JOURNAL OF FOREST SCIENCE, *64*, 2018 (5): 230–244

https://doi.org/10.17221/146/2017-JFS

Evaluation of distance methods for estimating population density in *Populus euphratica* Olivier natural stands (case study: Maroon riparian forests, Iran)

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Abstract

Basiri R., Moradi M., Kiani B., Maasumi Babaarabi M. (2018): Evaluation of distance methods for estimating population density in *Populus euphratica* Olivier natural stands (case study: Maroon riparian forests, Iran). J. For. Sci., 64: 230–244.

The aim of this study was to determine the performance of distance methods in terms of accuracy, precision, bias, consumed time and sampling efficiency in the Maroon riparian forests, Iran. 40 estimators were used to evaluate the density of *Populus euphratica* Olivier trees in pure and mixed stands. Fifty quadrates (30 × 30 m) were established in each stand. To evaluate the accuracy, precision, bias, consumed time and efficiency of sampling techniques, relative root mean square error – RRMSE (%), coefficient of variation – CV (%), relative bias – RBIAS (%), $t \times \text{RBIAS}^2$, $t \times E^2$, where t is study time and E (%) is sampling error at a confidence level of 95%, and efficiency ratio between method j and k (Ef_{jk}) were used. A compound of three basic distance estimators sampling method and n-tree were the best in both stands according to all criteria for density estimation. Moreover, variable area transect by Parker (g = 3) and quadrat method were the best methods for density estimation only in pure stand, while the angle order-point-centred quarter method was superior in mixed stand. Regarding to the results, we recommend the use of compound of three basic distances (BDAV3) and basic distance-nearest neighbour (BDNN2) for density estimation of *P. euphratica* stands in riparian forests.

Keywords: forest sampling; accuracy; efficiency; pure and mixed stands

Riparian forests are among the most diverse, dynamic and complex ecosystems of the world (Coroi et al. 2004). These ecosystems are located between aquatic and terrestrial ecosystems as ecotones (Cartisano et al. 2013) which improve soil and water quality and preserve biodiversity (Stromberg et al. 2010). *Populus euphratica* Olivier is one of the most important components of riparian forests in Iran and creates two types of pure and mixed stands (Sepehri, Bozorgmehr 2003). Inventory in a riparian forest is more difficult than in other upland areas because of highly variable structure and composition (Pabst, Spies 1999). Most inventories are conducted using a fixed area plot (Haxtema et al. 2012). There are limited studies on the use of distance methods in riparian forests (Haxtema et al. 2012). On the other hand, the complexity and diversity of these ecosystems will enable us to test simpler and less costly methods, such as distance methods in this type of forests. Different types of distance methods have been developed so far. Finding the easiest and least costly method, as well as the most accurate method, among all distance methods is of utmost importance for complex riparian communities.

In ecological research the main target of sampling is to reach an accurate and precise estimation of some attributes of plant communities (Borges Silva et al. 2017). Density is one of the important components of vegetation survey (Bonham 2013) and main problem in many fields of biology (Engeman et al. 1994).

A variety of densities including dense and scattered can be seen in *Populus* Linnaeus stands in riparian forests of Iran. Estimation of density is done on the basis of two major types of sampling, plot or quadrat method and plotless or distance method (Barbour et al. 1999). A quadrat method with a given area is robust when the sample size is adequate Krebs (2014) but can be labour intensive, especially when individuals are scattered or not easily accessible (Engeman et al. 1994; Hijbeek et al. 2013). Alternatively, plotless sampling or distance methods have been developed (Mitchell 2007). A variety of estimators have been proposed to estimate densities which have different efficiency and accuracy (Barbour et al. 1999; Krebs 2014) and their performance are different in a variety of densities (Engeman et al. 1994). Besides, it is proven not to be reliable in any conditions (White et al. 2008). Accordingly, two types of natural pure and mixed stands of *P. euphratica* with high and low densities or dispersed density were considered to be relevant for assessing the efficiency of estimators, respectively. The evaluation what estimator is suitable for natural pure and mixed stands is required.

Several researchers made comparisons of the performance of some density estimators. Engeman et al. (1994) found that the methods of ordered distance for the third closest individual and variable area transect sampling showed good performance. White et al. (2008) found no bias associated with the compound of three basic distance estimators. Nath et al. (2010) showed that the variable area transect estimator was more efficient than the fixed area plot. Askari et al. (2013) found that the basic distance involving the nearest neighbour and a compound of two basic distance estimators were suitable methods. Kiani et al. (2013) in their studies concluded that the variable area transect method with measurements to the 4th and 5th closest individuals in each transect was the best sampling. Khan et al. (2016) studied angle ordered estimators involving a point-centred quarter method and showed that the higher order point-centred quarter method provides higher accuracy. Borges Silva et al. (2017) found that the T-square sampling was the best method in terms of precision and accuracy.

Considering the extraordinary importance of time, cost-efficiency, labour efficiency for demanding field situations and awareness of the effect of different types of densities on the performance of distance methods, implementation of this research is necessary in riparian forests of Iran. Therefore, this study was conducted to introduce the most accurate, precise, unbiased and efficient distance method to estimate density of *P. euphratica* in natural pure and mixed stands of riparian forests in Iran without attempting to improve their performance separately.

MATERIAL AND METHODS

Study area

This study was conducted in Maroon riparian forests located in Behbahan, Khouzestan province, Iran. The study site is located between 50°09'37" to 50°10'25" of the east longitude and 30°38'53" to 30°39'38" of the north latitude with an altitude of 250–300 m a.s.l. Average annual rainfall and temperature are 350 mm and 24°C, respectively (Pourrezaei et al. 2010). This zone has a dry climate based on Emberger climate classification (Basiri et al. 2014). Woody species that naturally grow in the study area include *P. euphratica*, *Tamarix arceuthoides* Bunge and *Lycium shawii* R. Roemer & Schweinfurth, which have formed unique plant communities (Basiri et al. 2014). The study area is a plain near the Maroon River and has uniform physiography (Fig. 1).

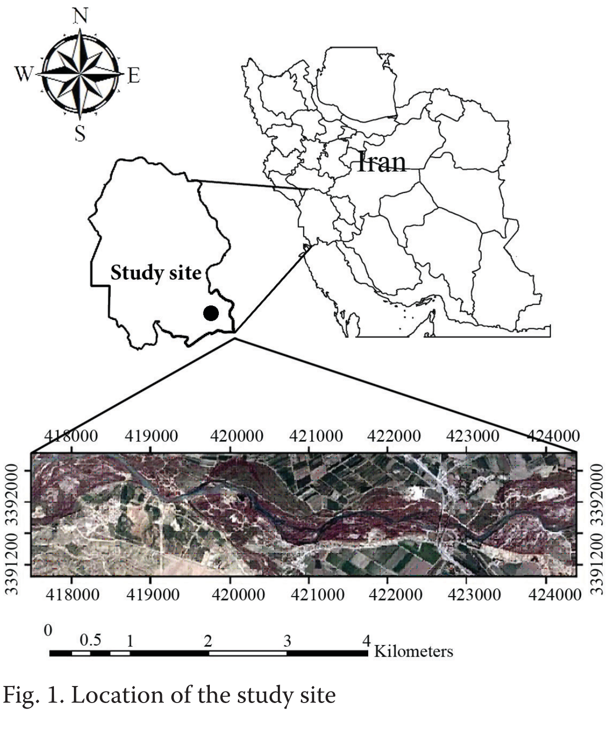

Fig. 1. Location of the study site

Methodology

Plot sampling. Two pure and mixed *P. euphratica* stands were selected and the boundaries of the two sites were taken using GPS. The location of all *P. euphratica* trees with DBH over 2.5 cm (Han et al. 2008) was determined (by measuring distance and azimuth) and the point map of trees was generated using Arc GIS software (Version 9.3, 2011). The pure and mixed stand area with 4.5 and 9.1 ha was specified showing a clumped spatial pattern (Maasumi Babaarabi et al. 2018). Fifty 30 × 30 m quadrates were established in the Arc GIS environment and in each quadrate distances to the southwest corner of the quadrate and azimuth were measured. All sampling methods that are described below were performed in computer using Arc GIS. Measuring distances in each method was conducted by "information" and "measures" tools. Full inventory data were used as a benchmark. To evaluate the efficiency of each method, a time study was performed on the basis of sampling processes.

