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ORIGINAL ARTICLE

Assessment of ecological plasticity and stability of sunflower hybrids (*Helianthus annuus* L.) in Ukrainian Steppe

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Modern hybrids of sunflower show a pronounced response to changes in agrometeorological conditions of their growing. The research was carried out during 2013-2015 under conditions of insufficient moisture in the Southern steppe of Ukraine. Field and mathematical-statistical methods were used. A comparative assessment of levels of ecological stability was made for 7 sunflower hybrids (the company "Pioneer"). The application of plasticity and stability analysis by the Eberhard-Russell method allows carrying out an integrated assessment of new hybrids in terms of their adaptability to growing conditions and a reaction norm of genotypes to cultivation technology. In the dry steppe zone the sunflower realizes 45% of its genetic yield potential. The highest yield of the studied hybrids was observed in 2013 when, despite the unfavourable hydrothermal index of the year, the minimum relative air humidity during the flowering period was optimal (61.8%). A certain number of genotypes are characterized by the average group value of the plasticity index of yield (i.e. close to 1), namely: PR64LE19, PR64LE71, PR64LE11, PR64A71. Stability ranges from 0.29 in the hybrid PR64LE11 to 32.51 in the hybrid PR64LE19. The hybrids PR64LE71 and PR64LE19 change their ecological plasticity under varying growing conditions. The hybrid PR64F66 is less responsive to varying environments than the whole set of hybrids on average but, compared to others, exhibits average stability. The best results were shown by the hybrids PR64F50 and PR64A89, since they are more sensitive to varying environments and more stable than other hybrids. Growing hybrids of different levels of intensity, genetically and biologically diverse, allows the effective exploitation of agroecological potential of different zones.
Key words: sunflower; agrometeorological conditions; adaptability; stable yield; mathematical-statistical methods

Introduction

Plant breeders are challenged to create highly productive sunflower hybrids resistant to unfavourable biotic and abiotic environmental factors (Henckel, 1982; Heydecker, 1977; Mohamed, 2010). In recent years, significant fluctuations of hydrothermal indices between years have occurred even in the same soil and climatic locations thereby providing a significant effect on the exhibition of individual characteristics and properties of agricultural crops and, as a result, of their macrocharacteristics, including yield (Starichenko et al., 2014; Ali et al., 2006). This introduces the issue of increasing requirements to adaptive capacities of created hybrids of sunflower. Highly adapted hybrids are the key to a stable yield in varying agrometeorological conditions and different eco-geographical zones (Kyrychenko et al., 2011). The assessment of adaptive and stability capacities of seed material is a prerequisite for the selection of highly adaptive forms (Benihana, 2014).

At the present stage of the science development, methods of mathematical modeling (especially such as cluster analysis, the Eberhard-Russell method for studying stability and plasticity, etc.) are playing an increasingly important role in the adequate evaluation of hybrids of sunflower (Dimitrov, 2015).

According to V.D. Medynets, plasticity is the ability of a variety to adapt to different environmental conditions. Other definition of the plasticity is given by S.A. Eberhart and W.A. Russell understanding it as a positive reaction of a genotype to the improvement of growing conditions (Korzun, 2011).

An ecological plasticity of a genotype is defined by Eberhart and Russell (Eberhart, 1966) and Tai (Tai, 1971) as its ability to demonstrate an adequate response to changes in the production conditions, and Mamontova (Mamontova, 1980), Pakudin, and Lopatina (Pakudin, 1984) understand this as a genotype ability to form a stable yield of high quality under different soil and climatic conditions, and respond to the improvement of cultivation technology.

Ecological plasticity of a variety (hybrid) is its biological ability to adapt to environmental conditions.

Adaptability of a hybrid should be also viewed in the context of stability (Bantayehu, 2009). Methods for the ecological stability assessment differ by the complexity of their calculations and applied approaches such as regression, variance, cluster approach, etc. (Moskalets, 2015).
Each year, new hybrids of sunflower are added in the State Register of Plant Varieties Suitable for Dissemination in Ukraine (Table 1).

