIELOU'S INDEX OF NONRANDOMNESS

Pielou's index of nonrandomness is

$$\alpha = \pi\rho\bar{\omega}$$

where

ρ = point density per unit area

and

$\bar{\omega}$ = average squared distance between a randomly chosen position and the nearest point.

1/ Care must be taken that the process of choosing a random point is indeed random. For instance, finding a random position and then choosing the nearest point is not random but is biased toward points away from cluster centers. A better method consists of listing all the points and choosing one randomly from this list.

2/ If using a p% confidence interval, there is a (100-p)% probability of a random distribution yielding an index value outside the confidence interval.

The average $\bar{\omega}$ is taken over a designated number n of samples. It can be shown (Pielou 1959, 1969; Mountford 1961) that in a random distribution, α has an expected value[3/]

$$E [\alpha] = 1.$$

In a regular distribution, α would be expected to be significantly less than one, whereas in an aggregated distribution, α would be expected to be significantly more than one. In a random distribution, α has the probability density function

$$f(\alpha) = n^n \alpha^{n-1} e^{-n\alpha} / \Gamma(n)$$

where

$\Gamma(n) = (n-1)!$ is the gamma function evaluated at n.

$2n\alpha$ is distributed like χ^2 with 2n degrees of freedom. Confidence intervals can then be specified for α by referring to a χ^2 distribution table (Pearson and Hartley 1962).

n	99%		95%	
20	0.518	0.611	1.484	1.669
30	0.592	0.675	1.388	1.533
40	0.640	0.714	1.333	1.454
50	0.673	0.742	1.296	1.402
60	0.692	0.759	1.264	1.355
70	0.713	0.776	1.244	1.327
80	0.730	0.790	1.228	1.305
90	0.745	0.802	1.214	1.287
100	0.757	0.811	1.203	1.271
120	0.777	0.827	1.185	1.247
150	0.799	0.845	1.165	1.220
200	0.825	0.865	1.142	1.189
300	0.856	0.889	1.115	1.153
400	0.875	0.904	1.100	1.132
500	0.888	0.914	1.089	1.118

Table 1. Confidence intervals for α with random distribution.[4/]

3/ It is assumed that the point density ρ is predetermined and is not estimated by sampling methods. Mountford (1961) has shown that, even when ρ is estimated by sampling, $E [\alpha] = 1$.

4/ Pielou 1959. Note the corrected values for 99% confidence intervals. Pielou's table tabulates values for 98% confidence intervals.

For example, by using a 95% confidence interval with n = 200, a hypothesis of randomness is acceptable if $.865 \leq \alpha \leq 1.142$.

HOPKINS AND SKELLAM'S INDEX OF NONRANDOMNESS

Hopkins and Skellam's index of nonrandomness is

$$A = \Sigma\omega_1 \, / \, \Sigma\omega_2$$

where

ω_1 = squared distance between a randomly chosen position and the nearest point

and

ω_2 = squared distance between a randomly chosen point and the nearest neighboring point.

Both summations are taken over a designated number n of samples. It can be shown (Hopkins and Skellam 1954; Pielou 1969) that in a random distribution, A has an expected value

$$E\ [A] = 1.$$

In a regular distribution, A would be expected to be significantly less than one, whereas in an aggregated distribution, A would be expected to be significantly greater than one. In a random distribution,

$$x = A/\ (A+1)$$

has the probability density function

$$f(x) = x^{n-1}\,(1-x)^{n-1} \,/\, B(n,n)$$

where $0 \leq x \leq 1$ and $B(n,n) = \Gamma(n) \cdot \Gamma(n) \,/\, \Gamma(2n)$. Confidence intervals can then be specified for A as follows. For a smaller number of samples ($n \leq 50$), the probability that x is within a certain interval can be obtained from tables of the incomplete beta function (Pearson and Hartley 1962; Pearson 1968). The function f(x) has a mean value of .5 and variance of $1/4(2n + 1)$, and it rapidly tends to normality as n increases. For larger numbers of samples ($n > 50$), it is then sufficient to take

$$X = 2(x - .5)\sqrt{2n+1}$$

as a standard normal variate and refer to tables of the standard normal integral (Pearson and Hartley 1962).

n	99%		95%	
20	0.436	0.533	1.875	2.296
30	0.510	0.600	1.667	1.962
40	0.558	0.641	1.556	1.792
50	0.594	0.673	1.484	1.685
60	0.621	0.698	1.434	1.612
70	0.643	0.717	1.395	1.554
80	0.663	0.732	1.365	1.509
90	0.679	0.746	1.341	1.474
100	0.692	0.757	1.321	1.444
120	0.715	0.776	1.289	1.398
150	0.741	0.797	1.255	1.349
200	0.772	0.822	1.217	1.295
300	0.810	0.852	1.174	1.235
400	0.833	0.870	1.149	1.200
500	0.849	0.883	1.132	1.177

Table 2. Confidence intervals for A with random distribution.

For example, by using a 95% confidence interval with n = 200, a hypothesis of randomness is acceptable if $.822 \leq A \leq 1.217$.

CLARK AND EVANS' INDEX OF NONRANDOMNESS

Clark and Evans' index of nonrandomness is [5/]

$$R = 2 - 2\sqrt{\rho}\,\bar{r}$$

where

ρ = point density per unit area

and

$\bar{r}$ = average distance between a randomly chosen point and the nearest neighboring point.

The average $\bar{r}$ is taken over a designated number n of samples. It can be shown (Clark and Evans 1954;

5/ Clark and Evans' original index is $R = 2\sqrt{\rho}\,\bar{r}$. Their expression is adjusted here to permit regular distributions to have index values less than one and aggregated distributions to have index values greater than one, rather than the converse. This is consistent with the other indices of nonrandomness.

Morisita 1954; Thompson 1956; Pielou 1969) that in a random distribution, R has an expected value

$$E\ [R] = 1.$$

In a regular distribution, R would be expected to be significantly less than one, whereas in an aggregated distribution, R would be expected to be significantly greater than one. In a random distribution, $\bar{r}$ can be approximated by a normal distribution with mean

$$E\ [\bar{r}\ ] = 1/2\sqrt{\rho}$$

and variance

$$Var\ [\bar{r}\ ] = (4-\pi)/4\pi\rho n.$$

Hence R has mean

$$\mu = E\ [R\ ] = 1$$

and variance

$$\sigma^2 = Var\ [R\ ] = (4-\pi\ )\ /\pi n.$$

Confidence intervals can then be specified using

$$(R-\mu\ )\ /\ \sigma = (R-1)\ /\ \sqrt{(4-\pi\ )\ /\pi\ n}$$

as a standard normal variate and referring to tables of the standard normal integral (Pearson and Hartley 1962).

	99%		95%	
n				
20	0.699	0.771	1.229	1.301
30	0.754	0.813	1.187	1.246
40	0.787	0.838	1.162	1.213
50	0.810	0.855	1.145	1.190
60	0.826	0.868	1.132	1.174
70	0.839	0.878	1.122	1.161
80	0.849	0.885	1.115	1.151
90	0.858	0.892	1.108	1.142
100	0.865	0.898	1.102	1.135
120	0.877	0.906	1.094	1.123
150	0.890	0.916	1.084	1.110
200	0.905	0.928	1.072	1.095
300	0.922	0.941	1.059	1.078
400	0.933	0.949	1.051	1.067
500	0.940	0.954	1.046	1.060

Table 3. Confidence intervals for R with random distribution.

For example, by using a 95% confidence interval with n = 200, a hypothesis of randomness is acceptable if $.928 \leq R \leq 1.072$.

APPLICATIONS

These three indices of nonrandomness may be applied to point spatial patterns in two-dimensional regions. For example, they may be used for studying the distribution of a population of sedentary organisms dispersed over a continuous surface. They are used extensively at the Pacific Forest Research Centre, Victoria, British Columbia, for measuring the distribution of trees on forest plots. They have also provided a means of testing the distribution of forest stands when applied to stand centroids (Stauffer 1977a, in preparation). Furthermore, by reversing sampling procedure for derivation of the index, these algorithms have led to the development of methods of generating artificial stands of trees with appropriate spatial distribution (Stauffer 1977b, in preparation; cf. Newnham 1968).

Originally developed for points in two-dimensional space, they may be generalized to other dimensions so that points on a line or in three-dimensional space may also be examined for distribution (Stauffer 1977c, in preparation). For example, spatial patterns of various organisms in the soil, atmosphere, or water may be measured; i.e., organisms such as defoliators, pathogens, or soil fauna.

