Agronomy Research **24**(3), 208–222, 2026
https://doi.org/10.15159/AR.26.076

Clarification of the limits of the impact of forest shelterbelts on corn yield under climate change

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Received: January 12th, 2026; Accepted: July 27th, 2026; Published: October 6th, 2026

Abstract. In modern climatic and economic conditions, the effectiveness of the agroforestry reclamation system, in particular shelterbelts, in Ukraine remains insufficient. The main confirmation of this is the instability and decrease in crop yields in years with adverse weather conditions. Given the trends of global warming, when almost every agricultural year is characterized by increased aridity, temperature anomalies and moisture deficiency, the importance of shelterbelts in regulating the microclimate of agrolandscapes is significantly increasing. At the same time, scientific research aimed at determining the spatial boundaries and intensity of the impact of forest belts on crop productivity in new climatic realities is limited. Field research was conducted during 2022–2024 within the right-bank part of the Forest-Steppe Zone of Ukraine on black soil. About 25 shelterbelts of various types and designs were selected for analysis. The object of the study was corn, for which both yield indicators and the main biometric characteristics of plants were evaluated. The influence of the main and auxiliary windbreaks was studied at distances of 1, 10, 100, 200, 300, 400 and 500 m in the direction perpendicular to the windbreaks. At each of the specified distances, the density of productive stems, the average height of plants, the mass of a thousand grains, the number, length and diameter of per plant, as well as the total yield of corn grain were determined. The results of the studies showed that the highest yield indicators were formed at a distance of about 300 m from the main windbreak, where they exceeded the level at a distance of 500 m by 21.0%. Stable high yield values were observed in the zone of 100–300 m. On average, corn productivity near (at a distance of 100-300 m) the main forest belts was 22.6% higher than in the zone of influence of auxiliary plantations. The maximum yield near the auxiliary blowing forest belt was noted at a distance of 100 m, after which its gradual decrease was recorded.

Key words: *Zea mays* L., agroforestry, field protection afforestation, climate aridization, productivity of agrocenoses, species.

INTRODUCTION

Forest protection strips, being part of the natural sphere of territorial ecosystems, perform a number of important, unique ecological, economic and social functions. They influence water exchange and the state of ecosystems, prevent water and wind erosion of soils, prevent the formation of ravines and landslides, consolidate sandy ravines and regulate the level of groundwater, preserve landscapes, perform a multifunctional role in improving the environment, contribute to obtaining guaranteed yields of agricultural products, and increase soil fertility (Vdovenko et al., 2018; Didur, 2019; Farionik et al., 2022; Okrushko, 2022).

All forest shelterbelts are divided into open, open and dense by design, depending on the proportion of light in their transverse state. Each type of forest belt has its own characteristics both in terms of its positive impact on agroecosystems and in terms of its structure and biometric parameters (Mazur et al., 2019; Mazur et al., 2020a; Hendrawat et al., 2021).

According to another classification regarding the placement of shelterbelts relative to the direction of prevailing winds, they are divided into main ones, which are placed transversely to the direction of prevailing winds, and auxiliary ones, which are placed transversely to the main shelterbelts or along the direction of prevailing winds (Petrichenko et al., 2017; Hnatiuk et al., 2019; Amilia et al., 2021; Mazur et al., 2021a; Bondarenko et al., 2022; Li et al., 2022; Bakhmat et al., 2023).

In the conditions of climate change, the effectiveness of forest belts in performing environmental protection functions is significantly reduced. The agrobiological and ecological conditions of their functioning are deteriorating. In this regard, it is relevant to study the features of the development of field shelterbelts in conditions of climatic extremes in order to ensure their full implementation of the soil-protective and ecosystem-stabilizing role in terms of increasing crop yield (Battistini et al., 2018; Kaletnik & Lutkovska, 2020; Lutkovska, 2020).