Table 1. Dynamics of records of sunflower hybrids in the State Register of Plants Suitable for Dissemination in Ukraine for the period 2013–2015

Index	Year			
	2013	2014	2015	Rate of changes, %
Total number of varieties and hybrids (items)	449	494	642	143.0
Number of varieties and hybrids of Ukrainian selection (items)	129	152	176	136.4
Number of varieties and hybrids of foreign selection (items)	320	342	466	145.6
Percentage of varieties and hybrids of Ukrainian selection (%)	28.7	30.7	27.4	-1.3
Percentage of varieties and hybrids of foreign selection (%)	71.3	69.3	72.6	1.3

The total number of applicants of hybrids of this culture is increasing as well. In 2013, the State Register added 449 sunflower hybrids from 60 applicants, and in 2015 their number was already 624 and 71, respectively. As we see, only for the last 3 years the number of applicants has increased by 11 companies, and the number of hybrids by 193 items (State Register 2015). French companies rapidly increase their number of sunflower hybrid seed on the market, being absolute leaders in the Ukrainian State Register (202 hybrids in 2015 compared to 164 hybrids in 2013). Ukrainian companies rank second with 176 hybrids in 2015 compared to 129 in 2013, and the third place is occupied by the Serbian selection companies with 73 hybrids in 2015 compared to 43 hybrids in 2013.
The growth rate of the number of hybrids of foreign selection exceeds that of national varieties and hybrids by almost 10%. The success of these hybrids lies in the index of their yield, which in situ is higher than that of domestic hybrids. Increased productivity of a crop is the basis for raising profits and the main factor in the production intensification (Chutamard, 2011). Therefore, in our view, the evaluation of studied hybrids according to parameters of their ecological plasticity and stability is very important.
The purpose of the research is to assess how new sunflower hybrids of the company “Pioneer” respond to growing conditions under insufficient moisture in the Southern steppe of Ukraine.

Material and methods

To investigate ecological plasticity and stability of modern sunflower hybrids to the growing conditions we selected hybrids PR64LE19, PR64LE71, PR64LE11, PR64A89, PR64A71, PR64F66, and PR64F50 of the company “Pioneer”. The research was carried out in the zone of unstable humidity in demonstration plots of Ltd "Energy 2000" (Melitopol district, Zaporizhzhia region, Ukraine) during 2013-2015.
The soil of study plots is represented by southern chernozem. The relief of the area is flat. The arable layer (0-30 cm) of the study plots contains 2.6% of humus, 89.1 mg of light hydrolyzed nitrogen, 283.6 mg of movable phosphorus, and 133.9 mg of exchangeable potassium per kg of soil.
The hydrothermal coefficient (HTC) – indicator of moisture content of the territory (Tsupenko, 1990). According to the following formula:

$$HTC = \frac{\sum K}{\sum T} \cdot 10 \qquad (1)$$

∑к – rrainfalls during the growing season (above +10 °C), mm;
∑T – the sum of active (above +10 °C) temperatures, °C.
Basic indices of agrometeorological conditions varied between years of the research (Table 2). The amount of active temperatures and crop heat units (CHU) showed no significant difference between years. Minimum relative air humidity during the flowering season is critically important for the formation of yield of sunflower plants. For the normal pollination process, this value should exceed 40 - 45%. Thus, 2014 was the least favourable year for the sunflower pollination.

Table 2. Agrometeorological conditions of Melitopol district (Zaporizhzhia region, Ukraine) during 2013-2015

Year	Rainfall during the growing season, mm	The sum of active (above +10 °C) temperatures, °C	CHU*	Minimum relative air humidity during flowering, %
2013	120.1	2996	3519	61.8
2014	233.4	2869	3375	36.9
2015	154.5	2756	3225	45.8

* Crop Heat Units (Brown 1993).

In 2013–2015, soil moisture conditions did not vary significantly both in the amount of rainfall and evenness of its distribution (Fig. 1). The hydrothermal coefficient constituted 0.70 - 0.81, and 2013 was very dry (HTC = 0.40), especially during the germination and formation of achenes.

