A COMPARISON OF DISTANCE SAMPLING METHODS IN SAXAUL (HALLOXYLON AMMODENDRON C.A. MEY BUNG E) SHRUB-LANDS

ABSTRACT: The primarily goal of plot-less sampling methods is to reduce costs and rapid survey of plant communities. First full inventory was conducted in two 30-ha sites of Saxaul populations geo-morphologically different. In first site (site I), population had random pattern while in second site (site II) clumped pattern was observed. Crown diameters and spatial situation of all trees were recorded using distance and azimuth. Data were transferred to computer and stem map was generated with ArcGIS Software. Distance sampling methods include point-centred quarter method (PCQ), joint-point method (JP), Random pairs method (RP), T-Square method (T-Sq) and Quartered neighbour methods beside fixed area plot (FAP), n-tree and variable area transect (VAT) methods were conducted on generated stem maps. A time study was done aiding indices determined in field works. In site I, point centred quarter estimator with measurements to the second closest individual in each quadrant had the lowest relative bias (RBIAS) in estimating density followed by 3-tree and closest individual methods. In clumped pattern (site II), variable area transect method with measurements to the 4th and 5th closest individuals in each transect brought the best results. The most time consuming methods after fixed area plot, were point centred quarter estimators while methods considering measurement to the closest individual were rapid. Considering RBIAS and Time together, VAT method was the best sampling method in clumped pattern followed by point centred quarter estimator with measurements to the second closest individual in each quadrant and closest individual estimators. In random pattern, point centred quarter estimator with measurements to the second closest individual in each quadrant was the best method followed by 3-tree and closest individual estimators. But for estimating cover per unit area N-tree methods performed well. As in this site, VAT method located in 4th grade, and due to simplicity of field works related to this method, in the case that the investigator would not be able to clearly define spatial pattern of the population, this method can be recommended as well.

KEY WORDS: accuracy, density, inventory, percent cover, plot-less methods, time study

1. INTRODUCTION

Quantitative data are essential to characterize plant communities. Some form of sampling is required because total counts of individuals in plant populations are generally impractical and need plenty of energy and resources (Sparks et al. 2002, Xunzhi and Jintun 2009). In sampling vegetations, minimum effort and time is our major concern (Cottam and Curtis 1954). There are two
main sampling methods: plot-based methods and plot-less methods. In plot-based methods there is a plot with defined shape and area, all plants are measured within plot. But in plot-less methods we measure distances, either from a random point to $g^{th}$ nearest individual or from an individual to its nearest neighbour (Picard and Bar-Hen 2007).

Plot-less methods could be assumed as quadrates in the form of a line or a point with no dimension (Barbour et al. 1987). The advantages of plot-less sampling are: 1) saving time; because we don’t need to establish a sample plot; 2) minimize subjective error; because we don’t need to control trees in the sample plot boundaries (Cox 1990).

Distance sampling (plot-less sampling) has a long history in forest inventories. In forest inventories, the distance and attributes of interest are measured on the k-trees closest to a sample point (Magnussen et al. 2008). When quadrat sampling is difficult or too costly (e.g. in low dense populations or mountain areas) distance sampling is favoured (Sheil et al. 2003, Picard et al. 2005). Distance methods measure different distances between plants. The results of this technique can provide important information about inter-species and intra-species relationships in plant communities. Distance methods can help determine spatial pattern of plants (e.g. random, clustered or dispersed) are ecologically important. Without distance sampling methods, it is difficult to determine inter and intra-specific relationships in plant communities (Barbour et al. 1987).

If the density is low, it is impractical to search beyond a certain distance for the nearest individual especially in some desert vegetations. The distance methods were developed as an alternative to quadrat (plot) methods for estimating population density and cover. Distance methods do not require laying out quadrat in the field, thus are less labour intensive comparing with quadrat sampling. Many methods have been developed to estimate density using distance measures; here we present most estimators. All these methods are essentially based on the distance measures from event-to-event or from point-to-event.

A variety of estimators have been proposed to estimate density in different spatial patterns (e.g., Cottam 1947, Morisita 1957, Pollard 1971, Batcheler 1975, Diggle 1975, Lewis 1975, Parker 1979, etc.). Attempts also have been made to modify these estimators to improve their robustness specially when nonrandom spatial patterns are assumed (e.g. Diggle 1975, Engeman and Sugihara 1998, Klein and Vilkco 2006, Kiani et al. 2011). However, little comparative information is available in the literature where a large group of estimators are as-

Fig. 1. Location of study area: Sites I and II.
sessed. In this paper we examine, the relative bias and needed time of many plot-less density estimators (PDEs) in two fully enumerated datasets. Our aim is to produce a thorough study of a variety of PDEs to see which perform well over *Haloxylon ammodendron* populations.