These indices can be hand-calculated in the field or in the laboratory. Better still, the calculation can be done by computer. Programs are available from Computing Services at the Pacific Forest Research Centre to calculate these indices: Pielou's index of nonrandomness (PTEST), Hopkins and Skellam's index of nonrandomness (HSTEST), and Clark and Evans' index of nonrandomness (CETEST). See Appendices I-III and Stauffer (1976a, 1976b, 1976c) for details. These computer programs have been used extensively on both simulated and actual forestry plots (Appendix IV). The simulated plots include sites with regular, random, and aggregated spacing. The actual plots include plots of coastal British Columbia Douglas-fir from sites at Shawnigan Lake (Crown and Brett 1975).

COMPARISON OF THE INDICES

Of the three indices of nonrandomness, Pielou's index is the best (cf. Holgate 1965; Payandeh 1970). It involves only position to point distances, whereas Hopkins and Skellam's index involves point-

to-point distances as well as position-to-position distances; Clark and Evans' index involves only point-to-point distances. For this reason, Hopkins and Skellam's method and Clark and Evans' method tend to measure the concentration of points within clusters. Pielou's method of just choosing random positions is able to detect holes in spatial pattern. Furthermore, Hopkins and Skellam's index has the largest confidence intervals and tends to vary considerably even for random patterns. Clark and Evans' index has the smallest confidence intervals but tends to place index values for both random and nonrandom distributions within these limits.[6/] Hopkins and Skellam's index requires the greatest amount of calculation and computer time, while Clark and Evans' requires the least amount of time, but only slightly less than Pielou's. For these reasons, Pielou's index is recommended as a good measure combining high sensitivity for distinguishing between random and nonrandom distribution with a minimum amount of calculation.

ACKNOWLEDGMENTS

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6/ With all three indices, bias owing to edge effect has proven to be negligible and may be ignored.

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APPENDIX I:

THE FORTRAN IV PROGRAM PTEST

```
C*************************************************************************
C
C      PROGRAM: PTEST
C
C      DESCRIPTION: CALCULATES PIELOU'S INDEX OF NONRANDOMNESS
C            ALPHA=PI*RHO*OMEGA
C         WHERE
C            RHO=POINT DENSITY PER UNIT AREA
C            OMEGA=AVERAGE SQUARED DISTANCE BETWEEN A RANDOMLY CHOSEN
C               POSITION AND THE NEAREST POINT
C
C      REFERENCES:
C         PIELOU, E.C. 1959. THE USE OF POINT-TO-PLANT DISTANCES IN
C            THE STUDY OF THE PATTERN OF PLANT POPULATIONS. J.ECOL.47:
C            607-613.
C         MOUNTFORD, M.D. 1961. ON E.C. PIELOU'S INDEX OF NONRANDOM-
C            NESS. J.ECOL.49: 271-275.
C
C      VARIABLES:
C         NOROWS=WIDTH OF PLOT
C         NOCOLS=LENGTH OF PLOT
C         NOTREE=NUMBER OF POINTS IN PLOT
C         NOSAMP=NUMBER OF SAMPLES IN PIELOU'S INDEX CALCULATION
C         X(I)=X-COORDINATE OF THE I-TH POINT
C         Y(I)=Y-COORDINATE OF THE I-TH POINT
C         RHO=POINT DENSITY PER UNIT AREA
C         OMEGA=AVERAGE SQUARED DISTANCE BETWEEN A RANDOMLY CHOSEN
C            POSITION AND THE NEAREST POINT
C         ALPHA=PIELOU'S INDEX OF NONRANDOMNESS
C
C      SUBPROGRAMS: DISTSQ, PLOT; IFIX, AMOD, SECNDS, ACC, CLOSE,
C         ASSIGN, FLOAT, RAN
C
C      DATE: 20 AUGUST 1976
C
C      AUTHOR: E.C. PIELOU
C
C      PROGRAM DESIGNER: M.B. STAUFFER
C
C*************************************************************************
       COMMON /LIST/NOROWS,NOCOLS,NOTREE,X(2000),Y(2000)
       DISTSQ(A,B,C,D)=(A-C)*(A-C)+(B-D)*(B-D)
       N1=IFIX(AMOD(SECNDS(0.),32000.))
       N2=1
C
C.....WRITE INTERACTIVE TERMINAL INFORMATION; READ INPUT
C
       WRITE(5,10)
 10    FORMAT(' THIS PROGRAM CALCULATES PIELOU''S INDEX OF NONRANDOMNESS.
      1 THE COORDINATES',/,' OF THE POINTS WHOSE SPATIAL PATTERN IS TO BE
      2 DETERMINED MUST BE INPUT IN')
       WRITE(5,20)
 20    FORMAT(' ONE OF THE FOLLOWING TWO WAYS:',/,'     1) USING IBM DATA
      1CARDS ON THE CARD READER (INPUT ONE SET OF COORDI-')
       WRITE(5,30)
 30    FORMAT(' NATES (X,Y) PER CARD WITH FORMAT(2F8.3)), OR',/,'     2) U
      1SING A FORMATTED SEQUENTIAL DATA FILE MAP.DAT;1 (INPUT ONE SET OF'
```

```
     2)