Statistical analyses. To evaluate the accuracy, precision and bias of sampling techniques, relative root mean square error – RRMSE (%) (White et al. 2008), coefficient of variation – CV (%) (Nath et al. 2010) and relative bias – RBIAS (%) (White et al. 2008) were used. RRMSE, CV and RBIAS were calculated by Eqs 1–3:

$$\mathrm{RRMSE}=\sqrt{\frac{\sum(\hat{\lambda}-\lambda)^2/\lambda^2}{P}} \tag{1}$$

where:
λ – real density,
$\hat{\lambda}$ – estimated density,
P – iteration in bootstrapping.

$$\mathrm{CV}=\frac{\mathrm{SD}}{\bar{X}}\times 100 \tag{2}$$

where:
SD – standard deviation,
$\bar{X}$ – bootstrap mean.

$$\mathrm{RBIAS}=\frac{(\sum\hat{\lambda}/P)-\lambda}{\lambda}\times 100 \tag{3}$$

All parameters should be low to confirm the accuracy, precision and bias of the method. RRMSE, CV and RBIAS values below 5% indicate that a sampling method is highly reliable (Nath et al. 2010). For evaluating the efficiency of estimators, three criteria were used including $t\times\mathrm{RBIAS}^2$, $t\times E^2$ (Husch et al. 1982) and Ef_{jk} (Husch 1963), where *t* is study time, *E* (%) is sampling error at a confidence level of 95% and Ef_{jk} is efficiency ratio between method *j* and *k* (Eq. 4):

$$\mathrm{Ef}_{jk}=(\mathrm{C}_j^2\times t_j)/(\mathrm{C}_k^2\times t_k) \tag{4}$$

where:
C_j, C_k – coefficient of variation of method *j* and *k*,
t_j, t_k – time required for each sample unit with method *j* and *k*.

In this research, fixed area plot sampling was considered as method *k*. The low values of these estimators indicate their higher efficiency. Finally, to find the best method based on all criteria, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) algorithm as a multi-criteria decision method (MCDM) was used. This technique was proposed by Hwang and Yoon (1981) and it is a well-known method for classical MCDM that has been effectively used for solving many different problems. It has some advantages including simplicity, rationality, and comprehensibility, and good computational efficiency (Zavadskas et al. 2016). We used Shannon's entropy method for determining the degree of importance of alternative suppliers in TOPSIS algorithm processes. This method is one of the most powerful MCDM tools (Ghorbani et al. 2012).

Common estimators attributed to distance methods include: basic distance involving two types of measurements developed by Cottam and Curtis (1956) and Byth and Ripley (1980), one involving the measurement of a distance from a random sampling point to the closest individual and the other from an individual to the nearest neighbour. Ordered distance that was developed by Morisita (1957) and Pollard (1971) includes measuring trees from a random point to the g^{th} closest individuals. The joint-point method that was developed by Batcheler (1975) includes three measurements: 1 – the closest individual, 2 – the nearest neighbour, 3 – the second nearest neighbour (Table 1). Angle ordered is well-known as the point-centred quarter method which is described as the area around the sampling point divided into four quarters and the distance to the closest individual in each quarter or distance to the g^{th} closest individuals in each quarter or distance between the two closest individuals in each quarter or distance between the closest individual in each quarter and closest individual in other quarter is measured. T-square estimators are recognized as methods to eliminate a bias caused by nonrandomness associated with the nearest neighbour distance measurement (Besag,

Table 1. Summary of the density estimators used in the study area

Estimator	Equation	Reference
Basic distance-closest individual (BDCI1)	$\lambda_1 = 1/\left[4(\sum r_i / n)^2\right]$	Cottam and Curtis (1956)
Basic distance-closest individual (BDCI2)	$\lambda_2 = n / (\pi \sum r_i^2)$	Byth and Ripley (1980)
Basic distance-nearest neighbour (BDNN1)	$\lambda_3 = 1/\left[2.778(\sum z_i / n)^2\right]$	Cottam and Curtis (1956)
Basic distance-nearest neighbour (BDNN2)	$\lambda_4 = n / (\pi \sum z_i^2)$	Byth and Ripley (1980)
Basic distance-second nearest neighbour (BD2N)	$\lambda_5 = 1/\left[2.778(\sum m_i / n)^2\right]$	Cottam and Curtis (1956)
Basic distance-compound (BDAV2)	$\lambda_6 = (\lambda_1 + \lambda_3)/2$	Diggle (1975)
Basic distance-compound (BDAV3)	$\lambda_7 = (\lambda_1 + \lambda_3 + \lambda_5)/3$	Engeman and Sugihara (1998)
Ordered distance-closest individual (OD1C)	$\lambda_8 = (n-1)/\pi \sum r_{i1}^2$	Morisita (1957), Pollard (1971)
Ordered distance-second closest individual (OD2C)	$\lambda_9 = (2n-1)/\pi \sum r_{i2}^2$	Morisita (1957), Pollard (1971)
Ordered distance-third closest individual (OD3C)	$\lambda_{10} = (3n-1)/\pi \sum r_{i3}^2$	Morisita (1957), Pollard (1971)
Joint-point	$f = p/n$	Batcheler (1975)
	$\log E(\mathrm{CV}) = -1.0319 + 0.4892 f^2 - 0.7182 f^4 + 0.6095 f^6$	Batcheler (1975)
	$d = P / (\pi \sum r_i^2)$	Batcheler (1975)
	$A1 = 1/E(\mathrm{CV})\left[((P\sum r_i^2 - (\sum r_i)^2) n^2 N)/(\sum r_i \sum z_i p^3))\right]$	Batcheler (1975)
	$A2 = 1/E(\mathrm{CV})\left[((P\sum r_i^2 - (\sum r_i)^2) n^2 N)/(\sum r_i \sum m_i p^3))\right]$	Batcheler (1975)
	$a = 1 + 2.473 f$	Batcheler (1975)
	$b = 1 + 2.717 f$	Batcheler (1975)
	$\lambda_{11} = (d/2a)(b^{A1} + b^{A2})$	Batcheler (1975)
Angle order-point-centred quarter method (PCQM1)	$\lambda_{12} = 4(4n-1)/\pi \sum r_{ij}^2$	Pollard (1971)
(PCQM2)	$\lambda_{13} = 1/\left[(\sum\sum r_{ij})/4n^2\right]$	Cottam and Curtis (1956)
PCQM3	$\lambda_{14} = (3 - 1/\pi n)\sum\sum 1/r_{ij}^2$	Morisita (1971)
PCQM2	$\lambda_{15} = (2 - 1/\pi n)\sum\sum 1/r_{ij}^2$	Morisita (1971)
PCQM3	$\lambda_{16} = (44/\pi n)\sum 1/\sum r_{ij}^2$	Morisita (1957)
PCQM2	$\lambda_{17} = (28/\pi n)\sum 1/\sum r_{ij}^2$	Morisita (1957)
PCQM1	$\lambda_{18} = (12/\pi n)\sum 1/\sum r_{ij}^2$	Morisita (1957)
Quartered neighbour method (PCQMQN)	$\lambda_{19} = 1/\left[(\frac{\sum\sum q_{ij}^2}{4})/n\right]$	Zhu and Zhang (2009)