2. STUDY AREA

Two 30-ha rectangular sites were selected in March 2010 in *Haloxylon ammodendron* shrub-lands each 500 × 600 meters dimensions. These sites were located in Siahkooh protected area (53°42'N, 32°32'E), about 70 km north of Ardakan, Iran (Fig. 1). Here, *Haloxylon ammodendron* makes about 4200 hectares area shrub-land (Iran-nejad Parizi et al. 2006). Site I was located in the edge of Siahkooh playa and was completely flat with sandy soil while site II was located in mountainside and was sloped with gravel soil. *Haloxylon ammodendron* is a xerophytes desert tree and due to its great drought resistance and saline tolerance occurs naturally in various habitats in Asian and African deserts. As a dominant desert plant, *H. ammodendron* plays an important role in the structure and function of the whole ecosystem, reducing wind speed and ameliorating the forest microclimate, thus facilitating the settlement and growth of other desert plants (Sheng et al. 2005). This species grows in all central and south-eastern deserts of Iran (Sabeti 1994).

3. STUDY DESIGN

Each site divided to about 111 square quadrates each 30 × 30 meters dimensions. In each quadrant distance to southwest corner of quadrat, azimuth and crown diameters were measured and recorded so that all shrubs were measured, identified and mapped. Data entered in Microsoft Excel and then imported to Arc GIS 9.3 software. Stem maps of plants were generated (Fig. 2) and spatial pattern of plants determined using nearest neighbour index in Arc Map software. Finally real density and cover per hectare were computed to be used in comparisons and to calculate relative bias of estimators.

All sampling methods were conducted in computer using ArcGIS capabilities. Measuring distances and crown diameters in each method was done via 'Information' and 'Measure' tools. Data were recorded and density and cover per hectare were calculated and compared to real values, resulted from full enumerating. To assess the efficiency of each method, a time study was conducted. First the sampling process of the method was divided into some steps. For example movement between random points, finding nearest individual, measuring crown diameters, recording diameters, etc.

We measured average time needed for one meter movement in the field (0.87 s m⁻¹). We also calculated the needed time to measuring one meter crown diameter (1.8 s m⁻¹), movement between trees (1.31 s m⁻¹) and recording diameters (2s per tree) with chronometer. Then in ArcGIS environment, moved distances and crown diameters were measured and multiplied with the indices to calculate the time needed for each step. The sum of these times is the total time needed to conduct each method.

4. METHODS

We consider 40 methods for estimating density but we provide only brief descriptions and references. We also propose a modification for point centred quarter method. We attempt to group estimators into subsections based on the use of similar measurement methods. The formulas and references relating to the estimators used in this study are as follow:

**closest Individual methods (NI)**

These distance methods involve measure distance from randomly placed sample points to the closest individual in the population (point-to-individual) and include:

\[
λ_1 = \frac{1}{4\int \left( \sum r_i/n \right)^2} \quad (1)
\]

\[
λ_2 = \frac{n}{\pi \sum r_i^2} \quad (2)
\]

where: \( \lambda \) is estimated density, \( r \) is distance between random point and closest individual, \( r^2 \) is squared \( r \) and \( n \) is sample size. To calculate cover per hectare, average crown area of the measured trees was multiplied in estimated density. This technique was used for other plot-less sampling methods.
Nearest Neighbour methods (NN and 2NN)

These methods involve two measurements: from random points to the closest individual in the population and from closest individuals to their nearest neighbour. An additional measurement is made from the nearest neighbour to its nearest neighbour (second nearest neighbour or 2NN). They include:

\[ \lambda_3 = \frac{1}{2.778 \left( \sum z_i^2 / n \right)^2} \] (3)

\[ \lambda_4 = \frac{n}{\pi \sum z_i^2} \] (4)

\[ \lambda_5 = \frac{1}{2.778 \left( \sum m_i / n \right)^2} \] (5)

where: \( \lambda \) is estimated density, \( z_i \) is distance between closest individual and its nearest neighbour, \( z_i^2 \) is squared \( z_i \), \( m_i \) is distance between nearest neighbour and second nearest neighbour and \( n \) is sample size.

Compound methods (COMP)

Diggle (1975) and Engeman and Sugihara (1998) discuss the use of compound estimators that are simply a mean of NI and NN methods. They include:

\[ \lambda_6 = \frac{\lambda_1 + \lambda_3}{2} \] (6)

\[ \lambda_7 = \frac{\lambda_1 + \lambda_3 + \lambda_5}{3} \] (7)

Ordered Distance methods (OD)

The method involves measuring the distance from the random sampling point to the \( g \)-th closest individual (hence the ordering). Pollard (1971) demonstrated that, for the random spatial pattern, as \( g \) increases, the variance of the density estimate decreases. However, he also indicated that using \( g > 3 \) may be impractical in the field. We therefore consider \( g = 1, 2 \) and 3. Estimators include:

\[ \lambda_g = \frac{(n - 1)}{\pi \sum r_i^2} \] (8)

\[ \lambda_g = \frac{(2n - 1)}{\pi \sum r_{i2}^2} \] (9)

\[ \lambda_g = \frac{(3n - 1)}{\pi \sum r_{i3}^2} \] (10)

Where: \( r_i \) is distance between random point and closest individual, \( r_{i2} \) is distance from random point to second closest individual, \( r_{i3} \) is distance from random point to third closest individual and \( n \) is sample size.