Studies show the positive ecological and economic role of forest shelterbelts in agrolandscapes, which consists in the fact that they occupy a small area in the structure of the agrolandscape and are powerful and durable, environmentally safe means of biological soil improvement, protect soils from wind and water erosion, while retaining deflation products, preserve and improve their fertility, thus increasing the yield of agricultural crops by an average of 15–20%. In Ukraine, within the boundaries of agricultural lands, there are 1.2 million hectares of protective forest plantations of a specific purpose, of which 440 thousand hectares are field shelterbelts. But such a number of field shelterbelts cannot ensure consistently high yields of agricultural products within the boundaries of all agricultural lands. Existing agroforestry forest plantations protect o40% of arable land (Mazur et al., 2021b; Bulgakov et al., 2023).

Scientific research has established that one hectare of shelterbelts is capable of providing effective protection for 20 to 30 hectares of arable land. Taking into account these indicators, it can be stated that in Ukraine, significant areas of agricultural land are under the influence of the system of shelterbelts (Petrychenko et al., 2018). This contributes to a more rational use of land resources, increased stability of agricultural production and reduced costs for growing agricultural products by reducing the negative impact of adverse natural factors (Butenko et al., 2020; Pantsyreva, 2021). Depending on the orientation to the prevailing winds, shelterbelts are divided into main and

auxiliary. They differ not only in spatial location, but also in the species composition of tree plantations, width, number of rows, as well as in the features of care and maintenance. The combination of main and auxiliary forest belts forms a holistic system of agroforestry ameliorative complexes, within which each element performs a specific function and interacts with other components. The functioning of such a network provides comprehensive ecological protection of agroecosystems from the effects of wind erosion, droughts, temperature fluctuations and other adverse natural phenomena. As a result, a sustainable positive ecological effect is formed, which is manifested in improving the microclimate, preserving soil fertility and increasing the productivity of agricultural lands (Lee et al., 2012; Ivanyshyn et al., 2021).

In Ukraine, about 13 million hectares of agricultural land are protected by field protection forest belts, which corresponds to 30% of the total area of agricultural land. Taking into account other types of forest belts: riverbank, roadside, farm, forest belts near water sources, forest belts adjacent to fields, gardens, nurseries, forest and steppe areas, the total area of protective agricultural landscapes is 40% of the total territory. Currently, the area of protective forest plantations on agricultural lands in Ukraine is 1.5%, while the scientifically justified area should be at least 3.0–3.5% (Mazur et al., 2020b; Tsyhanskyi 2021; Farionik et al., 2023).

Global experience of agroforestry in regions with soil and climatic conditions similar to Ukraine (in particular, in the US corn belt) confirms the role of forest belts as a 'thermal buffer', which reduces transpiration and protects corn crops from temperature stress. Studies show that under conditions of progressive aridification, the spatial boundaries of forest belt efficiency change, which requires accurate modeling of plantation design for sustainable climate-optimized agriculture (Guimarães et al., 2013; Jiang et al., 2018).

At the same time, under current natural and climatic and economic conditions, the agroforestry and amelioration infrastructure of shelterbelts in Ukraine remains ineffective (Didur et al., 2019; Demyanyuk et al., 2019; Tokarchuk et al., 2020; Mazur et al., 2021c). This is evidenced by the decrease in crop yields in years with adverse weather factors (Onufran & Netis, 2017; Li, et al., 2022). Given the trends of global warming, when most growing seasons are characterized by increased climatic stress, the potential of shelterbelts in stabilizing agricultural production can significantly increase (Puyu et al., 2021; Titarenko et al., 2022; Snitynskyi, et al., 2023). However, today scientific research aimed at clarifying the spatial boundaries and intensity of the impact of shelterbelts on crop yields under climate change is extremely limited. In this regard, the tasks formulated in the work are timely and scientifically sound.

The scientific problem is the aggravation of moisture deficit due to climate change, which requires a review of the boundaries of the effective influence of forest belts on corn yield. The hypothesis of the study is based on the assumption that under aridization conditions, the zone of positive influence of forest belts on corn yield is transformed and narrowed, which requires quantitative clarification and modeling. Based on this, the purpose of the research is to quantitatively clarify the spatial boundaries of the effective influence of forest shelterbelts on corn productivity under conditions of modern climate change. The formulation is aimed at determining the patterns of yield distribution to optimize crop placement.

