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## DESIGNING PROTECTIVE ECOTONES TO REDUCE ACOUSTIC LOAD ON THE RAILWAY LINES

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According to the results of the analysis of domestic and foreign literary sources, one of the most innovative ways of ensuring the stability of anthropogenically modified ecosystems is proposed, that is the creation of a system of protective type ecotones, which will allow providing ecological safety on the railways using exclusively natural environmental restoration mechanisms. On the experimental areas, we have described the taxonomic structure of forestry groups and phytocoenotic activity of species in forest grouping. We have also calculated the closeness, viability of the tree-stands, and also the projective shelter. To determine the noise effect, the noise-permeability of forest strips and the scattering of sound-currents from planting action have been analyzed. Based on research and calculations, a zone of sound shadow is determined depending on the size of the obstacle and the length of the sound wave. The acoustic effect of reducing the sound level is determined by such factors as bandwidth, dendrological composition, and design of plantations. The one-factor dispersion analysis allowed confirming that the investigated sections of the tracks of Lviv Railways differ significantly from each other according to these data. The results of the research were also subject to correlation analysis. The coefficients of pair correlation of structural indices of protective type ecotones were calculated with reduction of acoustic load on sections of the tracks of Lviv Railways. Therefore, the interrelation with the distance, the horizontal closure of the tree canopy, the distance between the trees, the height of the shaft and the crown density were reliably established. On this basis, the multiplicity regression equation for complex estimation of acoustic load reduction and prediction of noise reduction with specified parameters of protective type ecotones were calculated.

**Keywords:** protective type ecotones; forest groupings; closeness; viability; noise-permeability; scattering of sound streams; acoustic effect; coefficient of pair correlation

Road traffic noise is one of the most common environmental problems in the EU, which has negative consequences for society (Aasvang et al., 2011, Alekseev and Kadyskina, 1977; Blidberg, 2011; Croy, Smith and Waye, 2013; Diduh, 1982). Noise pollution affects the quality of human life and is in the second place after the problem of air pollution (de Vos, 2016). At present, according to the World Health Organization (WHO), about 210 million people in the EU are regularly exposed to more than 55 decibels (dBA) of traffic noise, which is at a level when noise has a negative impact on humans.

In this work, it is proposed to evaluate the role of structural parameters of consortive protective ecotones (CPE) in reducing the level of acoustic load on adjacent agrocoenoses and residential areas and derive equations that allow calculating noise abatement on the rail tracks.

### Material and method

The study of PFP parameters took place on trial plots (TP). The trees were described by species and viability (VA). The tree tally data were recorded on tally sheets. The measurement of

tree diameters was carried out with a caliper. The plantation's height was measured by using the EB-1 hypsometer. The species composition of the vegetation on the trial plots was found during the processing of 60 geobotanical descriptions. The structural and comparative analysis of the floristic composition of the plots was carried out using the biomorph classifications of (I.G. Serebryakov and K. Raunkier 1934), the linear system of living forms of V.M. Golubev, the ecomorph and coenomorph systems of A.L. Belgard.

The determination of the noise effect implies the determination of the noise-penetration of forest strips and the dispersion of sound streams under the action of the stands. The studies were carried out using a noise-level meter spectral analyzer and a portable OCTAVA-110A vibrometer. The measurement error of the noise-level meter in the normal conditions of application for a plane 1,000 Hz frequency wave and a level of 94 dB, which propagates in the reference direction (orthogonal to the plane of the microphone capsule membrane) in a free acoustic field, at the S characteristic, does not exceed 0.7 dBA.

The noise-level meter is installed at a distance of 1 m from the ground taking into account the terrain of the territory. Only flat areas were selected for the study to prevent changes

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in the turbulent regime. The measurements were carried out in the CPE in leafless condition in March and October and in a leafy state in May and August. The measurements were carried out in cloudy weather.

Noise level measurements were taken at different distances from the tracks. The following observation points were established: 2 m from the tracks – point 1; at a distance of 5 m – in front of the forest strip – point 2; point 3, in the strip – at a distance of 50 m from the tracks; point 4, in the strip – at a distance of 100 m from the tracks; point 5, in the strip – at a distance of 150 m and point 6, behind the strip – at a distance of 200 m from the tracks.

