EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology 2022, 23(5), 145–152
https://doi.org/10.12912/27197050/151917
ISSN 2719-7050, License CC-BY 4.0

Received: 2022.06.29
Accepted: 2022.07.18
Published: 2022.08.01

Ecological Assessment of Conditions for Sorghum (*Sorghum Bicolor*) Cultivation Based on the Determination of its Yield Plasticity

Svitlana Tretiakova[1*], Viktoriia Voitovska[2], Nataliia Klymovych[1], Svitlana Maslovata[1], Mykhailo Osipov[1], Liudmyla Khudik[1], Oleksandra Polunina[1], Vitalii Prykhodko[1], Andrii Novak[1], Oksana Strilets[2]

[1] Uman National University of Horticulture, 1 Instytutska St., Uman, 20305, Ukraine

[2] Institute of Bioenergy Crops and Sugar Beet NAAS, 25 Klinichna St., Kyiv, 03110, Ukraine

* Corresponding author's e-mail: fuck_privatbank@ukr.net

ABSTRACT

In Ukraine, sorghum is grown in an area of 41000–49000 ha, with the yield ranging over years from 0.99 t/ha (2001) to 4.63 t/ha (2018). Such differences in productivity may be explained by the fact that, in recent decades, the value of degree-days in the Steppe zone increased from 3145 °C (1990) to 3550 °C (2019), and in the Forest Steppe zone by 445 °C. At the same time, the current annual precipitation in Ukraine is 578 mm, while sustainable farming requires 700 mm. In Steppe, which is a traditional sorghum cultivation zone, the change in climatic conditions led to insufficient soil moisture, with weather conditions influencing the formation of sorghum grain yield. The assessment of the stability and plasticity of the sorghum yield allows us to conclude that cultivation of this crop will not be effective without irrigation, adjustment of the cultivation technology or introduction of the varieties adapted to drought and high temperature. On the contrary, in Forest Steppe, conditions for obtaining high yields of sorghum improved in recent decades. Thus, in Vinnytsia region, favorable conditions formed in the years 2011–2020, in Kyiv region 2001–2005 and 2011–2015, and Poltava and Cherkasy regions 2006–2020. However, in Vinnytsia region, in the years 2001–2005, and in Kyiv region 2006–2010, low yield plasticity was caused by the negative impact of the extreme drought. Consequently, to reach high crop productivity and stable grain yield, it is necessary to introduce an ecologically sound sown area structure and use varieties of different genetic and geographical origins that are more resistant to the impact of adverse environment.

Keywords: sorghum, yield, sown area, croppage.

INTRODUCTION

Sorghum (*Sorghum bicolor*) rightly ranks fifth among the major grain crops (Trouche et al., 2014). It belongs to plant species capable of forming a high yield under a variety of cultivation conditions, moisture supply, soil types, and temperature regimes (Ndiaye et al., 2019; Perrier et al., 2017).

Due to its physiological features, the crop can adapt to drought stress and high temperature, suspend physiological processes or form a developed root system under limited life factors (Borrell et al., 2014; Zegada-Lizarazu and Monti, 2012). Thus, the transpiration coefficient of sorghum is 300, while in corn, the coefficient is 338, winter wheat 513, and soybean 520. Therefore, even under insignificant moisture stock in the soil, sorghum plants continue to grow and develop (Potgieter et al., 2016; Fu et al., 2016).

The genotype's ability to respond to changes in the growing environment, including those caused by weather conditions, is known as phenotypic plasticity (Sultan 2000). Plants constantly adapt to the conditions of the environment in which they grow. An indicator of the level of plant adaptation to changes in the environment is phenotypic plasticity. Although crop plasticity has been studied since the early 1900s, new scientific coverage of the concept of yield plasticity and stability appeared only in recent decades (Hughes et al. 2002; Agrawal 2001; Schlichting, 2002).