Table 1. to be continued

Estimator	Equation	Reference
New PCQM	$\lambda_{20} = 1/(\sum k_{ij}/4n)$	Kiani et al. (2013)
T-square (TS1)	$\lambda_{21} = 2n/\pi\sum t_i^2$	Besag and Gleaves (1973)
T-square (TS2)	$\lambda_{22} = n^2/\left[2\sum r_i(\sqrt{2}\sum t_i\right]$	Byth (1982)
T-square-basic (TSBA)	$\lambda_{23} = 2n/\left[(\pi\sum r_i^2) + (0.5\pi\sum t_i^2)\right]$	Diggle (1975)
T-square-reduced bias (TSRB)	$\lambda_{24} = n/\left[\pi(\sum r_i^2 \times 0.5\sum t_i^2)^{0.5}\right]$	Diggle (1975)
Variable area transect (VAT3)	$\lambda_{25} = 3n - 1/w\sum l_i$	Parker (1979)
Variable area transect (VAT4)	$\lambda_{26} = 4n - 1/w\sum l_i$	Parker (1979)
Variable area transect (VAT5)	$\lambda_{27} = 5n - 1/w\sum l_i$	Parker (1979)
Variable area transect (VAT3)	$\lambda_{28} = \left[2\sum 1/l_i\right]/nw$	Morisita (1957)
Variable area transect (VAT4)	$\lambda_{29} = \left[3\sum 1/l_i\right]/nw$	Morisita (1957)
Variable area transect (VAT5)	$\lambda_{30} = \left[4\sum 1/l_i\right]/nw$	Morisita (1957)
Random pairs (RP)	$\lambda_{31} = 1/\left[0.8\sum(p_i/n)\right]^2$	Cottam and Curtis (1949)
Quadrat method (QUAD)	$\lambda_{32} = \sum q_i/(u_i w_i n)$	Seber (1982)
3-tree sampling usual	$\lambda_{33} = 1/n\left[\sum(2.5/A_i)\right]$	Borges Silva et al. (2017)
4-tree sampling usual	$\lambda_{34} = 1/n\left[\sum(3.5/A_i)\right]$	Borges Silva et al. (2017)
5-tree sampling usual	$\lambda_{35} = 1/n\left[\sum(4.5/A_i)\right]$	Borges Silva et al. (2017)
6-tree sampling usual	$\lambda_{36} = 1/n\left[\sum(5.5/A_i)\right]$	Borges Silva et al. (2017)
3-tree sampling adjusted	$\lambda_{37} = 1/n\left[\sum(3/A_i)\right]$	Borges Silva et al. (2017)
4-tree sampling adjusted	$\lambda_{38} = 1/n\left[\sum(4/A_i)\right]$	Borges Silva et al. (2017)
5-tree sampling adjusted	$\lambda_{39} = 1/n\left[\sum(5/A_i)\right]$	Borges Silva et al. (2017)
6-tree sampling adjusted	$\lambda_{40} = 1/n\left[\sum(6/A_i)\right]$	Borges Silva et al. (2017)

λ_i – estimated density, r_i – distance to the closest individual, n – sample size, z_i – distance between the closest individual and its nearest neighbour, m_i – distance between the nearest neighbour and the second nearest neighbour, r_{i1}, r_{i2}, r_{i3} – point distance from the first, second and third closest individual, f – ratio, p – number of sample points in which tree is measured, E – sampling error, CV – coefficient of variation, d – density, P – iteration in bootstrapping, $A1$, $A2$, a, b – defined coefficients, N – total sample points, r_{ij} – distance from random point i to the closest individual in quarter j, q_{ij} – distance between the two closest individuals in each quarter, k_{ij} – distance between the closest individual in each quarter and the closest individual in other quarter, t_i – distance from the closest individual to the nearest neighbour on the other side of the perpendicular line, w – transect width, l_i – distance from sampling point to the third, fourth or fifth individual, p_i – distance between the closest individual and the nearest neighbour on the other perpendicular side at the sampling point, q_i – number of plants, u_i – length of quadrat, w_i – width of quadrat, A_i – plot area

Gleaves 1973). The nearest neighbour distance is a 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 sampling point to that closest individual. Variable area transect methods include the transect with a fixed width that is searched from a sampling point until the g^{th} individual is encountered in the strip. This method was developed by Morisita (1957) and Parker (1979). Random pairs technique involves selecting the closest tree to a random sample point and establishing an imaginary line at a 90-degree angle to a line joining the point and its nearest neighbour. This method was developed by Cottam and Curtis (1949). The quadrat method was used for the first time by Pound and Clements (1898) for measuring the vegetation characteristics such as density. *n*-Tree sampling included a number of trees (*n*) closest to a sampling point that were selected and the respective distances were measured. This method was developed by Prodan (1968) and Kleinn and Vilčko (2006).

In this research, 40 estimators were used to estimate density of stands (Table 1). Most of these methods are described in various references so we provide only brief descriptions and abbreviations according to Table 1.

RESULTS

Estimated tree density

The results of 40 estimators in two pure and mixed stands of *P. euphratica* showed that tree density ranged from 88.4 to 851.7 in pure stand and from 46.8 to 228.4 individuals per hectare in mixed stands. Totally 57.5 and 45% of estimators in pure and mixed stands, respectively, tended to underestimate density (Figs 2a, b).

According to general results, ordered distance-closest individual – OD1C (λ_8) and basic distance-closest individual – BDCI1 (λ_1) estimators had the lowest negative bias in pure and mixed stands, respectively.

