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GROWTH AND YIELD CAPACITY OF QUINOA (*Chenopodium quinoa* Willd.) DEPENDING ON THE SOWING RATE IN THE CONDITIONS OF THE NORTH-EASTERN FOREST-STEPPE OF UKRAINE

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Abstract

The paper presents aimed research results of the density level effect on quinoa plant development, yield and yield components to ensure maximum efficiency of crop rowing under regional conditions. Research was carried out for 2020-2022 in area of North-Eastern Forest-Steppe of Ukraine with the quinoa variety of Quartet. Several sowing rates 0.8; 1.2; 1.6 and 2.0 million seed per ha) were studied. According to the results a continuous sowing technology with a sowing rate of 1.6 million similar seeds per ha is recommended. It provides a pre-harvest density of 1.37 million plant/ha and yield of 2.12 t/ha. Development and formation of the main crop of seeds ensures the main inflorescence of the central stem. The average yield index and weight of 1000 seeds were 27.9% and 2.82 g, respectively. For obtaining larger seeds (1000 seed weight > 3.0 g), it is advisable to reduce the sowing rate to 1.2 million seed/ha. Yield shortage at this sowing rate in some years can be up to 0.08 t/ha.

Kea words*: crop density, development, growth, quinoa, yield.*

INTRODUCTION

Quinoa (*Chenopodium quinoa* Willd.) is one of the perspective species for sustainable agricultural production in different parts of the world. The crop combines a high adaptability to environmental stressors with unique dietary properties. Interest in quinoa production grows nowdays in different regions - Europe, North America, Asia and China (Jacobsen, 2003; Navruz-Varli & Sanlier, 2016; Präger et al., 2018; Asher et al., 2020; Afzal et al., 2022). The ecological diversity of quinoa is wide, the cultivation of this crop is possible in different types of agroecosystems. Therefore, crop of this type opens up new opportunities for regional development. However, taking into account the need for sustainable development of agricultural production, quinoa crop management should be developed in accordance with the dynamics of its wide biodiversity (Prommarak, 2014; Rojas et al., 2015; Bazile et al., 2016). A high level of crop yield is the main goal of growing plants in agrocenosis, it is achieved by variation and improvement of technology elements (Sellami et al., 2021). Agronomic methods (sowing rate, plant density, fertilizer application, tillage system, terms of sowing and irrigation) affect the abiotic environment of crop and impact growth processes and yield formation (Ali et al., 2020; Zulkadir et al., 2020; Cruz Díaz et al., 2021; Kakabouki et al., 2021). The prospect of obtaining high yields from the minimum possible area and with minimum energy consumption can be the key to successful agricultural production (Beaman et al., 2009; Isobe et al., 2015; Sief et al., 2015). Therefore, one of the important technological method that affects the yield is the sowing rate (Lescovar et al., 2000). For each crop and specific production system, there is an optimal cropping structure capable of making the most of the available resources (water and nutrients) and providing the maximum potential return that can be achieved in that environment (Spehar & Santos, 2005; Geren et al., 2015). At the same time, sowing rates that determine the crops density depend on many abiotic and biotic factors: genotype, temperature, humidity, soil characteristics, etc. (Maliro et al., 2017; Naneli et al., 2017; Songül et al., 2020)

Quinoa (*Chenopodium quinoa* Willd.) traditionally grows with a high plant density, without thinning, nor weeding or hilling (Gomez

Pando et al., 2015). But it needs well-drained and well-leveled seedbed with optimal humidity for germination. Due to the small seeds, the crop is high sensitive to a sufficient level of moisture (Jacobsen et al., 2003). The way of sowing is crucial for the quinoa cultivation, because of the slow plant growth until the bud formation phase and possible competition with weeds, which can affect the yield. The weeds control in crops is difficult, therefore, optimal plant density is important to reduce weed competition. An increase in phytomass production per unit area can prevent weed expansion and positively influence the yield. Various experiments show similar level of yields can be reach with different plant density rates, because quinoa is able to fill in the gap spaces by changing its branches habitus (Jacobsen, 2015). Different sowing methods and planting density rates of quinoa are practised. Many studies were carried out on different sowing methods of quinoa: broadcasting, ridges, raise bed and row cropping (Basra et al., 2014; Iqbal et al., 2017; Dao et al., 2020). The rate of sowing quinoa seeds depends on the method of sowing, and varies quite widely (Spehar & Da Silva Rocha, 2009; Önkür & Keskin, 2019; Dao et al., 2020; Asher et al., 2022). With appropriate climatic environmental factors and elaborated technology, photosynthetic and assimilative activity can be enhanced and a well-developed plant capable of producing a high yield can be obtained (Idinoba et al., 2002; Gesinski, 2008; Ruiz & Bertero, 2008; Gonzalez et al., 2012; Hirich et al., 2014; Naneli et al., 2017; Ali, et al., 2020).