Joint-Point method (JP)

This method proposed and advanced by Batcheler in 1971 and 1975. An estimate of density is made by using the measurements on the distance to the closest individual, the distance to the nearest neighbour and the second nearest neighbour. Application of the correction factors involves a series of calculations.

\[ f = P / N \] (11)
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Log E(CV) = -1.0319 + 0.4892 \hat{f} - 0.7182 \hat{f}^4 + 0.6095 \hat{f}^6 
(12)

d = p / [ \sum r_i^2 + (n-p) R^2 ]
(13)

A1 = 1/ E(CV) [\sqrt{((p \sum r_i^2 - (\sum r_i)^2) n2 N)} / (\sum r_i \sum z_i p_j)]
(14)

A2 = 1/ E(CV) [\sqrt{((p \sum r_i^2 - (\sum r_i)^2) n2 N)} / (\sum r_i \sum m_i p_j)]
(15)

a = 1 + 2.473 \hat{f}
(16)

b = 1 + 2.717 \hat{f}
(17)

\lambda_{11} = (d/2a) [b A1 + b A2]
(18)

where: \( p \) is number of sample points included a measured tree, \( N \) is total sample points, \( f \) is a ratio, \( r \) is distance between random point to closest individual, \( z \) is distance between closest individual and it's nearest neighbour, \( m \) is distance between nearest neighbour and second nearest neighbour, \( n \) is sample size and \( \lambda \) is estimated density.

**Point Centred Quarter methods (PCQ)**

This is an old method applied in ecological sampling. First the area around the random point is divided into four quarters. Then the distance to the closest individual in each quarter is measured. Cottam et al. (1953) presented an empirical development of the method and Morisita (1954) provided theoretical development. Morisita (1957) later derived the angle order sampling method where the area around the random sampling point is divided into \( k \) equiangular sectors and the distance to the \( g \)th closest individual in each sector is measured.

The angle-order method presumes to overcome the problem of non-randomly distributed individuals by assuming that the area can be divided into fractions where the individuals are arranged randomly (Engeman et al. 1994). See Mitchell (2007) for more information about this method.

**In Quartered Neighbours method (PCQ-N)** proposed by Xunzhi and Jintun (2009), the area around each sampling point is divided into four quadrants. Then the distance from the closest individual in each quadrant to its nearest neighbour is measured in the same quadrant (\( a_1, a_2, a_3, \) and \( a_4 \)). The average of them is calculated as

\[ a = (a_1 + a_2 + a_3 + a_4) / 4 \]

Tree density could be estimated using the following function:

\[ \lambda = 1/a^2 \]
(19)

where: \( \lambda \) is the population density.

In our proposed method (PCQN), the area around each sampling point is divided into four quadrants. Closest individual in all quadrants is found. Then distances between these plants are measured and mean distance is used to calculate density in the same way as Xunzhi and Jintun (2009).

We consider nine estimators in this section and we define \( k \) as the number of equiangular sectors about the random sample point (we use \( k = 4 \) for each estimator), \( g \) as the number of individuals to be located in each sector of the area around the random sampling point (each estimator uses a value of \( g = 1−3 \)). The estimators include:

- **PCQ Pollard (1971)**
  \[ \lambda_{12} = 4(4n-1) / \pi \sum r_{ij}^2 \]
  (20)

- **PCQ Cottam and Curtis (1954)**
  \[ \lambda_{13} = 1 / (\sum r_{ij}/4n) \]
  (21)

- **PCQ Morisita (1971)**
  for \( g = 3 \)
  \[ \lambda_{14} = (3-1 / \pi n) \sum 1/ r_{ij}^2 \]
  (22)

- **PCQ Morisita (1971)**
  for \( g = 2 \)
  \[ \lambda_{15} = (2-1 / \pi n) \sum 1/ r_{ij}^2 \]
  (23)

- **PCQ Morisita (1957)**
  for \( g = 3 \)
  \[ \lambda_{16} = (44 / \pi n) \sum 1/ \sum r_{ij}^2 \]
  (24)

- **PCQ Morisita (1957)**
  for \( g = 2 \)
  \[ \lambda_{17} = (28 / \pi n) \sum 1/ \sum r_{ij}^2 \]
  (25)

- **PCQ Morisita (1957)**
  for \( g = 1 \)
  \[ \lambda_{18} = (12 / \pi n) \sum 1/ \sum r_{ij}^2 \]
  (26)

- **PCQQN Xunzhi and Jintun (2009)**
  \[ \lambda_{19} = 1 / [\sum q_i^2 / 4n] \]
  (27)

- **PCQN (this paper)**
  \[ \lambda_{20} = 1 / (\sum k_{ij}/4n) \]
  (28)
where: \( r_{ij} \) is distance from random point \( i \) to closest individual in quarter \( j \), \( q_{ij} \) is distance between closest individual in each quarter to its nearest neighbour, \( k_{ij} \) is distance between closest individual in each quarter to closest individual in another quarter, \( n \) is sample size and \( \lambda \) is estimated density.