Being unpretentious to cultivation conditions, sorghum is a relevant crop for Ukraine (Fedorchuk et al., 2017), as drought is an increasingly dangerous phenomenon, which requires the improvement of regional agricultural practices and the selection of drought-resistant crops. Thus, in the Southern Steppe, the probability of atmospheric drought in combination with soil drought during the period of active vegetation reaches 90% (Semenova, 2015).

However, in recent decades, excessively high air temperatures, irregular precipitation, or soil moisture deficiency moved to Forest Steppe, known as a zone of unstable and sufficient moisture (Semenova, 2015). Therefore, the issue of searching and replacing traditional crops not only for Steppe but also Forest Steppe and Polissia is quite relevant.

The purpose of the research was to assess the ecological plasticity of the sorghum yield in different soil and climatic regions of Ukraine.

MATERIALS AND METHODS

To assess the ecological plasticity of sorghum productivity, the indicators of yield, sown area and croppage by the regions of Ukraine for the period from 2001 to 2021 were determined using regional data and the data by the State Statistics Service of Ukraine. The data of the Autonomous Republic of Crimea were not analyzed, since Crimea's agriculture is carried out under irrigation, and therefore does not reflect the real shortage of life factors (State Statistics Service of Ukraine, 2022).

Stability and plasticity were determined according to the Eberhard and Russel method, which allows for assessment of the level of productivity by plasticity (b), which is a reflection of the regression of a crop on the change in cultivation conditions and the stability (W) of this reaction. The interaction sum of squares for environmental conditions is divided into two parts – the linear component of the regression (b) and the nonlinear, which is determined by the mean square deviation from the regression line (W) (Eberhart and Russell, 1966).

Consequently, sorghum productivity in regions with a low plasticity value (b) and W is limited by environmental factors; however, these limitations do not lead to a drastic decrease in productivity, although cultivation of sorghum in such conditions is unprofitable as plant needs in life factors are not provided even in better years. However, in regions with a highly plastic effect on the plant productivity and low W value, a high level of productivity can be obtained at the optimal values of the major environmental factors (Eberhart and Russell, 1966).

Determination of the indicators of sorghum ecological stability and plasticity was performed using PTC Mathcad Prime 3.1 application package. Standard deviation and coefficient of variation were calculated in the Statistica 12.0 application. In the calculations, only data from the complete five-year period were used. In the absence of data on at least one year of the five-year period, this period was omitted (Ermantraut et. al., 2007).

RESULTS AND DISCUSSION

In Ukraine, the production of sorghum has spread over the past decades due to rather a high level of crop productivity, than an increase in sown area (Table 1).

Moreover, it is large plantations where it is difficult to ensure a high level of sorghum productivity from year to year. Consequently, the determination of suitable regions in terms of the agro-climatic conditions contributes to obtaining stable high yields.

In order not to take into account the changes caused by the agitated demand for sorghum grain and the further decrease in sown area due to a significant decrease in cost prices, we will analyze the average indicators of sorghum productivity for the period 2000‒2021 (Table 2).

In the Steppe zone, specifically in Dnipropetrovsk, Donetsk, Zaporizhzhia, Kirovohrad, Luhansk, Mykolaiv, Odesa, and Kherson regions, sorghum demonstrates a stable high yield and croppage, as these regions ensure the most suitable climatic conditions for sorghum cultivation. Good yields of the crop can also be obtained in the Forest Steppe zone in Vinnytsia, Kyiv, Poltava, Kharkiv, and Cherkasy regions. However, attempts to grow sorghum in Polissia zone and some regions of Forest Steppe (Volyn, Ivano-Frankivsk, Lviv, Rivne, Ternopil, Khmelnytskyi, and Chernivtsi regions) have had no significant success.