In order to analyze the results obtained, the program 110\_UTIL-Light was used. The noise level for each type of railway transport on the section of the Lviv-Stryi railway was determined on a 10-km zone where, under normal conditions, the train speed is unchanged. The following sources of acoustic pollution were studied: electric trains, freight and passenger trains. In order to obtain objective results, the condition of the plantings was taken into account, that is, in leafless and leafy states.

### Results and discussion

CPE reduces the noise level on railway tracks by attenuating sound vibrations at the moment of their passage through branches, leaves and needle-foliage. Sound, getting into the crown, finds itself as if in another medium, which, having much greater than air acoustic resistance, reflects and dissipates up to 74% and absorbs up to 26% of sound energy. In summer, plantings reduce noise by 7–8 dB, in winter – by 3–4 dB.

The measurement of noise level from electric trains was carried out under conditions of a single noise source, moving at a speed of 60 km.h<sup>-1</sup>. The study showed that there are insignificant differences in the noise level, depending on the condition of the plantings. The measurement of noise level from passenger trains was carried out under conditions of a single noise source which

moves at a speed of 90 km.h<sup>-1</sup>. The measurement of noise measurement from freight trains was carried out under conditions of a single noise source, moving at a speed of 90 km.h<sup>-1</sup>. The parallel measurement of the acoustic pollution level at the Lviv-Stryi railway section confirms the hypothesis that the CPE plays the role of a noise pollution filter, cutting down and partially dissipating the noise. The studies have revealed the general tendency towards reduction of noise level from all the investigated sources of noise by 20 dBA, which enhances comfort on the territory adjoining to the rail tracks. In a leafy state, CPE performs the role of a sound waves scatterer better than in a leafless state. Fluctuations in the noise level depending on the state of the plantation is 4–6 dBA, which is an indicator of the greater noise absorbing efficiency of the plantations in a leafy state.

According to the calculation scheme and the value of the specific sound absorption by green plantations, we determine the estimated elements. The distance from the noise source to the crown of the first CPE strip is  $r_1 = 0.5 + 1.75 = 2.25$  m, the width of strips in the CPE is  $B_1 = 0.5 + 1.5 + 3.5 + 2.5 = 8$  m,  $B_2 = 2.5 + 3.5 + 3.5 + 1.3 + 0.5 = 11.3$  m, the width of the gaps between the strips of green plantations  $A_1 = 4.5 + 0.7 - 2.5 + 1.0 - 2.5 = 1.2$  m,  $A_2 = 1.5 - 0.5 = 1.0$  m, the number of rows in the CPE is  $z = 2$  and the specific absorption coefficient of sound energy is  $\beta = 0.15$ . Then, the noise reduction efficiency of this CPE is equal to:

$$L_{e\beta} = 10 \cdot \lg \left( \frac{2.25 + 19.3 + 2.2}{2.25} \right) + 1.5 \cdot 2 + 0.15 \cdot 19.3 = 16.1 \text{ dBA} \quad (1)$$

The sound waves reaching CPE are absorbed by leaves and branches of the trees. The most effective for the absorption of noise pollution are those plants that have thick leaves on thin branches. To obtain a noticeable noise-protection effect, plantings should be thick and have a dense green mass of crowns of the trees and bushes. The acoustic effect of reducing the sound level is determined by factors such as the width of the strip, the dendrological composition and the structure of the stands. Green

**Table 1** The results of acoustic pollution measurement on the railway section Lviv – Stryi

Point	Distance from the tracks (m)	Noise level, dBA	
		leafless state	leafy state
		winter (January)	summer (July)
<b>Left side</b>			
1	2	96.2	95.6
2	50	90.4	89.3
3	150	82.9	79.8
4	200	68.5	65.4
<b>Right side</b>			
1	2	97.4	95.1
2	50	91.3	88.0
3	150	83.4	78.6
4	200	69.1	65.7

plantings, formed as special noise protection strips, can have the effect of reducing the noise level by 8 dBA. The high effect is achieved by plantings of 20 m wide consisting of five rows of coniferous trees and two rows of shrubs. However, it is more effective to plant several dense strips of trees at such a distance from each other so that their crowns do not close. In this case, each row of trees acting as a dense hedge reduces noise by 1–2 dB, becoming a new obstacle in the way of its movement, shielding it. The space between the rows covered with grassy vegetation also participates in the absorption of sound waves.