MATERIALS AND METHODS

Field research was conducted in the conditions of the research farm 'Agronomichne' of Vinnytsia Field observations were conducted during 2022–2024 within the Vinnytsia district of Vinnytsia region, in the Forest-Steppe zone of Right-Bank Ukraine on chernozem soils. About 25 field shelterbelts were worked out. The soils in the studied area are fertile podzolized and leached chernozems, and the relief is widely undulating flat with lowlands, which is due to the location within the Dnieper Upland. The territory is not very dissected, the rivers have shallow valleys, the reclamation network is poorly developed, and the process of soil erosion is not pronounced. The groundwater level is about 7 meters (Butenko et al., 2020).

The climatic conditions of the studied area are characterized by a moderately continental type. The average annual air temperature is about 7.0 °C, while after 2000 there is a tendency for it to increase to 8.0 °C. The annual amount of atmospheric precipitation is variable and ranges from 489–634 mm. The duration of the growing season is on average about 208 days. In the summer period, westerly winds dominate, while in the winter season, easterly air currents prevail. Summer in the region is long, moderately warm and marked by sufficient humidity, while winter is relatively short and mild. The average temperature of the coldest month (January) is –5.8 °C, and the warmest (July) is +18.3 °C.

The main adverse meteorological phenomena characteristic of this area include snowstorms, which can last from 6 to 20 days per year, frequent fogs in the cold season(37–60 days), as well as hail, which is observed on average for 3–5 days per year.The duration of daylight varies widely - from 8 hours in winter to 16.5 hours in summer. During 2022–2024, systematic observations and detailed analysis of weather conditions in the studied area were carried out, the results of which are presented in Table 1.

Table 1. Weather conditions in the years of research, according to the Vinnytsia Regional Center for Hydrometeorology, 2022–2024

Month	Average monthly air temperature, °C			Amount of precipitation per month, mm		
	Years			Years		
	2022	2023	2024	2022	2023	2024
January	-1.3	0.9	-1.6	23.7	19.0	67.4
February	1.8	0.4	5.0	7.2	42.0	37.6
March	2.0	5.3	5.0	13.3	36.0	35.5
April	8.5	8.5	12.1	52.4	92.0	83.1
May	14.8	15.3	15.7	24.0	3.3	23.4
June	20.4	19.3	21.6	36.5	75.0	90.1
July	21.1	21.3	24.5	28.0	64.0	57.8
August	21.8	22.7	22.1	44.1	32.0	32.8
September	13.3	17.8	18.8	101.0	33.0	21.8
October	10.1	11.4	10.1	4.6	34.0	25.4
November	0.9	4.4	4.1	0	58.0	23.5
December	-0.3	1.0	2.2	0	54.0	37.4
Average annual	9.4	10.7	11.6	334.8	542.3	535.8
Medium-term	7.0			634		

The average annual temperature in 2022 was 9.4 °C, which is 2.4 °C above the long-term average; January was the coldest month with an average monthly temperature of minus 1.3 °C, and July and August were the warmest months with an average monthly temperature of 21.1–21.8 °C. The growing season began in early April and lasted until the end of October.

In 2022, 334.8 mm of precipitation fell, which is 1.9 times less than the long-term norm. The most precipitation fell in September – 101 mm, which was 33% of the annual norm. There was no precipitation at all in November and December 2023 was very warm. The average annual temperature was 10.7 °C, which is 3.7 °C above the long-term average. The year was characterized by the fact that no month had an average monthly temperature below 0 °C. The coldest month was February with an average monthly temperature of 0.4 °C. The average monthly temperature was 22.7 °C. The growing season began in early March and lasted until the end of November, lasting about 240 days.

The amount of precipitation in 2023 was 542.3 mm, which is 91.7 mm less than the average annual norm. The least amount of precipitation fell in May – 3.3 mm, and the most – in April – 92 mm.

In 2024, the average annual air temperature was 11.6 °C. This was 4.6 °C higher than the (long-term average value) temperature. The highest average monthly air temperature was recorded in July – 24.5 °C, and the lowest – in January, minus 1.6 °C. In general, the growing season lasted from mid-February to mid-November and was about 270 days.

The amount of precipitation during 2024 was 535.8 mm. This was 98 mm less than the average multi-year value. The most precipitation fell in June – 90.1 mm, and the least – in September – 21.8 mm.

