

Model-based assessment of Romania's climatic suitability for the extension of fig, Chinese persimmon and jujube crops

E. Chitu ^{1*}, M. Calinescu ¹, I. Mazilu ¹, M. Coman ¹ and E. Mateescu ²

¹Research Institute for Fruit Growing Pitesti, Romania

² National Meteorological Administration, Bucuresti Romania

*Corresponding author email: emilchitu@gmail.com

ABSTRACT

The warming trends of Romania's climate create favourable conditions for growing sub-tropical species. Meanwhile, low temperatures during the winter period do not always follow a similar increasing tendency throughout the country. The objective of this work was to use some models that would identify areas where climate conditions are likely to be suitable for fig, Chinese persimmon and jujube orchards over Romania. The models identified the areas where temperatures (minimum and cardinal of growing season ones), growing season duration and rainfall conditions are likely to be suitable for fig, jujube and persimmon orchards over Romania. Low minimum temperatures, which drop once in four years in most areas below the frost resistance of fig and persimmon species during the winter, was the most important climatic factor, by limiting their spatial distribution in Romania. The irrigation of persimmon crops increased the maximum suitability score by 0.8 units (0-4 range) and expanded the favourable area of the species. Most of Romania's surface is suitable for jujube cultivation, excepting the mountainous and some areas where the minimum temperatures with 25% probabilities decrease below the frost resistance limit (-23°C). Nevertheless within the favourable climate regions, the thermal regime is variable and, therefore, there are some areas restricted by low minimum temperature. The heterogeneity and dynamics of climatic factors on the Romanian territory underlines the importance of models for calculating climatic suitability as a decision tool in establishing fig, Chinese persimmon and jujube orchards.

Keywords: cardinal and frost temperatures, rainfall, growth season duration, sub-tropical species, warming tendency

INTRODUCTION

The warming trends of Romania's climate (Piticar and Ristoiu, 2012; Birsan *et al.*, 2014, Busuioc *et al.*, 2014; Chitu *et al.*, 2015; Dumitrescu *et al.*, 2015), create favourable conditions for growing sub-tropical species. However, due to the continental climate with varied influences from oceanic to arid and Sub-Mediterranean to those determined by the complex relief, not all areas lend themselves to the cultivation of warm climate species.

Therefore, most often, climate change is treated from the perspective of the warming trend, which is true and very well scientifically confirmed (Sima *et al.*, 2015; Bandoc *et al.*, 2018; 2022; Zait and Schwartz, 2018; Muscalu *et al.*, 2020; Micu *et al.*, 2022). However, another

environmental factor decisive for the productivity or even the survival of horticultural crops is the minimum temperature during the winter period (Chitu *et al.*, 2016).

On the global warming trend background, climatic accidents such as late spring frosts can also cause damages. Croitoru and Piticar (2013) cite studies relating to the significant increase in extreme maximum temperatures, in duration, frequency and intensity, while simultaneously registering a significant decrease in minimum temperatures either globally or regionally, or even in smaller areas. The authors report results regarding the strong increasing trend of maximum temperatures, while minimum are becoming less extreme. Other authors (Bucur and Babes, 2016) present an increase in the frequency and intensity of frosts during the winter period responsible for damage to vine plantations, but also in temperatures over 30 and even exceeding 35 degrees during the summer. According to the authors, the strongest warming trends were observed in Transylvania, Moldova and coastal areas. Dumitrescu *et al.* (2015) also mentioned the decreasing tendency of cold related weather parameters and an increasing (and consistent) trend of warming indices.

Knowing the degree of suitability of climatic factors in the case of a fruit tree species is an important step in the identification of potential new fruit tree species from a certain area/fruit tree basin. Most models to determine the climatic suitability of an area for fruit crops compares the major climatic preferences of the species with the geographical distribution of climate variables.

For species *Ficus carica* L. and *Dyospiros kaki* L. under study (Table 1), preferences for climatic factors were adapted after Bowen and Hollinger (2004a, 2004b).