Quinoa is a relatively new crop for Europe and the generally accepted level of sowing density recommended for its cultivation is difficult to determine. Differences in the crops density, as a result of the sowing rate, are related to the characteristics of the soil cover, soil fertility and its general characteristics, genotype. A single unified recommendation for all the variety of growing conditions is impossible. Further research is needed on the efficiency of resource use in terms of water, fertilizer and radiation use. Today, the quinoa (as well as the crop product market) in Ukraine is considered mainly as a product of organic farming. This approach requires a number of additional characteristics of the variety, namely, the ability of the crop to compete with weeds, the simultaneity of plant maturation and a short growing season that allows mechanized crop harvesting without desiccation. These characteristics were the foundation for the creation and development of the basic technology for growing the Quartet variety. There are no studies on the influence of sowing rates/population density quinoa on growth and yield performance in the North-Eastern Forest-Steppe region of Ukraine. This work aimed to investigate the effects of sowing rate on quinoa variety of Quartet on plant growth, yield components and yield capacity to ensure maximum crop efficiency under regional conditions.

MATERIALS AND METHODS

Field experiments were carried out at the Sumy National Agrarian University (Sumy, Ukraine) during 2020-2022 seasons as part of the program for the creation and development of the basic technology for growing quinoa variety of Quartet. The research area is characterized by the following average long-term indicators: the annual average daily air temperature is +7.4°C; annual amount of precipitation - 593 mm (in autumn - 139; in winter - 122: in spring - 132; in summer - 200). The transition of average daily temperatures through the +10°C point: in the downward direction - the 3rd decade of September, in the upward direction - the 2nd decade of April. The sum of active (> +10) temperatures for April - September period is 2768°C. A common characteristic of the research period (2020, 2021 and 2022) was lower temperatures and higher precipitation in spring (compared to the multi-year average), which requires later planting dates for quinoa. This causes delay in the seedling emergence and low intensity of plant growth processes in the juvenile phases of development. After seedling phase, plant growth was limited by low night temperatures. The second half of the plant growing season, on the contrary, was characterized by higher temperatures and moisture deficit (compared to the multi-year average).

The soil of the experimental field was typical for the North-Eastern Forest Steppe of Ukraine and was classified as heavy, loamy, medium-humus chernozem on a loam, with high fertility potencial. According to the results of agrochemical analysis (spring 2020), the soil was characterized by the following parameters: the reaction of the soil solution – pH 6.1, the humus content in the arable layer - 3.8%. Spring barley was the predecessor for all years of research. The main cultivation of the soil was improved plowing to the depth of 22-24 cm, which was carried out in the second decade of October. Spring cultivation included early spring harrowing and pre-sowing cultivation with the mineral fertilizers application in the form of nitroammophos at the rate of $N_{30}P_{30}K_{30}$. Quinoa was sown in the last decade of April with a selection seeder (Klen 1.5 C) to the depth of 2.5 cm. The width of the row spacing was 15.0 cm. The plot area was $15m^2$ (1.5 x 10 m). After sowing, the plot was rolled with ring-spur rollers. At the beginning of the branching phase, the crops were fed with nitrogen (ammonium nitrate) at the rate of 15 kg of active substance/ha. Variants of the experiment included four sowing rates, namely 0.8; 1.2; 1.6 and 2.0 million seed per ha. For experimental plots randomized desigh with three repetitions was applied.