In general, for all years of observation, the highest average annual temperature was set in 2024 –11.6 °C, and the lowest – in 2022 – 9.4 °C, which was 2.2 °C less. The most precipitation per year fell in 2023 – 542.3 mm, and the least – in 2022 – 334.8 mm, which was 207.5 mm less. Thus, the most favorable year in terms of meteorological parameters for plant vegetation was 2023, and the least favorable was 2022.

According to the research program, it was necessary to analyze the existing shelterbelts adjacent to corn crops for grain in terms of their structures (blow-through (The area of light transmission through the tree crown is 60–70%), openwork (15–30%), dense (10%)) and by location relative to the prevailing winds (main, auxiliary) by species composition: main, secondary, single species, bushes; also evaluated the metric parameters of the shelterbelts: number of rows of trees, pcs., distance between trees in rows, distance between trees in a row, width of the forest belt, height of the forest belt, trunk circumference at a height of 1.3 m.This allowed to study the impact of shelterbelts on the yield and biometric parameters of corn. The impact on corn crops of the main and auxiliary shelterbelts at a distance of 1 m, 10 m, 100 m, 200 m, 300 m, 400 m, 500 m per pendicular to the shelterbelt was studied. The following indicators were determined at the specified transverse distances from the forest protection strips: density of productive stems, pcs. m^{-2}; plant height, cm; mass of a thousand seeds, g; number of heads on one corn plant, pcs.; length of the corn head, cm; diameter of the corn head, cm; grain yield, c ha^{-1}. For all observations, mathematical statistical calculations were performed using the indicators of correlation-regression dependence and statistical deviation (Nechiporovich, 1967).

The study was conducted on designated test polygons within each forest strip with a length of 100 m in four repetitions. The number of rows of trees in each forest strip, the distance of trees between rows and in rows, the width and height of the forest strip, and the girth of the tree trunk at a height of 1.3 m were determined. For this, standardized methods were used.

Observations were made of Amaros hybrid corn crops at distances of 1, 10, 100, 200, 300, 400, 500 m perpendicular to the main and auxiliary shelterbelts. For this, the corresponding distances were measured with a measuring tape. Accounting plots of 1 m^2 in six replicates were laid out.

The research was conducted within the limits of the intensive technology of growing corn for grain, generally accepted for the forest-steppe zone, adapted to modern climate changes. The predecessor of corn in crop rotation was winter wheat. The tillage system was based on the principles of maximum moisture conservation and included plowing to a depth of 25–27 cm, early spring harrowing to seal in moisture, and pre-sowing cultivation to a depth of seed wrapping (5–6 cm).

The fertilization system was designed to achieve the planned yield and provided for the application of basic mineral nutrition in the norm of $N_{120}P_{80}K_{80}$. Sowing was carried out in the first decade of May with an optimal plant density for the harvesting period of 60–70 thousand/ha. Crop protection from weeds, pests (in particular, corn stem borer) and diseases was provided by an integrated system that combined the application of soil and preventive herbicides, as well as insecticidal treatment during the growing season. Harvesting was carried out by combine harvester in the phase of full grain ripeness with its mass reduced to basic moisture indicators (14%).

The density of productive corn stalks was recorded in the phase of full grain maturity immediately before harvesting by continuous counting of plants in 1 m^2 plots in six replicates for each studied distance from the forest strip. Plant height was determined in the grain formation phase in three replicates for 10 adjacent plants in each plot. Measurements were made using a telescopic measuring rod from the soil surface to the upper node of the corn panicle.

The mass of 1,000 seeds was determined according to the requirements. For this purpose, two samples of 500 seeds were taken from the clean fraction of cleaned and dried grain of each replicate, which were weighed on laboratory electronic scales of the third accuracy class (with an error of up to 0.01 g). The average value of two weighings was taken as the final result, if the difference between them did not exceed the limits allowed by the standard (BTU-CENTER, 2023).

