Criteria of ecological plasticity, stability, and adaptability of potato varieties based on yield

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Abstract. The influence of the physiological and biochemical parameters of the leaves of 12 potato varieties on the formation, plasticity, and stability of the potato crop has been studied. The experiments were carried out on the territory of the Samara Research Institute of Agriculture – branch of the SamSRC RAS (53°03' N, 49°25' E) in the period 2019-2022. Average potato yields varied in the range of 14.2-25.7 t/ha. The highest yield was the first planting year. With an increase in the duration of reproduction, yield losses ranged from 25 to 50% due to a decrease in the mass of tubers. The coefficient of variation in yield varied in the range of 24-60% depending on the genotype. Criteria of ecological plasticity and stability of potato of different genetic origin are such indicators as leaf dryness or its hydration, the content of phenolic compounds in the leaves, the content of lipid oxidation products, and the state of the membranes. The amplitudes of variation of leaf indicators can serve as a measure of plasticity. Adaptive capacity is related to the content of proline, the ratio of membrane lipids and proteins, and the number of stomata.

1 Introduction

Currently, the agro-industrial complex faces the task of increasing crop yields, obtaining high-quality crop products that can provide sufficient food for the rapidly growing population of the planet in a changing climate [1]. Potato (*Solanum tuberosum* L.) is the most commonly cultivated tuberous food crop. The high ability of adaptation of this crop to different climatic conditions contributed to its spread on five continents of the Earth [2]. In this regard, potato is the fourth most important food crop in the world after wheat, rice, and corn [3].

Potato is a unique crop with the main biological feature – vegetative reproduction. With this method of reproduction, the reproduction of new offspring plants occurs from separate vegetative organs of the mother plant, there is no generational change, and genetically homogeneous groups of individuals are formed. Therefore, valuable varietal characteristics are fixed and preserved in potato, but at the same time a process of degeneration occurs. It is believed that the variety, high-yielding in the first years, gradually loses productivity and

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lives in production for no more than 5-8 years [4]. This determines the need for quantitative evaluation of varieties in the reproduction process.

To date, experimental material has been accumulated on the significant effect of environmental conditions on the quantitative and qualitative characteristics of potato. [5, 6]. An ecological approach to assessing the variability of quantitative traits and their adaptability allows the selection of promising potato genotypes for different growing areas.

The main economically useful feature of potato is the yield of tubers [7, 8]. The formation of the crop yield is carried out during the production process – a complex and integrated function of plants, which is based on genetically determined processes of growth and development [9]. The growth rate and the size of the leaf surface are one of the important prerequisites for the accumulation of economically useful biomass and potato crop formation. The size of the leaf surface determines the absorption activity of solar radiation and is the main factor on which the yield depends. Tubers, being the storage organs of the potato plant, are formed due to the accumulation of photosynthesis products on the tops of stolons. Sucrose produced by photosynthetic active initial leaves is transported through the phloem to developing tubers [10]. After unloading, sucrose is split by sucrose invertases or synthases to hexoses, which are then further metabolized to support growth and development [11]. Thus, the process of photosynthesis and the transported amount of its products into tubers are the determining factors for the growth of tubers [12].

In turn, the efficiency of the photosynthetic apparatus depends on the content of pigments and on CO_2 intake through the stomata. Photosynthetic pigments ensure the adsorption of light quanta, and the stomatal apparatus regulates the absorption of CO_2 and water loss due to transpiration, depending on the density and size of the stomata. The pigments are integrated into the membranes of chloroplasts and are bound to proteins. The quantitative content and ratio of pigments in the leaf may reflect the peculiarities of photosynthetic apparatus adaptation as a whole and provide its functional diagnostics [13]. Lipids ensure the integrity of membranes and the functional activity of membrane proteins involved in ion homeostasis, photochemical, electron transport, and other processes [14, 15]. Low molecular weight antioxidants, such as phenolic compounds and amino acids, perform protective functions, protecting the cell from the negative effects of external and internal factors [16, 17, 18].

We have previously shown that the key characteristics determining the high yield and adaptive capacity of potato are the number of stomata per unit area of the leaf, the specific surface density of the leaf, and the content of photosynthetic pigments. The quantitative values of these parameters, along with the number of tubers and the average weight of the tuber, determine the differentiation of plants according to the degree of yield and variety maturity period [19]. In addition, we have established the relationship between the yield of potato varieties and their field virus resistance [20]. Nevertheless, the question of the dynamics of physiological and biochemical processes during long-term use of the variety and their impact on yield remained open.