Planting trees in the strip can be in lines or quincunx with a distance between the trees being no more than 4 m and the tree height not less than 5–8 m, and the height of shrubs – 1.5–2 m. It should be noted that quincunx planting is more efficient for noise reduction. Green plantings of conifers are more effective for noise protection than deciduous ones and do not depend on the time of year.

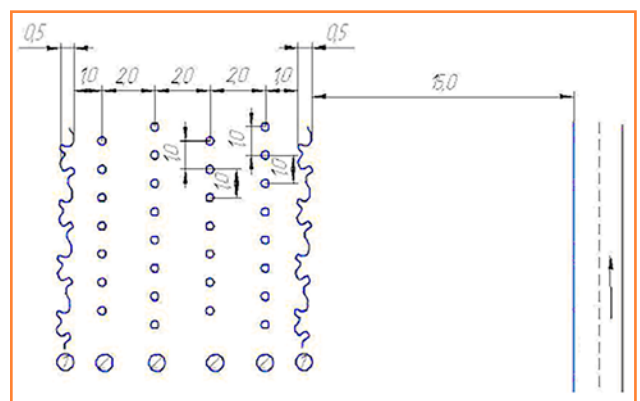
**CPE description by structural indicators**

As can be seen from Fig. 1, the level of noise generated on railway tracks penetrates into the depth of CPE differently. For each object under study, it is peculiar. Therefore, to say that noise reduction is associated only with the distance is not wholly true.

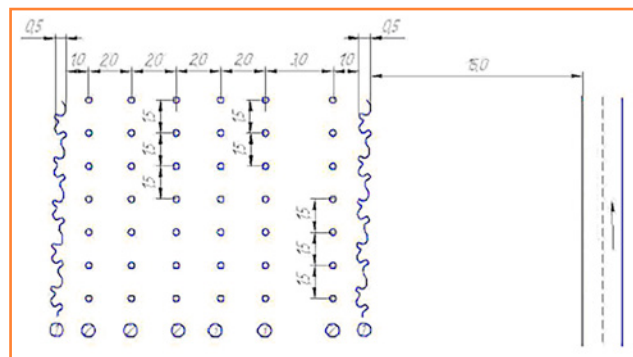
For each point of recording the noise level on the Lviv railways, trial plots (TP) were established and a description of the CPE was made according to structural parameters: the stand canopy density, the distance between the trees,

the height of the tree trunks, the density of the crown of the trees and bushes (the area occupied by a TP, in percentage). The stand canopy density was taken into account to a certain point on the given TP.

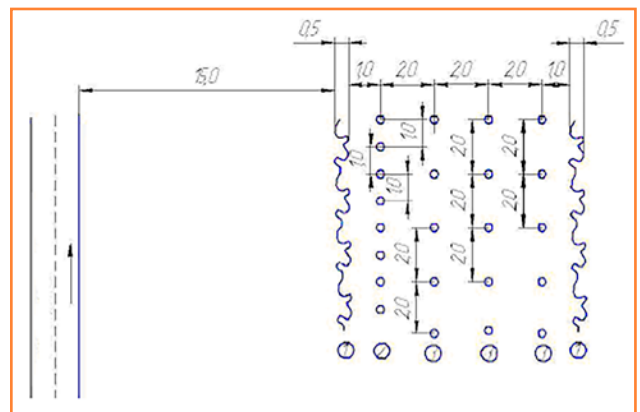
On the railway section Lviv-Sambir (Fig. 1a), predominant are TPs with a half-open type of spatial structure (HOTSS), characterized by stand density of 0.6 to 0.3. The trees are located at a distance of 3.0 m from each other, the height of the trunk is 6.0–7.0 m, and the density of the crown is from 60 to 40%. On the railway section, there are shrubs 0.5–0.7 m high which occupy an insignificant part of the TPs, less than 2%. When describing the structural parameters of the CPE,