**T-Square methods (T-SQ)**

T-square estimators are known as methods to remove bias due to non-randomness in distribution pattern. Needed distance to calculate density (\( t_i \)) is the distance from the closest individual to its nearest neighbour on the far side of the half-plane defined by the line through the closest individual that is perpendicular to the line from the random point to that closest individual. We consider following estimators:

\[
\begin{align*}
\text{TSQ Besag and Gleaves (1973)} & : & \lambda_{21} & = 2n / \pi \sum t_i^2 & (29) \\
\text{TSQ Byth (1982)} & : & \lambda_{22} & = n^2 / [2 \sum r_i (\sqrt{2} \sum t_i)] & (30) \\
\text{TSQ Diggle (1975)} & : & \lambda_{23} & = 2n / [\pi \sum r_i^2 + 0.5 (\pi \sum t_i^2)] & (31) \\
\text{TSQ Diggle (1976) for clumped pattern} & : & \lambda_{24} & = n / [\pi (\sum r_i^2 + 0.5 \sum t_i^2)]^{1/2} & (32)
\end{align*}
\]

\[ \text{where: } r_i \text{ is distance from random point to closest individual, } t_i \text{ is distance from closest individual to nearest neighbour on the far side of the perpendicular line.} \]

**Variable Area Transect (VAT)**

Another PDE estimator we included is the variable area transect method proposed by Parker in 1979. It is a combination of distance and quadrate methods, because a fixed-width (strip) transect is searched from a random point until the \( g^{th} \) individual is encountered in the strip. In our study \( g \) ranged from 3 to 5. Transect width considered 20 meters according to previous study from the authors (Kiani et al. 2011). Another estimator by Morisita (proposed in 1957) was tested as a robust estimator for clumped pattern. Totally six estimators were considered as follow:

\[
\begin{align*}
\text{VAT (Parker 1979)} & : & \text{for } g = 4 & \lambda_{25} = 4n-1 / w \sum t_i & (33) \\
\text{VAT (Parker 1979)} & : & \text{for } g = 5 & \lambda_{26} = 5n-1 / w \sum t_i & (34) \\
\text{VAT (Morisita 1957)} & : & \text{for } g = 3 & \lambda_{27} = [2 \sum l_i] / n w & (35) \\
\text{VAT (Morisita 1957)} & : & \text{for } g = 4 & \lambda_{28} = [3 \sum l_i] / n w & (36) \\
\text{VAT (Morisita 1957)} & : & \text{for } g = 5 & \lambda_{29} = [4 \sum l_i] / n w & (37)
\end{align*}
\]

\[ \text{where: } l_i \text{ is distance from random point to third, fourth or fifth individual, } w \text{ is transect width, } n \text{ is sample size and } \lambda \text{ is estimated density.} \]

**Random Pairs method (RP)**

Cottam and Curtis (1949) first described the random-pairs method (Marcy 1988). This technique involves selecting the closest tree to a random sample point and establishing an imaginary line at a 90-deg angle to a line joining the point and its nearest neighbour. This line forms a 180-deg exclusion angle on the side of the line in which the nearest plant is located. The distance between the nearest plant and its nearest neighbour outside the exclusion angle is then measured.

\[ \begin{align*}
\text{RP Cottam and Curtis (1949)} & : & \lambda_{31} & = 1 / [0.8 \sum (p_i / n)]^2 & (39) \\
\text{where: } p_i & \text{ is the distance from nearest individual to its nearest neighbour in another side of perpendicular line in random point } i, & \\
& n \text{ is sample size and } \lambda \text{ is estimated density.} \\
\end{align*} \]

**Fixed Area Plot method (FAP)**

We include fixed area plot estimation of density and cover for the purposes of general comparison. We used 1.000 m\(^2\) circular plots with 17.86 meters radius. First density and cover per hectare were calculated for each plot separately. Then mean density and cover determined and expanded for a hectare of population.

\[ \begin{align*}
\text{FAP } \lambda_{32} & = 1 / n \left[ \sum (k_i / 1000) \right] & (40) \\
\text{where: } k_i & \text{ is number of plants in 1.000 m}^2 \text{ plots, } n \text{ is sample size and } \lambda \text{ is estimated density.}
\end{align*} \]
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*N-tree methods*

