Environmental Plasticity and Stability of Introduced Euramerican Poplar Hybrids Depending on Climate Variation

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Abstract. Euramerican poplars are used in many countries of the world, but they are not always suitable for the cold climate of the northern regions. In particular, they are not winter-resistant enough for Russia’s conditions. Field testing of 23 clones from 10 varieties of these poplars in the forest steppe of the Central Black Earth Region of Russia allowed identifying varieties that are winter-resistant in these conditions. They have high survival and productivity. The study of them during various periods of growth, using the Eberhart and Russell method, made it possible to identify a number of varieties with not only high productivity and survival, but also with considerable environmental plasticity to the changing weather and climatic conditions of the region.

1. Introduction

Research of the euramerican poplar hybrids and their practical use are carried out in many countries of the world [1]. Euramerican poplar hybrids are particularly widespread. However, not all of these hybrids are highly ecological adaptable, which prevents their cultivation in countries with unfavorable climatic conditions. Therefore, their ability to adapt to new conditions must be taken into account when introducing them.

In the Voronezh region of the Central Chernozem Region, studies of these varieties were conducted at different sites, but their greatest representation was at the Semiluky populetum of the Voronezh region, established in the spring of 1974. 30 clones of different cultivars of euramerican hybrids of black poplars were collected in there. A number of cultivars: ‘I-214’ (4 clones), ‘I-455’ (1 clone), ‘I-154’ (1 clone) and ‘Sacrau-79’ (1 clone) – had frozen out and died in the first years of cultivation. Others 23 clones of 10 cultivars, so-called ‘old varieties’ [2] showed good results of survival and growth. But not all of them had the same results by the age of the economic exploitability.

It is important to assess the response of certain poplar cultivars to changing climatic conditions of the environment [3, 4]. In agriculture, varieties are already widely bred based on their reaction to changes in environmental conditions. The works of Russian researchers on studying the ecological plasticity and stability of various potato varieties in a wide range of climatic conditions are widely...
known: in the Bryansk region [5], in the Chelyabinsk region [6], in the Kirov region [7], in the Tyumen’ region [8] and in the Kamchatka Krai [9]. A large amount of research is carried out to assess the environmental plasticity and stability of various varieties of winter crops (rye and wheat) in the Bryansk region [10-12], in the Samara region [13] and in the Kirov region [14], spring wheat varieties in the Kemerovo region [15] and in the Omsk region [16], spring triticale varieties in the Middle Amur region [17], and legume varieties – chickpeas in the Omsk region [18], peas in the Nizhny Novgorod region [19], soy in various climatic provinces of Ukraine [20] and so on. Abroad, much attention is also paid to the plasticity of various traits in agricultural crops [21, 22].

Among tree species, in researching of environmental plasticity and stability, more attention is also paid to varieties of agricultural fruit, nut and cocoa plants. E.g., studies on the ecological plasticity of various plum varieties in the Krasnodar Region [23] and in the Chelyabinsk region [24], hazel varieties in the Volgograd region [25] and phenotypic plasticity of cocoa varieties in Brazil [26].

When evaluating forest woody plants, in Russia such works were significantly less [27, 28]. But abroad in recent times it became relevant to determinate the phenotypic plasticity of different traits in forest species, especially among tropical woods [29-31].

Recently, abroad there are more and more publications about the assessment of ecological stability and phenotypic plasticity of poplars because of their fast growing. E.g., the study of intersectional poplar hybrids in four Mediterranean provinces of Spain [32], the study of the phenotypic response of black poplars to various water and drought regimes in France [33, 34], the assessment of adaptation and genotype yield stability of various Australian clones of Populus deltoides W. Bartram ex Marshall and Populus canadensis Moench in different environmental conditions in Paraná River Delta, Argentina [35, 36] and so on.

At the same time, the listed publications considered different approaches to evaluating the productivity of the tested plants. Thus, when developing general approaches [3]; evaluating the ecological stability of poplars in semi-desert conditions [27] and the ecological stability of geographical spruce ‘races’ [28] etc., plants growing in different edaphotypes were evaluated. In this case, soil-geographical and climate factors were taken into account when assessing the impact of the environment. In the same works with potatoes in the Bryansk region in 2005-2007 [5]; spring wheat of soft varieties in the Omsk region in 2008-2013 [16] and plums in the Chelyabinsk region in 2014-2018 [24] the main focus was on the influence of weather and climate conditions. Since there are no similar works with poplars in Russia, we tried to investigate the relationship of their productivity and stability with climate factors.