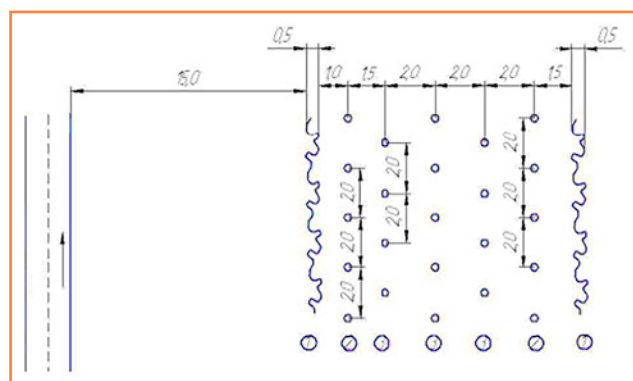
c) The CPE plan of the Lviv- Rava-Ruska section of the Lviv railways



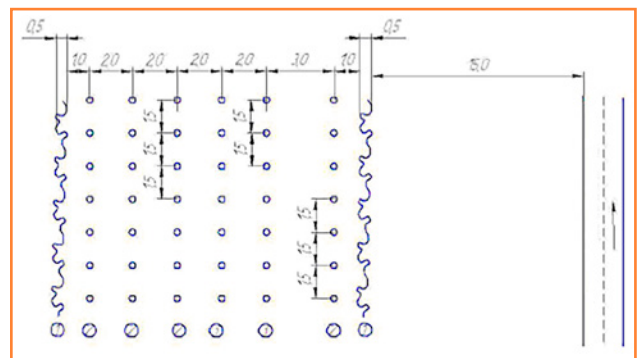
a) The CPE plan of the Lviv-Sambor section of the Lviv railways



d) The CPE plan of the Lviv-Kovel section of the Lviv railways



b) The CPE plan of the Lviv-Ivano-Frankivsk section of the Lviv railways



e) The CPE plan of the Lviv-Krasne section of the Lviv railways

**Figure 1** The CPE plans of the Lviv railways sections

they were not taken into account, since they are below the height of the noise measurement.

The Lviv-iv. Frankivsk railway section (Fig. 1b) is characterized by a TP with a closed type of spatial structure (CTSS) and the stand canopy density being between 0.98 and 0.72. The plant spacing is 4.0 m and 2.8 m, the trunk height being 5.0 m and 8.0 m, and the crown density – 60–70%. Shrubs are not encountered on any TP.

The Lviv – Rava-Ruska railway section (Fig. 1c) is characterized by the presence of shrubs on the territory of the trial plots which cover the under-tree space. The stand canopy density is low: 0.5–0.2, there are also plantations that are characterized by a very low stand canopy density: up to 0.14. According to the height of the trunks and the density of the crown, there can be distinguished two groups:

1. with a distance of 4.0–5.0 m, the height of the trunk of 2.0–3.0 m, and the crown density of 80–70%;
2. the distance is 2.5–3.5 m, the height of the trunk is 3.5–8.0 m, and the crown density is 50–60%.

On the Lviv-Kovel railway section (Fig. 1d), the same as for the Lviv – Rava-Ruska railway section, the test plots have a low stand canopy density: from 0.58 to 0.24. The tree

grows in the CPE with a distance of 4.5 m between them, the height of the trunk is 2.0–2.5 m, and crown density is high: 80–90%. On this section of the railway tracks, there are 2 TPs which have shrubs covering the under-tree space.

On the Lviv-Krasne railway section (Fig. 1e), the trial plots are characterized with the stand canopy density of 0.88 to 0.4. According to the height of the trunk and the density of the crown, there can be distinguished two groups: with the plant spacing of 4.0–4.5 m, the height of the trunk being 3.5–4.0 m, and the crown density is 70%; the plant spacing is 3.0–3.5 m, the height of the trunk being 5.0–7.0 m, and the crown density is 60–70%. As on the Lviv-Sambir section, shrubs growing here are 0.5 to 0.9 m high.

To further investigate the influence of CPE structural parameters on the noise level, linearization of the distance data was carried out.