      WRITE(5,40)
 40   FORMAT(' COORDINATES (X,Y) PER RECORD WITH FORMAT(2F8.3)).')
      WRITE(5,50)
 50   FORMAT(/,' PLOT WIDTH (VERTICAL OR Y-AXIS DISTANCE)=? (INPUT AN IN
     1TEGER <= "9999")',/,'  '$)
      NOROWS=ACC(IER)
      WRITE(5,60)
 60   FORMAT(' PLOT LENGTH (HORIZONTAL OR X-AXIS DISTANCE)=? (INPUT AN I
     1NTEGER <=',/,' "9999") '$)
      NOCOLS=ACC(IER)
      WRITE(5,70)
 70   FORMAT(' NUMBER OF POINTS=? (INPUT AN INTEGER <= "9999"; IF UNKNOW
     1N, INPUT "0")',/,'  '$)
      NOTREE=ACC(IER)
      IF (NOTREE.EQ.0) NOTREE=30000
      WRITE(5,80)
 80   FORMAT(' NUMBER OF SAMPLES=? (INPUT AN INTEGER <= "9999"; RECOMMEN
     1DED VALUE IS',/,' "200") '$)
      NOSAMP=ACC(IER)
      WRITE(5,90)
 90   FORMAT(' DO YOU WANT THE PLOT GRAPHED? (IF THE ANSWER IS "NO", INP
     1UT "0"; IF THE',/,' ANSWER IS "YES", INPUT "1") '$)
      N=ACC(IER)
      WRITE(5,100)
 100  FORMAT(' DO YOU WANT THE POINT LOCATIONS READ FROM THE CARD READER
     1 OR FROM A DATA',/,'  FILE? (IF USING THE CARD READER, INPUT "0";
     2IF USING A DATA FILE, INPUT',/,' "1") '$)
      M=ACC(IER)
      CALL CLOSE(5)
      IF (M.EQ.1) GO TO 110
      CALL ASSIGN(4,'CR:',3)
      GO TO 120
 110  CALL ASSIGN(4,'MAP.DAT;1',9)
 120  READ(4,130,END=140)(X(I),Y(I), I=1,NOTREE)
 130  FORMAT(2F8.3)
      GO TO 150
 140  NOTREE=I-1
C
C.....CALCULATE PIELOU'S INDEX OF NONRANDOMNESS
C
 150  PI=3.14159
      RHO=FLOAT(NOTREE)/FLOAT(NOROWS*NOCOLS)
      SUM=0.0
      DO 170 I=1,NOSAMP
      B=FLOAT(NOCOLS)*RAN(N1,N2)
      C=FLOAT(NOROWS)*RAN(N1,N2)
      D=99999.0
      DO 160 J=1,NOTREE
      E=DISTSQ(X(J),Y(J),B,C)
 160  IF (E.LT.D) D=E
 170  SUM=SUM+D
      OMEGA=SUM/FLOAT(NOSAMP)
      ALPHA=PI*RHO*OMEGA
C
C.....WRITE OUTPUT
C
```

```
      WRITE(6,180)
  180 FORMAT(//,51X,'PIELOU''S INDEX OF NONRANDOMNESS',/,51X,'******** *
     1**** ** ************')
      WRITE(6,190)
  190 FORMAT(////,' DESCRIPTION: THIS PROGRAM CALCULATES PIELOU''S INDEX
     1 OF NONRANDOMNESS')
      WRITE(6,200)
  200 FORMAT('        ALPHA=PI*RHO*OMEGA')
      WRITE(6,210)
  210 FORMAT('    WHERE')
      WRITE(6,220)
  220 FORMAT('        RHO=POINT DENSITY PER UNIT AREA')
      WRITE(6,230)
  230 FORMAT('        OMEGA=AVERAGE SQUARED DISTANCE BETWEEN A RANDOMLY C
     1HOSEN POSITION AND THE NEAREST POINT')
      WRITE(6,240)
  240 FORMAT(/,' REFERENCES:')
      WRITE(6,250)
  250 FORMAT('    PIELOU, E.C. 1959. THE USE OF POINT-TO-PLANT DISTANCES
     1 IN THE STUDY OF THE PATTERN OF PLANT POPULATIONS. J.ECOL.47: 607-
     2613.')
      WRITE(6,260)
  260 FORMAT('    MOUNTFORD, M.D. 1961. ON E.C. PIELOU''S INDEX OF NONRA
     1NDOMNESS. J.ECOL.49: 271-275.')
      WRITE(6,270)
  270 FORMAT(/,' AUTHOR: E.C. PIELOU')
      WRITE(6,280)
  280 FORMAT(/,' PROGRAM DESIGNER: H.B. STAUFFER')
      IF (N.EQ.1.AND.NOROWS.LE.65.AND.NOCOLS.LE.65) CALL PLOT
      WRITE(6,290) NOROWS,NOCOLS,NOTREE,NOSAMP,ALPHA
  290 FORMAT(//,14X,'PLOT WIDTH=',I4,5X,'PLOT LENGTH=',I4,5X,'NUMBER OF
     1POINTS=',I4,5X,'NUMBER OF SAMPLES=',I4,5X,'ALPHA=',F6.3)
      STOP
      END
C*******************************************************************************
C
C     SUBPROGRAM: PLOT
C
C     DESCRIPTION: PLOTS THE SITE
C
C*******************************************************************************
      SUBROUTINE PLOT
      COMMON /LIST/NOROWS,NOCOLS,NOTREE,X(2000),Y(2000)
      DIMENSION MATRIX(66,132),IA(7)
      DATA IBLANK,IPOINT,IAST/' ','.','*'/
      DATA IA/'0','1','2','3','4','5','6'/
C
C.....FILL A MATRIX TO REPRESENT THE PLOTTED SITE
C
      DO 1010 I=1,NOROWS+1
      DO 1010 J=1,2*NOCOLS+2
 1010 MATRIX(I,J)=IBLANK
      DO 1020 I=1,NOROWS+1,NOROWS
      DO 1020 J=2,2*NOCOLS+2,2
 1020 MATRIX(I,J)=IPOINT
      DO 1030 J=2,2*NOCOLS+2,2*NOCOLS
```

```
      DO 1030 I=1,NOROWS+1
 1030 MATRIX(I,J)=IPOINT
      DO 1040 J=22,2*NOCOLS-1,20
      MATRIX(1,J)=IA(J/20+1)
 1040 MATRIX(NOROWS+1,J)=IA(J/20+1)
      DO 1050 J=23,2*NOCOLS,20
      MATRIX(1,J)=IA(1)
 1050 MATRIX(NOROWS+1,J)=IA(1)
      DO 1060 I=11,NOROWS-2,10
      MATRIX(I,1)=IA(I/10+1)
 1060 MATRIX(I,2*NOCOLS+1)=IA(I/10+1)
      DO 1070 I=11,NOROWS-2,10
      MATRIX(I,2)=IA(1)
 1070 MATRIX(I,2*NOCOLS+2)=IA(1)
      DO 1080 I=1,NOTREE
      IX=IFIX(X(I)+.5)
      IY=IFIX(Y(I)+.5)
 1080 MATRIX(IY+1,2*IX+2)=IAST
C
C.....WRITE MATRIX OUTPUT
C
      WRITE(6,1090)
 1090 FORMAT(////,' SITE:',/)
      DO 1110 I=1,NOROWS+1
      WRITE(6,1100)(MATRIX(I,J),J=1,2*NOCOLS+2)
 1100 FORMAT(1X,132A1)
 1110 CONTINUE
      RETURN
      END
```