The corn grain yield was recorded by the method of continuous manual cutting of ears from accounting plots with an area of 1 m^2 in six replicates. The ears cleaned of wrappers were subjected to mechanical threshing. The actual grain moisture content during harvesting was determined using a portable digital moisture meter. The conversion of the actual grain yield from an area of 1 m^2 to the net yield at a standard 14% humidity (calculated per 1 ha) was carried out according to the generally accepted formula:

$$Y = m \cdot (100 - W_f) / (100 - W_{st}) \cdot 10 \quad (1)$$

where: Y – grain yield, reduced to standard moisture content (t ha^{-1}); m – mass of actually harvested threshed grain from 1 m^2 (kg); Wf – actual grain moisture content during harvesting (%); Wst – standard (base) grain moisture content (14%).

The obtained experimental data were processed by mathematical statistics methods using the Microsoft Excel 2019 application package. The research results are presented in the form of the arithmetic mean and its standard error of the mean (M±m). To assess the probability of the difference between the experimental variants (depending on the distance from the forest protection strip), the paired Student t-test was used. Differences

at the significance level ($p < 0.05$) were considered statistically significant (marked in the text and tables with the symbol *) (Ushkarenko et al., 2013).

RESULTS AND DISCUSSION

Our research revealed that the corn crops were adjacent to the main and auxiliary windbreaks. Analysis of the studied windbreaks by tree species composition showed that the main species is lanceolate ash (*Fraxipus laçeolata* Bor. (*F. viridis* Michx.)). In all the studied auxiliary windbreaks, no secondary tree species were found, and in the main windbreaks, the secondary species was pedunculate oak (*Quercus robur* L.) (Table 2.).

Table 2. Agrobiological parameters of the structure of blown main and auxiliary field shelterbelts of the Right-Bank Forest-Steppe, 2022–2024

Forest strip parameters	Value	
View of the forest belt in the direction of the prevailing winds	Main	Auxiliary
Main breed	Lanceolate ash (*Fraxinus lanceolata* Bor. (*F. viridis* Michx.))	Lanceolate ash (*Fraxinus lanceolata* Bor. (*F. viridis* Michx.))
Secondary breed	Common oak (*Quercus robur* L.)	-
Single breeds	Heart-leaved linden (*Tilia cordata* Mill.)	-

The single species in the main forest strip was the heart-leaved linden (*Tilia cordata* Mill), and the secondary forest strip did not have single tree species. All secondary forest strips did not have shrubs in their composition. Thus, it was established that the studied secondary forest strips had the lowest species diversity. Also, all the main forest strips were more diverse in species composition than the secondary ones.

Observation of the metric parameters of the forest strips showed that the secondary forest strip had 5 rows of trees, and the secondary forest strip had 4 rows (Table 3).

Table 3. Metric parameters of the structure of blown field shelterbelts of the Right-Bank Forest-Steppe, 2022–2024

Forest strip parameters	Value	
View of the forest belt in the direction of the prevailing winds	Main	Auxiliary
Number of rows of trees, pcs.	5	4
Tree spacing between rows, designed/actual, m	1.0 / 1.0	3.0 / 3.0
Distance between trees in a row, designed / actual, m	2.0 / 5.0	2.0 / 4.0
Width of the forest strip, m	7	12
Height of the forest belt, m	15	14
Trunk girth at a height of 1.3 m, m	1.7	1.5

The forest protection strips established in the 1960s and 1970s are characterized by certain differences in the tree placement scheme both within the rows and between them. In this regard, a comparative analysis of the design parameters of tree planting at the time of the forest strips' creation and their actual state to date was carried out. Particular attention was paid to comparing the designed and actual distances between trees and rows. The results of the observations showed that the distances between the rows of trees

in the forest protection strips in most cases correspond to the design values, which ensures a clear visualization of the rows. Thus, in the main blown forest strips, the row spacing was minimal and amounted to 1.0 m, while in the auxiliary blown forest strips this indicator was significantly larger and reached 3.0 m.

In contrast, the distances between trees within one row underwent significant changes during the operation of the plantations. In the main blown forest shelterbelt, the design distance between trees was 2.0 m, while the actual distance increased to 5.0 m, which indicates the preservation of only two trees out of five planted and corresponds to 60% thinning. In the blown auxiliary forest belts, the actual distance between trees in rows was 4.0 m compared to the design 2.0 m, which corresponds to the loss of about 50% of trees.