For the Chinese jujube (*Zyzyphus jujuba* Mill.), since little systematic research has been carried out in Romania, the data on the multiannual influence of the continental climate on the growth and development of this species were taken from the specialized literature that describes the conditions of maximum climatic favourability, especially from China. Thus, for the duration of the vegetation period, the interval of 100 – 180 days was the one established by Ming and Sun, 1986. At the same time, Chinese jujube remains in the dormant stage from the middle of October through the winter until the end of January (Kim *et al.*, 1982).

Jujubes have been shown to grow and fruit well in the hot and arid areas. Tagiev, 1992 mentioned that it can tolerate in Azerbaijan in summer, temperatures up to 36°C. Its growth is very slow in regions where the summers are cool, and the number of fruits produced is small, as compared with the fast growth, abundant and regular fruiting in zones where the temperature reaches sometimes up to 40°C (Thomas, 1924). The average daily temperature for areas currently growing jujube in Western Australia ranges from 10 to 28°C (Crawford *et al.*, 2013) and that's why we chose the temperature of 28°C as the maximum optimum of jujube. Because of its late flowering, the jujube is free from spring frost injury.

Regarding frost resistance, tolerance to low temperatures seems to be due to cultivar differences (Kucherova and Sin'ko, 1984; Sin'ko *et al.*, 1987; Ivanova *et al.*, 1989). Wild forms of Chinese jujube are also resistant to low temperatures.

Because there are large oscillations between Chinese jujube frost resistance level according to different authors (-10 to -20°C, Ming and Sun, 1986; -22°C, Thomas 1924, -30°C, Troyan and Kruglyakov, 1972), we selected the lowest temperatures from the hardiness map of dominant jujube producing provinces (-23°C, 6-8 China hardiness zones).

In China, Hebei, Henan, Shandong, Shanxi, and Shaanxi there are the five dominant jujube-producing provinces (90 per cent of the total production), but in the last 20 years, jujube orchards from the Xinjiang region, where the climate is arid and hot, have produced the best quality fruits in China (Liu, 2008).

Chinese jujubes grow in China in areas with annual rainfall sum between 87 and 2,000 mm (Liu, 2008) and in Western Australia, are currently grown in areas where precipitation ranges from around 200 to 1,000 mm annually (Crawford *et al.*, 2013).

Table 1. Indicators of climatic suitability for the three studied species, used in the algorithms of the estimation models

Scientific name	Growing days no.		Cardinal temperatures (°C)				Rainfall (mm)		Frost resistance (°C)
	Min.	Max.	Maximum		Minimum		Min.	Max.	
			absolute	optimum	optimum	absolute			
<i>Ficus carica</i> L.	120	300	38	26	16	4	700	1200	-18
<i>Dyospiros kaki</i> L.	150	200	35	31	20	8	900	1500	-20
<i>Zyzyphus jujuba</i> Mill.	100	180	36	28	20	7	500	800	-23

The objective of this work was to apply some models that would identify areas where climate conditions are likely to be suitable for fig, persimmon and jujube orchards over Romania.

MATERIALS AND METHODS

The models applied in the study tried to identify the areas where temperature (frost, duration and the weight of cardinal hourly values in the growing season) and rainfall conditions are likely to be suitable for fig, persimmon and Chinese jujube orchards over Romania.

The methodology adapted to the climatic conditions of Romania was applied. The methodology processed multiannual climatological databases from 121 meteorological stations, from the interval 1989-2018 (30 years), taken from National Meteorological Administration Bucharest, as follows:

- Multiannual average daily values of mean, minimum and maximum air temperatures, plus the standard deviation of minimum and maximum temperatures (5 columns of weather data x 366 days/year x 121 weather stations). These values were necessary to establish the thermal suitability and the duration of the vegetation period;
- The lowest minimum temperature of each year from 1989 to 2018 (30 annual minimum thermal values x 121 stations), values used to establish frost suitability;
- Annual rainfall, from the interval 1989 – 2018 (30 annual precipitation x 121 localities), used for precipitation suitability.

The mapping of the zones of climatic suitability of fruit tree species was done according to the four climatic parameters included in table 1 (duration of the growing period, thermal favourability during the growing season, favourability to frost and rainfall), by assigning them scores from 0 at 4, for each representative weather stations. Score 0 meant completely unfavourable location – excluding culture and score 4 very favourable location.