APPENDIX II

THE FORTRAN IV PROGRAM HSTEST

```
C*************************************************************************
C
C      PROGRAM: HSTEST
C
C      DESCRIPTION: CALCULATES HOPKINS AND SKELLAM'S INDEX OF NONRAN-
C         DOMNESS
C            A=SUMMATION(OMEGA1)/SUMMATION(OMEGA2)
C         WHERE
C            OMEGA1=SQUARED DISTANCE BETWEEN A RANDOMLY CHOSEN POSI-
C               TION AND THE NEAREST POINT
C            OMEGA2=SQUARED DISTANCE BETWEEN A RANDOMLY CHOSEN POINT
C               AND THE NEAREST NEIGHBORING POINT
C
C      REFERENCE:
C         HOPKINS, B. AND J.G. SKELLAM 1954. A METHOD FOR DETERMIN-
C            ING THE TYPE OF DISTRIBUTION OF PLANT INDIVIDUALS. ANN.
C            BOT.LOND. N.S.18: 213-227.
C
C      SPECIAL VARIABLES:
C         NOROWS=WIDTH OF PLOT
C         NOCOLS=LENGTH OF PLOT
C         NOTREE=NUMBER OF POINTS IN PLOT
C         NOSAMP=NUMBER OF SAMPLES IN HOPKINS AND SKELLAM'S INDEX
C            CALCULATION
C         X(I)=X-COORDINATE OF THE I-TH POINT
C         Y(I)=Y-COORDINATE OF THE I-TH POINT
C         OMEGA1=SQUARED DISTANCE BETWEEN A RANDOMLY CHOSEN POSI-
C            TION AND THE NEAREST POINT
C         OMEGA2=SQUARED DISTANCE BETWEEN A RANDOMLY CHOSEN POINT
C            AND THE NEAREST NEIGHBORING POINT
C         A=HOPKINS AND SKELLAM'S INDEX OF NONRANDOMNESS
C
C      SUBPROGRAMS: DISTSQ, PLOT; IFIX, AMOD, SECNDS, ACC, CLOSE,
C         ASSIGN, FLOAT, RAN
C
C      DATE: 20 AUGUST 1976
C
C      AUTHOR: B. HOPKINS AND J.G. SKELLAM
C
C      PROGRAM DESIGNER: H.B. STAUFFER
C
C*************************************************************************
       COMMON /LIST/NOROWS,NOCOLS,NOTREE,X(2000),Y(2000)
       DISTSQ(A,B,C,D)=(A-C)*(A-C)+(B-D)*(B-D)
       N1=IFIX(AMOD(SECNDS(0.),32000.))
       N2=1
C
C.....WRITE INTERACTIVE TERMINAL INFORMATION; READ INPUT
C
       WRITE(5,10)
 10    FORMAT(' THIS PROGRAM CALCULATES HOPKINS AND SKELLAM''S INDEX OF N
      1ONRANDOMNESS.',/,' THE COORDINATES OF THE POINTS WHOSE SPATIAL PAT
      2TERN IS TO BE DETERMINED')
       WRITE(5,20)
 20    FORMAT(' MUST BE INPUT IN ONE OF THE FOLLOWING TWO WAYS:',/,'    1
      1) USING IBM DATA CARDS ON THE CARD READER (INPUT ONE SET OF COORDI
      2-')
```

```
      WRITE(5,30)
 30   FORMAT(' NATES (X,Y) PER CARD WITH FORMAT(2F8.3)), OR',/,'     2) U
     1SING A FORMATTED SEQUENTIAL DATA FILE MAP.DAT;1 (INPUT ONE SET')
      WRITE(5,40)
 40   FORMAT(' OF COORDINATES (X,Y) PER RECORD WITH FORMAT(2F8.3)).')
      WRITE(5,50)
 50   FORMAT(/,' PLOT WIDTH (VERTICAL OR Y-AXIS DISTANCE)=? (INPUT AN IN
     1TEGER <= "9999")',/,'  '$)
      NOROWS=ACC(IER)
      WRITE(5,60)
 60   FORMAT(' PLOT LENGTH (HORIZONTAL OR X-AXIS DISTANCE)=? (INPUT AN I
     1NTEGER <=',/,' "9999") '$)
      NOCOLS=ACC(IER)
      WRITE(5,70)
 70   FORMAT(' NUMBER OF POINTS=? (INPUT AN INTEGER <= "9999"; IF UNKNOW
     1N, INPUT "0")',/,'  '$)
      NOTREE=ACC(IER)
      IF (NOTREE.EQ.0) NOTREE=30000
      WRITE(5,80)
 80   FORMAT(' NUMBER OF SAMPLES=? (INPUT AN INTEGER <= "9999"; RECOMMEN
     1DED VALUE IS',/,' "200") '$)
      NOSAMP=ACC(IER)
      WRITE(5,90)
 90   FORMAT(' DO YOU WANT THE PLOT GRAPHED? (IF THE ANSWER IS "NO", INP
     1UT "0"; IF THE',/,' ANSWER IS "YES", INPUT "1") '$)
      N=ACC(IER)
      WRITE(5,100)
 100  FORMAT(' DO YOU WANT THE POINT LOCATIONS READ FROM THE CARD READER
     1 OR FROM A DATA',/,' FILE? (IF USING THE CARD READER, INPUT "0"; I
     2F USING A DATA FILE, INPUT',/,' "1") '$)
      M=ACC(IER)
      CALL CLOSE(5)
      IF (M.EQ.1) GO TO 110
      CALL ASSIGN(4,'CR:',3)
      GO TO 120
 110  CALL ASSIGN(4,'MAP.DAT;1',9)
 120  READ(4,130,END=140)(X(I),Y(I), I=1,NOTREE)
 130  FORMAT(2F8.3)
      GO TO 150
 140  NOTREE=I-1
C
C.....CALCULATE HOPKINS AND SKELLAM'S INDEX OF NONRANDOMNESS
C
 150  SUM1=0.0
      DO 170 I=1,NOSAMP
      B=FLOAT(NOCOLS)*RAN(N1,N2)
      C=FLOAT(NOROWS)*RAN(N1,N2)
      D=99999.0
      DO 160 J=1,NOTREE
      E=DISTSQ(X(J),Y(J),B,C)
 160  IF (E.LT.D) D=E
 170  SUM1=SUM1+D
      SUM2=0.0
      DO 190 I=1,NOSAMP
      K=IFIX(FLOAT(NOTREE)*RAN(N1,N2))+1
      IF (K.EQ.NOTREE+1) K=NOTREE
      B=X(K)
```

```
      C=Y(K)
      D=99999.0
      DO 180 J=1,NOTREE
      IF (J.EQ.K) GO TO 180
      E=DISTSQ(X(J),Y(J),B,C)
      IF (E.LT.D) D=E
  180 CONTINUE
  190 SUM2=SUM2+D
      A=SUM1/SUM2
C
C.....WRITE OUTPUT
C
      WRITE(6,200)
  200 FORMAT(//,45X,'HOPKINS AND SKELLAM''S INDEX OF NONRANDOMNESS',/,45
     1X,'******** *** ********** ***** ** **************')
      WRITE(6,210)
  210 FORMAT(////,' DESCRIPTION: THIS PROGRAM CALCULATES HOPKINS AND SKE
     1LLAM''S INDEX OF NONRANDOMNESS')
      WRITE(6,220)
  220 FORMAT('        A=SUMMATION(OMEGA1)/SUMMATION(OMEGA2)')
      WRITE(6,230)
  230 FORMAT('    WHERE')
      WRITE(6,240)
  240 FORMAT('        OMEGA1=SQUARED DISTANCE BETWEEN A RANDOMLY CHOSEN P
     1OSITION AND THE NEAREST POINT')
      WRITE(6,250)
  250 FORMAT('        OMEGA2=SQUARED DISTANCE BETWEEN A RANDOMLY CHOSEN P
     1OINT AND THE NEAREST NEIGHBORING POINT')
      WRITE(6,260)
  260 FORMAT(/,' REFERENCE:')
      WRITE(6,270)
  270 FORMAT('    HOPKINS, B. AND J.G. SKELLAM 1954. A METHOD FOR DETERM
     1INING THE TYPE OF DISTRIBUTION OF PLANT INDIVIDUALS. ANN.BOT.LOND.
     2 N.S.')
      WRITE(6,280)
  280 FORMAT('        18: 213-227')
      WRITE(6,290)
  290 FORMAT(/,' AUTHOR: B. HOPKINS AND J.G. SKELLAM')
      WRITE(6,300)
  300 FORMAT(/,' PROGRAM DESIGNER: H.B. STAUFFER')
      IF (N.EQ.1.AND.NOROWS.LE.65.AND.NOCOLS.LE.65) CALL PLOT
      WRITE(6,310) NOROWS,NOCOLS,NOTREE,NOSAMP,A
  310 FORMAT(//,16X,'PLOT WIDTH=',I4,5X,'PLOT LENGTH=',I4,5X,'NUMBER OF
     1POINTS=',I4,5X,'NUMBER OF SAMPLES=',I4,5X,'A=',F6.3)
      STOP
      END
C*******************************************************************************
C
C     SUBPROGRAM: PLOT
C
C     DESCRIPTION: PLOTS THE SITE
C
C*******************************************************************************
      SUBROUTINE PLOT
      COMMON /LIST/NOROWS,NOCOLS,NOTREE,X(2000),Y(2000)
      DIMENSION MATRIX(66,132),IA(7)
      DATA IBLANK,IPOINT,IAST/' ','.','*'/
```

```
      DATA IA/'0','1','2','3','4','5','6'/
C
C.....FILL A MATRIX TO REPRESENT THE PLOTTED SITE
C
      DO 1010 I=1,NOROWS+1
      DO 1010 J=1,2*NOCOLS+2
 1010 MATRIX(I,J)=IBLANK
      DO 1020 I=1,NOROWS+1,NOROWS
      DO 1020 J=2,2*NOCOLS+2,2
 1020 MATRIX(I,J)=IPOINT
      DO 1030 J=2,2*NOCOLS+2,2*NOCOLS
      DO 1030 I=1,NOROWS+1
 1030 MATRIX(I,J)=IPOINT
      DO 1040 J=22,2*NOCOLS-1,20
      MATRIX(1,J)=IA(J/20+1)
 1040 MATRIX(NOROWS+1,J)=IA(J/20+1)
      DO 1050 J=23,2*NOCOLS,20
      MATRIX(1,J)=IA(1)
 1050 MATRIX(NOROWS+1,J)=IA(1)
      DO 1060 I=11,NOROWS-2,10
      MATRIX(I,1)=IA(I/10+1)
 1060 MATRIX(I,2*NOCOLS+1)=IA(I/10+1)
      DO 1070 I=11,NOROWS-2,10
      MATRIX(1,2)=IA(1)
 1070 MATRIX(I,2*NOCOLS+2)=IA(1)
      DO 1080 I=1,NOTREE
      IX=IFIX(X(I)+.5)
      IY=IFIX(Y(I)+.5)
 1080 MATRIX(IY+1,2*IX+2)=IAST
C
C.....WRITE MATRIX OUTPUT
C
      WRITE(6,1090)
 1090 FORMAT(////,' SITE:',/)
      DO 1110 I=1,NOROWS+1
      WRITE(6,1100)(MATRIX(I,J),J=1,2*NOCOLS+2)
 1100 FORMAT(1X,132A1)
 1110 CONTINUE
      RETURN
      END
```

APPENDIX III:

THE FORTRAN IV PROGRAM CETEST

```
C*************************************************************************
C
C     PROGRAM: CETEST
C
C     DESCRIPTION: CALCULATES CLARK AND EVANS' INDEX OF NONRAN-
C        DOMNESS
C           R=2.0-2.0*SQRT(RHO)*RBAR
C        WHERE
C           RHO=POINT DENSITY PER UNIT AREA
C           RBAR=AVERAGE DISTANCE BETWEEN A RANDOMLY CHOSEN POINT
C              AND THE NEAREST NEIGHBORING POINT
C
C     REFERENCE:
C        CLARK, P.J. AND F.C. EVANS 1954, DISTANCE TO NEAREST
C           NEIGHBOR AS A MEASURE OF SPATIAL RELATIONSHIPS IN
C           POPULATIONS, ECOLOGY 35: 445-453
C
C     VARIABLES:
C        NOROWS=WIDTH OF PLOT
C        NOCOLS=LENGTH OF PLOT
C        NOTREE=NUMBER OF POINTS IN PLOT
C        NOSAMP=NUMBER OF SAMPLES IN CLARK AND EVANS' INDEX
C           CALCULATION
C        X(I)=X-COORDINATE OF THE I-TH POINT
C        Y(I)=Y-COORDINATE OF THE I-TH POINT
C        RHO=POINT DENSITY PER UNIT AREA
C        RBAR=AVERAGE DISTANCE BETWEEN A RANDOMLY CHOSEN POINT
C           AND THE NEAREST NEIGHBORING POINT
C        R=CLARK AND EVANS' INDEX OF NONRANDOMNESS
C
C     SUBPROGRAMS: DISTSQ, PLOT; IFIX, AMOD, SECNDS, ACC, CLOSE,
C        ASSIGN, FLOAT, RAN
C
C     DATE: 20 AUGUST 1976
C
C     AUTHOR: P.J. CLARK AND F.C. EVANS
C
C     PROGRAM DESIGNER: H.B. STAUFFER
C
C*************************************************************************
      COMMON /LIST/NOROWS,NOCOLS,NOTREE,X(2000),Y(2000)
      DISTSQ(A,B,C,D)=(A-C)*(A-C)+(B-D)*(B-D)
      N1=IFIX(AMOD(SECNDS(0.),32000.))
      N2=1
C
C.....WRITE INTERACTIVE TERMINAL INFORMATION; READ INPUT
C
      WRITE(5,10)
 10   FORMAT(' THIS PROGRAM CALCULATES CLARK AND EVANS'' INDEX OF NONRAN
     1DOMNESS. THE',/,' COORDINATES OF THE POINTS WHOSE SPATIAL PATTERN
     2IS TO BE DETERMINED MUST')
      WRITE(5,20)
 20   FORMAT(' BE INPUT IN ONE OF THE FOLLOWING TWO WAYS:',/,'     1) USI
     1NG IBM DATA CARDS ON THE CARD READER (INPUT ONE SET OF COORDI-')
      WRITE(5,30)
 30   FORMAT(' NATES (X,Y) PER CARD WITH FORMAT(2F8.3)), OR',/,'     2) U
     1SING FORMATTED SEQUENTIAL DATA FILE MAP.DAT;1 (INPUT ONE SET OF')
```

```
      WRITE(5,40)
 40   FORMAT(' COORDINATES (X,Y) PER RECORD WITH FORMAT(2F8.3)).')
      WRITE(5,50)
 50   FORMAT(/,' PLOT WIDTH (VERTICAL OR Y-AXIS DISTANCE)=? (INPUT AN IN
     1TEGER <= "9999")',/,'  '$)
      NOROWS=ACC(IER)
      WRITE(5,60)
 60   FORMAT(' PLOT LENGTH (HORIZONTAL OR X-AXIS DISTANCE)=? (INPUT AN I
     1NTEGER <=',/,' "9999") '$)
      NOCOLS=ACC(IER)
      WRITE(5,70)
 70   FORMAT(' NUMBER OF POINTS=? (INPUT AN INTEGER <= "9999"; IF UNKNOW
     1N, INPUT "0")',/,'  '$)
      NOTREE=ACC(IER)
      IF (NOTREE.EQ.0) NOTREE=30000
      WRITE(5,80)
 80   FORMAT(' NUMBER OF SAMPLES=? (INPUT AN INTEGER <= "9999"; RECOMMEN
     1DED VALUE IS',/,' "200") '$)
      NOSAMP=ACC(IER)
      WRITE(5,90)
 90   FORMAT(' DO YOU WANT THE PLOT GRAPHED? (IF THE ANSWER IS "NO", INP
     1UT "0"; IF THE',/,' ANSWER IS "YES", INPUT "1") '$)
      N=ACC(IER)
      WRITE(5,100)
 100  FORMAT(' DO YOU WANT THE POINT LOCATIONS READ FROM THE CARD READER
     1 OR FROM A DATA',/,' FILE? (IF USING THE CARD READER, INPUT "0"; I
     2F USING A DATA FILE, INPUT',/,' "1") '$)
      M=ACC(IER)
      CALL CLOSE(5)
      IF (M.EQ.1) GO TO 110
      CALL ASSIGN(4,'CR:',3)
      GO TO 120
 110  CALL ASSIGN(4,'MAP.DAT;1',9)
 120  READ(4,130,END=140)(X(I),Y(I), I=1,NOTREE)
 130  FORMAT(2F6.3)
      GO TO 150
 140  NOTREE=I-1
C
C.....CALCULATE CLARK AND EVANS' INDEX OF NONRANDOMNESS
C
 150  RHO=FLOAT(NOTREE)/FLOAT(NOROWS*NOROWS)
      SUM=0.0
      DO 170 I=1,NOSAMP
      K=IFIX(FLOAT(NOTREE)*RAN(N1,N2))+1
      IF (K.EQ.NOTREE+1) K=NOTREE
      B=X(K)
      C=Y(K)
      D=99999.0
      DO 160 J=1,NOTREE
      IF (J.EQ.K) GO TO 160
      E=DISTSQ(X(J),Y(J),B,C)
      IF (E.LT.D) D=E
 160  CONTINUE
 170  SUM=SUM+SQRT(D)
      RBAR=SUM/FLOAT(NOSAMP)
      R=2.0-2.0*SQRT(RHO)*RBAR
C
```

```
C.....WRITE OUTPUT
C
      WRITE(6,180)
 180  FORMAT(//,47X,'CLARK AND EVANS'' INDEX OF NONRANDOMNESS',/,47X,'**
     1*** *** ****** ***** ** **************')
      WRITE(6,190)
 190  FORMAT(////,' DESCRIPTION: THIS PROGRAM CALCULATES CLARK AND EVANS
     1'' INDEX OF NONRANDOMNESS')
      WRITE(6,200)
 200  FORMAT('        R=2.0-2.0*SQRT(RHO)*RBAR')
      WRITE(6,210)
 210  FORMAT('     WHERE')
      WRITE(6,220)
 220  FORMAT('        RHO=POINT DENSITY PER UNIT AREA')
      WRITE(6,230)
 230  FORMAT('        RBAR=AVERAGE DISTANCE BETWEEN A RANDOMLY CHOSEN POI
     1NT AND THE NEAREST NEIGHBORING POINT')
      WRITE(6,240)
 240  FORMAT(/,' REFERENCE:')
      WRITE(6,250)
 250  FORMAT('     CLARK, P.J. AND F.C. EVANS 1954. DISTANCE TO NEAREST N
     1EIGHBOR AS A MEASURE OF SPATIAL RELATIONSHIPS IN POPULATIONS. ECOL
     2OGY')
      WRITE(6,260)
 260  FORMAT('        35: 445-453.')
      WRITE(6,270)
 270  FORMAT(/,' AUTHOR: P.J. CLARK AND F.C. EVANS')
      WRITE(6,280)
 280  FORMAT(/,' PROGRAM DESIGNER: H.B. STAUFFER')
      IF (N.EQ.1.AND.NOROWS.LE.65.AND.NOCOLS.LE.65) CALL PLOT
      WRITE(6,290) NOROWS,NOCOLS,NOTREE,NOSAMP,R
 290  FORMAT(//,16X,'PLOT WIDTH=',I4,5X,'PLOT LENGTH=',I4,5X,'NUMBER OF
     1POINTS=',I4,5X,'NUMBER OF SAMPLES=',I4,5X,'R=',F6.3)
      STOP
      END
C*******************************************************************************
C
C     SUBPROGRAM: PLOT
C
C     DESCRIPTION: PLOTS THE SITE
C
C*******************************************************************************
      SUBROUTINE PLOT
      COMMON /LIST/NOROWS,NOCOLS,NOTREE,X(2000),Y(2000)
      DIMENSION MATRIX(66,132),IA(7)
      DATA IBLANK,IPOINT,IAST/' ','.','*'/
      DATA IA/'0','1','2','3','4','5','6'/
C
C.....FILL A MATRIX TO REPRESENT THE PLOTTED SITE
C
      DO 1010 I=1,NOROWS+1
      DO 1010 J=1,2*NOCOLS+2
 1010 MATRIX(I,J)=IBLANK
      DO 1020 I=1,NOROWS+1,NOROWS
      DO 1020 J=2,2*NOCOLS+2,2
 1020 MATRIX(I,J)=IPOINT
      DO 1030 J=2,2*NOCOLS+2,2*NOCOLS
```

```
      DO 1050 I=1,NOROWS+1
 1030 MATRIX(I,J)=IPOINT
      DO 1040 J=22,2*NOCOLS-1,20
      MATRIX(1,J)=IA(J/20+1)
 1040 MATRIX(NOROWS+1,J)=IA(J/20+1)
      DO 1050 J=23,2*NOCOLS,20
      MATRIX(1,J)=IA(1)
 1050 MATRIX(NOROWS+1,J)=IA(1)
      DO 1060 I=11,NOROWS-2,10
      MATRIX(I,1)=IA(I/10+1)
 1060 MATRIX(I,2*NOCOLS+1)=IA(I/10+1)
      DO 1070 I=11,NOROWS-2,10
      MATRIX(I,2)=IA(1)
 1070 MATRIX(I,2*NOCOLS+2)=IA(1)
      DO 1080 I=1,NOTREE
      IX=IFIX(X(I)+.5)
      IY=IFIX(Y(I)+.5)
 1080 MATRIX(IY+1,2*IX+2)=IAST
C
C.....WRITE MATRIX OUTPUT
C
      WRITE(6,1090)
 1090 FORMAT(////,' SITE:',/)
      DO 1110 I=1,NOROWS+1
      WRITE(6,1100)(MATRIX(I,J),J=1,2*NOCOLS+2)
 1100 FORMAT(1X,132A1)
 1110 CONTINUE
      RETURN
      END
```