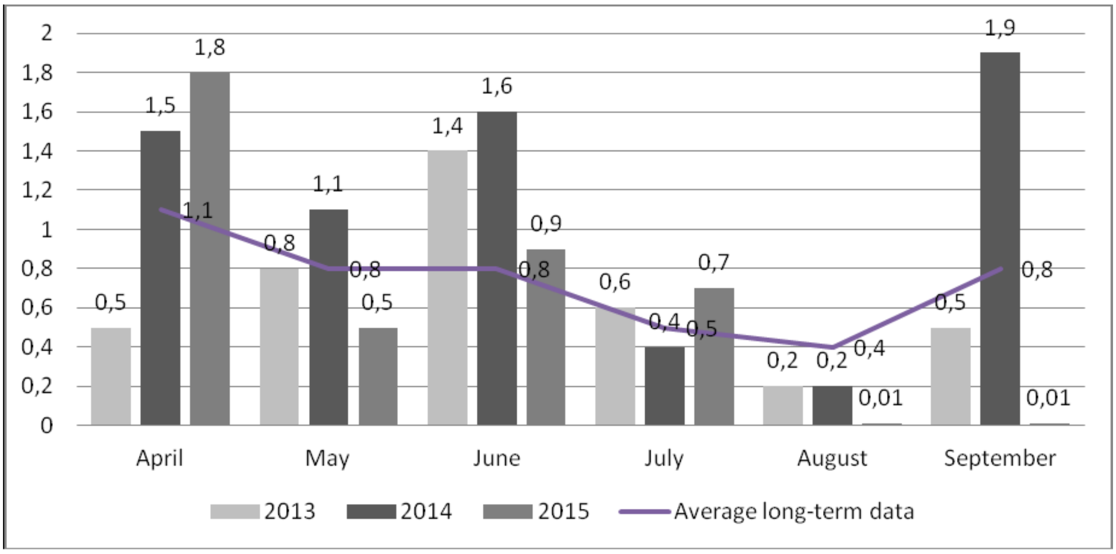

Figure. 1. Hydrothermal coefficient of the vegetation season in the years of research

Sunflower seeds were sown at the beginning of the third decade of April with the sowing norm equalling 55,000 pcs/ha and row spacing of 70 cm. The forecrop was winter wheat. “Maxim XL” (active substance: mefenoxam, 10 g/l and fludioxonil, 25 g/l) and “Cruiser” (active substance: thiamethoxam, 350 g/l) (Yashchuk et al., 2016) were used for seed disinfection. Experimental studies were carried out according to the method of field experiment (Dospekhov, 1985).
The Eberhard-Russell method (Eberhart, 1966) was used to analyze features of ecological manifestation of plasticity and stability as the main commercially valuable traits of sunflower. The total homeostasis of hybrids (H_{om}) was determined by B. Hangildin’s formula (Hangildin 1984). The results of research were processed by statistical methods, including analysis of variance and cluster analysis.

Results and discussion

New sunflower hybrids, according to their genetic potential productivity and level of adaptation to complex agroecological conditions, exceed currently growing and well studied hybrids. Various estimates show that the contribution of new hybrids to the general increase of the crop yield reaches circa 30 - 40% with the prospect of increasing to 60 - 80%.
The implementation of early- and ultra early-maturing forms has enabled expansion of sunflower crops to the northern, western and north-western regions of Ukraine. A natural potential of modern hybrids is rather high but not fully used in the production process.
The most complete and rapid implementation of selection achievements is possible only if accompanied with a deep study of selection and genetic morphoagrobiological traits and properties of new genotypes and the development of agrotechnologies which would correspond to these properties in the areas of hybridization and commercial turnover of hybrids.
Analysis of sunflower yield in recent years (2005 - 2015) indicates that the best agricultural companies are successfully realizing the yield potential of intensive hybrids of sunflower reaching 2.11-2.76 t ha^{-1} in the years with favourable agroclimatic conditions and 1.49-1.91 t ha^{-1} in unfavourable years. At the same time, the efficiency of sunflower seed production in Zaporizhzhia region depends on agroclimatic conditions and in unfavourable years (2007, 2012, 2014) drops by almost 1.6 times compared to favourable years (2011, 2015) (Figure 2).
In the dry steppe zone, the sunflower realizes its genetic potential by 45%.
Wide variability of quantitative and qualitative traits in years with contrast amount of precipitation along with unstable productivity, underdevelopment of traits and properties in the same selection forms in the zone of insufficient moisture confront plant breeders with the need to plan properties of each new variety in two versions taking into account the limiting factors determining their development: for dry years and for years with sufficient moisture for plants.
In this case, not only further increase of potential productivity of the variety under optimal growing conditions is expected, but also increase of its lower threshold of yield under extreme conditions with approximately equal intensity compared to actual yields of the crop in this ecological zone. This approach will enable better use of environmental factors as a differentiation background for choosing and evaluating the selection material.