Thus, the purpose of this work was to establish the survival, growth, productivity and environmental plasticity and stability of the so-called ‘old’ euramerican hybrids of black poplars, depending on the variability of climatic conditions in the forest-steppe zone of the Central Black Earth Region of Russia.

2. Methods and materials

The research was carried out at the Semiluky populetum of the Voronezh region (located 30 km from Voronezh), which was laid in the spring of 1974 under supervising of A P Tsarev in accordance with the methodology of field experience [37, 38]. Soil preparation before planting – autumn plowing to a depth of 30 cm. The planting was carried out by stem cuttings of various varieties and clones of poplars. The land area was 4.6 hectares, size 296×155 m. The soil is Typical Chernozem. The terrain is a weak dividing slope to the Veduga River. The water table is 4-5 m. The forest type is D2. The plant placement was 5x4 m. The experiment was performed in 4 repetitions. Placement of plots in repetitions is randomized. The number of ramets (plants of one clone) in the plot is 6. Each clone is represented by 24 plants on an area of 480 m² (20 m² × 6 ramets × 4 repetitions).

The experiment included 84 representatives of various sections of poplars (white, black, balsam and hybrids between them). It is including, as noted above, 30 clones of euramerican hybrids of black poplars obtained from various foreign countries (Bulgaria, GDR, Romania, etc.) and regions of the former Soviet Union. Over time, 10 cultivars, each included from 1 to 4 clones, showed the best indices of survival and growth. This list includes the following so-called ‘old’ varieties: ‘Bachelieri’ (clone No. 30),...
'Brabantica' (clones No. 36, 56, 158), 'Vernirubens' (clone No. 54), 'Gelrica' (clones No. 21, 80), 'Caroline' (clone No. 162), 'Marilandica' (clones No. 34, 88, X), 'Regenerata' (clones No. 78, 79, 90, 116), 'Robusta' (clones No. 60, 66, 156), 'Sacrau-59' (clone No. 161), 'Serotina' (clone No. 19).

To assess ecological plasticity and stability, we used the average indices of plant survival and growth over 20 years, which were divided into 5-year periods of ontogenesis in accordance with age classes for fast-growing woody plants [39]. The age of the initial assessment was made after five years, when the growth of poplars reached a plateau, after which their growth ranks are stabilized [40]. The final measurements were timed to the age of economic exploitability in various sections of Populus L. close to 25 years [41], inter alia for Eupopulus L. [42], for white poplars [43], for black pyramidal poplars [44], for balsam poplars [45] and for intersectional hybrids [46-48].

For the studied varieties, the survival, height, diameter, trunk volume, wood stock, average and current annual increment (c. a. i.), as well as environmental plasticity and stability were evaluated.

Survival was taken into account as a percentage of the number of planted trees. The height was measured using the German altimeter 'Blume Leiss'. To obtain the diameter, the circumference was measured at a height of 1.3 m using a measuring tape and then recalculated. The volume of trunks for this study was determined by the formula (1):

\[ V = \frac{\pi \cdot D^2 \cdot H \cdot f}{10000} \text{ (m}^3) \]  

(1)

where: \( V \)– trunk volume, in m\(^3\); \( H \) – trunk height, in m; \( D \) – diameter of the trunk at a height on the basic area (of 1.3 m), in cm; \( f \) – is the trunk shape coefficient, which for poplar, equal to 0.39 [49]; \( \pi = 3.14 \).

Wood stocks were determined using the formula (2):

\[ W = \frac{V \cdot N \cdot S}{100} \text{ (m}^3/\text{ha}), \]  

(2)

where: \( V \)– average volume of the trunk (m\(^3\)); \( S \) – survival of the plants (%); \( N \) – planting density per ha (500 trees/ha).

Average \((Z_{m.a.i.})\) and current increments \((Z_{c.a.i.})\) were determined based on the obtained wood stocks. All indices were averaged over 5-year periods, as customary in the taxation of fast-growing tree species [50]. In addition, it was also necessary to take into account the fact that woody perennials have a somewhat deferred response to weather fluctuations compared with annual plants. Therefore, the assessment of their response to weather changes over five-year periods allows us to obtain more objective indices.

Climate indices of the assessment periods of productivity and ecological plasticity and stability of poplars were taken from archival data of the Voronezh hydro meteorological station and from available literature sources [51, 52]. Actual and averaged data for 5-year periods are shown in table 1.