To establish the degree of thermal suitability of a station for the 3 species, the 366 daily multiannual values of air temperatures: averages, minimum with a probability of 25% and maximum with a probability of 75% (the normal law was used to calculate the probabilities of the distribution of values, after accepting normality by the Shapiro – Wilk test), were transformed into hourly temperatures using sinusoidal functions. It is known that trees are in continuous interaction with the momentary temperature and not with the daily average.

With this subroutine, the daily sum of hours with temperatures between the cardinal thermal values presented in table 1 was calculated: sum no. 1 - the number of hours between the absolute maximum and the optimum maximum, sum no. 2 - between maximum optimum and minimum optimum and sum no. 3 - between optimum minimum and absolute

minimum. To convert the daily sums of the three intervals of the species' vegetation period into daily suitability scores (from 0 to 4), we proceeded to multiply the sum no. 1 and 3 by 3 and the sum no. 2 by 5, after which the sum was divided into the 24 hours of a day. A value between 0 and 4 of daily favourability was thus obtained. To determine the annual suitability, the sum of the daily favourability scores per growing season was calculated and then was divided by the number of days in the growing season of the year.

The first day of the growing season was considered the day when the average maximum temperature exceeded the absolute minimum of the species, and the last day of the growing season was considered the first day in the second half of the year when the average minimum temperature fell below 0 °C. All calculations were performed in Microsoft Office EXCEL files, for each weather station (121) and species (3).

In order to establish the degree of suitability regarding growing season duration (GSD), reference levels were calculated as follows: a score of 0 was assigned if the growing season duration of the species in the respective locality, determined as above, was lower than the minimum limit (Lmin) of the species GSD from table 1; score 1 if GSD was between Lmin and Lmin + (0.125*species range GSD amplitude - Ampl); score 2 if it was between Lmin*1.125 and Lmin + (0.25*Ampl); a score of 3 was assigned if the GSD was between Lmin + (0.25*Ampl) and Lmin + (0.375*Ampl) and a score of 4 if the GSD was above this latter threshold.

In order to establish the degree of favourability to frosts in winter, an updated annual database (30 years, 1989-2018) with the minimum temperature values recorded in each year was used. The value of the minimum temperature with the probability of achievement of 25% (value that appears once every 4 years) was established as a benchmark for awarding the 0 score of suitability. If the species' frost tolerance limit (Table 1) was less than or equal to this temperature, a score of 0 was given and the area was considered unfavourable for that species. Next, favourability scores 1, 2, 3 and 4 were awarded, adding one degree Celsius to the species' threshold.

To establish the degree of suitability of precipitation, the average value for the interval 1989-2018 of the annual amount of rainfall was used. In order to assign favourable grades, the multiannual averages of the localities were compared with the minimum and maximum limits and the amplitude between the minimum and maximum limit of each species. The more the precipitation value was lower than the minimum limits and higher than the maximum limits of the species in table 1, the greater the penalty was.

To obtain the 121 grades of global climate favourability, the following formula was applied in Microsoft Office EXCEL: Climatic favourability score = [thermal favourability score]*([frost favourability score]*[precipitation favourability score]*[vegetation period duration favourability score]) / 64^{0.3}).

To calculate the score of climatic favourability with the optimization of the aero-hydric regime of the soils through irrigation and/or drainage, was assigned, within the above formula, the maximum score 4, for the suitability of rainfall.

In general, in the zoning methodology, the range between score 0 and 0.5 was considered unfavourable for the respective species; the range between 0.5 and 1.5 score was considered slightly favourable; the range between 1.5 and 2.5 moderately favourable; the range between 2.5 and 3.5 favourable, and scores higher than 3.5 gave the respective location the qualification of very (extremely) suitable, which, of course, does not exclude the application of the basic technological measures for the respective crop.

Climate suitability maps without irrigation and maps with irrigation (with optimization of soil water regime) of the three species and 30-year period (1989-2018) were created using Surfer® Version 9.11.947 Surface Mapping System (Golden Software, Inc.) software. A data grid was created using the default kriging routine.