The main blown forest shelterbelt had the smallest width among the studied stands – 7 m, while the width of the auxiliary was 5 m larger and amounted to 12 m. The height of trees in all forest belts was close and fluctuated within 14–15 m.At the same time, the largest trunk girth was recorded in the trees of the main blown forest belt – 1.7 m, which exceeded the similar indicator in the auxiliary stands by 0.2 m.

Under conditions of sufficient moisture, the optimal density of corn sowing for grain in Ukraine should not exceed 75 thousand plants per hectare. Further increase of this indicator to 100 thousand plants ha^{-1} practically does not provide an increase in yield, and its excess may lead to its decrease.

Analysis of corn sowing density at different distances from the main shelterbelt showed its variation within 71.4-100 thousand plants/ha. Maximum density values were observed at distances of 400 and 500 m from the shelterbelt, while the minimum values were at a distance of 10 m. At the same time, the dominant indicator was 85.7 thousand plants/ha, which was recorded at distances of 1, 100, 200 and 300 m from the shelterbelt, which is reflected in Table 4.

Table 4. Corn crop productivity indicators depending on the distance to the main field shelterbelt, average 2022–2024, M±m

Performance indicators	Distance from the forest shelterbelt, m						
	1	10	100	200	300	400	500
Plant density, thousand pcs. ha^{-1}	85.7 ± 0.1*	71.4 ± 0.2*	85.7 ± 0.1*	85.7 ± 0.1*	85.7 ± 0.2*	100.0 ± 0.1	100.0 ± 0.1
Plant height, cm	200 ± 7*	270 ± 12*	290 ± 8*	320 ± 5*	330 ± 4	340 ± 5	340 ± 6
Number of buds on a plant, pcs.	1 ± 0.2	1 ± 0.2	1 ± 0.2	1 ± .1	1 ± 0.2	1 ± 0.2	1 ± 0.2
Length of the beginning, cm	17 ± 3*	20 ± 2	22 ± 4	22 ± 3	23 ± 3	23 ± 2	21 ± 2
Diameter of the beginning, cm	5 ± 1	8 ± 2	8 ± 1	8 ± 2	8 ± 1	6 ± 2	7 ± 2
Mass of a thousand seeds, g	235 ± 3*	236 ± 2*	236 ± 3*	236 ± *	235 ± *	231 ± 4	228 ± 4

Note: M±m – arithmetic mean ± standard error of the mean. * – the difference between the experimental variants is statistically significant at $p < 0.05$.

The height of corn plants ranged from 200 to 340 cm. The tallest plants were at a distance of 400 and 500 m from the shelterbelt with the highest plant density. The lowest

height was achieved by corn plants at a distance of 1 m from the shelterbelt, where the effect of competition between trees for light and corn plants was evident. Subsequently, with increasing distance from the shelterbelt, the height of corn plants increased. At all distances from the shelterbelt, one shoot was found on one corn plant. However, they had different length and diameter parameters. The length of the beginning ranged from 17 to 23 cm. The longest shoot was found at a distance of 300 and 400 m from the shelterbelt, and the shortest at a distance of 1 m.There was a tendency for the shoot length to increase from a distance of 1 m to 300–400 m with a subsequent decrease in this indicator.

The diameter of the beginning, depending on the distance to the shelterbelt, was 5–8 cm. The largest diameter was observed at a distance of 10–300 m, and the smallest at a distance of 1 m.Starting from a distance of 400 m from the shelterbelt, the diameter of the corn cob begins to decrease.

The mass of a thousand corn seeds was from 228 to 236 g. The largest mass was found on plants growing at a distance of 10–200 m from the shelterbelt, and the smallest at a distance of 500 m.There is a tendency for the mass of a thousand seeds to increase from a distance of 1 m to 10 m from the shelterbelt, then this indicator stabilizes and begins to decrease from a distance of 300 m from the shelterbelt.

Observations of similar parameters of corn crops in relation to the auxiliary shelterbelt showed that the plant density varied from 57.1 to 85.7 thousand plants ha^{-1}. The highest plant density was observed at a distance from the shelterbelts of 1–100 m, and the lowest at a distance of 200 m and 500 m.The density of corn plants at a distance of 100–300 the main shelterbelt was 16.3% higher than near the auxiliary shelterbelt (Table 5).