**Table 1.** The annual temperatures and precipitation in Voronezh region.

| Years | Minimum t °C | Maximum t °C | Average t °C | Annual precipitation, mm |
|-------|--------------|--------------|--------------|--------------------------|
| 1979  | 1.9          | 10.4         | 6.2          | 566                      |
| 1980  | 0.9          | 8.9          | 4.8          | 845                      |
| 1981  | 3.5          | 11.8         | 7.5          | 676                      |
| 1982  | 2.7          | 10.7         | 6.4          | 614                      |
| 1983  | 3.3          | 2.1          | 7.4          | 518                      |
| Average for the period 1979-1983 | 2.46      | 10.78        | 6.46         | 643.8                    |
| 1984  | 2.0          | 10.8         | 6.0          | 422                      |
| 1985  | 1.1          | 10.0         | 5.2          | 672                      |
| 1986  | 1.5          | 11.2         | 6.0          | 476                      |
The study of ecological plasticity and stability of poplar cultivars was performed using the Joint Linear Regression proposed by Yates and Cochran [53], modified by Finlay and Wilkinson [54], Eberhart and Russell [55], and modified for domestic conditions [3, 4]. In a slightly modified form for assessing especially the climate impact, it can be presented as a formula (3).

\[ X_{ij} = \bar{X}_i + r_i l_j + d_{ij}, \]  

(3)

where: 
\(i = 1, 2, 3, \ldots, V\) – the sequence number of the tested variety;  
\(j = 1, 2, 3, \ldots, n\) – the ordinal number of the test period;  
\(X_{ij}\) – productivity of the \(i\)th variety in the \(j\)th test period;  
\(\bar{X}_i\) – average productivity of the \(i\)th variety for all test periods;  
\(l_j\) – index of environmental conditions for the \(j\)th test period (formula 4);  
\(r_i\) – the regression coefficient of the \(i\)th variety on changing of wood stock productivity (formula 5);  
\(d_{ij}\) – deviation from the regression line of the \(i\)th variety in the \(j\)th test period;  
\(V\) – the number of tested varieties;  
\(n\) – the number of test periods.

From the above formula, it can be seen that the method of S. Eberhart and W. Russell, according to which the environmental stability of the studied cultivars was assessed, uses two main parameters:

1) Productivity regression coefficient \((r_i)\) for changes in environmental conditions, which allows us to characterize varieties by their plasticity.

2) The standard deviation of actual productivity indices from the regression line, which characterizes the stability of productivity \((S^2)\) in various conditions.

The algorithm for calculating these indices consists of several stages:

1. Calculating environment indices \(l_j\) (formula 4);
2. The definition of the regression coefficient \(r_i\) (formula 5);
3. Setting the theoretical values of current increments (formula 6);
4. Calculating the size of deviations of theoretical values from actual values;
5. Setting the values of the stability variance \(S^2\) (formula 7).

All of these formulas are listed in the next section. Processing of field-testing materials was carried out in the Excel electronic program.
3. Results and discussion

Plant growth rates from 6 to 25 years are shown in table 2. The data from the table 2 shows the cultivar ‘Regenerata’ was the most productive. The wood stock of this cultivar on average for 4 clones of ‘Regenerata’ poplar by the age of economic exploitability was 789 m³/ha. One of its clones (‘Regenerata-78’) at this age showed a colossal productivity of 1 151 m³/ha [42]. Close to the average wood stock for 4 clones were cultivars ‘Gelrica’, ‘Serotina’ and ‘Brabantica’ exceeding 600 m³/ha. The poplars ‘Marilandica’ and ‘Bachelieri’ had the lowest wood stocks (less than 400 m³/ha). The average increments for these 10 cultivars were also ranked accordingly. The ranking of current increments was similar only for the first six cultivars. These ranks for the last four cultivars were different in compare with the wood stock and average increments ranks.

If we analyze the values of current annual increments in different periods of ontogenesis, we can note that for the most varieties (9 out of 10, except for the ‘Serotina’ cultivar), in the periods of 6-10 and 16-20 years, the current increments were higher than in the periods of 11-15 and 21-25 years.

The productivity ranks coincide with the ranks of the average annual precipitation for the same periods (table 1). I.e. the lower amount of annual precipitation is due to arid phenomena of the growing season, which could affect the current annual increments of plants.