Table 1. Sorghum yield, croppage, and sown area (FAO STAT Crops statistics, 2022)

Country	2018			2019			2020		
	Yield (t/ha)	Area (ha)	Croppage (t)	Yield (t/ha)	Area (ha)	Croppage (t)	Yield (t/ha)	Area (ha)	Croppage (t)
Azerbaijan	1.80	110	198	1.86	140	261	3.41	131	447
Kazakhstan	0.78	2952	2305	0.79	8287	6612	0.53	7828	4160
Kyrgyzstan	1.79	29	52	2.54	11	28	2.36	11	26
Moldova	4.04	1143	4616	6.69	7310	48908	1.97	6351	12539
Ukraine	4,63	41900	193980	4.10	46800	192030	2.25	47200	106560
Uzbekistan	8.75	800	7000	9.31	716	6670	9:40	727	6840

Table 2. Long-term annual indicators of yield, sown area and croppage of sorghum by regions of Ukraine (average for 2001−2021)

Region*	Yield (t/ha)	Area (1000 ha)	Croppage (t/ha)
Ukraine total	2.46	46.3	134.1
Vinnytsia	2.50	0.73	3.0
Volyn	-	-	-
Dnipropetrovsk	2.28	5.27	12.4
Donetsk	2.23	4.85	10.4
Zhytomyr	1.33	0.44	1.0
Zakarpattia	0.75	0.02	0.1
Zaporizhzhia	1.98	3.15	6.1
Ivano-Frankivsk	-	-	-
Kyiv	3.33	0.65	2.9
Kirovohrad	3.10	2.82	10.8
Luhansk	2.83	5.50	16.4
Lviv	0.72	0.02	0.1
Mykolaiv	2.13	8.17	17.6
Odesa	2.30	6.31	14.3
Poltava	3.11	1.42	5.9
Rivne	-	-	-
Sumy	2.39	0.38	1.4
Ternopil	-	-	-
Kharkiv	2.41	2.09	6.2
Kherson	1.94	6.78	12.9
Khmelnytskyi	0.66	0.05	0.2
Cherkasy	3.75	1.91	9.5
Chernivtsi	1.22	0.04	0.1
Chernihiv	1.68	0.16	0.8

Note: *Data of the Autonomous Republic of Crimea, which differ significantly from other regions of Ukraine in terms of cultivation conditions, is not included.

Such differences in the general efficiency of growing sorghum may be explained by the fact that in the conditions of Polissia and partly Forest-Steppe, there is a lack of effective air temperatures necessary for the full growth and development cycle of sorghum. Thus, the degree-days in Steppe increased from 3145 °C (in 1990) to 3550 °C (in 2019), in Forest Steppe by 445 °C, and in Polissia by 450 °C. That is, at present, the value of degree-days in Forest Steppe is higher than that in Steppe in 1990 (3150 °C), and in Polissia, the value is slightly lower − 2950 °C.

The annual precipitation value in Ukraine is 578 mm, while sustainable farming requires 700 mm. However, the forecasts for a drastic decrease in precipitation over the past 20 years have not been realized and, on average, the amount of precipitation has not decreased although the distribution has changed. Thus, in Ukraine, in the last five years, precipitation (total) has decreased by only 1.5−2%, while in Donetsk, Zaporizhzhia, Vinnytsia, Kyiv, Ternopil, Khmelnytskyi, Rivne, Cherkasy, Chernihiv and Zakarpattia regions by 7–12%.

Therefore, the calculation of indicators of standard deviation and coefficients of variation of sorghum grain yield can indirectly indicate the unevenness and change in the conditions of cultivation in the regions of Ukraine (Table 3).

From 2001 and 2005, a very large variation in yields was observed in Vinnytsia, Dnipropetrovsk, Zaporizhzhia, Kyiv, Luhansk, Kherson, and Chernihiv regions and somewhat lesser in Donetsk, Kirovohrad, Mykolaiv, Odesa, Poltava, Sumy, Kharkiv, and Cherkasy regions. However, from 2006 to 2010, a large variation in yield was observed in Dnipropetrovsk, Donetsk, Zaporizhzhia, Kirovohrad, Mykolaiv, Poltava, Kharkiv, Kherson, and Cherkasy regions, while a very large variation was in Vinnytsia, Sumy and Khmelnytskyi regions.