*N-tree* sampling is based on selection of the *n* trees (generally *n* = 1–7) closest to a sampling point located in the plant population. Plot shape is circular and is based on a radius from sampling point to the centre of the *n*th tree closest to the point. All *n* trees in the plot are measured (Lynch and Witter 2003). To calculate cover per hectare first cover per unit area is calculated for each plot separately. Then average of these values will be used. In our study we considered *n* = 3-6. Also for each case, the radius of plot was measured once to mid diameter of tree *n* (usual method). Again was measured to half distance between trees *n* and *n+1* (adjusted method). We expect this technique lead to bias reduction of *n*-tree sampling methods. In addition we tested 8 variants for *n*-tree sampling as follow:

\[
\begin{align*}
\text{3-tree usual} & \quad \lambda_{33} = 1/n \left[\sum \left(2.5/A_i\right)\right] \\
\text{4-tree usual} & \quad \lambda_{34} = 1/n \left[\sum \left(3.5/A_i\right)\right] \\
\text{5-tree usual} & \quad \lambda_{35} = 1/n \left[\sum \left(4.5/A_i\right)\right] \\
\text{6-tree usual - Prodan (1969)} & \quad \lambda_{36} = 1/n \left[\sum \left(5.5/A_i\right)\right] \\
\text{3-tree adjusted} & \quad \lambda_{37} = 1/n \left[\sum \left(3/A_i\right)\right] \\
\text{4-tree adjusted} & \quad \lambda_{38} = 1/n \left[\sum \left(4/A_i\right)\right] \\
\text{5-tree adjusted} & \quad \lambda_{39} = 1/n \left[\sum \left(5/A_i\right)\right] \\
\text{6-tree adjusted} & \quad \lambda_{40} = 1/n \left[\sum \left(6/A_i\right)\right]
\end{align*}
\]

where:

\[n\] is sample size, \[\lambda\] is estimated density and \[A_i\] is plot area and in each plot is calculated separately using the following equation:

\[A_i = \pi r_i^2\]

where: \(r_i\) is plot radius and in normal method prolongs to mid diameter of *n*th tree but in adjusted methods prolongs to half distance between *n* and *n+1* trees.

5. RESULTS

The results from the 40 estimators for sites I and II are summarized as the relative bias (RBIAS) for each estimator (Tables 1 and 2). We can make some general observations about the results. From Tables 1 and 2 we see that the quality of estimation generally decreased as the populations deviated from a random pattern (site I) to clumped pattern (site II).

The clumped pattern (Table 2) posed a greater problem for some estimators (\(\lambda_3, \lambda_9\)) in estimating density and for (\(\lambda_2, \lambda_3, \lambda_9, \lambda_{10}, \lambda_{20}, \lambda_{40}\)) estimating cover. In random pattern (Table 1) 38 estimators underestimated density while in clumped pattern 28 estimators performed in this way. Similar results can be seen for cover per unit area.

The FAP estimator outperformed most of other estimators, although a comparison of effort involved, according to time needed, showed that this method is more time consuming than other estimators. Surprisingly PCQ method in random pattern outperformed FAP method in estimating density. Also in clumped pattern VAT method was immediately after FAP method. We can see that RBIAS results for the FAP estimator were all near zero for density estimation. This assures on the suitable sample size and plot shape in this study.

It can be see that the best-performing estimators overall require locating > 1 population individual per sample point. NI estimators located at the end of ranking according to relative bias except \(\lambda_2\) in random pattern.