RESULTS AND DISCUSSIONS

Considering fig species, in the conditions where irrigation is not applied, there are major restrictions regarding the climatic suitability of the crop due especially to the minimum temperatures in the winter period below the resistance limit of the plantations (-18°C), on large areas of the country's territory (scores between 0 and 0.2, figure 1). The most favourable areas are the Oravitei Depression and the Gataiei Plain which have maximum score of 3.0 (climate area with Mediterranean influence), the Strehaia Plain, the Blahnita Plain (1.4-2.3), Eastern Dobrogea and especially South- East part (1.8-2.4), the Cotmeana Platform (1.5-2.2), the Arad Plain (0.8-1.9), as well as the Salaj Depression (0.6-1.8).

In the conditions where irrigation is applied in the plantations (Figure 2), the degree of suitability is higher, the areas being wider, and the scores higher, reaching a maximum of 3.4 (favourable area) in the South-Eastern part of Dobrogea, especially the Platform Coastline, Negru Voda Plateau of Mangalia and Istria. In addition to the areas of higher suitability previously shown, the fig tree also has areas neighbouring the cities of Timisoara and Ramnicu Sarat.

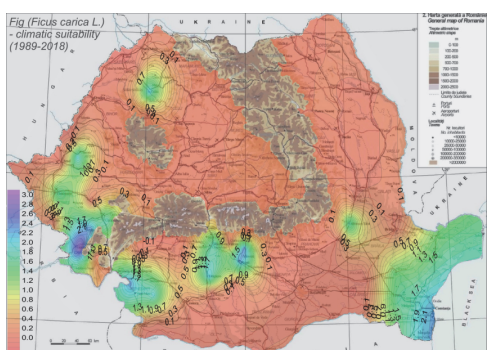


Figure 1. Climatic suitability of Romania for fig (*Ficus carica* L.) – non-irrigated

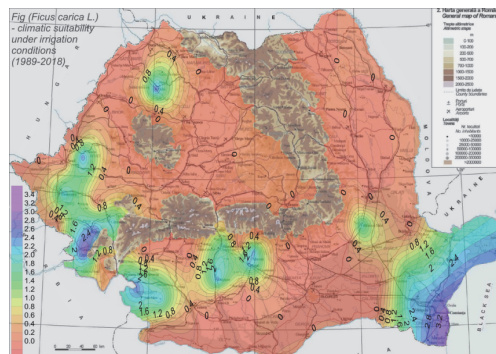


Figure 2. Climatic suitability of Romania for fig (*Ficus carica* L.) - irrigated

Persimmon also encounters less suitable conditions (Figure 3, 4), especially due to its reduced resistance to frost (-20°C). Chinese persimmon has great restrictions regarding the location of the orchards in the territory of the country (scores between 0 and 2.4, in non-irrigated regime and between 0 and 3.2 in irrigated regime).

In non-irrigated regime, the area of the species is excluded from the central and Eastern part of Transylvania (minimum temperatures below the resistance threshold of the species, of -20°C), from almost all of Moldova, from Baragan and from Dobrogea especially due to the drought, as well as from the plain of Vlasia, Gavanu-Burdea and Romanati. Also, with low scores in the irrigated regime, below 0.2, the central and Eastern part of Transylvania, the Barlad and Suceava Plateaus, but also the Vlasiei Plain and Gavanu Burdea with very cold winters, are pointed out.

More favourable in the non-irrigated regime are the Southern hills (over 1.3) and a strip from North to South, from Baia Mare to Oravita towns (over 1.4). The greatest climatic suitability with irrigation is found in the Eastern and especially South-Eastern part of Dobrogea (over 2.6, with a maximum score of 3), in the Oravitei Depression and the Gataiei Plain which even reach scores of over 2.8, the Cotmeana Platform (over 2.6), as well as Strehaia and Blahnita Plain (over 2.4).