In the years 2011−2015, sorghum yield significantly varied in Dnipropetrovsk, Donetsk, Zaporizhzhia, Kyiv, Kirovohrad, Mykolaiv, Odesa, Sumy, and Kherson regions, in 2016−2020 in Dnipropetrovsk, Donetsk, Kyiv, Kirovohrad, Mykolaiv, Odesa, Poltava, Kherson, and Cherkasy region. Extreme variation was in Vinnytsia and Zhytomyr regions.

Noteworthy, the analysis of the sorghum yield variation by regions and periods cannot be unambiguously interpreted, because significant differences in the coefficients of variation can be caused by both the negative (or positive) impact of cultivation conditions and an increase in yield, which is associated with the improvement of the cultivation technology in the regions not long ago started growing sorghum, in particular, Vinnytsia and Zhytomyr regions.

Therefore, to more accurately determine the environmental conditions for the formation of sorghum yield, we calculated indicators of ecological and plasticity and stability according to the Eberhard and Russel method (Table 4).

According to the Eberhard and Russell method, the regression coefficient (b) is an indicator of crop plasticity to the cultivation conditions. Therefore, in terms of sorghum yield, the regions with the values of the coefficient b > 1 are highly plastic and 1 > b = 0 relatively low-plastic. In addition to the regression coefficient, the stability of this response was calculated by the degree of deviation W.

The low plasticity of yield in a region indicates that plants are not able to achieve a high level of productivity, and therefore this region is

Table 3. Standard deviation and coefficient of variation of sorghum yield by regions of Ukraine

Region	2001–2005		2006–2010		2011–2015		2016–2020	
	Standard deviation	Coefficient of variation	Standard deviation	Coefficient of variation	Standard deviation	Coefficient of variation	Standard deviation	Coefficient of variation
Ukraine	0.66	40.8	0.27	13.7	0.78	29.3	0.98	27.8
Vinnytsia	0.32	77.1	1.20	70.1	0.27	7.3	2.80	53.6
Dnipropetrovsk	1.07	59.4	0.46	25.4	0.93	43.7	1.11	35.3
Donetsk	0.50	31.7	0.42	21.8	0.59	23.9	0.71	26
Zhytomyr	-	-	-	-	-	-	3.21	84.5
Zaporizhzhia	0.67	57.6	0.59	35.1	1.04	47.8	0.38	15.6
Kyiv	1.18	54.6	0.36	18.8	1.25	35.7	1.90	35.9
Kirovohrad	0.75	43.5	0.52	21.1	1.03	26.7	1.45	34.5
Luhansk	1.37	88.4	0.30	15.3	0.23	6.6	0.89	19.8
Mykolaiv	70	48.8	0,79	38.2	1.11	45.1	0.62	23.8
Odesa	0.77	38.5	0.29	15.4	0.89	35.3	1.07	37.3
Poltava	0.18	43.9	1.60	45.1	0.37	8.8	0.92	21.7
Sumy	0.43	37.6	0.78	51	1.07	24.9	-	-
Kharkiv	0.36	48.6	0.47	25.0	0.53	14.7	0.63	18.1
Kherson	1.21	87.7	0.47	32	1.00	49.1	0.72	25.3
Khmelnytskyi	-	-	0.39	65.4	-	-	-	-
Cherkasy	0.44	24.8	0.74	23.5	0.69	16.5	1.52	26.3
Chernihiv	0.64	63.3	-	-	-	-	-	-