6. DISCUSSION

**NI estimators**

It is known that these estimators do not perform well when the spatial pattern deviates from random (Cottam et al. 1957). The results in the tables (1 and 2) indicate that these estimators performed poorly when applied to population with a clumped pattern both for density and cover per unit area estimations. This is not surprising because in comparison with the nearest neighbour or the second nearest neighbour methods, the closest individual measurement would give less adequate information about the distance between population individuals (Engeman et al. 1994). Heidari et al. (2011) showed that \(\lambda_2\) and \(\lambda_3\) estimators have relative bias -55.62 and -47.7 percents respectively and are not suitable for estimating density and cover in Oak populations with clumped pattern. In...
Table 1. Relative bias related to density and cover per hectare for 40 estimators (see text) in site I.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Bias</th>
<th>Cover (m² ha⁻¹)</th>
<th>Bias*</th>
<th>Density (ha⁻¹)</th>
<th>Description</th>
<th>Estimator</th>
</tr>
</thead>
<tbody>
<tr>
<td>3832.16</td>
<td>-11</td>
<td>456.3</td>
<td>-1.05</td>
<td>270</td>
<td>λ1 = NI (Cottam and Curtis (1956))</td>
<td>λ1</td>
</tr>
<tr>
<td>3832.16</td>
<td>-20.5</td>
<td>407.46</td>
<td>-11.64</td>
<td>241.1</td>
<td>λ2 = NI (Byth and Ripley (1980))</td>
<td>λ2</td>
</tr>
<tr>
<td>4596.62</td>
<td>-1.3</td>
<td>506.42</td>
<td>-2.77</td>
<td>265.3</td>
<td>λ3 = NN (Cottam and Curtis (1956))</td>
<td>λ3</td>
</tr>
<tr>
<td>4596.62</td>
<td>-32.9</td>
<td>343.9</td>
<td>-33.66</td>
<td>181</td>
<td>λ4 = NN (Byth and Ripley (1980))</td>
<td>λ4</td>
</tr>
<tr>
<td>5379.92</td>
<td>-1.53</td>
<td>505.08</td>
<td>-10.57</td>
<td>244</td>
<td>λ5 = 2NN (Cottam and Curtis (1956))</td>
<td>λ5</td>
</tr>
<tr>
<td>4596.62</td>
<td>-6.16</td>
<td>481.36</td>
<td>-1.92</td>
<td>267.65</td>
<td>λ6 = Compound 1 (Diggle 1975)</td>
<td>λ6</td>
</tr>
<tr>
<td>5379.92</td>
<td>-4.6</td>
<td>489.26</td>
<td>-4.82</td>
<td>259.7</td>
<td>λ7 = Compound 2 (Engeman et al 1994)</td>
<td>λ7</td>
</tr>
<tr>
<td>3832.16</td>
<td>-22.8</td>
<td>395.8</td>
<td>-14.17</td>
<td>234.2</td>
<td>λ8 = OD 1st individual (Morisita 1957)</td>
<td>λ8</td>
</tr>
<tr>
<td>4007</td>
<td>-7.9</td>
<td>472.15</td>
<td>-14.05</td>
<td>234.5</td>
<td>λ9 = OD 2nd individual (Morisita 1957)</td>
<td>λ9</td>
</tr>
<tr>
<td>4459.66</td>
<td>-20.4</td>
<td>408.24</td>
<td>-14.75</td>
<td>232.6</td>
<td>λ10 = OD 3rd individual (Morisita 1957)</td>
<td>λ10</td>
</tr>
<tr>
<td>5379.92</td>
<td>15.4</td>
<td>590.89</td>
<td>11.4</td>
<td>304</td>
<td>λ11 = JP (Batcheler 1975)</td>
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<tr>
<td>6784.43</td>
<td>-10.7</td>
<td>457.14</td>
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<td>240.6</td>
<td>λ12 = PCQ (Pollard 1971)</td>
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<tr>
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<td>-5.08</td>
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<td>391.01</td>
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<td>λ14</td>
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<tr>
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<td>438</td>
<td>-5.26</td>
<td>258.5</td>
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<td>-4.8</td>
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<tr>
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<td>9.48</td>
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<td>93.2</td>
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<tr>
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<tr>
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<td>493</td>
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<td>-15.3</td>
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<td>-6.91</td>
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<td>-7.28</td>
<td>253</td>
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<tr>
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<td>-12.04</td>
<td>240</td>
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<td>256.08</td>
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<tr>
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<td>519.5</td>
<td>-3.31</td>
<td>263.82</td>
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<td>λ36</td>
</tr>
<tr>
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<td>9.2</td>
<td>558.96</td>
<td>0.69</td>
<td>274.77</td>
<td>λ37 = 3-tree adjusted</td>
<td>λ37</td>
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<td>2.31</td>
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<td>260.82</td>
<td>λ38 = 4-tree adjusted</td>
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<td>0.69</td>
<td>515.4</td>
<td>-4.8</td>
<td>259.76</td>
<td>λ39 = 5-tree adjusted</td>
<td>λ39</td>
</tr>
<tr>
<td>8388.9</td>
<td>-0.43</td>
<td>509.62</td>
<td>-5.73</td>
<td>257.2</td>
<td>λ40 = 6-tree adjusted</td>
<td>λ40</td>
</tr>
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</table>

* Real density was 272.86 (ha⁻¹) and real cover per hectare was 511.84 (m² ha⁻¹).
Comparison of Distance Sampling Methods in shrublands