APPENDIX IV:

EXAMPLES OF SPATIAL PATTERNS AND THEIR CALCULATED INDEX VALUES

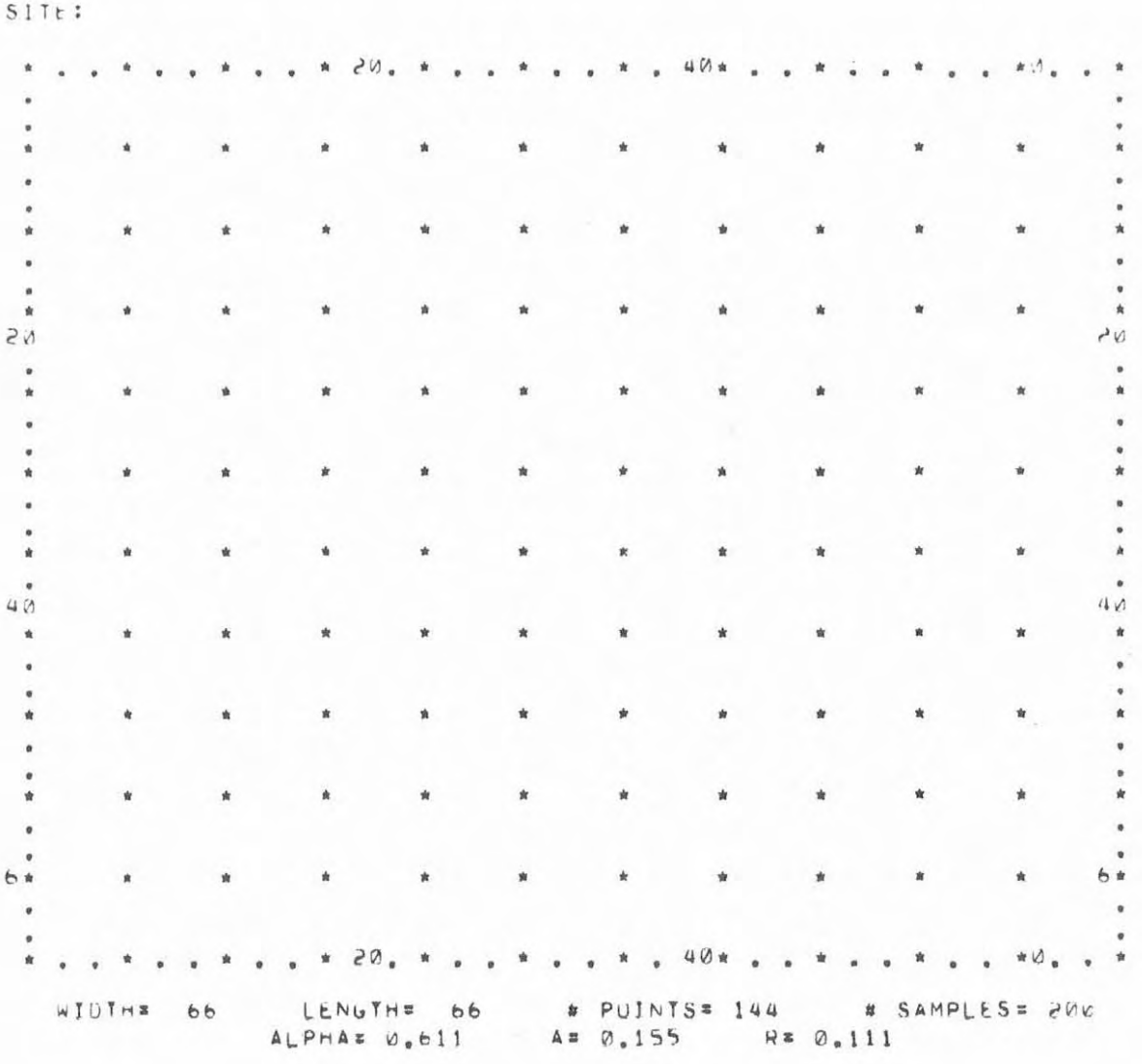

Figure 1. Calculated index values for simulated regular distribution.

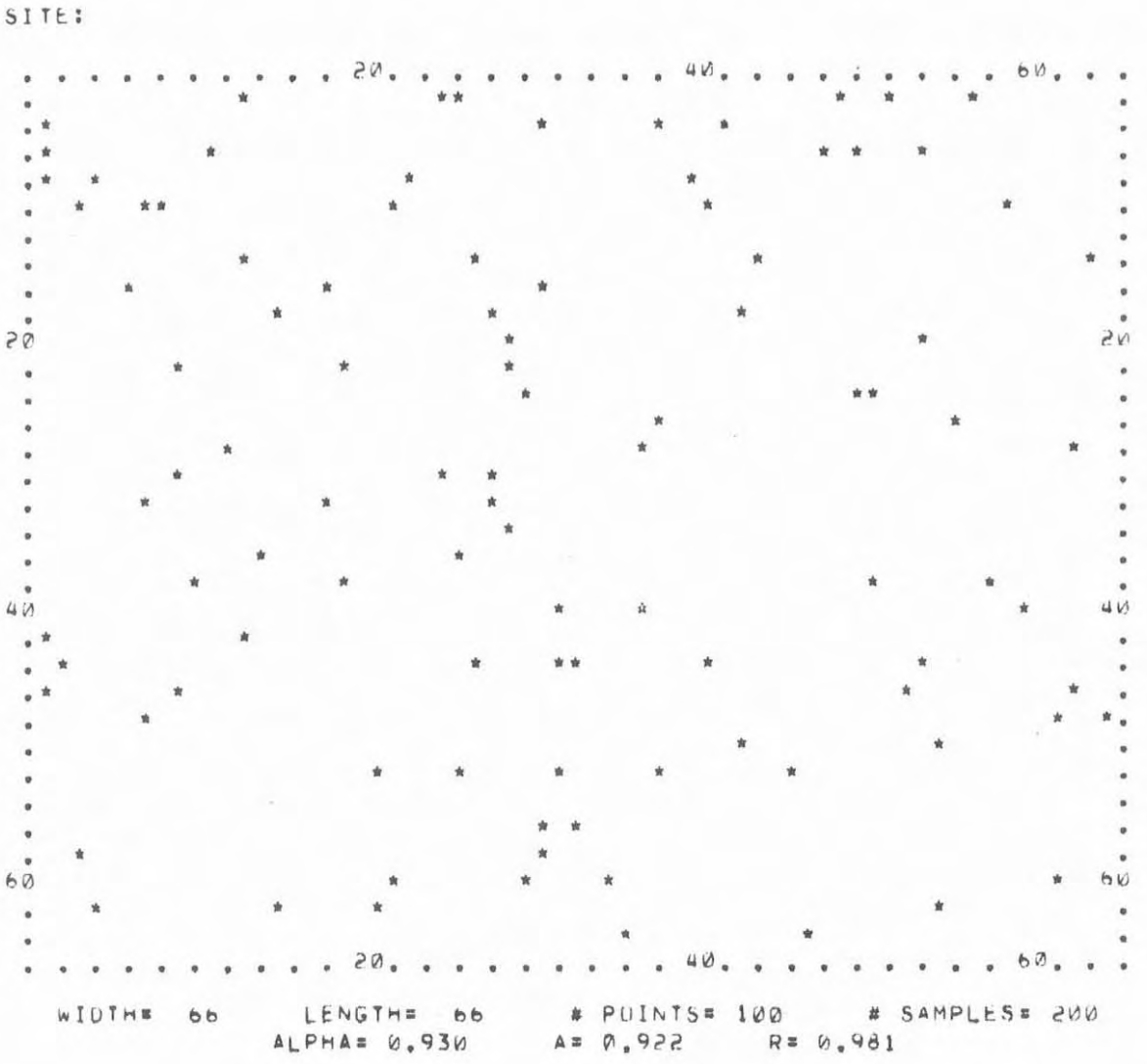

Figure 2. Calculated index values for simulated random distribution.