The purpose of this work is to evaluate potato varieties by the ecological plasticity of yield under long-term reproduction in the conditions of the Middle Volga region.

2 Materials and Methods

2.1 Plant material and field experiments

The objects of the study were potato plants of various ripeness groups: middle-early varieties Debut, Calibr, Krasa Meshchery, Serdolik, Sudarynya, Elixred; medium-ripening - Augustine, Brusnika, Zhigulevsky, Severnoye siyanie, Siversky, Signal. The experiments were carried out on the fields of Samara Scientific Research Agricultural Institute – branch of the SamSRC RAS (53°03' N, 49°25' E) in the period 2019-2022.

Planting of each variety was carried out in two rows, the width of the aisles was 75 cm, the distance between the plants was 32 cm. The plants were planted in four repetitions of 50 tubers each. The planting of tubers was carried out in the second decade of May. Soil: terrace chernozem, ordinary, low-humus, medium-thick, heavy loamy. Field experiments were laid in crop rotation (the predecessor of spring wheat) with conventional agricultural techniques without fertilizers and additional irrigation at the natural length of the day.

Tubers were harvested simultaneously in all potato varieties in the first decade of September. The yield of each variety was estimated by the mass of tubers per plant, the number of tubers per plant and the total yield t/ha.

2.2 Fixation of plant material, laboratory studies

For physiological and biochemical analyses, fully developed leaves of the middle part of the shoot of 3 random plants of each variety were selected. Leaf samples were taken during the phase of plant full flowering. From the average mass of each biological experiment, 0.1-0.5 g samples were made in three biological repetitions for each type of analysis. The material was fixed with liquid nitrogen immediately after the material was separated from the plant and weighed.

To calculate the number of stomata, the middle part of the leaves was fixed in a 3.5% solution of glutaraldehyde (Novochim, Russia) in a phosphate buffer (pH = 7.4) and stored in a refrigerator at a temperature of 8°C. Stomata were studied by the method of Palacci prints [21]. The epidermis casts were previewed under a Leica DMLS microscope (Leica Microsystems, Germany), then photographed under an Axioskop-40 microscope using an integrated AxioCam HRc video camera (Zeiss, Germany). Counting the number of stomata on the epidermal sections of the leaf in 20-fold repetition was carried out by light microscopy.

The hydration of tissues was calculated after drying the raw mass (raw m.) of leaves to a constant weight at a temperature of 60°C and expressed as % of the raw mass.

The pigment content, extraction and analysis of the main groups and classes of lipids were determined according to the methods given in [14]. The analysis of membrane proteins in plant material was carried out by the Lowry method using the Folin–Ciocalteu reagent [22].

The intensity of lipid peroxidation (LPO) in plant leaves was determined by the accumulation of malonic dialdehyde and its reaction with thiobarbituric acid at λ= 532 nm on a PE-3000-UV spectrophotometer (PromEcoLab, Shanghai, China) [23]. Plant leaves (0.5 g of raw m.) were homogenized in a porcelain mortar by hand with an isolation medium (0.1 M tris-HCl buffer pH = 7.6 containing 0.35 M NaCl). 2 ml of 0.5% thiobarbituric acid in 20% trichloroacetic acid was added to 3 ml of the homogenate and incubated in a boiling water bath for 30 minutes. After cooling, the optical density was recorded against the control (isolation medium + reagent).

The content of free proline was determined in leaf dry mass using an acidic ninhydrin reagent prepared without heating (1.25 g of ninhydrate + 30 ml of glacial acetic acid + 20 ml of 6 M H_3PO_4) [24]. The values of the proline content were calculated with a calibration curve, using chemically pure L-proline for its construction. The results were calculated for 1 g of dry weight (dry w.).

The parameters of ecological plasticity and stability of genotypes were determined by the Eberhart-Russell method [25].

2.3 Statistical analysis

The analysis of each component was carried out three times in each biological sample. In the figures, the results are presented in the form of the average values of the parameter (Mean) for a group of plants, their standard errors (SE), maximum (Max) and minimum (Min) values. Additionally, a discriminant analysis was carried out to establish differences between isolated groups of varieties in which a three-year data set was used. Calculations were performed using the programs Statistica 6.0 for Windows, Microsoft Excel 2007, Past 3, Statgraphics Centurion XVI.3.