Table 2. Relative bias related to density and cover per hectare for 40 estimators (see text) in site II.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Bias</th>
<th>Cover (m² ha⁻¹)</th>
<th>Bias</th>
<th>Density (ha⁻¹)</th>
<th>Description</th>
<th>Estimator</th>
</tr>
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<tr>
<td>5118</td>
<td>-41.35</td>
<td>264.3</td>
<td>-25.5</td>
<td>163</td>
<td>λ₁ = NI (Cottam and Curtis 1956)</td>
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<td>5118</td>
<td>-44.21</td>
<td>251.4</td>
<td>-31.35</td>
<td>150.2</td>
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<td>5934.33</td>
<td>16.77</td>
<td>526.26</td>
<td>12.43</td>
<td>246</td>
<td>λ₃ = NN (Cottam and Curtis 1956)</td>
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<tr>
<td>5934.33</td>
<td>-22.4</td>
<td>349.7</td>
<td>-25</td>
<td>164.1</td>
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<td>-12.28</td>
<td>395.28</td>
<td>-6.53</td>
<td>204.5</td>
<td>λ₆ = Compoun 1 (Diggle 1975)</td>
<td>λ₆</td>
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<td>-5.8</td>
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<td>λ₇ = Compound 2 (Engeman et al 1994))</td>
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<td>145.9</td>
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<tr>
<td>5178.56</td>
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<td>-11.7</td>
<td>193.2</td>
<td>λ₉ = OD 2nd individual (Morisita 1957)</td>
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<tr>
<td>5344.17</td>
<td>-18.2</td>
<td>368.64</td>
<td>-16.22</td>
<td>183.3</td>
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<td>λ₁₀</td>
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<tr>
<td>6725.55</td>
<td>-9</td>
<td>410</td>
<td>-8.6</td>
<td>200</td>
<td>λ₁₁ = JP (Batcheler 1975)</td>
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<td>8333.5</td>
<td>-12.81</td>
<td>392.9</td>
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<td>189.6</td>
<td>λ₁₂ = PCQ (Pollard 1971)</td>
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<td>14.78</td>
<td>517.28</td>
<td>4.6</td>
<td>228.2</td>
<td>λ₁₄ = PCQ (Morisita 1971) 3rd Individual</td>
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<td>-4.5</td>
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<td>-11.88</td>
<td>504.2</td>
<td>11.2</td>
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<td>72.8</td>
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<td>λ₂₂ = t-square (Byth 1982)</td>
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<td>408.8</td>
<td>-6.6</td>
<td>204.3</td>
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<td>175.7</td>
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<td>10.32</td>
<td>241.39</td>
<td>λ₄₀ = 6-tree adjusted</td>
<td>λ₄₀</td>
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</table>

* Real density was 218.8 (ha⁻¹) and real cover per hectare was 450.66 (m² ha⁻¹)
random pattern the λ2 performed well in estimating density not cover per unit area while other estimator λ3 resulted in -11.4 percent relative bias. These two estimators performed poorly at the clumped pattern both for density estimation and cover per hectare.

**NN and 2NN estimators**

We were hopeful that these estimators perform better than NI estimators because they use two or three measurements. This was true except the λ5 estimator proposed by Byth and Ripley (1980) had among the worst performance properties of all estimators studied. The λ6 estimator performed the best of the estimators in this group for clumped pattern and lied in 7th and 8th place for estimating density and cover respectively. While in random pattern the λ4 performed better than other estimators.

**Compound methods (COMP)**

Compound estimators outperformed NI estimators except λ6. But in contrast to NN and 2NN methods various results were achieved. For example in random pattern λ4 and λ6 and in clumped pattern λ6 estimators outperformed the compound methods. Overall λ8 estimator proposed by Engeman et al (1994) outperformed λ7 from Diggle (1975) in our study.

**Ordered distance estimators (OD)**

The accuracy among these estimators improved where the number of individuals located at each random point (g) was 2, both in random and clumped patterns. Ordered distance estimators performed poorly and they were located in second half of ranking table. This was equal for both density and cover per unit area estimations. Nielson et al (2004) suggested first considering a level of n = 20 (sample size) for any field investigation using the OD method, and then increasing g rather than n if time and costs permit. They concluded that best results achieve when g = 4 or 5, while in our study using n = 35 the best results achieved for g = 2.

**Point centred quarter estimators (PCQ)**

In random pattern (Table 1) the λ18 estimator performed the best. Surprisingly it was better than FAP method in estimating density. This justifies Beason and Haucke (1975). They concluded that point centred quarter method provides the most accurate estimate of density. Cottam and Curtis (1956) concluded that this method is the least susceptible to subjective bias than the closest individual, the nearest neighbour, and the random-pairs methods.

In our study it was in the midrange RBIAS performance of all PDEs to estimating cover. The λ18 estimator was one of the best ones for the clumped pattern and located immediately after FAP and VAT estimators.

Overall PCQ estimators proposed by Morisita (1957) outperformed the standard method.

All PCQ estimators located in the mid-range of the ranking table in estimating cover per area.

The λ18, λ19 and λ20 estimators generally resulted in an RBIAS from the other PCQ estimators in this group. Time study showed that this group locates in the range of most time consuming estimators. Similar results achieved in study of Moosaee Sanjerehei and Basiri (2008) where PCQ method was so slow than other estimators. It is because each of the PCQ estimators requires keeping track around the random point and locating a total of 4 population individuals (for λ13, λ14, λ19 and λ21), 8 (for λ14, λ18 and λ20) and 12 individuals (for λ15 and λ17) at each random point respectively. This represents considerable effort in difficult field situations and is contrary to the reason for favouring PDEs over quadrates (Engeman et al. 1994).