Table 5. Corn crop productivity indicators depending on the distance to the auxiliary forest shelterbelt, average 2022–2024, M±m

Performance indicators	Distance from the forest shelterbelt, m						
	1	10	100	200	300	400	500
Plant density, thousand pcs. ha^{-1}	85.7 ± 0.1*	85.7 ± 0.1*	85.7 ± 0.2*	57.1 ± 0.2*	71.4 ± 0.2*	71.4 ± 0.2*	57.1 ± 0.2
Plant height, cm	220 ± 4*	270 ± 5	320 ± 7*	300 ± 4*	320 ± 6*	280 ± 5	280 ± 5
Number of buds on a plant, pcs.	1 ± 0.2	1 ± 0.2	1 ± 0.2	1 ± 0.2	1 ± 0.2	1 ± 0.2	1 ± 0.2
Length of the beginning, cm	16 ± 3	17 ± 2	23 ± 3*	23 ± 2*	23 ± 3*	17 ± 3	19 ± 3
Diameter of the beginning, cm	6 ± 2	7 ± 1	7 ± 2	7 ± 2	7 ± 1	6 ± 2	7 ± 2
Mass of a thousand seeds, g	235 ± 4*	236 ± 3*	236 ± 3*	236 ± 3*	235 ± 4*	231 ± 3	228 ± 4

Note: M ± m – arithmetic mean ± standard error of the mean. * – the difference between the experimental variants is statistically significant at $p < 0.05$.

The height of corn plants near the auxiliary shelterbelt was 220–320 cm. The tallest plants were at a distance of 100 and 300 m, and the lowest at a distance of 1 m. An increase in the height of corn plants was observed from a distance of 1 m to 100 m, and from a distance of 400 m – a decrease in height. Corn plants near the main shelterbelt

were found to be 5% taller than plants growing near the auxiliary shelterbelt. In general, the average height of corn plants near the main shelterbelt was 4.9% higher (Fig. 1).

The number of was similar to the corn plants growing near the main forest shelterbelt – one each. The length of the corn ears near the auxiliary forest belt was 16–23 cm. The longest ears were at a distance of 100–300 m, and the shortest – at a distance of 1 m. There is a tendency for the length of the corn ears to increase from 1 m to 100 m from the auxiliary forest belt with subsequent stabilization of this indicator over a distance of 100–300 m and subsequent decrease in length. It was found that the average length of one ear of corn growing near the main forest shelterbelt was 6.1% greater than near the auxiliary forest belt (Fig. 2).

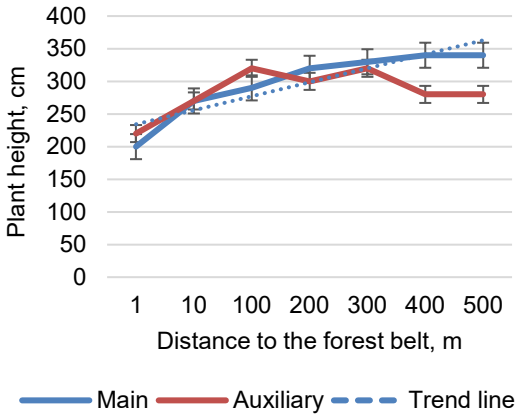

Figure 1. Dynamics of corn plant height depending on the distance from the main and auxiliary shelterbelt, mid-2022–2024.

The diameter of the corn cob was 6–7 cm. The smallest diameter was established at a distance of 1 and 400 m, and at the remaining distances – 7 cm. The average diameter of the corn cobs near the auxiliary forest strip was 5.4% smaller than near the main one.

The mass of a thousand corn seeds at a distance of 1–500 m from the forest shelterbelt near the main field shelterbelt was 228–236 g. The largest seed mass was found at a distance of 10–200 m, and the smallest – at a distance of 500 m. There is a tendency for the mass of a thousand seeds to increase from 1 to 10 m, then stabilization at the maximum value for 10–200 m with a subsequent decrease in mass. The mass of a thousand seeds did not depend on the type of field shelterbelt adjacent to the corn sowing (Table 5).