Comparison of sampling techniques

Accuracy: RRMSE (%). RRMSE was used as an accuracy parameter. Among estimators, basic distance-compound – BDAV3 (λ_7, 3.1%), quadrat method – QUAD (λ_{32}, 3.9%) and variable area transect – VAT5 (Morisita 1957) (λ_{30}, 5%) methods were recognized within the range of ± 5% and good accuracy in pure stand (Fig. 3a). The other estimators were out of range. Only BDAV3 (λ_7) sampling

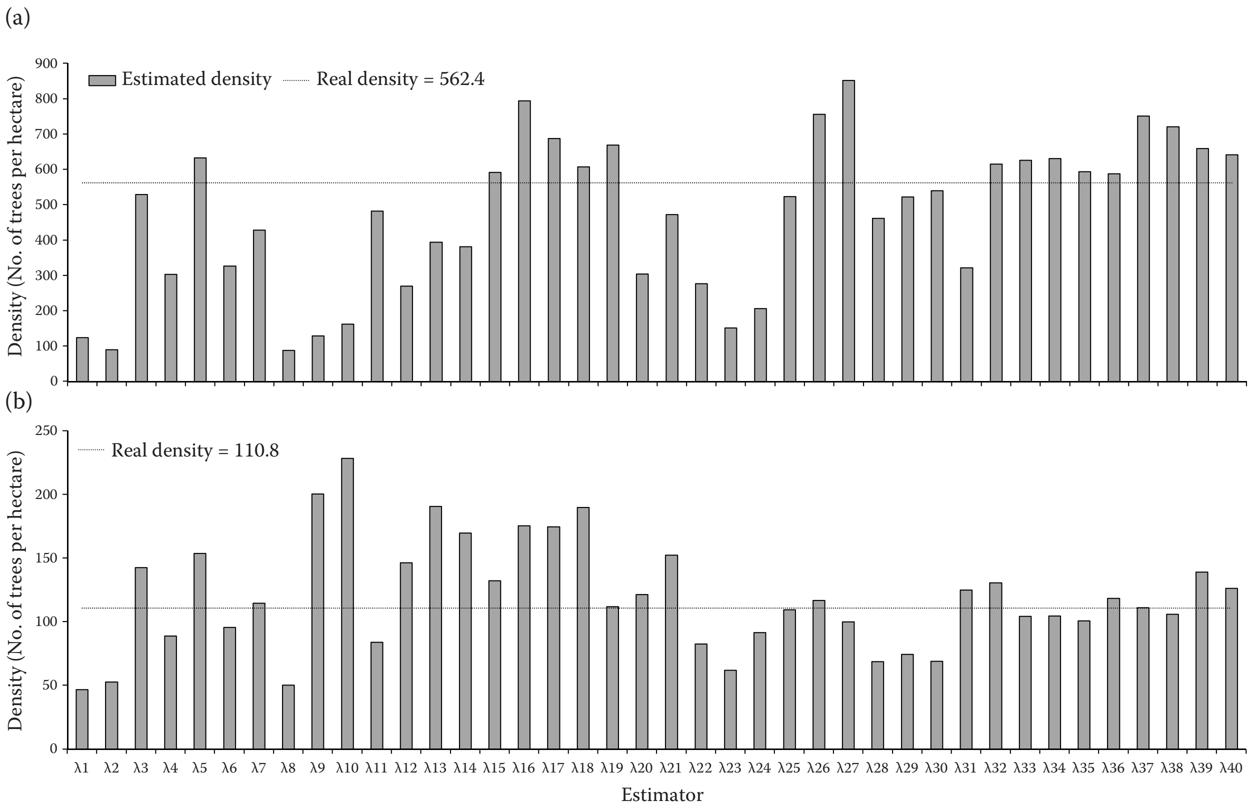

Fig. 2. Comparison of density estimators with each other and with real density in pure (a), mixed (b) stand

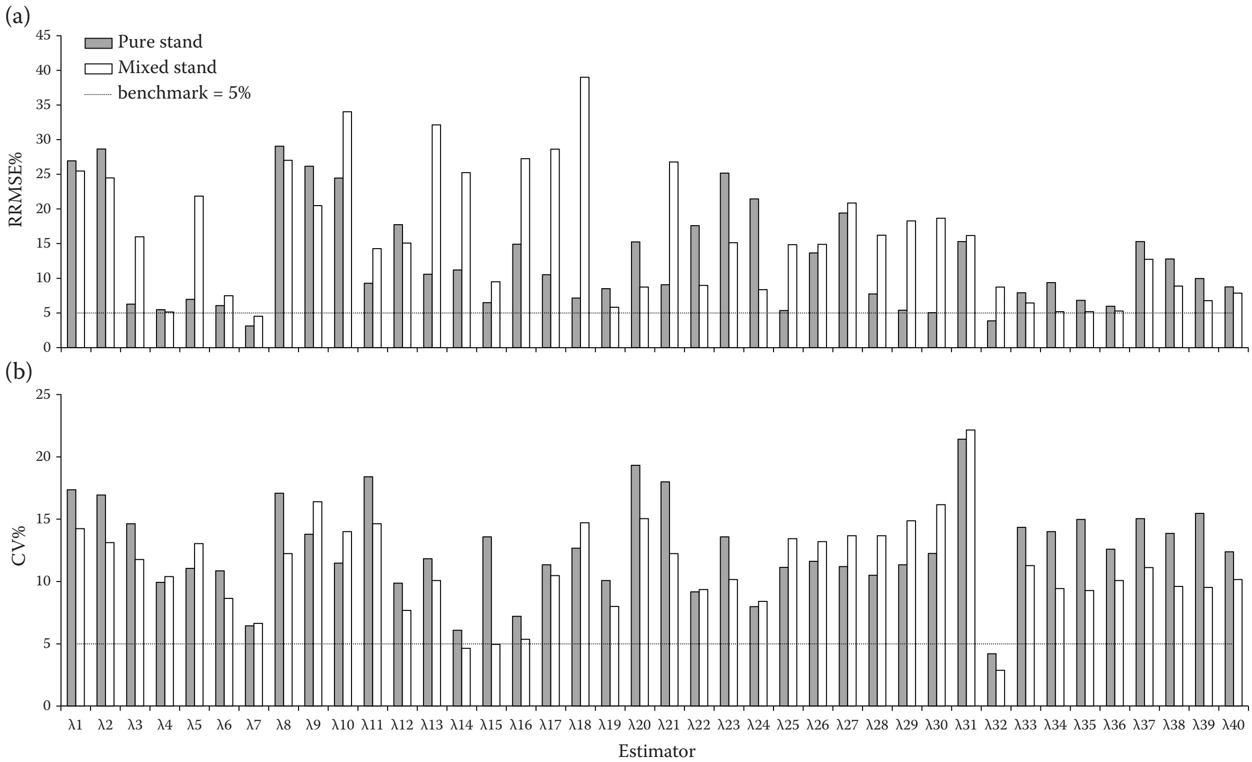

Fig. 3. Relative root mean square error – RRMSE (%) (a), coefficient of variation – CV (%) (b) of estimators in pure and mixed stands

was located within ± 5% (4.5%) and was considered to be good in mixed stand (Fig. 3a).

Precision: CV (%). CV (%) was applied as a precision parameter. Among estimators, QUAD sampling (λ_{32}, 4.2% in pure and 2.9% in mixed stands) was performed as the good estimators in both stands (Fig. 3b). In mixed stand, point-centred quarter method – PCQM3 (Morisita 1971) (λ_{14}) and PCQM2 (Morisita 1971) (λ_{15}) were located in the next ranks. The other estimators in pure stand were out of range (± 5%).

Bias: RBIAS (%). RBIAS (%) was used as a parameter of bias. In pure stand, BDAV3 (λ_7, 0.2%), basic distance-nearest neighbour – BDNN1 (λ_3, –2.3%), 6-tree usual (λ_{36}, 4.2%), 5-tree usual (λ_{35}, 4.8%), VAT5 (Morisita 1957) (λ_{30}, –4.9%) and PCQM2 (Morisita 1971) (λ_{15}, 5%) methods were located within ± 5%. So, these methods are very good (Fig. 4). The other estimators were out of range (Fig. 4).