Single-factor variance analysis of the CPE by noise level and structural parameters. In the process of analyzing and generalizing the results obtained, it was found that none of the studied indicators at each railway track section of the Lviv railways had a clear relationship with a decrease in noise level. Using them, it is rather difficult to give with a sufficient degree of reliability an estimate of noise reduction by the

**Table 2** Single-factor variance analysis of CPE by noise level and structural parameters.

Source of variations	Sum of squares	Degrees of freedom	Dispersion	Fpoz	Probability	Fst	Strength of factor influence
<b>Single-factor variance analysis by noise level</b>							
Between groups	1,057.5	5	211.5	4.19	99.86	2.28	12.80
Inside the groups	7,212.1	143	50.4				
Total	8,269.6	148					
<b>Single-factor variance analysis by crown density</b>							
Between groups	4.37	5	0.87	51.20	99.98	2.28	68.07
Inside the groups	2.05	120	0.02				
Total	6.42	125					
<b>Single-factor variance analysis by distance between trees</b>							
Between groups	57.83	5	11.57	31.27	99.98	2.29	56.58
Inside the groups	44.38	120	0.37				
Total	102.21	125					
<b>Single-factor variance analysis by shrubs</b>							
Between groups	489.39	5	97.88	4.93	99.99	2.29	17.03
Inside the groups	2,383.97	120	19.87				
Total	2,873.36	125					
<b>Single-factor variance analysis by trunk height</b>							
Between groups	431.28	5	86.26	63.77	99.99	2.29	72.66
Inside the groups	162.32	120	1.35				
Total	593.59	125					
<b>Single-factor variance analysis by stand canopy density</b>							
Between groups	12,684.94	5	2,536.99	20.68	99.99	2.29	46.29
Inside the groups	14,719.03	120	122.66				
Total	27,403.97	125					

structural components of CPE, therefore, they could not be recommended for each section of the railway tracks as diagnostic signs when selecting a CPE to reduce the acoustic load on the railway lines of the Lviv railways.

As a result, it was found out that the studied rail track sections of the Lviv railways differ in noise level. To determine the noise reduction values, the difference between the noise along the railway tracks and the point of recording the noise level behind the CPE was found. Therefore, a comprehensive assessment of the noise reduction on all the studied sections of the railway tracks is required in accordance with the significance of each studied indicator.

### Correlation analysis of structural parameters of CPE

The results of the study were subjected to a correlation analysis; pair correlation coefficients of structural parameters of CPE with the reduced acoustic loading on the sections of the rail tracks of the Lviv railways were calculated. As can be seen from this analysis, there is a close relationship between the distance, the horizontal closure of the tree canopy, the distance between the trees and the height of the trunk, the density of the crown. When describing the structural parameters on the trial plots, the presence of shrubs is taken into account only at a distance of no more than 105.0 m. When this condition is met, the shrubs are definitely associated with noise reduction.

To calculate the equations of multiple regressions, the most informative were selected, that is, for which the pair-correlation coefficients with a decrease in the acoustic load were reliable (at a significance level of 0.95).

Based on this, for a given set of structural parameters of CPE, multiple regression equations are calculated for a comprehensive assessment of the reduction in acoustic load. The only indicator that was not taken into account is the height of the trunk, since it is closely related to the plant spacing. As shown by the correlation analysis, the effect of shrubs was found only at a distance of 105.0 m; therefore, the coefficients of the multiple regression equation were calculated separately for shrubs as well. As a result, two multiple regression equations were obtained.

The equation for calculating noise reduction takes the form:

$$Y = 5.01 \ln X_1 - 2.84 X_2 - 1.23 X_3 + 0.07 X_4 - 5.07 \quad (2)$$

where:

$Y$  – the reduction in the level of acoustic load

- $X_1$  – the distance from the noise source to the point of recording the noise level
- $X_2$  – the stand canopy density
- $X_3$  – the distance between trees (m)
- $X_4$  – the crown density (%)

This equation is used only to calculate the reduction in the acoustic load on railway lines at a distance of no more than 200.0 m. The estimates of the coefficients and their reliability are given in Table 3.

The conducted research allowed identifying patterns of noise reduction not only due to the distance, but also structural parameters of CPE. The most significant of them were the canopy closure, the plant spacing, shrubs and the crown density. The equation of multiple regression is calculated, which allows predicting a reduction in the noise level with the given CPE parameters.

### Conclusions

On the basis of the investigated system of the spatial structure of CPE, the main principle of the establishment and functioning of PFPs on the railway lines is highlighted.