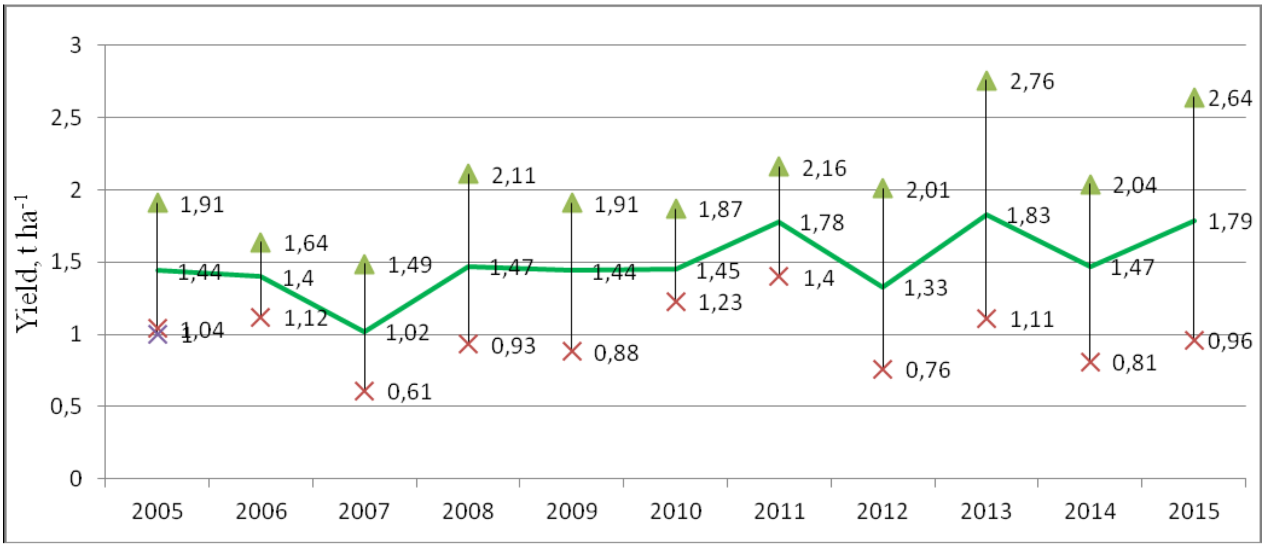

Figure 2. Sunflower yield dynamics in Zaporizhzhia region (with indices of maximum, minimum and average yield), t ha^{-1} (State Statistics).

Many recent works, discussing the issue of ecological plasticity, apply the Eberhart-Russel method. This is probably because it allows determining not only plasticity of any genotype, but also its stability. According to the Eberhart-Russel method, the sum of squares reflecting interaction of each variety with environments is divided into two parts: a linear regression component (bi) and its nonlinear part, determined by the mean squared deviation from the regression line (Si2).