The seed germination in field condition and the number of plants before harvesting were determined. The dates of seedling emergence, flowering, technological maturity were noted. In the phase of technological ripeness, plant height was determined, weight measurements were made for plants and seeds. To form samples for parameter analysis, plants were cut from one meter of a row at the edges and in the center of the plots. The sample number was 50 plants from one plot. The following indicators were determined:

- Weight of 1000 seeds (g): weight of two seed samples of 500 pcs.;
- Harvest index: weight of seeds / weight of the plant ×100;
- Seed yield: number of plants from the plot × weight of seeds.

The results were processed using the statistical package Statistics 10.0. For each sample, the mean and its standard error were determined. The reliability of the difference between the values was assessed by the results of one-factor analysis of variance.

RESULTS AND DISCUSSIONS

Formation of the crops structure. A long period of low soil temperatures in spring, which is typical for region, causes a significant extension of the seed germination phase, it lasts for 12-16 days. The final count of the seedling number was carried out in phase of mature (non-cotyledon) leaves (which appeared in 10% of the plants). Depending on the year conditions and the variant of the experiment, the field germination indicator varied from 71.14 to 89.93%. The average indicator value for the experiment was 83.5%. The lowest one was noted in 2020 and it averaged 75.75% (Table 1).

Table 1. Formation of quinoa crops density

Sowing rate, million seed/ha	Field germination, %			
	years			X
	2020	2021	2022	
0.8	75.92	88.29	85.42	83.21
1.2	71.14	87.58	85.61	81.44
1.6	79.5	87.88	86.74	84.62
2.0	76.72	89.83	88.19	84.91
$LSD_{0,05}$	3.54	2.14	2.58	
Plant density at harvest time, million / ha				
0.8	0.51	0.58	0.62	0.57
1.2	0.87	0.94	0.92	0.91
1.6	0.92	1.31	1.43	1.22
2.0	1.29	1.34	1.48	1.37
$LSD_{0.05}$	0.22	0.18	0.24	

This year, statistically significant difference between the indicator values was noted for plots with a sowing rate less or equal to ≥ 1.2 million seed/ha and more or equal to ≤ 1.6 million seed/ha. The average value of the field germination indicator for the variants was noted in 2021 and 2022: 88.35 and 86.49%, respectively. The dynamics of indicator changes these years was not of a systematic nature, and the difference between the variants was insignificant. The critical period in the plant development and the crop formation is the end of the seedling phase and the development of the first mature leaves. In the following phases of the quinoa vegetation, the main factor causing the "thinning" of plants is intraspecific competition.

In general, over a 3-year period, the plots were characterized by the following average indicators of pre-harvesting density: 0.57 million plant/ha (with sowing rate of 0.8 million seed/ha), 0.91; 1.22 and 1.37 million plant/ha with the rate of 1.2; 1.6 and 2.0 million seed/ha. In 2020, lower than average crop density values were noted. In 2021 and 2022, there was no difference between the indicators of the final density in the plots with the sowing rate of 1.6 and 2.0 million seed /ha.

Vegetative development of plants. A characteristic feature of most species of the Chenopodiaceae family is the ability to intensive growth, branching of the main stem and prolonging the vegetation period of plants in coenoses with a low level of competition. Quinoa can modify its habitus owing to developing many branches and in this way changing the canopy structure and use interrow spaces for additional yield formation (Jacobsen, 2015). But quinoa varieties differ in their ability/degree of branching. Spehar and Santos, (2005) reported as well the low population density in production crops leads to an increase in branching and yield.

For the experimental variants the average plant height was 87.47 cm. The range of this indicator varied from 73.08 cm in the plots with a sowing rate of 2.0 million seed / ha (2020) to 112.21 cm in the plots with the minimum sowing rate of 0.8 million seed/ha (2022) (Table 2).

Table 2. Plant height and weight depending on sowing rate

Sowing rate, million seed/ha	Height, cm			
	years			X
	2020	2021	2022	
0.8	76.42	98.42	112.27	95.7
1.2	73.4	89.64	103.41	88.9
1.6	73.88	85.38	98.38	85.9
2.0	73.08	82.36	82.72	79.4
LSD $_{0.05}$	3.02	2.96	3.12	
Weight, g				
0.8	7.12	7.62	8.41	7.72
1.2	6.74	8.14	8.86	7.91
1.6	4.78	5.68	7.68	6.05
2.0	4.22	6.14	6.04	5.47
LSD $_{0.05}$	0.35	0.52	0.32	

Annual height averages were 74.28 cm in 2020; 88.95 cm, 99.19 cm in 2021 and 2022. Statistically significant difference between plant height indicators depending on the sowing rate in 2020 was noted only between extreme variants with a sowing rate of 0.8 and 2.0 million seed/ha. In 2020 a statistically significant difference between plant height indicators depending on the sowing rate was noted only between extreme options with a seeding rate of 0.8 and 2.0 million seed/ha. In 2021 and 2022, the change in plant height with an increase in the sowing rate had a systemic nature and was statistically significant for each variant.