The correlation analysis of the structural parameters of CPE with a decrease in the noise level showed the following: for all the study objects, the correlation coefficient indicates a close relationship between the distance from the noise source and noise reduction ( $r = 0.79 \times 0.93$ ); on the Lviv-Sambir and the Lviv-Kovel railway sections, the obtained values of the correlation coefficient ( $r = 0.41 \times 0.4$ ) indicate an average relationship between the horizontal closure of the tree canopy and the reduction of noise – the higher the stand canopy density, the greater the noise reduction. The calculated criterion of significance of the correlation coefficient is equal to the theoretical one, which indicates a significant relationship between the investigated characteristics. On the Lviv-Kovel and the Lviv-Iv. Frankivsk railway sections, the correlation between the characteristics is weak ( $r = -0.18 \times 0.13$ ). On the Lviv-Iv. Frankivsk railway section, the resulting  $r = -0.61$ , that is, the lower the horizontal closure of the tree canopy, the greater the reduction in noise. This phenomenon is due to the fact that the trial plots located farther from the noise source are characterized by lower canopy density than the trial plots located closer to the noise source; on the Lviv-Sambir, the Lviv – Rava-Ruska, the Lviv – Kovel, the Lviv – Iv. Frankivsk railway sections, the obtained correlation coefficients for distance and noise reduction ( $r = -0.54 \times 0.46$ ) indicate an average relationship between the studied characteristics.

**Table 3** Estimation of the values of the coefficients and their reliability for the equation for calculating the reduction in the level of acoustic load on the railway lines

Parameters	Equation coefficients	Standard error	Student's test	Effect of factor (%)
Intercept term	-5.07	1.943	-2.61	–
$X_1$	5.01	0.358	13.99	54.75
$X_2$	-2.84	0.487	-5.83	31.04
$X_3$	-1.23	0.264	-4.68	13.44
$X_4$	0.07	0.018	3.84	0.77

$$R^2 = 0.96; F = 438.04; SE = 1.99$$

The calculated criteria of significance of the correlation coefficient are more theoretical, indicating a significant relationship between the investigated characteristics. It is found out that the smaller the distance between the trees, the greater the reduction in noise. On the Lviv-Iv.Frankivsk railway section, the trial plots have the same distance between the trees. Shrubs are present only on the trial plots of the Lviv-Kovel and the Lviv-Rava-Ruska railway sections. On the Lviv-Kovel railway section, there are only 2 trial plots where shrubs are encountered, so it is difficult to draw conclusions about their impact. The significant impact of shrubs on noise reduction was detected on the Lviv-Rava-Ruska railway section ( $r = 0.53$ ). On the trial plots with shrubs, noise reduction is much higher than without them; in all the objects studied, a connection was established with the height of the trunk and the level of the acoustic load. On the Lviv-Sambir, the Lviv-Kovel and the Lviv-Rava-Ruska railway sections, using the calculated correlation coefficient ( $r = 0.6 \times 0.54$ ), it was found out that increasing height of the trunk reduces the level of acoustic load to a larger extent. On the Lviv-Iv.Frankivsk and the Lviv-Kovel railway sections, using the correlation coefficient ( $r = -0.41 \times -0.54$ ), it was found out that with a reduction in the trunk height, the level of acoustic load also decreases ( $r = 0.6 \times 0.54$ ) on the trial sites of all sections of the Lviv railways, except the Lviv-Sambir and the Lviv-Ivan Frankivsk sections, it is reliably established that the higher the crown density, the greater the reduction in the acoustic load on the adjacent territory ( $r = -0.56 \times 0.47$ ). On the Lviv-Iv.Frankivsk section, the value of the correlation coefficient is lower than the theoretical value; therefore, the connection is not traced. On the Lviv-Sambir section, the correlation coefficient ( $r = -0.52$ ) indicates that with a decrease in the crown density, the decrease in the acoustic load is higher. But, just as for the Lviv-Rava-Ruska railway section, when identifying the relationship between the height of the trunk and reducing the acoustic load, for the recording points of the noise level located farther from

the noise source, the trial plots are characterized by low crown density. But, if we take the recording points of the acoustic load level approximately at an equal distance from the rail tracks, then the relationship is similar to the other studied railway sections of the Lviv railways.

The studies have revealed patterns of reducing the acoustic load at the expense of not only the distance but also the structural parameters of CPE. The most significant of them turned out to be: the stand canopy closure, the plant spacing, the presence of shrubs and the crown density.

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