3 Results and their discussion

The level of variability of a trait that allows the genotype to adapt to different environmental conditions is commonly called plasticity. The analysis of weather conditions during the research period for four years revealed a significant heterogeneity of the temperature regime and the soil moisture regime (Table 1). The hottest month in the first year was June, in the second – July. The third year was characterized by the highest temperatures for all four months of the growing season. The temperature regime in the last year of research was lower compared to the first year, with the exception of August. As for the humidification regime, during the periods of tubers setting and their mass increasing, the greatest amount of precipitation was observed in June of the third year of planting material use, and the least – in June of the first year. Consequently, the third and fourth years were characterized by an increased stress load on plants associated with soil and air drought and increased temperature conditions.

Table 1. Conditions of potato growing season during the years of research.

Month	2019	2020	2021	2022
Average monthly temperature, °C				
May	17.2	15.1	20.2	10.7
June	20.6	18.3	22.0	18.6
July	20.1	23.8	23.2	21.3
August	17.9	18.5	24.3	22.7
Precipitation per month, mm				
May	28.0	24.0	38.0	54.0
June	6.5	39.2	68.6	63.0
July	62.5	7.9	31.0	65.0
August	40.8	29.9	5.0	0.0

Against the background of generally unfavorable growing conditions, along with an increase in the duration of reproduction, a decrease in the yield of all the studied varieties was noted. Average potato yields varied in the range of 14.2-25.7 t/ha. The highest yield was the first planting year (Table 2). Crop losses by the second year averaged 5%. At the same time, both the yield and its losses largely depended on the variety characteristics. In particular, the yield of the Augustine and Brusnika varieties increased in the second year of planting, the Krasa Meschery and Elixred varieties remained at the same level, and the rest of the varieties, including the Gala standard variety, decreased by 7-39%. Starting from the third year, there was a general decrease in yield, which intensified by the fourth year (Figure 1 A). The coefficient of variation in yield varied in the range of 24-60%. Moreover, varieties with stability coefficients Si^2 less and close to one had less yield variability compared to other varieties. Less stable varieties are characterized by lower values of the bi coefficient, which indicates their higher ecological plasticity, in which changes in yield indicators correspond to changes in environmental conditions [20]. In the dynamics of the decrease in the yield of the studied varieties, the superiority of the varieties of the first years of planting by the average weight of one tuber is clearly traced (Fig. 1 C).

Table 2. Characteristics of potato varieties by yield and adaptability and stability parameters in the period 2019-2022.

Variety	Yield, t/ha								bi*	S^{2*}
	2019	2020	2021	2022	Av.	Min.	Max.	Cv		
Augustine	8.2	17.2	21.3	11.9	14.7	8.2	21.3	39.4	1.7	33.1
Brusnika	13.2	19.0	10.6	12.4	13.8	10.6	19.0	26.3	0.2	36.3
Debut	32.4	23.2	19.4	16.3	22.8	16.3	32.4	30.6	1.1	1.77
Calibr	19.3	14.3	11.4	12.7	14.4	11.4	19.3	24.0	0.5	4.53
Krasa Meschery	31.9	32.7	25.8	14.7	26.3	14.7	32.7	31.6	1.1	70.5
Sev. Siyanie	17.6	9.5	11.4	9.0	11.9	9.0	17.6	33.3	0.6	28.4
Serdolik	27.3	17.8	15.2	10.0	17.6	10.0	27.3	41.2	1.2	4.5
Siversky	40.0	24.4	22.6	5.9	23.2	5.9	40.0	60.0	2.2	67.3
Signal	26.8	20.2	16.6	12.0	18.9	12.0	26.8	33.0	1.0	2.1
Sudarynya	32.8	19.6	16.6	16.4	21.4	16.4	32.8	36.4	1.2	20.3
Elixred	23.2	21.4	10.5	7.1	17.9	10.5	23.2	32.0	1.2	24.4
Gala st.	25.1	25.3	10.3	13.6	18.6	10.3	10.3	41.7	0.9	33.1

*bi is the coefficient of ecological plasticity, S^2 is the coefficient of genotype stability.