Similar dynamics were observed for the plant weight indicator. The average (for the experiment) value of it was 6.9 g. The range of plant weight values varied from 4.22 g in the plots with a sowing rate of 2.0 million seed/ha in 2020 to 8.86 g in the variant with a rate of 1.2 million seed/ha in 2022.

For research years, the average value of the indicator was 7.72 g with a minimum sowing rate (0.8 million seed/ha), and 7.91; 6.05 and 5.47 g/plant in plots with a sowing rate of 1.2; 1.6 and 2.0 million seed/ha. The difference in plant weight indicators on plots with a sowing rate of 0.8 and 1.2 million seed/ha was insignificant. A significant decrease in the indicator (compared to the variant with the minimum sowing rate) was noted in 2020 and 2021 for plots with a density of 1.6 and 2.0 million seed/ha, while in 2022 - only for the variant with the highest sowing rate of 2.0 million seed/ha.

Minh et al. (2022) reported that plant density did not significantly affect plant height. Previous studies found witn the planting density increasing the competition in light leads to grow plant height of crops. But nutrient and water competition may lead to decrease of plant height and other growth indicators in the dense population because of lack in nutrients supply (Maliro et al., 2017; Erazzú et al., 2016; Eisa et al., 2018).

Realization of yield capacity potential. A clear difference between average values of plant productivity indicators on the variants was observed. Seed yield per plant decreased with increasing plant density due to the competition for light and nutrients among individuals as Gimplinger et al. (2008) reported. In our research a statistically significant decrease in the indicator value with an increase in the seeding rate was noted for all years of research. On average, for the experiment, the indicator value was 2.91 g in plots with a sowing rate of 0.8 million seed/ha. And there were 2.32; 1.78 and 1.5 g on variants with a sowing rate of 1.2; 1.6 and 2.0 million seed/ha. An important variety characteristic was the relative stability of the average plant productivity during the research years. The range of average annual variations was only 11.2%, changing from 2.01 g/plant in 2020 to 2.24 g/plant in 2022. More clearly, the difference in the plant was observed on thinned crops with a sowing rate of 0.8 and 1.2 million seed/ha, where it was 13.9-21.5% (Table 3).

Table 3. Plant productivity and harvest index depending on sowing rate

Sowing rate, million seed/ha	Plant productivity, g/plant			
	years			X
	2020	2021	2022	
0.8	2.73	2.89	3.11	2.91
1.2	2.09	2.33	2.54	2.32
1.6	1.81	1.73	1.80	1.78
2.0	1.44	1.54	1.52	1.50
$LSD_{0.05}$	0.19	0.18	0.19	
Harvest index, %				
0.8	38.45	38.03	37.02	37.83
1.2	31.19	28.77	28.54	29.50
1.6	37.71	30.35	23.38	30.48
2.0	34.29	25.25	25.33	28.29

On the contrary, the difference in variants with a sowing rate of 1.6-2.0 million seed/ha was no more than 7%.

The harvest index is an important characteristic of the variety and growing conditions. The average value of the indicator for the experiment was 30.8%. It varied from 23.44% in the plots with the sowing rate of 1.6 million seed/ha to 38.34% in the plots with the minimum sowing rate in 2020. For years of research, as well as for the average indicator in the experiment, a trend towards a decrease in index values was observed with higher sowing rates. At the same time, with an growth in the sowing rate and the actual pre-harvest sowing density, the difference between the indicators decreased.