The regression coefficient (bi) describes the average response of a hybrid on varying environments and enables prediction of a change in the investigated trait (in this case, a trait of yield) under existing experimental conditions. A higher value of the regression coefficient indicates a greater reaction norm of a hybrid to varying growing conditions. In most cases, *bi* is positive, but can take negative values under the influence of some abiotic or biotic factors: lodging of crops, damage by pests and diseases, etc. If the value of *bi* is close to zero, it indicates that the hybrid does not respond to varying growing conditions. The trait (yield) variability is shown by the stability coefficient σd2: the less deviation from 0, the more stable is a variety according to this particular trait. The regression coefficient of the yield across environments is generally referred to as the coefficient of ecological plasticity, while the variance in relation to regression is known as stability.

The sunflower production varied both between years and depending on a hybrid (Table 3). The highest yield was observed in 2013 when, in spite of the unfavourable hydrothermal coefficient of the year, the minimum relative air humidity during the flowering period was optimal (61.8%) (Yeremenko 2017). The hybrids, created in other climatic zones, are mostly adapted to their specific conditions and for 2-3 years of testing these varieties in Ukraine they have no time to reveal their level of tolerance to the whole set of possible biotic and abiotic stresses. Under unfavourable conditions they may demonstrate the lowest yield, as it occurred in 2014.

The average yield in the experiment is calculated by the formula:

$$Y=(\sum Yj/v*n) \quad (2)$$

where ∑Yj – the sum of yield per hybrids and years of research;
v – the number of hybrids;
n – the number of years.

At first, the index of environmental conditions (Ij) was determined for further calculation of the linear regression coefficient (bi):

$$Ij = [(\sum Yj/v) - \sum Yi/vn)] \quad (3)$$

∑Yj – the sum of yield of all hybrids in a particular year;
∑Yi – the sum of yield of all hybrids during all years of research;
v – the number of hybrids;
n – the number of years.

The aggregation of indices characterizes the variability of conditions under which the hybrids were grown in the experiment. The index of environmental conditions can take both positive and negative values. The best conditions for the growth and development of a genotype were in points with positive index values (2013 and 2015), while the worst conditions were in points with negative values (2014).

We calculated the regression coefficient (bi) for each of the hybrids:

$$bi = (\sum Yj * Ij) / (\sum Ij^2) \quad (4)$$

∑Yij – the sum of yield of a particular hybrid in a particular year;
Ij – the index of environmental conditions;
$\sum Ij^2$ - the sum of squares for the indices of environmental conditions.

Table 3. Productivity of sunflower hybrids (2013 - 2015)

Hybrid	Year			The sum of hybrid yields per years (∑Yi)	Average yield of hybrids (Yi)	Linear regression component (b_i)
	2013	2014	2015			
PR64LE19	2.69	1.31	3.01	**7.01**	**2.34**	**1.00**
PR64LE71	2.81	1.46	3.10	**7.37**	**2.46**	**0.98**
PR64LE11	2.76	1.30	2.27	**6.33**	**2.11**	**0.92**
PR64A89	3.23	1.35	2.31	**6.89**	**2.29**	**1.14**
PR64A71	3.19	1.67	2.41	**7.27**	**2.42**	**0.91**
PR64F66	3.28	1.91	2.51	**7.70**	**2.57**	**0.81**
PR64F50	3.06	1.05	2.24	**6.35**	**2.12**	**1.24**
∑Yj	**21.02**	**10.05**	**17.85**			
Yj	**30.0**	**14.4**	**25.5**	**48.92**	**2.33**	
Ij	**6.73**	**-8.94**	**2.20**			

Judging from the Eberhart and Russel calculation model the most valuable are those hybrids which have *bi>1*. These hybrids are considered as highly intensive. They respond well to the improvements in their growing conditions and are characterized by stable yields. The varieties with a high index of *bi* are less valuable as their high sensitivity is accompanied by a low stability of yield. Genotypes with *bi<1* are low sensitive to the improvements in their environmental conditions (half sensitive), but demonstrate rather high yield stability.

As a result of processing the experimental data we can conclude that only one sunflower hybrid (according to its plasticity indices basing on the trait of yield) can be considered as a low-plastic one: PR64F66. It demonstrates better results being exposed to adverse growing conditions, and improving conditions do not cause increase in its yield.