Note: *Presented are the data of complete five-year periods

Table 4. Stability (b) and plasticity (W) of sorghum yield by regions of Ukraine

Region	2001–2005		2006–2010		2011–2015		2016–2020	
	b	W	b	W	b	W	b	W
Vinnytsia	-0.20	3.17×10^4	4.08	6.24×10^4	0.16	1.34×10^5	0.28	1.84×10^5
Dnipropetrovsk	2.64	2.74×10^4	0.61	6.19×10^4	1,58	1.44×10^5	1.13	2.00×10^5
Donetsk	0.99	2.81×10^4	0.64	6.14×10^4	1.07	1.42×10^5	0.56	2.03×10^5
Zhytomyr	-*	-	-	-	-	-	2.09	1.95×10^5
Zaporizhzhia	1.56	2.94×10^4	1.13	6.25×10^4	2.16	1.44×10^5	-0.01	2.06×10^5
Kyiv	-3.33	2.64×10^4	0.73	6.14×10^4	1.87	1.35×10^5	2.16	1.83×10^5
Kirovohrad	0.32	2.77×10^4	1.62	5.90×10^4	1.75	1.33×10^5	1.73	1.91×10^5
Luhansk	3.40	2.82×10^4	-0.86	6.12×10^4	0.44	1.35×10^5	0.96	1.90×10^5
Mykolaiv	1.38	2.85×10^4	2.00	6.08×10^4	2.28	1.42×10^5	0.63	2.04×10^5
Odesa	1.69	2.69×10^4	0.43	6.17×10^4	1.98	1.42×10^5	0.56	2.02×10^5
Poltava	0.03	3.17×10^4	3.03	5.44×10^4	-0.14	1.30×10^5	1.02	1.91×10^5
Sumy	0.94	2.95×10^4	1.07	6.32×10^4	0.38	1.30×10^5	-	-
Kharkiv	-0.36	3.07×10^4	-0.29	6.17×10^4	-0.49	1.34×10^5	0.41	1.97×10^5
Kherson	2.79	2.87×10^4	0.90	6.35×10^4	1.63	1.45×10^5	0.64	2.02×10^5
Khmelnytskyi	-	-	0.61	6.75×10^4	-	-	-	-
Cherkasy	0.82	2.75×10^4	-0.74	5.62×10^4	-0.70	1.31×10^5	1.77	1.79×10^5
Chernihiv	-0.71	2.99×10^4	-	-	-	-	-	-

Note: *Presented are the data of complete five-year periods

Table 5. Ecological characteristics of the regions of sorghum cultivation by productivity

Region	2001–2005	2006–2010	2011–2015	2016–2020
Vinnytsia	Low plasticity	High plasticity	High ductility, intensive conditions	High plasticity, intensive conditions
Dnipropetrovsk	High plasticity, intensive conditions	Low plasticity	Low ductility	Low ductility
Donetsk	Low plasticity, limited life factors	Low plasticity	Low plasticity	Low plasticity
Zhytomyr	-	-	-	High plasticity
Zaporizhzhia	Low plasticity	Low plasticity	Low plasticity	Low plasticity
Kyiv	High plasticity, intensive conditions	Low plasticity	High plasticity, intensive conditions	High plasticity, intense conditions
Kirovohrad	Do not differ significantly from the average	High plasticity, intensive conditions	High plasticity, intensive conditions	High plasticity, intensive conditions
Luhansk	High plasticity, intensive conditions	Low plasticity	Do not differ significantly from the average	High plasticity, intensive conditions
Mykolaiv	Low plasticity, limited life factors	High plasticity, limited life factors	Low plasticity	Low plasticity
Odesa	High plasticity, intensive conditions	Low plasticity	Low plasticity	Low plasticity
Poltava	Low plasticity	High ductility, intensive conditions	High plasticity, intensive conditions	High plasticity, intensive conditions
Sumy	Low plasticity	Low plasticity	High plasticity, intensive conditions	-
Kharkiv	Low plasticity	Low plasticity	High plasticity, intensive conditions	Low plasticity
Kherson	High plasticity	Low plasticity	Low plasticity	Low plasticity
Khmelnytskyi	-	Low plasticity	-	-
Cherkasy	Do not differ significantly from the average	High plasticity, intensive conditions	High plasticity, intensive conditions	High plasticity, intensive conditions
Chernihiv	Low plasticity, limited life factors	-	-	-

Note: *Presented are the data of completed five-year periods not interesting in terms of sorghum cultivation. However, some scientists share an idea that the interaction of the genotype with the environment, that is, plasticity, is an obstacle to the developing genotypes with a stable response of phenotype to cultivation conditions in diverse environments (Sadras et al. 2009; Bloomfield et al. 2014).