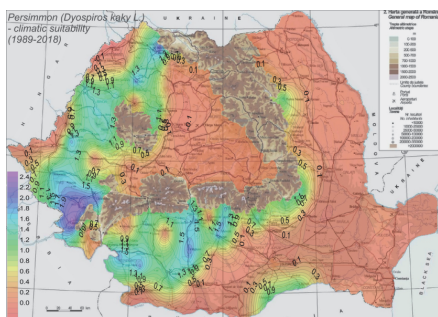


Figure 3. Climatic suitability of Romania for persimmon (*Dyospiros kaki* L.) - non-irrigated

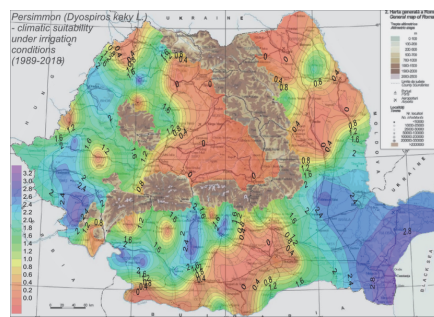


Figure 4. Climatic suitability of Romania for persimmon (*Dyospiros kaki* L.) -irrigated

From the point of view of climatic suitability, the Chinese jujube species (*Zyzyphus jujuba* Mill., Figure 5 and 6), presents reduced restrictions regarding the location of the culture in most areas of the country, the average score in non-irrigated conditions being 1.87 and 2.14 in the irrigated regime, both scores being close and moderately favourable due to the species' low rainfall requirements (Table 1).

The lowest grades, below 1.2 and the lowest climatic favourability, are in the Southern and Eastern part of Transylvania, the North of the Someșean Platform, the North of the Suceava Plateau with the Dragomirna Hills, the Central Moldavian Plateau and the North-East of the Mehedinți Plateau (in general, frequent frosts below the species' resistance threshold of -23°C).

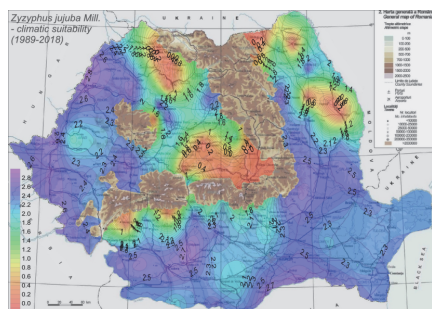


Figure 5. Climatic suitability of Romania for Chinese date (*Zyzyphus jujube* Mill.) – non-irrigated

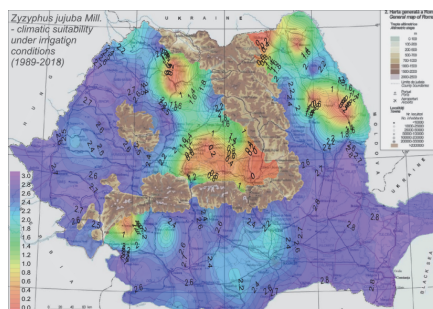


Figure 6. Climatic suitability of Romania for Chinese date (*Zyzyphus jujube* Mill.) – irrigated

The greatest climatic favourability with irrigation of orchards is found in the Plain of Covurluiului, Siretului, Brailei and Eastern Dobrogea (scores over 2.8), then in the Plains of Lugojului and Timisului, the Plains of Crisana, Strehaia, Blahnitei and Cotmeana Plateau (scores over 2.6).

CONCLUSIONS

The models identified the areas where climatic conditions are likely to be suitable for fig, persimmon and Chinese jujube orchards over Romania.

Fig's low frost resistance drastically limits its spatial distribution. As presented, the suitable areas for this species are few: Oravitei Depression, Gataiei Plain (3.0), Strehaia Plain, the Blahnița Plain (1.4-2.3), Eastern Dobrogea and especially South-East part (1.8-2.4), the

Cotmeana Platform (1.5-2.2), the Arad Plain (0.8-1.9), Timisoara and Ramnicu Sarat areas, as well as the Salaj Depression (0.6-1.8). In irrigated fig culture, the suitable areas extend in the South-eastern part of Dobrogea, especially the Platform Coastline, Negru Voda Plateau of Mangalia and Istria.