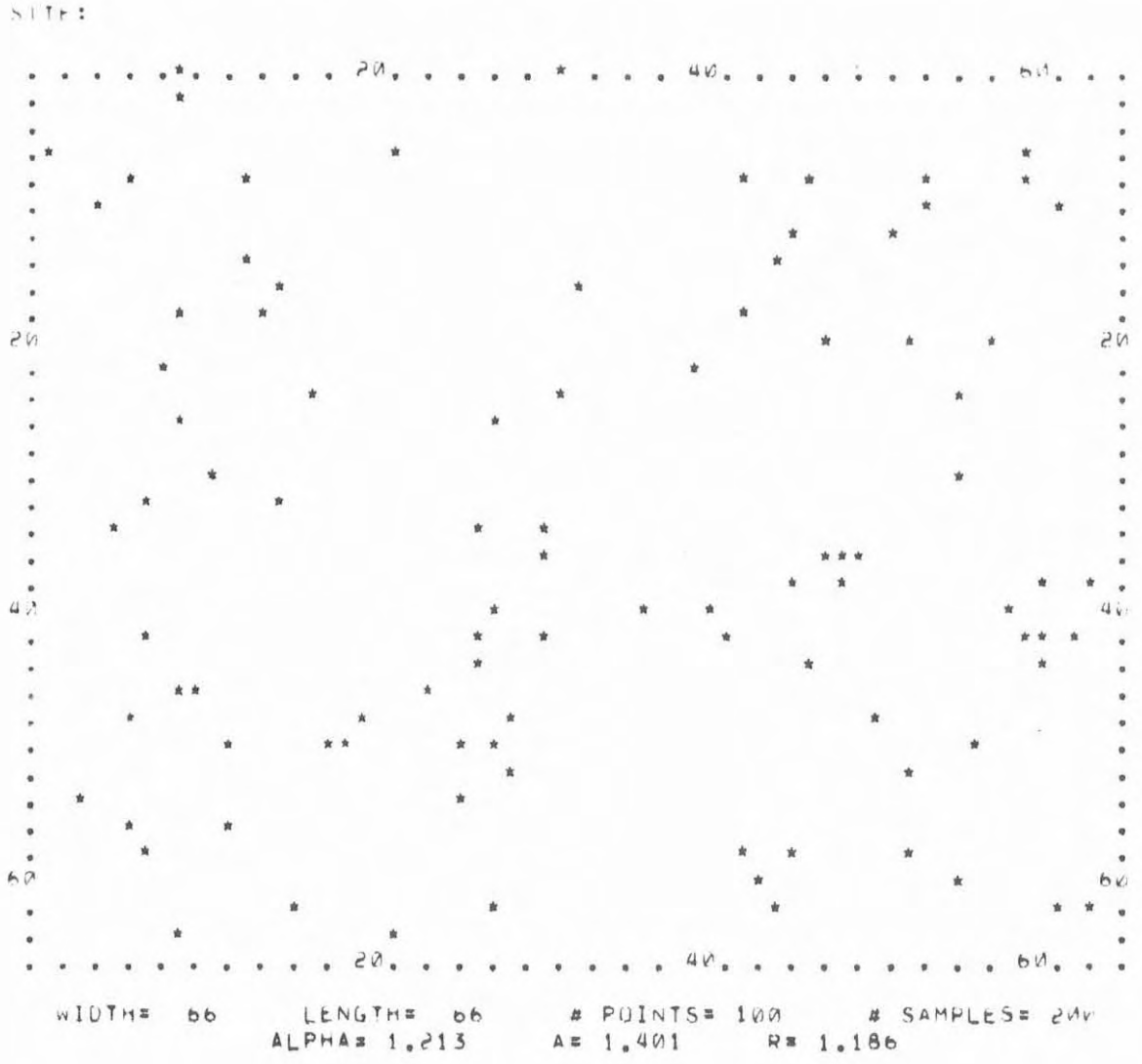

Figure 3. Calculated index values for simulated aggregated distribution.

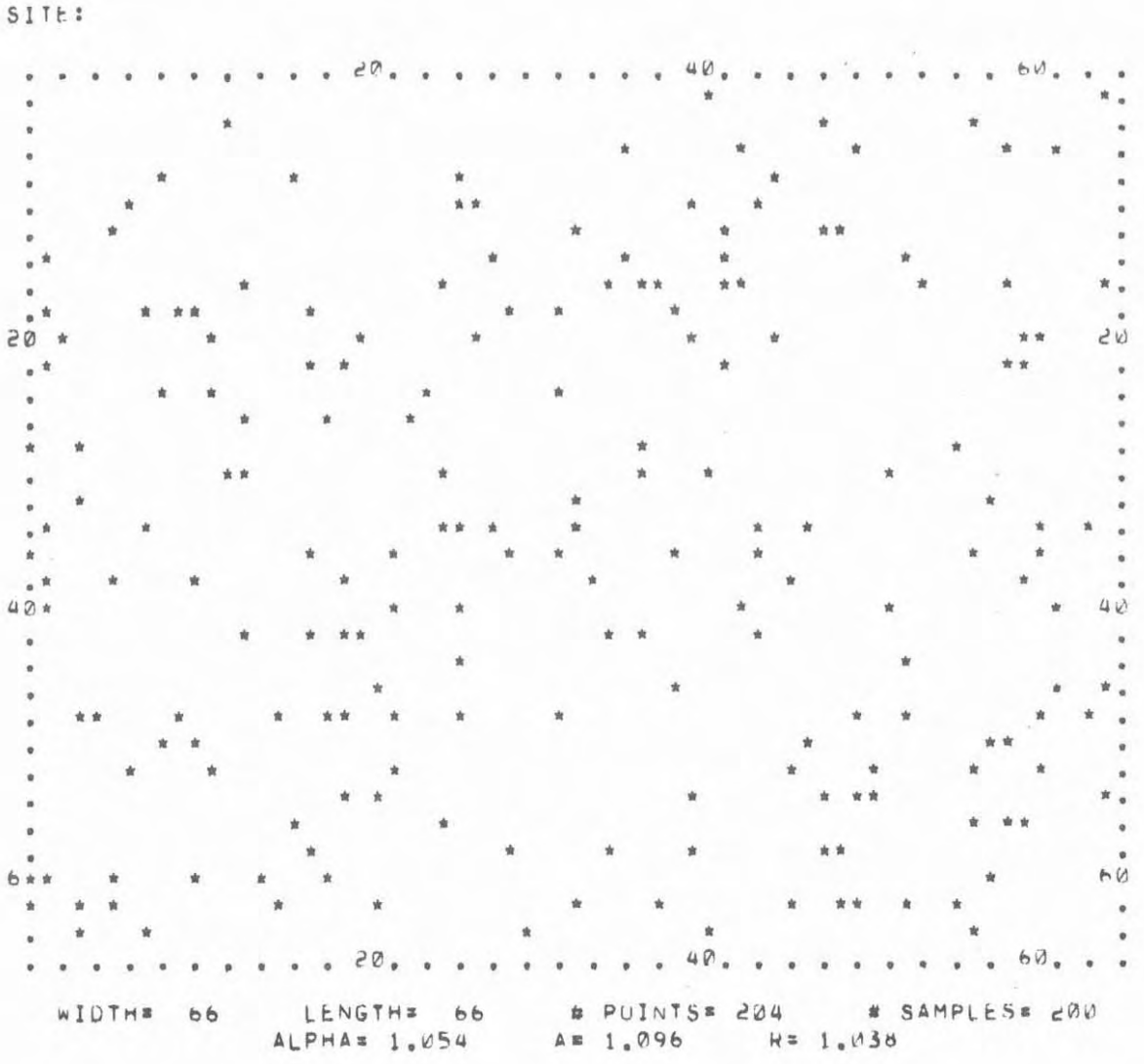

Figure 4. Calculated index values for Shawnigan Lake plot No. 6.