However, a certain number of genotypes demonstrate the average group value of plasticity of yield trait (i.e. close to 1), namely: PR64LE19, PR64LE71, PR64LE11, PR64A71. Consequently, they are more environment-dependent and their yield variability is determined by growing conditions.

Of the whole set of investigated hybrids, we should pay a special attention to two high-plastic genotypes, which progressively change their productivity under improving growing conditions. These are such hybrids as PR64A89 and PR64F50. However, a rapid increase in plasticity of hybrids leads to the reduction in their adaptability and stability, and strong efforts to raise the phenotype plasticity are not thereby recommended because this reinforces the hybrid sensitivity not only to favourable but also to adverse conditions.

Stress-tolerant hybrids are characterized by a relatively low reaction norm to varying growing conditions; their regression coefficient is less than one and with its further decrease their tolerance to adverse conditions grows. In our studies, such a hybrid was represented by PR64F66. Plants of this hybrid demonstrate less reduction of their yield in extreme conditions, and are less responsive to varying environmental factors.

Analysis of the stability was more interesting for us in terms of determining the average group constant, because the parameter of stability is more conventional than the plasticity index.

To determine the stability, the potential yield for each hybrid was at first determined according to the following formula (Table 4):

$$Yi = Xi + bi\ Ij \qquad (5)$$

Xi – the average yield of a particular hybrid for all years of research, t ha^{-1};

bi Ij – the product of the regression coefficient of a particular hybrid by the index of environmental conditions.

Potential yield of studied hybrids exceeds 2 t ha^{-1}, being rather good for the Southern steppe of Ukraine.

Table 4. Average yield of hybrids, t ha^{-1}

Hybrid	Year			Average yield of hybrids (Yi)
	2013	2014	2015	
PR64LE19	3.01	1.44	2.56	2.34
PR64LE71	3.11	1.58	2.67	2.46
PR64LE11	2.73	1.29	2.31	2.11
PR64A89	3.06	1.28	2.55	2.29
PR64A71	3.04	1.61	2.62	2.42
PR64F66	3.11	1.84	2.75	2.57
PR64F50	2.95	1.01	2.39	2.12

To determine the yield stability of sunflower hybrids we calculated the deviation of actual from potential yields (Table 5) according to the following formula:

$$\sigma ij = Yij - \widehat{Yij} \quad (6)$$

Yij – the actual yield of a particular hybrid in a particular year, t ha^{-1};
$\widehat{Yij}$ – the potential yield of a particular hybrid in a particular year, t ha^{-1}.

Mean squared deviation (stability) was computed by the formula:

$$\sigma d^2 = (\sum \sigma ij^2) / (n - 2) \quad (7)$$

$\sum \sigma ij^2$ – the sum of squares of deviation of the actual from potential yields;
n – the number of years.

According to calculations, given in Table 5, the stability ranges from 0.29 in the hybrid PR64LE11 to 32.51 in the hybrid PR64LE19. The less value of σd^2 indicates the less deviation of the actual from potential yields during all years of research thus confirming the stability of this hybrid. Such hybrids as PR64A89, PR64A71, and PR64F66 have similar levels of stability, ranging within 7.31 – 8.93. The hybrids PR64LE71 and PR64LE19 show significant deviations of yield with the stability values equalling to 29.11 and 32.51, relatively.
Plants of the hybrids PR64LE71 and PR64LE19 change their ecological plasticity under varying growing conditions (the regression coefficient makes up 1.00 and 0.98, relatively) but along with it these hybrids are unstable.