Area cultivated with persimmon is also limited by its frost resistance (-20°C). Applying irrigation improves the favourability score and expands the crop area. The most favourable areas of Chinese persimmon are the Southern hills (over 1.3) and a strip from North to South, from Baia Mare to the cities of Oravita (over 1.4), and to them are added, through the irrigation of the crop, areas from the Eastern and especially the South-eastern part of Dobrogea (2.6- 3 score), in Oravitei Depression and Gataiei Plain (scores over 2.8), Cotmeana Platform (over 2.6), as well as Strehaia and Blahnitei Plain (over 2.4). Some large areas in the North-East, South and the centre of the country remain unsuitable.

Chinese jujube (*Zyzyphus jujuba* Mill.) species is restricted only in areas where the temperature drops below -23°C: Southern and Eastern part of Transylvania, the North of the Somesean Platform, the North of the Suceava Plateau with the Dragomirna Hills, the Central Moldavian Plateau and the North-East of the Mehedinti Plateau. Therefore it finds climatic suitability, in irrigated culture, in the Plain of Covurluiului, Siretului, Brailei and Eastern Dobrogea (scores over 2.8), then in the Plains of Lugojului and Timisului, the Plains of Crisana, Strehaia, Blahnitei and Cotmeana Plateau (scores over 2.6).

According to the presented models, with some exceptions in the case of jujube, the decision to establish fig and persimmon crops on Romania's territory must be strongly sustained by prior climate favourability studies.

ACKNOWLEDGEMENTS

The study is part of the 2018–2022 research project “Analysis of the feasibility of growing on the Romanian territory goji, kiwi, northern banana, kaki, Chinese jujube, fig, mulberry species and the areas of suitability, cultivars and recommended growing technologies” which is supported jointly by The Academy of Agricultural and Forestry Sciences "Gheorghe Ionescu-Sisesti" and by the Research Institute for Fruit Growing Pitesti, Romania.

REFERENCES

1. Bandoc G., Prăvălie R., Patriche C., Dragomir E. and Tomescu M. (2018). Response of phenological events to climate warming in the southern and south-eastern regions of Romania. Stochastic environmental research and risk assessment, 32(4), 1113-1129.
2. Bandoc G., Piticar A., Patriche C., Roșca B. and Dragomir E. (2022). Climate Warming-Induced Changes in Plant Phenology in the Most Important Agricultural Region of Romania. Sustainability, 14(5), 2776.
3. Birsan M. V., Dumitrescu A., Micu D. M. and Cheval S. (2014). Changes in annual temperature extremes in the Carpathians since AD 1961. Natural Hazards, 74(3), 1899-1910.
4. Bowen R.C. and Hollinger, S.E. (2004a). Model to Determine Suitability of a Region for a Large Number of Crops, Illinois State Water Survey, University of Illinois Urbana-Champaign, <https://www.isws.illinois.edu/data/altcrops/croplist.asp?letter=a&nmeType=cmn>.
5. Bowen R.C. and Hollinger S.E. (2004b). Geographic screening of potential alternative crops. American Journal of Alternative Agriculture, Volume 19, issue 3 (September 1, 2004), ISSN: 0889-1893 DOI: 10.1079/RAF200473: 141-151.
6. Bucur G.M., and Babeș A.C. (2016). Research on trends in extreme weather conditions and their effects on grapevine in Romanian viticulture. Bulletin UASVM Cluj-Napoca, Horticulture, 73(2), 126-134.
7. Busuioc A., Dobrinescu A., Birsan M. V., Dumitrescu A. and Orzan A. (2015). Spatial and temporal variability of climate extremes in Romania and associated large-scale mechanisms. International Journal of Climatology, 35(7), 1278-1300.
8. Chitu E., Giosanu D., and Mateescu E. (2015). The Variability of Seasonal and Annual Extreme Temperature Trends of the Latest Three Decades in Romania. Agriculture and Agricultural Science Procedia. 6. 429-437. 10.1016/j.aaspro.2015.08.113.