The reasons for the decrease in the mass of tubers, as is known, may be the suppression of the tuber formation signal, as well as a violation of carbon transport to the acceptor organs. The lack of moisture noted in different months during the 4-year period under study can also affect tuber formation, reducing the number of germing tubers [8, 26, 27]. In our experiments, a decrease in yield occurred only due to a decrease in the mass of tubers (Fig. 1 A-C). This means that the carbon assimilated in the leaves as a result of photosynthesis is less included in the tuber starch, which is reflected in its mass decrease [3, 28].

The variability of leaf mass parameters was evaluated starting from the second year of reproduction. Thus, the hydration of the leaves, the content of pigments, and the diffusion of CO_2 through the stomatal apparatus characterize the photosynthetic activity of the leaves. The average values of these indicators did not have significant differences, nevertheless, we can note a tendency to decrease the dry weight of leaves (Fig. 1 D) due to an increase in water content, a decrease in the scope of variation in the quantitative content of pigments (Fig. 1 E), and the opposite direction in relation to the number of stomata parameter (Fig. F). In the content of components supporting the stability of cell membranes – proteins and lipids (Fig. 1 G – I), a decrease in the level of membrane lipids, as well as the lipid/protein ratio, was noted, which indicates a change in the regulation of energy and protein metabolism, and a shift of production processes to protective mechanisms [29]. Along with this, there is a change in the pro/antioxidant status in the cells of the leaf apparatus as a guarantee of tuber productivity. The induction of oxidative processes was assessed by the content of lipid peroxidation products (LPO). The data in Figure 1 J show that the oxidation processes are more likely to be related to the weather conditions of the year than to variety genetic characteristics. A different picture was observed with respect to components that perform a protective role, namely secondary metabolites. Thus, with an increase in the number of reproductions of the variety, the content of the amino acid proline in the leaves increases significantly (Fig. 1 K). The physiological significance of proline accumulation is associated with the ability to stabilize the structures of proteins and membranes due to the formation of hydrophilic shells, which prevents the inactivation of proteins by hydroxyl radicals and singlet oxygen [30].

It is well known that potato yield is largely associated with resistance to plant damage by fungal and viral diseases [31]. As our data showed, with an increase in the reproduction time of varieties, resistance to pathogens such as potato virus X (XVP) and potato virus Y (YVP) decreases, as well as the scale of variation in resistance of varieties to other types of diseases changes (Fig. 1 M – P).