Table 5. Deviations of actual from potential yields, t ha^{-1}

Hybrid	Year			Sum of squares of the yield deviation ($\sum \sigma ij^2$)	**Stability (σd^2)**	**Homeostasis, H_{om}**
	2011	2012	2013			
PR64LE19	-3.22	-1.31	4.52	32.51	**32.51**	**3.94**
PR64LE71	-3.04	-1.24	4.28	29.11	**29.11**	**4.20**
PR64LE11	0.30	0.12	-0.43	0.29	**0.29**	**4.21**
PR64A89	1.69	0.69	-2.37	8.93	**8.93**	**3.01**
PR64A71	1.52	0.62	-2.14	7.31	**7.31**	**5.21**
PR64F66	1.67	0.68	-2.35	8.81	**8.81**	**7.00**
PR64F50	1.07	0.43	-1.51	3.60	**3.60**	**2.29**

The similar stability level of the hybrids PR64A89, PR64A71, PR64F66 does not coincide with their ecological plasticity. Thus, the hybrid PR64F66 shows a weaker response to varying environmental conditions than the whole set of hybrids on average, but in comparison to others it is characterized by the average stability. Full conformity of changes in yield under varying growing conditions are demonstrated by the hybrids PR64LE11 ($bi = 0.92$) and PR64A71 ($bi = 0.91$), though the hybrid PR64LE11 is characterized by minimum deviation of actual yields equalling to 0.29, and the hybrid PR64A71 has the deviation value of 7.31. The hybrids PR64F50 ($bi = 1.24$) and PR64A89 ($bi = 1.14$) were find out to be fastidious to a high level of agrotechniques; their stability constituted 3.6 and 8.9, correspondingly.

To evaluate the stability of sunflower hybrids in our research we determined the index of homeostasis (H_{om}) that indicates commercial value of a hybrid.

$$H_{om} = x / (\sigma (x_{opt} - x_{lim}) \quad (8)$$

The more the value of this index, the more valuable is the hybrid in terms of its fitness to growing conditions. The hybrids PR64A71 and PR64F66 have the highest value of this index.
The regression lines of the hybrid yields were built to compare responses of the hybrids to environmental conditions (Figure 3).
The regression lines of the hybrids PR64F66, PR64A71, and PR64LE71 cross the ordinate higher than other investigated hybrids. It is explained by higher yield on average for all the studied points of research. The slope of the regression lines gives more information of the hybrids behaviour relative to each other. The hybrid PR64F50 is characterized by a very low sensitivity to improving growing conditions.

Reliability of differences between the regression coefficients can be tested by F-criteria, which expresses the ratio between the mean square of interaction «hybrids x conditions» and the mean square of generalized deviations:

$$F [(u - 1), u(n - 2)] \approx MS \quad (9)$$

«Hybrids x conditions» / MS of generalized deviations. In the example of evaluation of differences between the regression coefficients F is equal to: F=0.21.