9. Chitu E., Paltineanu C., Sumedrea D., Butac M., Militaru M., Tănăsescu N., Sirbu S., Jakab Z., Petre G., Caplan I. *et al.* (2016). The effect of the extreme values of the air temperature from the last two winters in Romania on the viability of the apricot, peach and sweet cherry flower buds. *Fruit Growing Research*, 32, 44-54.
10. Crawford R., Shan F.C. and McCarthy A. (2013). Chinese jujube: a developing industry in Australia. *Acta Horticulture* 993, 29-36. DOI: 10.17660/ActaHortic.2013.993.3. <https://doi.org/10.17660/ActaHorticulture.2013.993.3>
11. Croitoru A. E. and Piticar A. (2013). Changes in daily extreme temperatures in the extra-Carpathians regions of Romania. *International Journal of Climatology*, 33(8), 1987-2001).
12. Dumitrescu A., Bojariu R., Birsan M. V., Marin L., and Manea A. (2015). Recent climatic changes in Romania from observational data (1961–2013). *Theoretical and Applied Climatology*, 122(1), 111-119.
13. Ivanova A. S., Kucheroва T. P and Sin'ko L. T. (1989). The growth and frost hardiness of *Ziziphus* on skeletal soils of the Crimea [in Russian]. *Sbornik Nauchnykh Trudov Gosudarstvennyi Nikitskii Botanicheskii Sada* No. 108: 47-54.
14. Kim W. S., Kim Y. S., Lee U. G. and Yang W. M. (1982). Studies on dormancy, seasonal fluctuation of carbohydrate contents and activity of hydrolytic enzymes in *Ziziphus jujuba* Miller [in Korean]. *Journal of the Korean Society for Horticultural Sciences*, 23(3): 221-229.
15. Kucheroва T. P. and Sin'ko, L. T. (1984). Frost resistance of *Ziziphus* in the Crimean South Coast region. *Subtropicheskie Kul'tury*, 5: 102-108.
16. Liu M. (2008). China jujube development report. China Forestry Publishing House, Beijing, China.
17. Micu M.M., Dinu T.A., Fintineru G., Tudor V.C., Stoian E., Dumitru E.A., Stoicea P. and Iorga A. (2022). Climate Change—Between “Myth and Truth” in Romanian Farmers’ Perception. *Sustainability* 2022, 14, 8689. <https://doi.org/10.3390/su14148689>
18. Ming W. and Sun Y. (1986). Fruit trees and vegetables for arid and semi-arid areas in northwest China. *Journal of the Arid Environments*, 11: 3-16.
19. Muscalu A., Tudora C., Coța C., Gyorgy Z., Burnichi F. and Bârsan M. (2020). Climate changes and methods to protect vegetable crops. In *E3S Web of Conferences* (Vol. 180, p. 03016). EDP Sciences.
20. Piticar A. and Ristoiu D. (2012). Analysis of air temperature evolution in north-eastern Romania and evidence of warming trend. *Carpathian Journal of Earth and Environmental Sciences*, 7(4), 97-106.
21. Sima M., Popovici E. A., Bălțeanu D., Micu D. M., Kucsicsa G., Dragotă C. and Grigorescu I. (2015). A farmer-based analysis of climate change adaptation options of agriculture in the Bărăgan Plain, Romania. *Earth Perspectives*, 2(1), 1-21.
22. Sin'ko L. T., Kucheroва T. P. and Vil'de E. I. (1987). Resistance of *Ziziphus* to unfavourable environmental factors in the eastern Crimea. *Sbornik Nauchnykh Trudov, Gosudarstvennyi Nikitskii Botanicheskii Sada*, 102: 56-64.
23. Tagiev T. M. (1992). Promising areas for cultivating jujube in Azerbaijan. *Sadovodstvo i Vinogradstvo*, No. 1: 19-20.
24. Thomas C. C. (1924). The Chinese jujube. U.S. Department of Agriculture. Dept. Bui. 1215, 30 pp.
25. Troyan A. V. and Kruglyakov G. N. (1972). Produce with high vitamin content. *Sadovodstvo*, No. 12: 30.
26. Zait Y. and Schwartz A. (2018). Climate-related limitations on photosynthesis and drought-resistance strategies of *Ziziphus spina-christi*. *Frontiers in forests and global change*, 3.