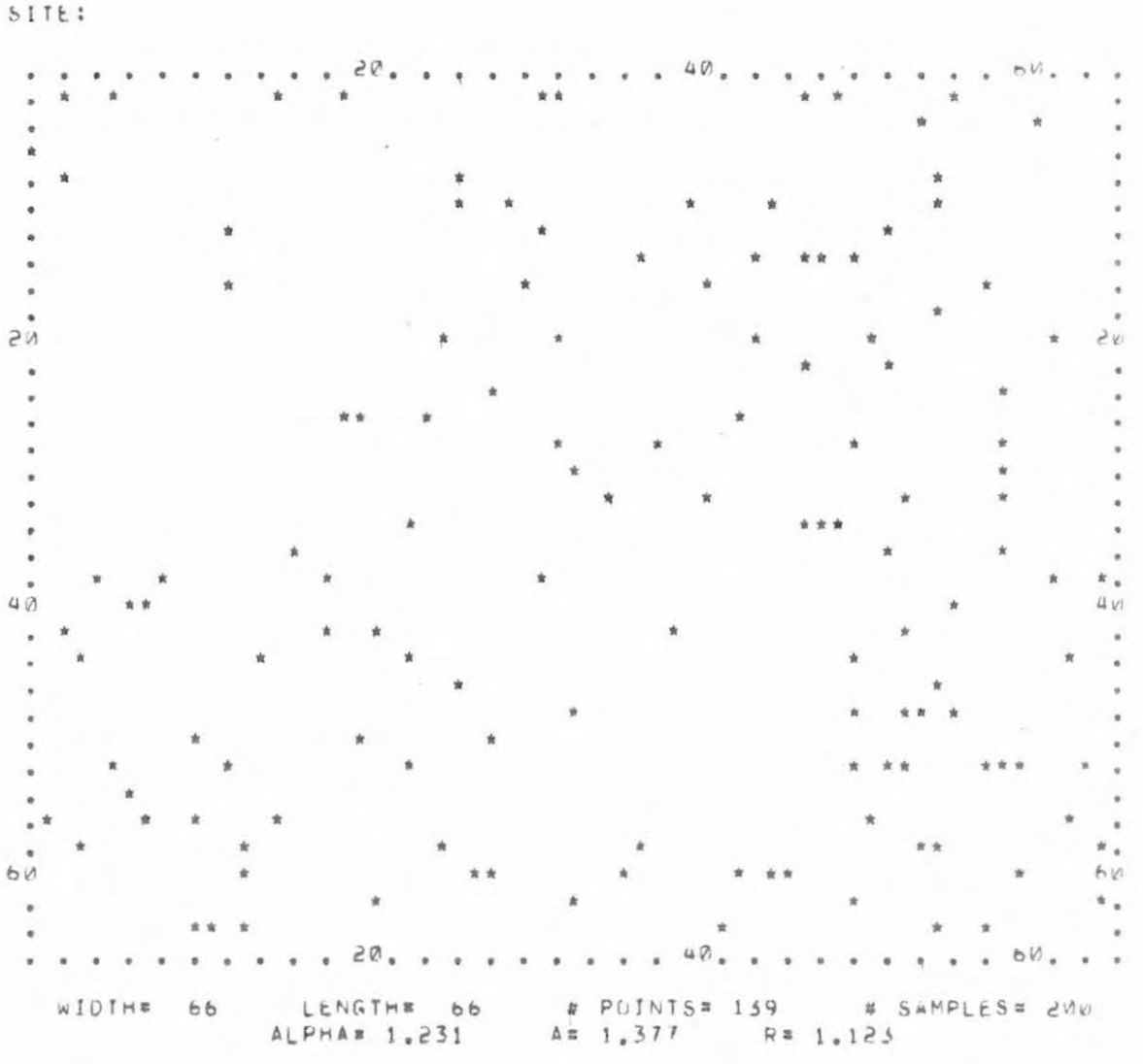

Figure 5. Calculated index values for Shawnigan Lake plot No. 9.

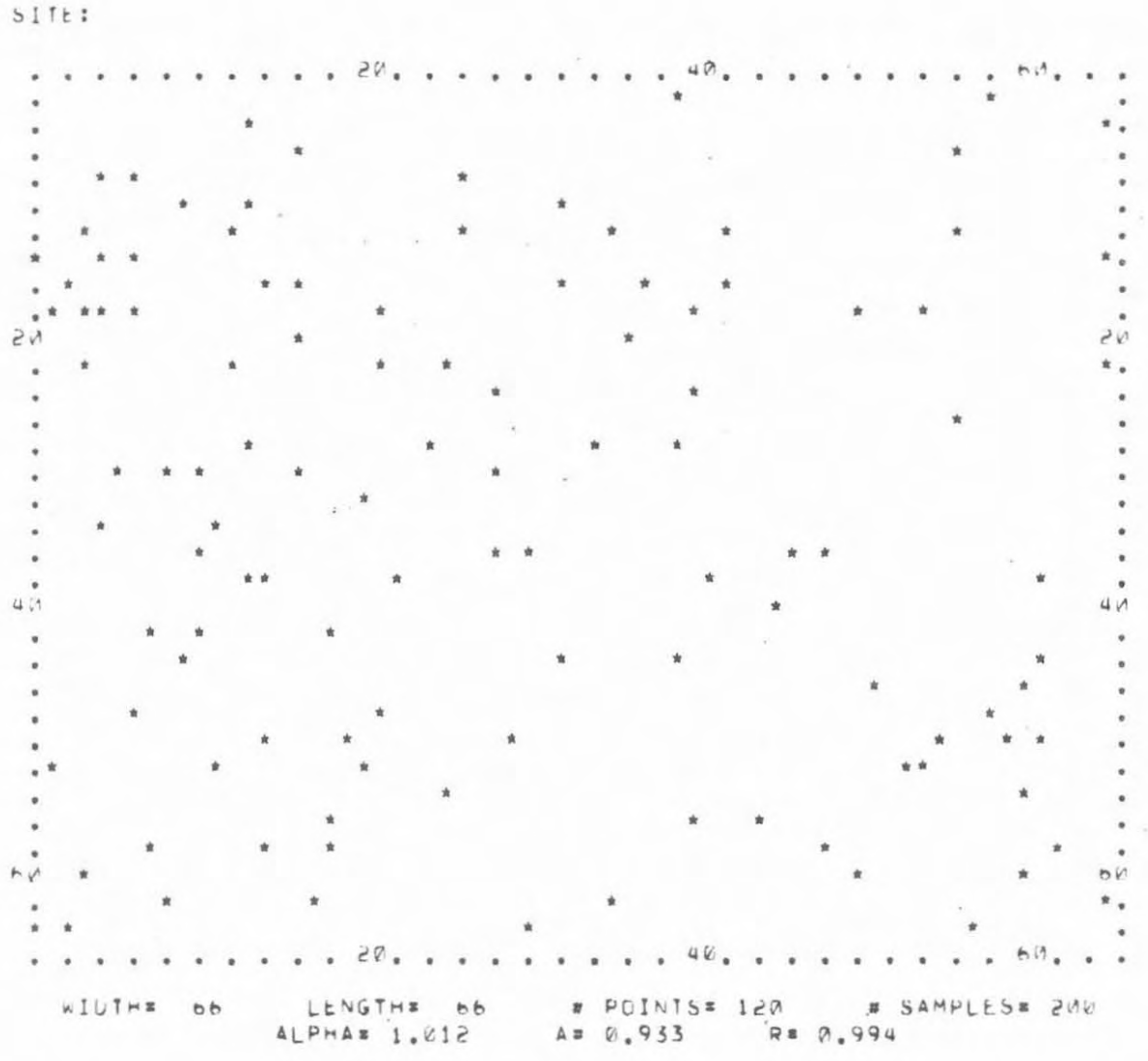

Figure 6. Calculated index values for Shawnigan Lake plot No. 18.