**Variable area transect (VAT)**

In clumped pattern VAT was the best-performing PDE method overall, comparable to λ18 in random pattern. Considering that the field worker needs only to search in one direction at each random point, it is probably the easiest method of sampling among the PDEs that require locating > 1 population individual. Dobrowski and Murphy (2006) showed that biases tended to decrease with increasing g. In our study the same results achieved in site II with clumped pattern. But VAT using g = 3 was superior to density estimation in random pattern. Time study showed that these estimators are very rapid
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...and decrease field efforts. They located immediately after NI and NN estimators according to needed time to perform sampling.

*T-square estimators*

The performances of the four T-square estimators in estimating density and cover were not similar. The usual T-square estimator $\lambda_{30}$, performed better than the other three in random spatial patterns. But in clumped pattern $\lambda_{33}$ proposed by Diggle (1976) was the best in this group as expected. Also $\lambda_{33}$ had lower RBIAS than $\lambda_{32}$ estimator. Inverse results achieved in study of Engeman et al. (1994) so that this estimator improved RRMSE performance over $\lambda_{32}$ in the aggregate patterns. Heidari et al. (2007) showed that none of the $\lambda_{31}$, $\lambda_{32}$ and $\lambda_{33}$ estimators could provide an acceptable estimate based on ±10% accepted accuracy; even though, the Byth estimator ($\lambda_{31}$) had more accuracy level for density and crown coverage.

In general these estimators were in the mid-range of performances among all of the PDEs tested in our study except $\lambda_{30}$ estimator in random pattern that located in 5th location of ranking table for estimating density.

*N-tree methods*

In both sites n-tree methods were of the best-performing methods overall and located in first half of the ranking table to estimate density and cover. However adjusted 3-tree method was the best method according to RBIAS. In the case of estimating cover per unit area, n-tree methods with $g = 5$ and $g = 6$ were better than other estimators as expected because they use more trees in calculations. Klein and Vilkco (2005) stated that all n-tree sampling methods overestimate density. They proposed two new estimators but it seems that these estimators need a lot of field efforts. We can see overestimating density in clumped pattern but in random pattern only 3-tree method overestimated density. Zobeyr (1978) showed that n-tree sampling techniques are not suitable for the natural forests of northern Iran because they consistently underestimate the true population parameters include diameter and basal area. He stated that clumped pattern may be the most reasonable cause of this behaviour. Our study showed that n-tree estimators can be used with some modifications in plant populations of desert areas. Lynch and Rusydi (1998) showed that 5-tree distance sampling using Prodan's estimator was most efficient of the point sampling and FAP methods with negligible bias for density and volume per hectare. This method was the best estimator for cover per unit area in our study.

In our study random pairs and joint-point methods ($\lambda_{32}$ and $\lambda_{40}$) were of the worst estimators and located in lower part of ranking tables. According to field efforts (needed time) they located in midrange of all tested estimators.

7. CONCLUSIONS

In the previous section we investigated results for accuracy and time needed to conduct 40 sampling methods included in this study. In the process we gained insight as to which are the best performing in random and clumped patterns. We conclude this paper based on the results presented and give some recommendations about what plot-less density estimators are preferable in study area. If an investigator would have an idea as to how much time is involved in making observations in the field, based on the results, our opinion as to the ranking of the ‘best performing’ PDEs would be $\lambda_{3}$, $\lambda_{3}$ and $\lambda_{4}$ followed by the OD, NN and VAT groups. When assessing an estimator’s performance, we prefer to emphasize how well it performs in non-random patterns, especially clumped patterns (Engeman et al. 1994). In terms of mean relative bias for clumped population, $\lambda_{38}$ was the best, followed by $\lambda_{31}$ and $\lambda_{26}$ estimators. For estimating cover per unit area, $\lambda_{38}$ followed by $\lambda_{25}$ and $\lambda_{9}$ estimators respectively. In random pattern $\lambda_{18}$ was the best estimator to estimate density and followed by $\lambda_{26}$ and $\lambda_{2}$ estimators. But in estimating cover per unit area n-tree methods were the best followed by $\lambda_{37}$ and $\lambda_{38}$ estimators.

In PCQ methods, estimation advantages are out-weighed by the practical difficulties and time needed to dividing the area around the sampling point into quadrants, deciding into which quadrant an individual belongs and measuring the $g^2$ closest individuals specially where $g > 1$.

In naturally occurring populations, spatial patterns and density usually are not
consistent across the area (Engeman et al. 1994). So it seems that for fixed effort in the field, it is more useful to sample more sample points and have less effort per point.

We consider the VAT and NI methods to be the most practical PDEs. Considering RBIAS and time together, VAT method was the best sampling method in clumped pattern followed by \( \lambda_1 \) and \( \lambda_2 \) estimators. In random pattern PCQ method proposed by Morisita (1957) was the best method followed by \( \lambda_2 \) and \( \lambda_2 \) estimators. But for estimating cover per area N-tree methods performed best. As in this site VAT method located in 5th location, and due to simplicity of field works related to this method, in the case that the investigator would not be able to clearly define what sort of spatial pattern is followed by the population to be sampled, this method can be recommended as well.

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8. REFERENCES


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