The main indicator of variety is yield. On average, for experiment, the inducator value was 1.67 t/ha in plots with a sowing rate of 0.8 million seed/ha, and 2.12; 2.17; 2.06 on variants with a rate of 1.2; 1.6 and 2.0 million seed/ha. Depending on the year conditions the average yield for the experiment ranged from 1.72 t/ha in 2020 to 2.06 t/ha (in 2021) and 2.23 t/ha (in 2022), respectively. The dynamics of weather conditions, data on the formation of crop density and vegetative development of plants make it possible to characterize the features of vegetation and the formation of quinoa productivity depending on the sowing rates in the conditions of the North-Eastern Forest Steppe of Ukraine (Table 4).

Table 4. Yield and 1000 seed weight depending on crops density

Sowing rate, million seed/ha	Yield, t/ha			
	Years			X
	2020	2021	2022	
0.8	1.39	1.68	1.93	1.67
1.2	1.82	2.19	2.34	2.12
1.6	1.83	2.27	2.42	2.17
2.0	1.83	2.09	2.25	2.06
$LSD_{0.05}$	0.08	0.06	0.06	
1000 seed weight (g)				
0.8	3.18	3.32	3.52	3.34
1.2	3.06	3.09	3.18	3.11
1.6	2.78	2.82	2.86	2.82
2.0	2.75	2.56	2.53	2.61
$LSD_{0.05}$	0.05	0.05	0.08	

The use of a sowing rate of 0.8 million seed/ha ensures the yield formation in the range of 1.39-1.93 t/ha with high indicator of 1000 seed weight at the level of 3.18-3.52 g. And with a harvest index of 37.2-38.45%. Regardless of the conditions of the research years, the use of a sowing rate of 1.2 million seed/ha ensured a statistically significant increase in productivity compared to the variant of 0.8 million seed/ha. This crops had a higher level of plant survival in the juvenile phases of development, which provided final density indicators close to the number of sown seeds. The indicator of pre-harvest density of plants in the plots of this variant was 75.8% of the sown seed number.

The plants had similar parameters of vegetative development, but the decrease in their seed productivity and a decrease in the harvest index was observed. The 1000 seed weight was in the range of 3.06-3.18 g. In reaserch of Wang et al. (2020) plant density did not affect seed quality (seed weight and protein content) significantly. The authors noted the need to take into account that an excessive increase in seeding density requires maximum provision of water and nitrogen.

The variant with a sowing rate of 1.6 million seed/ha showed the highest yield. Compared to the sowing rate of 1.2 million seed/ha, a statistically significant yield growth was noted in 2021 and 2022. At the same time, statistically significant decrease in the indicators of the average plant weight and seed productivity was observed. On this variant, in 2022, the minimum value of the harvest index was noted in the experiment - 23.38%. For research years a significant decrease in 1000 seed weight was noted: from 3.11 to 2.82 g (or by 10.1%).

The use of the maximum (for the experiment) sowing rate of 2.0 million/ha in 2021 and 2022 was accompanied by a statistically significant decrease in the harvest index. In the plots of this variant, the pre-harvest density was only 68.5% of the number of sown seeds. As noted by Minh et al. (2022), variation in quinoa plant density significantly affects seed number, 1000-seed weight, individual and actual yield. Lower row spacing (or more high crops density) increases crop-yield parameters but did not improve quinoa grain quality (Asher et al., 2022).

At the same time, the highest intensity of crops thinning occurred in the juvenile phases of plant development as a result of intraspecific competition. The plants had the minimum parameters of height and average weight in the experiment. A certain stabilization of the yield index values and to some extent of 1000 seed weight indicator was observed. The value of the latter decreased by 8.0% due to the indicators of 2021 and 2022.

CONCLUSIONS

According to the results of a 3-year field experiment with quinoa, carried out in the North-Eastern Forest-Steppe zone of Ukraine, a continuous sowing technology with a basic sowing rate of 1.6 million similar seeds per ha is recommended, which ensures a pre-harvest density of 1.37 million plant/ha, productivity of 2.12 t/ha. The formation of seeds under these conditions occurs mainly due to the inflorescence of the main stem. The average yield index and weight of 1000 seeds were 27.9% and 2.82 g, respectively. In order to obtain larger seeds (1000 seed weight > 3.0 g), it is advisable to reduce the sowing rate to 1.2 million seed/ha. Shortage of the yield at this sowing rate in some years can be up to 0.08 t/ha.

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