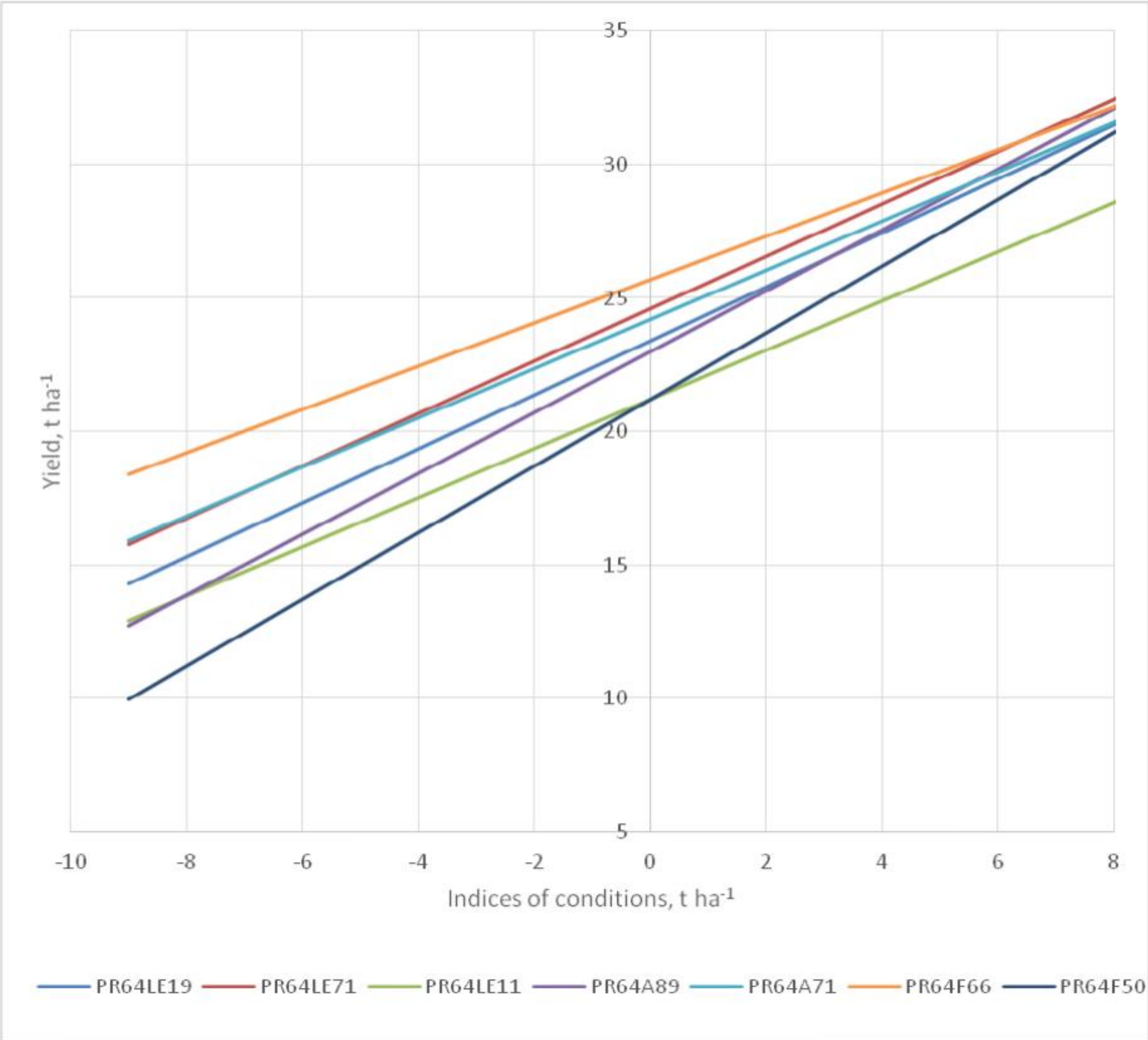

Figure 3. The regression lines of the hybrid yields showing their responses to varying environmental conditions.

The comparison of the obtained result with F_{table} (3.87) showed no significant differences between regression coefficients in this set of hybrids. It means that among the studied hybrids there are no those which stability of productivity is specific and significantly exceeds the variability among the whole set of hybrids. Thus, all variability in the productivity of these hybrids are associated only with environmental conditions but not with their genetic properties.

Conclusions

The application of the plasticity and stability analysis according to the Eberhard-Russell method allows carrying out an integrated assessment of new hybrids in terms of their adaptability to growing conditions and a reaction norm of genotypes to cultivation technology. In the dry steppe zone, the sunflower realizes 45% of its genetic potential. The highest yield of the studied hybrids was observed in 2013 when, in spite of the unfavourable hydrothermal coefficient of the year, the minimum relative air humidity during the flowering period was optimal (61.8%).

A certain number of genotypes are characterized by the average group value of the plasticity index of yield (i.e. close to 1), namely: PR64LE19, PR64LE71, PR64LE11, PR64A71. Stability ranges from 0.29 in the hybrid PR64LE11 to 32.51 in the hybrid PR64LE19. Plants of the hybrids PR64LE71 and PR64LE19 change their ecological plasticity under varying growing conditions (the regression coefficient makes up 1.00 and 0.98, relatively) but along with it these hybrids are unstable. The hybrid PR64F66 shows a weaker response to varying environmental conditions than the whole set of hybrids on average, but in comparison to others it is characterized by the average stability.

Among the studied hybrids there are no those which stability of productivity is specific and significantly exceeds the variability among the whole set of hybrids. Thus, all variability in the productivity of these hybrids are associated only with environmental conditions but not with their genetic properties.

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