Step 1. Using the method of Eberhart and Russell [55], the index of environmental conditions $I_j$ for each test period was calculated by the formula 4:

$$I_j = \frac{\sum_i x_{ij}}{v} - \frac{\sum_i \bar{x}_{ij}}{v_n},$$

(4)

Calculations have shown that for the period of ontogeny of poplars 6-10 years $I_1 = 2.83$; for the period of 11-15 years $I_2 = -3.53$; for the period of 16-20 years $I_3 = 6.14$; and for the period of 21-25 years $I_4 = -5.44$. In other words, the calculated indices of environmental conditions confirmed the empirical assumption about the influence of climate factors obtained from the analysis of data in tables 1 and 2.

Table 2. The productivity indices of euramerican poplars from the growth ranks stabilization to the economic exploitability.

| Cultivars  | Age, years | Diameters, cm | Heights, m | Trunk volumes, m³ | Survival, in shares of a unit | Wood stocks, m³/ha | Current increment, m³/ha/year |
|-----------|------------|---------------|------------|------------------|-----------------------------|-------------------|-----------------------------|
| ‘Bachelieri’ | 10         | 26.4          | 19.6       | 0.418            | 0.75                         | 157               | 29.0                        |
|           | 15         | 29.3          | 21.9       | 0.576            | 0.75                         | 216               | 11.8                        |
|           | 20         | 32.1          | 27.4       | 0.864            | 0.75                         | 302               | 21.7                        |
|           | 25         | 33.8          | 29.1       | 1.018            | 0.75                         | 382               | 11.5                        |
| ‘Brabantica’ | 10         | 26.2          | 18.7       | 0.393            | 0.85                         | 151               | 30.3                        |
|           | 15         | 31.2          | 21.4       | 0.638            | 0.85                         | 271               | 20.8                        |
|           | 20         | 36.8          | 27.2       | 1.128            | 0.85                         | 479               | 41.6                        |
|           | 25         | 39.4          | 29.8       | 1.416            | 0.85                         | 602               | 24.5                        |
| ‘Vernirubens’ | 10         | 25.5          | 19.2       | 0.382            | 0.92                         | 176               | 31.8                        |
|           | 15         | 30.6          | 22.4       | 0.642            | 0.92                         | 295               | 23.9                        |
|           | 20         | 33.8          | 27.8       | 0.972            | 0.92                         | 447               | 30.4                        |
|           | 25         | 36.0          | 29.6       | 1.174            | 0.92                         | 540               | 18.6                        |
| ‘Gelrica’ | 10         | 28.5          | 19.0       | 0.475            | 0.88                         | 209               | 38.2                        |
|           | 15         | 34.2          | 21.8       | 0.781            | 0.88                         | 343               | 26.9                        |
|           | 20         | 38.6          | 27.3       | 1.245            | 0.88                         | 548               | 40.9                        |
|           | 25         | 41.2          | 29.7       | 1.543            | 0.88                         | 679               | 26.2                        |
| ‘Caroline’ | 10         | 23.6          | 18.9       | 0.322            | 0.83                         | 134               | 21.6                        |
|           | 15         | 29.7          | 21.3       | 0.575            | 0.83                         | 239               | 21.0                        |
|           | 20         | 34.3          | 26.0       | 0.936            | 0.83                         | 389               | 29.0                        |
|           | 25         | 36.3          | 28.7       | 1.158            | 0.83                         | 480               | 18.4                        |
The values of the obtained environmental condition indices for each growth period are shown in Table 3.

Table 3. Regression coefficients, theoretical values of current annual increments and stability variance of euramerican poplar varieties.

| Cultivars   | Regression coefficients | Periods of ontogenesis, years | Theoretical values of \( Z_{c.a.i.} \), m³/ha/year | Deviation from the regression line \( d_i \) | Stability variance \( S^2 \) |
|-------------|-------------------------|-------------------------------|-----------------------------------------------|-----------------------------------|------------------------|
| 'Bachelieri' | 1.26                    | 6-10                          | 22.1                                         | 6.9                               | 37.4                   |
|             |                         | 11-15                         | 14.0                                         | -2.2                              |                        |
|             |                         | 16-20                         | 26.3                                         | -4.6                              |                        |
|             |                         | 21-25                         | 11.6                                         | 0.1                               |                        |
| 'Brabantica'| 1.53                    | 6-10                          | 33.6                                         | -3.4                              | 21.1                   |
|             |                         | 11-15                         | 23.9                                         | -3.1                              |                        |
|             |                         | 16-20                         | 38.7                                         | 2.9                               |                        |
|             |                         | 21-25                         | 21.0                                         | 3.6                               |                        |
| 'Vernirubens'| 1.04                   | 6-10                          | 29.1                                         | 2.7                               | 8.8                    |
|             |                         | 11-15                         | 22.5                                         | 1.4                               |                        |
|             |                         | 16-20                         | 32.5                                         | -2.2                              |                        |
|             |                         | 21-25                         | 20.5                                         | -1.9                              |                        |
| 'Gelrica'   | 1.38                    | 6-10                          | 37.0                                         | 1.2                               | 2.1                    |
|             |                         | 11-15                         | 28.2                                         | -1.2                              |                        |