In mixed stand, 4-tree usual (λ_{34}, –0.3%), 6-tree usual (λ_{36}, 1.6%), 5-tree usual (λ_{35}, –2%), 3-tree usual (λ_{33}, 2.4%), BDAV3 (λ_7, 3.1%) and BDNN2 (λ_4, –4.7%) estimators were shown to perform well (Fig. 4).

Time-consuming process study. Among estimators, BDCI1 (λ_1), BDCI2 (λ_2) and OD1C (λ_8) methods each with 920 s were found the lowest time in both stands. PCQM3 (Morisita 1971) (λ_{14}) and PCQM3 (Morisita 1957) (λ_{16}) methods with 4,370 s required the highest time in pure stand (Fig. 5). In mixed stand, the highest time was re-

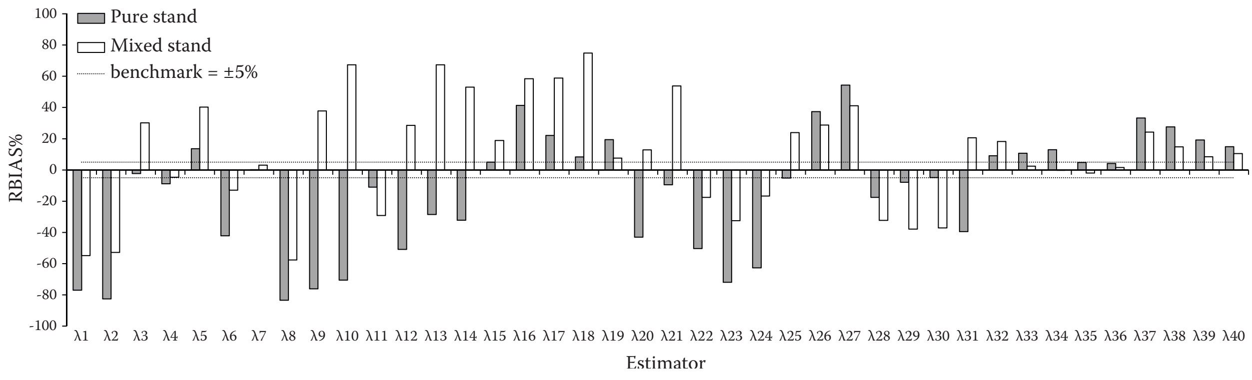

Fig. 4. Relative bias – RBIAS (%) comparison among estimators in pure and mixed stands

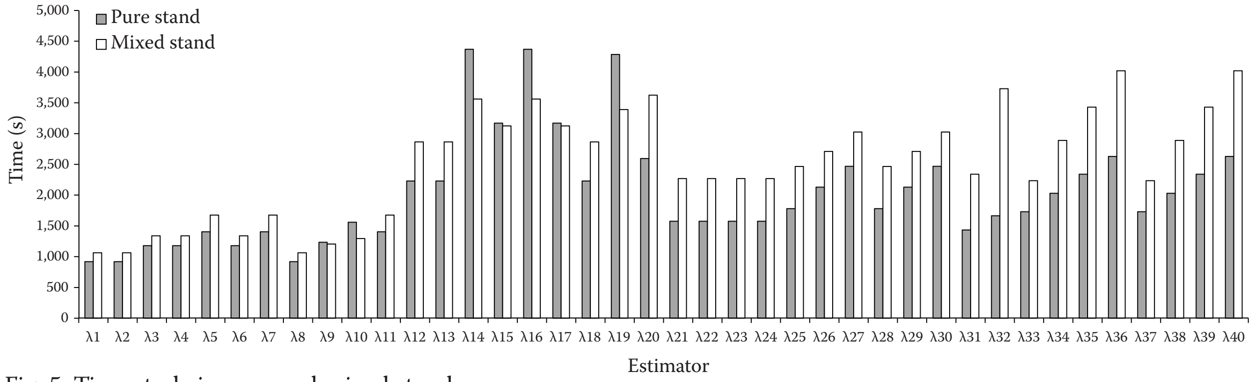

Fig. 5. Time study in pure and mixed stands

lated to 6-tree usual (λ_{36}) and 6-tree adjusted (λ_{40}) methods with 4,020 s (Fig. 5).

Efficiency. To compare the efficiency of sampling methods we used three parameters, $t \times$ RBIAS^2 and Ef$_{jk}$. QUAD (λ_{32}) was found the best method in both stands with values of 159,907 and 116,973 in terms of sampling error and time-consuming process study ($t \times E^2$) (Fig. 6a). In terms of relative bias and time-consuming process study ($t \times$ RBIAS^2), BDAV3 (λ_7, 56), BDNN1 (λ_3, 6,242), 6-tree usual (λ_{36}, 46,393) and VAT5 (Morisita 1957) (λ_{30}, 48,131) methods were found the best methods in