Physiological and environmental factors that influence sorghum productivity and plant response to drought are well studied by scientists (Vadez et al., 2011; Borrell et al., 2014). That is, when assessing the impact of environmental factors, we can talk about the ability to predict the response of sorghum genotypes to different cultivation conditions (Ndiaye et al., 2019). And therefore, it is interesting to determine the ecological characteristics of regions and their suitability for the cultivation of sorghum.

Based on the calculation of the stability and plasticity of sorghum yield, we described the environmental characteristics of the cultivation conditions (Table 5).

Regarding the regions in which sorghum has been traditionally growing, namely Dnipropetrovsk, Donetsk, and Odesa (Steppe), conditions for high plasticity of sorghum yield contribute to the realization of the crop biological potential were only in the years 2001−2005. Now the regions have unfavorable climatic conditions from the point of view of sorghum cultivation. However, in Luhansk region, the weather conditions differentiated and were favorable for obtaining high sorghum productivity in the periods 2001−2005 and 2016−2020.

At the same time, Kirovohrad region, which is a transition from Steppe to Forest Steppe, is interesting for sorghum cultivation. Thus, good indicators of the suitability of cultivation conditions for sorghum were in the period 2006−2020. However, Zaporizhzhia, Mykolaiv, and Kherson regions mostly can provide limited life factors that do not contribute to obtaining a high level of crop productivity.

The study of four five-year periods shows us that the conditions in Steppe may be considered extreme for sorghum cultivation. That is, growing sorghum is impossible without irrigation or organization of cultivation technology in such a way that plants would not be exposed to high temperatures and moisture deficiency in critical growth stages.

In Forest Steppe, under the conditions of global climate change, there were mainly favorable conditions for sorghum cultivation. Thus, in Vinnytsia region, favorable conditions were in the years 2011−2020, in Kyiv region 2001−2005 and 2011−2015, and in Poltava and Cherkasy regions 2006−2020. However, there were also unfavorable periods in Vinnytsia region in the years 2001−2005 and Kyiv region 2006−2010. Low yield plasticity was caused by the negative impact of the extreme drought.

Poor yields of sorghum are obtained in Khmelnytskyi, Sumy, and Kharkiv regions. However, in the last two regions, sometimes good periods occur, for example, 2011−2015; however, they are related to the impact of high air temperature within a given five-year period, rather than drastic climate changes.

In addition, the conditions of Polissia are not suitable for the industrial cultivation of sorghum, because the data obtained from the analysis of the ecological plasticity of the crop yield indicate its low plasticity and the absence of favorable conditions for the formation of a high level of productivity.

It should not be forgotten that low phenotypic plasticity can be used as a useful feature. Thus, it was the goal of a breeding program (Semchenko and Zobel 2005), as a stage in the development of tolerant genotypes able to survive difficult conditions with just a slight decrease in yield (Negin and Moshelion 2016). However, it is traditionally believed that plants can resist environmental constraints due to the manifestation of a high level of plasticity (Des Marais et al. 2013; Palmer et al. 2012). After all, sorghum has a fairly high genotypic diversity (Sinha and Kumaravadivel 2016). Therefore, cultivation of varieties of different genetic and geographical origins can contribute to obtaining high yields even in regions with moisture deficiency and severe droughts.

CONCLUSIONS

Study of long-term data on yields, sown area, and croppage of sorghum shows that traditional high spread of the crop is observed in the zone of insufficient moisture – Steppe, specifically Dnipropetrovsk, Donetsk, Zaporizhzhia, Kirovohrad, Luhansk, Mykolaiv, Odesa and Kherson regions and in the zone of unstable and sufficient moisture – Forest Steppe, particularly Vinnytsia, Kyiv, Poltava, Kharkiv and Cherkasy regions.