As a result, the periods of 1979-1983 and 1989-1993 were more favorable for the growth of the tested varieties than the periods of 1984-1988 and 1994-1998.

**Step 2.** The index of environmental conditions allowed us to calculate the regression coefficient \( r_i \) of each variety by the level of current increment (formula 5):

\[
r_i = \frac{\sum_j i_j f_j}{\sum_j i_j^2}
\]  

The values of the obtained environmental condition indices for each growth period are shown in table 3.
The variance of stability \( S_i^2 \) was determined by the formula 7:

\[
S_i^2 = \frac{\sum d_{ij}^2}{n-2},
\]

The study of the obtained data showed that the varieties ‘Gelrica’, ‘Marilandica’, ‘Vernirubens’ and ‘Caroline’ have the highest ecological stability in changing climatic conditions (the stability variance ranged from 2.1 to 9.3 units). Varieties ‘Sacrau’, ‘Brabantica’, ‘Regenerata’, ‘Robusta’ and ‘Bachelieri’
with variances from 17 to 37 units can be classified as medium stable. The ‘Serotina’ variety with stability variance of more than 100 units was the least stable in varying climatic conditions.

For our study, obtained values of stability variance seem quite high (table 3). But in some other studies, high values of stability variance are quite common. For example, in the study of the yield of ‘Altai Jubilee’ plum in the Chelyabinsk region of Russia, the variance ranged from 21.3 to 102.5 [24], and in the study of potato productivity in the Bryansk region, the variance values were obtained from 11 to 2,306 units [5].

When studying the geographical races of spruce trees in the North of European Russia in the second age class, the stability variance for survival ranged from 0.8 to 123.2, and for wood stock – from 0.50 to 52.2 [28]. Unfortunately, these sources do not specify the algorithm and the calculation of obtaining these indices, so it is impossible to understand the reason for such a wide range of data.

These discrepancies were taken into account when interpreting our results. In general, the data obtained in the study, the results of which are described above, allow us to more objectively assess the stability of various euramerican hybrids to varying climatic weather conditions.

4. Conclusion
The data obtained in the course of a long-term study of the growth and stability of euramerican hybrids of black poplars in the Central Black Earth Region of European Russia allow us drawing the following conclusions.

From the set of euramerican poplar varieties in the studied region, 10 poplar varieties were identified, which proved to be highly productive and stable in this region. There were ‘Bachelieri’, ‘Brabantica’, ‘Vernirubens’, ‘Gelrica’, ‘Caroline-162’, ‘Marilandica’, ‘Regenerata’, ‘Robusta’, ‘Sacrau’ and ‘Serotina’.

The study of the growth and stability of these poplars showed that at various stages of their ontogeny, these indices were closely dependent on the variation of climate and weather factors. Thus, during periods of growth with high precipitation, the current increments in the vast majority of the studied plants increased and, conversely, during periods with low precipitation, they decreased. At the same time, the index of environmental conditions for favorable periods of growth was 2.83 – 6.14, and for unfavorable periods (-3.53) – (-5.44).

Assessment of ecological plasticity by regression coefficient and ecological stability by variance of deviations showed that different varieties differ in their adaptability to changing climatic conditions. In the forest-steppe zone environment variety ‘Brabantica’ was the most plastic, and variety ‘Gelrica’ was the most stable in growth rate.

In general, the obtained data on the environmental plasticity and stability of euramerican poplar varieties during field tests in the Central Forest-Steppe allow us to determine the impact of weather conditions on their productivity. And data on the ecological plasticity and stability of individual varieties allow more rational use the existing gene pool of poplars in their practical cultivation.

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