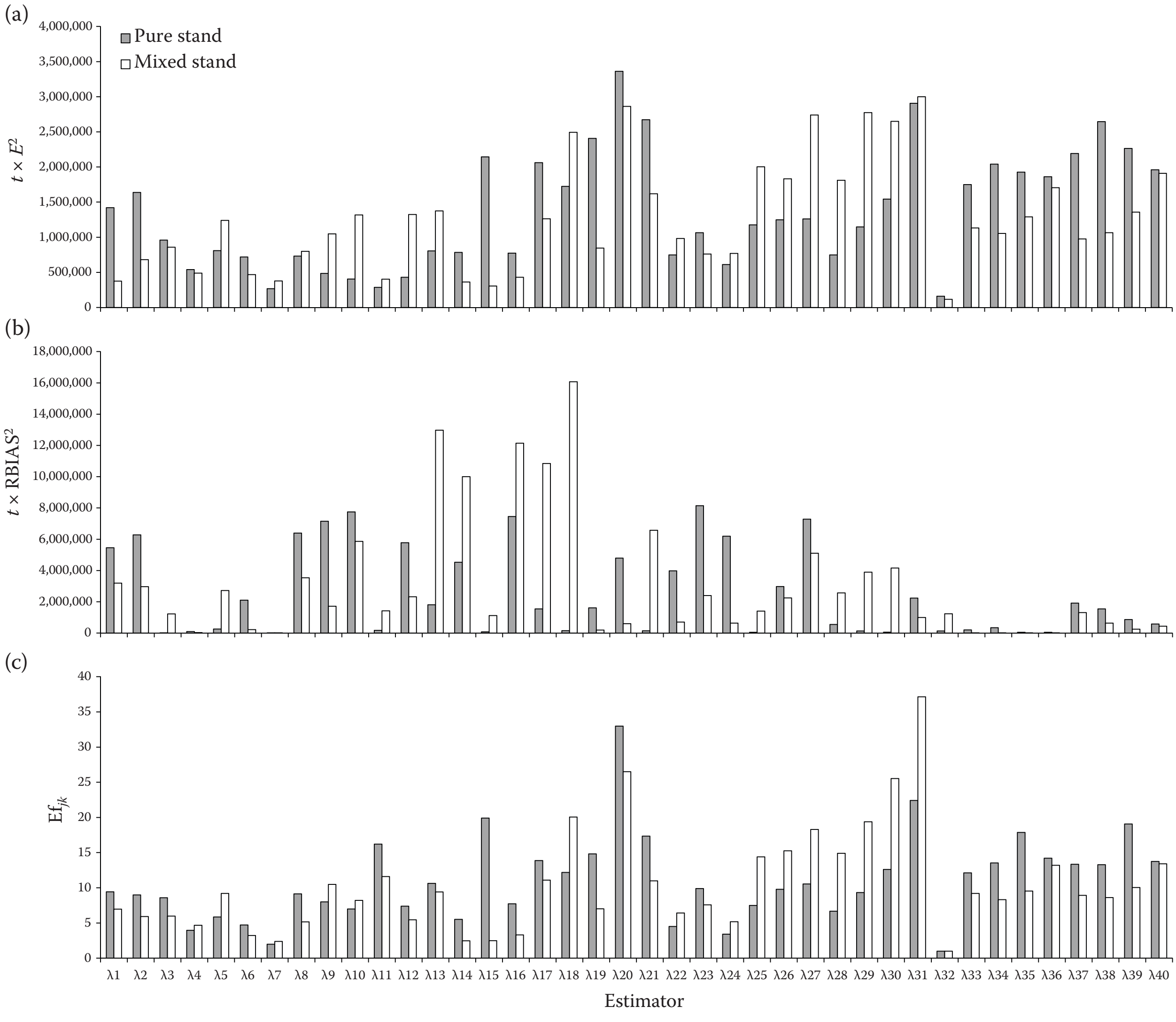

Fig. 6. Comparison of $t \times E^2$ (a), $t \times$ RBIAS^2 (b), Ef$_{jk}$ (c) among estimators in pure and mixed stands

t – study time, E (%) – sampling error at a confidence level of 95%, RBIAS (%) – relative bias, Ef$_{jk}$ – efficiency ratio between method j and k

pure stand (Fig. 6b) and 4-tree usual (λ_{34}, 260), 6-tree usual (λ_{36}, 10,291), 3-tree usual (λ_{33}, 12,874) and 5-tree usual (λ_{35}, 13,720) samplings were well efficient in mixed stand (Fig. 6b). QUAD (λ_{32}, 1) was found the most efficient followed by BDAV3 (λ_7) method (2 in pure and 2.4 in mixed stands) was obtained in both stands in terms of Ef_{jk} (Fig. 6c).

TOPSIS algorithm results. From the point of view of accuracy, precision and bias, VAT5 (Morisita 1957) (λ_{30}) followed by BDAV3 (λ_7) and QUAD (λ_{32}) with the highest relative closeness to the ideal solution 0.93, 0.93 and 0.92, respectively, were the best methods that were recognized in pure stand. PCQM2 (Morisita 1971) (λ_{15}, 0.91) and BDNN2 (λ_4, 0.91) were found in next ranks (Fig. 7a). 5-tree usual (λ_{35}) followed by 5-tree adjusted (λ_{39}) and T-square – TS2 (λ_{22}) with the highest relative closeness to the ideal solution 0.81, 0.80 and 0.80 were the best methods that were recognized in mixed stand. PCQM2 (Morisita 1971) (λ_{15}, 0.78) and QUAD (λ_{32}, 0.77) were immediately after TS2 (λ_{22}) with values of 0.80 and 0.80 (Fig. 7a).

From the point of view of efficiency, QUAD (λ_{32}) followed by basic distance second-nearest neighbour – BD2N (λ_5) and BDNN1 (λ_3) with the highest relative closeness to the ideal solution 0.99, 0.93 and 0.92, respectively, were recognized the best methods in pure stand (Fig. 7b). BDNN1 (λ_3) and BDAV3 (λ_7) were immediately after BD2N (λ_5) with values of 0.92 and 0.91. VAT3 (Parker 1979) (λ_{25}) followed by PCQM3 (Morisita 1971) (λ_{14}) and PCQM1 (λ_{12}) with the highest relative closeness to

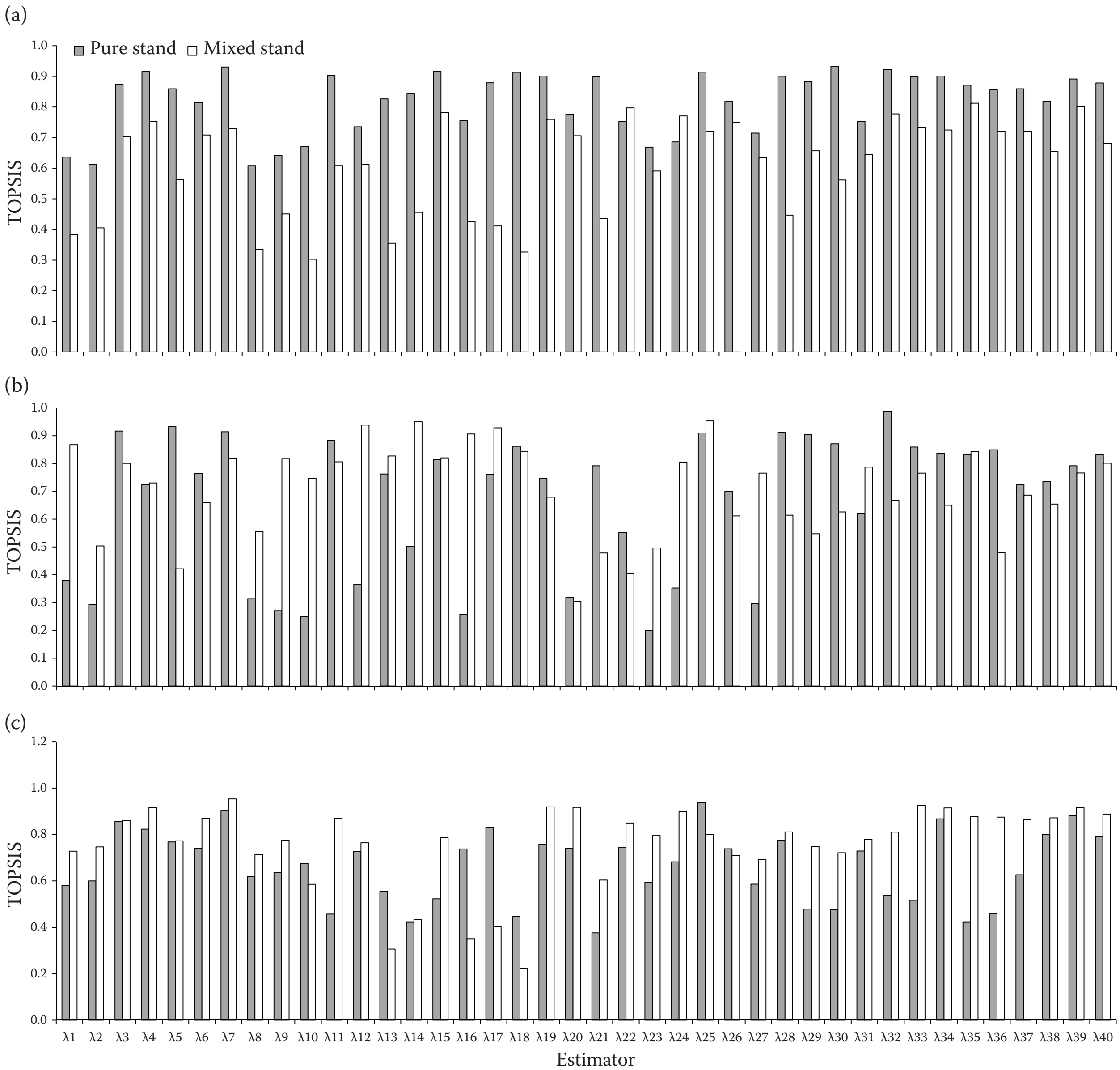

Fig. 7. Comparison of TOPSIS values in terms of accuracy, precision and bias (a), efficiency (b), all parameters (c) in pure and mixed stands

the ideal solution 0.95, 0.94 and 0.93, respectively, were recognized the best methods in mixed stand. PCQM2 (Morisita 1957) (λ_{17}, 0.92) and BDCI1 (λ_1, 0.91) were located after PCQM1 (λ_{12}) (Fig. 7b).