Analysis of the sorghum yield data for the period from 2001 to 2021 shows us that the conditions of the Steppe regions of Ukraine are extreme for the formation of sorghum yield, i.e., the cultivation of the crop is impossible without irrigation and organization of cultivation technology in such a way that plants do not undergo the influence of high temperature and soil moisture deficiency in the critical growth stages.

In Forest Steppe, conditions for obtaining high productivity of sorghum have improved in recent decades. Thus, better conditions for cultivation formed in Vinnytsia region in the period 2011–2020, in Kyiv region 2001–2005 and 2011–2015, and Poltava and Cherkasy regions 2006–2020. However, in Vinnytsia region in the years 2001–2005 and Kyiv region 2006–2010, low yield plasticity was caused by the negative impact of the extreme drought.

The regions of Polissia (sufficient and excessive moisture) cannot provide the conditions for high sorghum productivity compared to other agro-climatic zones; therefore, commercial cultivation of the crop in these regions is risky.

REFERENCES

1. Agrawal A.A. 2001. Phenotypic plasticity in the interactions and evolution of species. Science, 294, 321–326. https://doi.org/10.1126/science.1060701
2. Awan Z.K., Naseem Z., Masood S.A., Nasir B., Sarwar F., Amin E., Qurban A. 2015. How to improve *Sorghum bicolor* (L) Moench production: an overview. Life Sci J, 12(3s), 99–103.
3. Bloomfield J.A., Rose T.J., King G.J. 2014. Sustainable harvest: managing plasticity for resilient crops. Plant Biotechnol J, 12, 517–533. https://doi.org/10.1111/pbi.12198
4. Borrell A.K., Mullet J.E., George-Jaeggli B., van Oosterom E.J., Hammer G.L., Klein P.E., et al. 2014. Drought adaptation of stay-green sorghum is associated with canopy development, leaf anatomy, root growth, and water uptake. J. Exp. Bot., 65, 6251–6263. https://doi.org/10.1093/jxb/eru232
5. Des Marais D.L., Hernandez K.M., Juenger T.E. 2013. Genotype-by-environment interaction and plasticity: exploring genomic responses of plants to the abiotic environment. Annu Rev Ecol Evol Syst, 44, 5–29. https://doi.org/10.1146/annurev-ecolsys-110512-135806
6. Eberhart S.A., Russell W.A. 1966. Stability Parameters for Comparing Varieties. Crop Sci., 6, 36–40. https://doi.org/10.2135/cropsci1966.011183x000600010011x
7. El Naim A.M., Ibrahim M.I., Mohammed E.A., Elshiekh A.I. 2012. Evaluation of some local sorghum (Sorghum bicolor L. Moench) genotypes in rain-fed. Int J Plant Res, 2(1), 15–20. https://doi.org/10.5923/j.plant.20120201.03
8. Ermantraut E.R., Prysiazhniuk O.I., Shevchenko I.L. 2007. Statistical analysis of agronomic study data in the Statistica 6.0 software suite. Kyiv: PolihrafKonsaltynh.
9. FAO STAT Crops statistics. 2022. http://www.fao.org/faostat/en/#data/QC
10. Fedorchuk M.I., Kokovixin S.V., Kalens`ka S.M., Raxmetov D.B., Fedorchuk V.G., Filipova I.M., Ptashy`ns`ka O.V., Kovalenko O.A., Drobit`ko A.V., Panfilova A.V. 2017. Scientific and theoretical foundations and practical aspects of the formation of ecologically safe technologies of cultivation and processing of sorghum in the steppe zone of Ukraine] Kherson.
11. Fu T., Ko J., Wall G.W., Pinter P.J., Kimball B.A., Ottman M.J., et al. 2016. Simulation of climate change impacts on grain sorghum production grown under free air CO2 enrichment. Int. Agrophys., 30, 311–322. https://doi.org/10.1515/intag-2016-0007
12. Hughes K.A., Burleson M.H., and Rodd F.H. 2002. Is phenotypic plasticity adaptive? in Biodemography of Fertility, Rodgers, J.L. and Kohler, H.C., Eds., Dordrecht, Netherlands: Kluwer, 23–42.
13. Ndiaye M., Adam M., Ganyo K.K., Guissé A., Cissé N., Muller B. 2019. Genotype-environment interaction: trade-offs between the agronomic performance and stability of dual-purpose sorghum (*Sorghum bicolor* L. Moench) genotypes in Senegal. Agronomy, 9, 1–16. https://doi.org/10.3390/agronomy9120867
14. Ndiaye M., Muller B., Ganyo K.K. et al. 2021. Phenotypic plasticity of plant traits contributing to grain and biomass yield of dual-purpose sorghum. Planta, 253, 82. https://doi.org/10.1007/s00425-021-03599-z
15. Negin B., Moshelion M. 2016. The advantages of functional phenotyping in pre-field screening for drought-tolerant crops. Funct Plant Biol, 44, 107–118. https://doi.org/10.1071/FP16156
16. Palmer A.R. 2012. Developmental plasticity and the origin of novel forms: unveiling cryptic genetic variation via "Use and Disuse." J Exp Zoo B Mol Dev Evol, 318, 466–479. https://doi.org/10.1002/jez.b.21447
17. Perrier L., Rouan L., Jaffuel S., Clément-Vidal A., Roques S., Soutiras A., Baptiste C., Bastianelli D., Fabre D., Dubois C., Pot D. and Luquet D. 2017. Plasticity of Sorghum Stem Biomass Accumulation in Response to Water Deficit: A Multiscale Analysis from Internode Tissue to Plant Level. Front. Plant Sci., 8, 1516. https://doi.org/10.3389/fpls.2017.01516