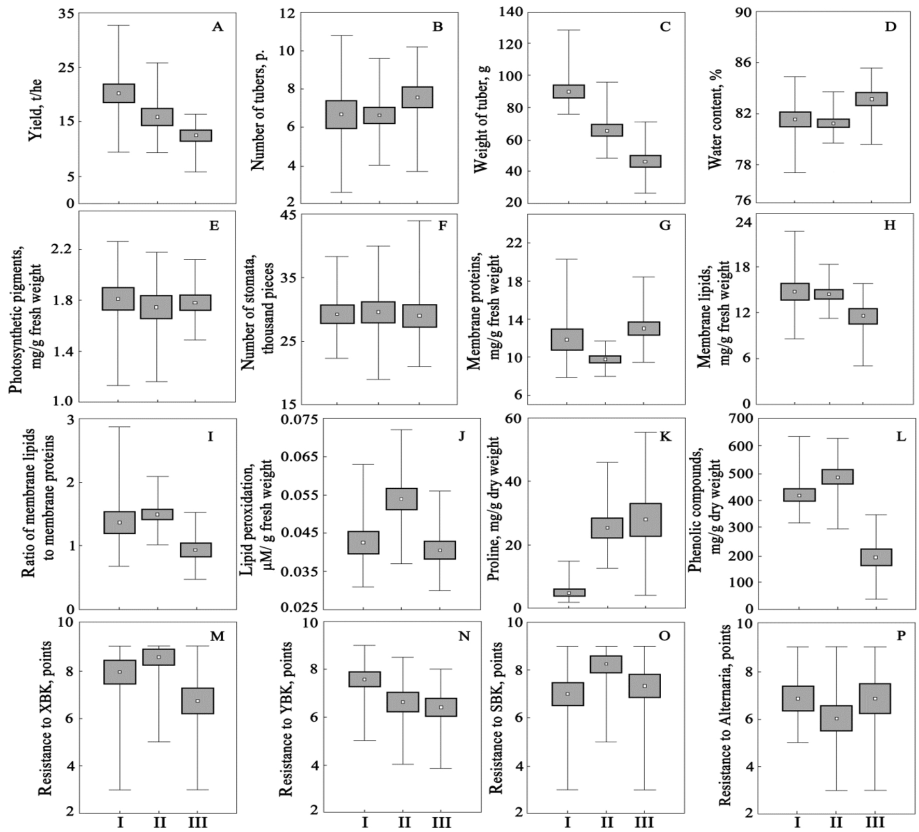

Fig. 1. Dynamics of yield, physiological and biochemical parameters and leaves and stability of potato varieties. A – yield in t/ha, B – number of tubers per plant, C – average weight of one tuber, D – water content in the leaves, E – photosynthetic pigments, F – number of stomata per unit area of the leaf, G – membrane-bound proteins, H –lipids, I - ratio of lipids/proteins, J – LPO products, K – proline, L – phenolic compounds, M – resistance to XVP, N – resistance to YVP, O – resistance to SBK, P – resistance to Alternaria blight; I – second year of planting, II – third year of planting, III – fourth year.

The use of the discriminant analysis method based on the entire set of analyzed parameters showed a clear differentiation of potato genotypes depending on the conditions of the year (Fig. 2A). In terms of significance ($P < 0.05$), both discriminant functions were reliable. The greatest contribution to the separation of varieties depending on the conditions of the year was made by: leaf dryness (19%), the content of phenolic compounds in the leaves (18%), lipid oxidation processes (11%), and the content of membrane proteins (10%). Changes in these traits caused by the influence of external factors (in this case, soil and climatic conditions of the growing season) are non-heritable, characterize the reactions of potato varieties to growing conditions.

The value of a potato variety is determined by a set of indicators of adaptive ability and genotype stability for any valuable attribute and, first of all, by yield. The ranking of varieties according to the degree of adaptability (bi) and stability of varieties (S2) also revealed three independent groups. This approach showed that genotypes with a high degree of adaptation differed from less adaptive ones by criteria such as proline content (27%), ratio of membrane lipids/membrane proteins in leaves (24%), number of stomata (22%), and LPO level (20%) ($P < 0.05$) (Fig. 2. B). Together, these physiological and biochemical characteristics contributed more than 90% of the total contribution to the separation of the selected groups of varieties.

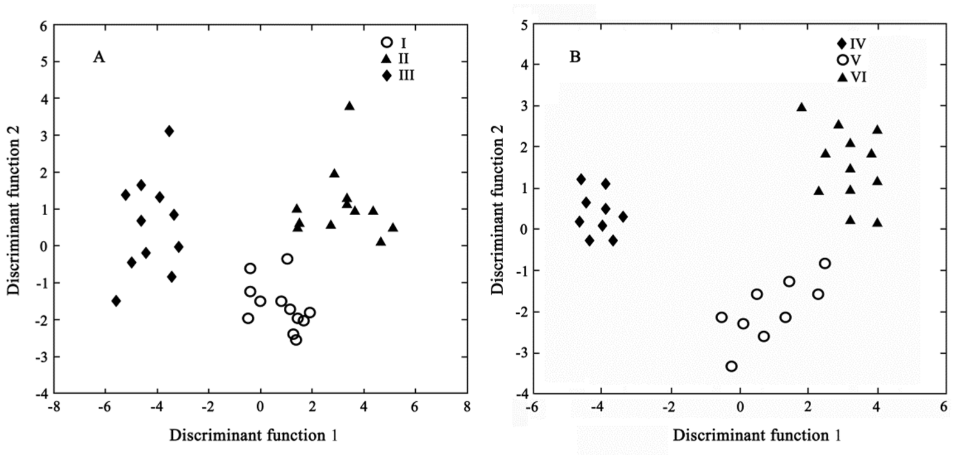

Fig. 2. Data of discriminant analysis of absolute values of potato leaf parameters depending on the conditions of the year (n=36) (A) and depending on the coefficients of yield variation (n=36) (B). I – second year of planting, II – third year, III – fourth year; IV – highly adaptive varieties, V – medium-adaptive, VI – low-adaptive.

4 Conclusion

The results obtained allow to conclude that the criteria of ecological plasticity and stability of potato of different genetic origin are such indicators as leaf dryness or its hydration, content of phenolic compounds in the leaves, content of lipid oxidation products, and state of membranes, the amplitude of variation of leaf parameters can serve as a measure of plasticity. Differentiation of varieties by adaptive ability is associated with such indicators as content of proline, ratio of membrane lipids/membrane proteins, number of stomata.

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