Regarding all criteria, VAT3 (Parker 1979) (λ_{25}) followed by BDAV3 (λ_7) and 5-tree adjusted (λ_{39}) with the highest relative closeness to the ideal solution 0.93, 0.90 and 0.88, respectively, were recognized the best methods in pure stand (Fig. 7c). 4-tree usual (λ_{34}) and BDNN1 (λ_3) were immediately after 5-tree adjusted (λ_{39}) with values of 0.87 and 0.86. BDAV3 (λ_7, 0.95) followed by 3-tree usual (λ_{33}) and quartered neighbour method – PCQMQN (λ_{19}) with the highest relative closeness to the ideal solution 0.93 and 0.92 were recognized the best methods in mixed stand. New PCQM (λ_{20}) and BDNN2 (λ_4) were immediately after PCQMQN (λ_{19}) with values of 0.92 and 0.91.

Summary results for the best methods

The best methods are summarized in Table 2 based on accuracy, precision, efficiency, time study and three forms of TOPSIS algorithm.

As can be seen in Table 2, for estimators that were studied, various results were obtained in pure and mixed stands. In general, we can consider the BDAV3 (λ_7) method as the best sampling in both stands in terms of all criteria. The above method plus the QUAD (λ_{32}) and VAT3 (Parker 1979) (λ_{25}) were also the best methods in pure stand in terms of most criteria while in mixed stand, *n*-tree and PCQM sampling group were the most commonly used in terms of many criteria.

DISCUSSION

Tree density

The tree density values (trees per hectare of *P. euphratica*) obtained in the present research are within the range of the results obtained in a previous survey in this region (Maasumi Babaarabi et al. 2018). This confirms the wide variation in tree density that can be found in the riparian forests dominated by *P. euphratica* and will have implications in estimating and managing reforestation in a broader program.

Sampling methods (accuracy, precision, bias)

The best and efficient estimator is the one the precision and accuracy of which are the highest and the bias of which is the lowest and the amount

Table 2. Summary results for the best methods in pure and mixed stands

Stands	Criteria	The best method
Pure	accuracy (RRMSE)	λ_7-λ_{32}-λ_{30}
	precision (CV)	λ_{32}
	bias (RBIAS)	λ_7-λ_3-λ_{36}-λ_{35}-λ_{30}-λ_{15}
	time-consuming process study	λ_1-λ_2-λ_8
	efficiency ($t \times E^2$)	λ_{32}-λ_7-λ_{11}
	efficiency ($t \times$ RBIAS^2)	λ_7-λ_3-λ_{36}-λ_{25}
	efficiency (Ef_{jk})	λ_{32}-λ_7-λ_{24}-λ_4
	three criteria compound (accuracy, precision, bias)	λ_{30}-λ_7-λ_{32}-λ_{15}-λ_4
	three efficiency criteria compound	λ_{32}-λ_5-λ_3-λ_7
	all criteria	λ_{25}-λ_7-λ_{39}-λ_3
Mixed	accuracy (RRMSE)	λ_7
	precision (CV)	λ_{32}-λ_{14}-λ_{15}
	bias (RBIAS)	λ_{34}-λ_{36}-λ_{35}-λ_{33}-λ_7-λ_4
	time consuming process study	λ_1-λ_2-λ_8
	efficiency ($t \times E^2$)	λ_{14}-λ_{15}-λ_{10}-λ_{12}
	efficiency ($t \times$ RBIAS^2)	λ_{34}-λ_{36}-λ_{33}-λ_{35}
	efficiency (Ef_{jk})	λ_{32}-λ_7-λ_{14}-λ_{15}
	three criteria compound (accuracy, precision, bias)	λ_{35}-λ_{39}-λ_{22}-λ_{15}-λ_{32}
	three efficiency criteria compound	λ_{25}-λ_{14}-λ_{12}-λ_{17}-λ_1
	all criteria	λ_7-λ_{33}-λ_{19}-λ_{20}-λ_4

RRMSE (%) – relative root mean square error, CV (%) – coefficient of variation, RBIAS (%) – relative bias, t – study time, E (%) – sampling error at a confidence level of 95%, Ef_{jk} – efficiency ratio between method j and k

of fieldwork can be minimized. VAT3 estimator (Parker 1979) was the best estimator in pure stand. The low RBIAS of VAT sampling is the most important reason for choosing this method. Engeman and Sugihara (1998) and Dobrowski and Murphy (2006) found that the VAT method was robust and more efficient. Kiani et al. (2013) showed that the VAT method was the best sampling method in all patterns in terms of RBIAS and time together. This confirms the finding of our study. White et al. (2008) found that the VAT3 (Parker 1979) method performed moderately well. Sheil et al. (2003) showed that the performance of VAT sampling was high in terms of easy and quick performance. This is consistent with the finding of Sheil et al. (2003) and White et al. (2008). Although some researchers reported that basic distance estimators showed poor performance for the clumped spatial pattern (Pollard 1971), they performed much better in this study than the other methods with the exception of QUAD method in pure stand. These methods were also better methods in terms of all criteria with the exception of precision than the others in pure stand. Estimators of basic distance use information from three distances (closest individual, nearest neighbour and second nearest neighbour) and it may help to explain why they are generally robust in pure stand in this study. Among basic distances, BDAV3 estimator was the best estimator in pure stand; it was also expected due to the simultaneous use of three types of distances in calculations, it provides more complete information than other basic estimators. Different results have been obtained for the compound method in various studies. In the Engeman et al. (1994) study, BDAV3 estimator performed poorly at the clumped pattern. Kiani et al. (2013) did not get a suitable result in their study in all spatial patterns. Askari et al. (2013) found that BDAV3 estimator was good for estimation of shrub density in the clumped pattern. White et al. (2008) found the mid-best performance for all cases. Our results confirm the finding of White et al. (2008) and Askari et al. (2013). In mixed stand, various results were obtained. Generally, three methods were chosen as the better method than the others, basic distance, angle ordered and *n*-tree sampling. The reasons for choosing these methods are the low RMSE, minimum relative bias and high weight effect in the TOPSIS algorithm. Two estimators BDAV3 and BDNN2 were obtained for the basic distance method. The BDAV3 has already been discussed. The reason for choosing this estimator is the lower RMSE and RBIAS than in the other estimators. Kiani et al. (2013) did not get a suitable result about BDNN2 in their study in all spatial patterns. Askari et al. (2013) found that BDNN2 was good for estimation of shrub density in the clumped pattern. The reasons for obtaining different results in different sources may be other conditions such as spatial patterns, low and high density and distribution of trees. Our results confirm the finding of Askari et al. (2013). In angle ordered methods, the area around the random point is divided into four 90° quadrants and finds individuals who are separated in each quadrant. It is obvious that these methods are known as the slowest method. The angle ordered sampling found good precision for density estimation (Beasom, Haucke 1975) but according to Borges Silva et al. (2017), some estimators, for example the one produced by Morisita (1957), showed moderately poor precision. Some estimators of this method were slightly unbiased in the study of Borges Silva et al. (2017).