18. Potgieter A.B., Lobell D.B., Hammer G.L., Jordan D.R., Davis P., Brider J. 2016. Yield trends under varying environmental conditions for sorghum and wheat across Australia. Agric. For. Meteorol. 228, 276–285. DOI: 10.1016/j.agrformet.2016.07.004
19. Schlichting C.D. 2002. Phenotypic plasticity in plants. Plant Species Biol., 17, 85–88. https://doi.org/10.1046/j.1442-1984.2002.00083.x
20. Semchenko M., Zobel K. 2005. The effect of breeding on allometry and phenotypic plasticity in four varieties of oat (*Avena sativa* L.). Field Crop Res., 93, 151–168.
21. Semenova I.G. 2015. The spatial and temporal distribution of droughts in Ukraine under the future climate changes. Physical geography and geomorphology, 1(77), 144-150.
22. Sinha S., Kumaravadivel N. 2016. Understanding genetic diversity of sorghum using quantitative traits. Scientifica (cairo), 2016, 3075023. https://doi.org/10.1155/2016/3075023
23. State Statistics Service of Ukraine. 2022. www.ukrstat.gov.ua
24. Sultan S.E. 2000. Phenotypic plasticity for plant development, function and life history. Trends Plant Sci, 5, 537–542. https://doi.org/10.1016/s1360-1385(00)01797-0
25. Trouche G., Bastianelli D., Hamadou T.C., Chantereau J., Rami J.F., Pot D. 2014. Exploring the variability of a photoperiod-insensitive sorghum genetic panel for stem composition and related traits in temperate environments. Field Crops Res., 166, 72–81. https://doi.org/10.1016/j.fcr.2014.06.008
26. Vadez V., Deshpande S.P., Kholova J., Hammer G.L., Borrell A.K., Talwar H.S., et al. 2011. Stay-green quantitative trait loci's effects on water extraction, transpiration efficiency and seed yield depend on recipient parent background. Funct. Plant Biol. 38, 553–566. https://doi.org/10.1071/FP11073
27. Zegada-Lizarazu W., Monti A. 2012. Water uptake efficiency and above-and belowground biomass development of sweet sorghum and maize under different water regimes. Plant Soil., 351, 47–60. https://doi.org/10.1007/s11104-011-0928-2