Sampling methods (efficiency)

The efficiency of angle ordered methods has always been described by some authors (Sparks et al. 2002; Dahdouh-Guebas, Koedam 2006) regardless of different density. This confirms the finding of our study. Among angle ordered estimators, PCQMQN and new PCQM were the best estimators. Zhu and Zhang (2009) found that the performance of PCQMQN was better than the other distance methods especially in terms of precision. This method and new PCQM proposed by Kiani et al. (2013) obtained a suitable rank in mixed stand in our study and need further study, because there is little information about these estimators in references. In *n*-tree sampling, trees are measured within a circular plot with the radius *n*. As *n* increases, the plot area increases and naturally the measurement time increases, especially in mixed stand where trees are more scattered than in pure stand. The present results were similar to those reported by Moosaee Sanjerehei and Basiri (2008) and Kiani et al. (2013). According to the research of Lynch and Rusidi (1999), *n*-tree for $n = 3$, 4 and 5 with both usual and adjusted were the efficient techniques compared (they had the lower efficiency ratio than the others) for density estimation. In this study, 3-tree sampling usual was the best estimator. This confirms the finding of our results while Haxtema et al. (2012) inferred that *n*-tree for density estimation was poor in riparian forests. One reason for this result was related to the edge-effect which can be problematic issue in long and narrow riparian forests. This is not consistent with our results because we have corrected this effect by selecting an indicator area. The TOPSIS algorithm showed that considering efficiency, QUAD, BD2N, BDNN1 and BDAV3 were recognized the best methods in pure stand. QUAD as previously mentioned and as most researchers admitted, is more statistically efficient for density estimation (Nath et al. 2010; Haxtema et al. 2012; Hou et al. 2015). Sadeghi Kaji et al. (2014) showed that the performance of QUAD was good. The performance of BD2N and BDNN1 was poor (Engeman et al. 1994; White et al. 2008). This is not similar to the finding of Sheikholeslami et al. (2017). As the distances among trees increase, the denominator of the formulas (BD2N, BDNN1 and BDAV3) increases and the density decreases. The other reason for choosing these methods gives more weight to $t \times$ RBIAS^2 measure in the TOPSIS algorithm. Our results confirm the finding of Sheikholeslami et al. (2017). Some PCQM estimators and VAT3 (Parker 1979) were evaluated as suitable in mixed stand. Beasom and Haucke (1975) showed that PCQM methods were the most efficient for estimating density. Kiani et al. (2013) did not approve PCQM sampling due to practical difficulties and time needed to perform the estimators of PCQM method while they evaluated the VAT method appropriately. One of the reasons for choosing the VAT method in mixed stand is related to its low density compared to pure stand because the VAT method has low efficiency at high densities. As density increases, the counting is difficult in VAT method, when the tree population is dense (Parker 1979). This confirms the finding of our results.

Sampling methods (time-consuming process study)

The time-consuming process study showed that the quite time efficient methods were obtained for basic distance estimators. The nearest individual was cost-time in both stands. The shorter time of measurements in a group of nearest individual methods is evident because of a simple structure of these methods and only one distance measured. In pure stand, BDAV3 estimator was recognized as the preferred method in terms of each criterion with the exception of precision criteria. The performance of this method has been discussed previously. In mixed stand, the two estimators of PCQM and *n*-tree showed relative superiority in terms of each criterion. PCQM estimators showed better performance in terms of precision, $t \times E^2$, and Ef_{jk} while *n*-tree showed better performance in terms of RBIAS and $t \times$ RBIAS^2. The PCQM sampling found good precision for density estimation (Beasom, Haucke 1975) but according to Borges Silva et al. (2017), the PCQM method produced by Morisita (1957) showed a moderately poor precision in random and clumped patterns. This is not consistent with our results but it confirms the finding of Kiani et al. (2013). Unbiased density estimators for *n*-tree sampling existed in all patterns (Jonsson et al. 1992). Kiani et al. (2013) found that 3-tree adjusted was the best estimator according to bias. This confirms the finding of our results.

Sampling methods (TOPSIS algorithm)

The TOPSIS algorithm showed that considering accuracy, precision and bias together, VAT5 (Morisita 1957), BDAV3, QUAD, PCQM2 (Morisita 1971) and BDNN2 were recognized the best methods in pure stand. 5-tree usual, 5-tree adjusted, TS2, PCQM2 (Morisita 1971) and QUAD were found the best methods in mixed stand. The reasons for choosing these methods were high accuracy and precision and low bias. Engeman and Sugihara (1998) found that VAT sampling was most significantly improved by increasing *g* and also providing an optimal balance between the quality of estimation and labour in the field. Engeman and Sugihara (1998) also showed that the Morisita (1957) estimation formula for VAT sampling produced unsuitable results especially in the clumped pattern. This was not confirmed by the finding of our study. The performance of BDAV3 was confirmed earlier. QUAD sampling with adequate size would usually yield unbiased and accurate estimates of density (Krebs 2014). This method is one of the oldest techniques in forest sampling and is commonly used throughout the world (Haxtema et al. 2012). Bryant et al. (2004) and Kleinn and Vilčko (2006) showed that the QUAD method had the highest accuracy, more precision and lowest bias. This is consistent with our study but performance of QUAD was reported poor in terms of precision in the clumped pattern (Lessard et al. 2002). In some studies this method has been inferred unbiased for all spatial patterns (Palley, Horwitz 1961). PCQM methods showed the best overall performance (Engeman et al. 1994). PCQM methods with $g \geq 3$ are often impractical in the field. This is because of the difficulty of determining which individual is the g^{th}

(Dobrowski, Murphy 2006). In this research, $g = 2$ was the best. The BDNN2 method had high accuracy in a high density stands (Sheikholeslami et al. 2017). The reason given is that the longer the distance between the trees, the lower the estimated density. *n*-Tree sampling was the best method in mixed stand. Haxtema et al. (2012) inferred that *n*-tree for density estimation was poor in riparian forests. The reason for the poor performance of this method is attributed to the non-uniform scattered pattern of trees. This is not consistent with our results. Haxtema et al. (2012) found that as n ($n > 4$) increases, the accuracy of this method increases significantly. This is consistent with our results. n in the present study was obtained 5. T-square estimator (Byth 1982) was recognized as the mid-range of the performance among all methods and overall pattern in Engeman et al. (1994) and Kiani et al. (2013) study. This is consistent with our results.

CONCLUSIONS

The good performance of distance methods in our study was confirmed for natural pure and mixed stands of *P. euphratica*. The basic distance estimators such as BDNN1, BDNN2 and BDAV3 and *n*-tree were recognized suitable for both stands in comparison with other methods. These methods were recommended for sampling of riparian forests in both stands. VAT3 (Parker 1979) and QUAD can be recommended for pure stand. PCQMQN and new PCQM can be recommended for mixed stand.

Acknowledgement

We thank Mr. V. Rahimi for his help in field works. We also thank Dr. B. Kiani for his help in the analysis of data.

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Received for publication November 8, 2017
Accepted after corrections May 21, 2018