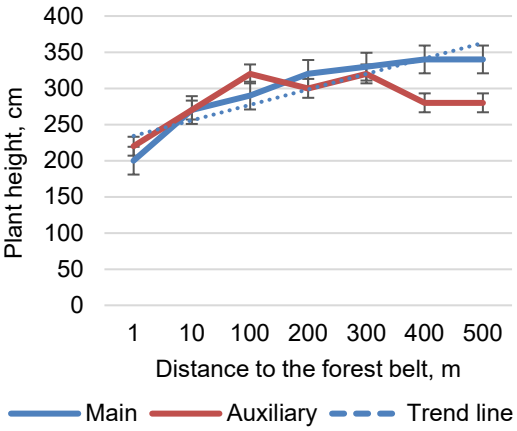

Figure 2. Dynamics of the length of the beginning of corn depending on the distance from the main and auxiliary shelterbelt, mid-2022–2024.

Observation of the level of corn yield at different distances from the shelterbelts showed that near the main shelterbelt the grain yield varied from 2.37 t ha^{-1} at a distance of 1 m to 9.03 t ha^{-1} at a distance of 300 m from the main shelterbelt. There was a tendency for the yield to increase from 1 m to 300 m with its subsequent decrease from 400 to 500 m.

A significant increase in corn grain yield was observed from a distance of 10 m to a distance of 100 m to the main shelterbelt, which was 33.5%, from 1 m to 10 m – 58.2%. At a distance of 100 m and 200 m from the main shelterbelt the level of corn grain yield was the same – 8.53 t ha^{-1}. At a distance of 200 m to 300 m, it increased by another 5.5%. At a distance of 300 m to 400 m from the main field shelterbelt, corn grain yield decreased by 19.2%, and from 400 m to 500 m, by another 2.3% (Fig. 3).

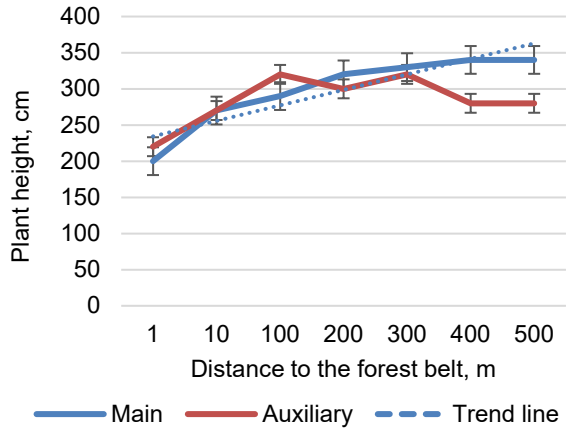

Figure 3. Dynamics of corn yield depending on the distance from shelterbelts, t ha^{-1}, mid-2022–2024.

Near the auxiliary shelterbelt, corn grain yield varied from 3.11 t ha^{-1}at a distance of 1 m from the forest belt to 7.53 t ha^{-1} at a distance of 100 m from the forest belt. The average corn yield near the main shelterbelt was 22.6% higher than near the auxiliary forest belt. Only at a distance of 1 m from the auxiliary shelterbelt was corn yield 23.8% higher than at this distance from the main shelterbelt. At a distance of 1 m to 10 m from the auxiliary shelterbelt, corn grain yield increased by 33.7%; from 10 m to 100 m – by 37.7%; from 100 m to 200 m – decreased by 8.4%; from 200 m to 300 m – by another 17.8% less; at a distance of 300 m to 400 m – by another 10.6% less, and at a distance of 400 m to 500 m – decreased by 8.7%.

An average positive correlation was found between the yield of corn grain and the distance of plants from the main shelterbelt ($r = 0.4962$) with a coefficient of determination $R_2 = 0.2462$. That is, there is a trend as the distance from the main shelterbelt increases, the yield of corn increases (Fig. 4).

A high positive correlation was found between corn grain yield and: plant height near the main shelterbelt ($r = 0.8450$); stem length ($r = 0.9413$); stem diameter ($r = 0.7582$).

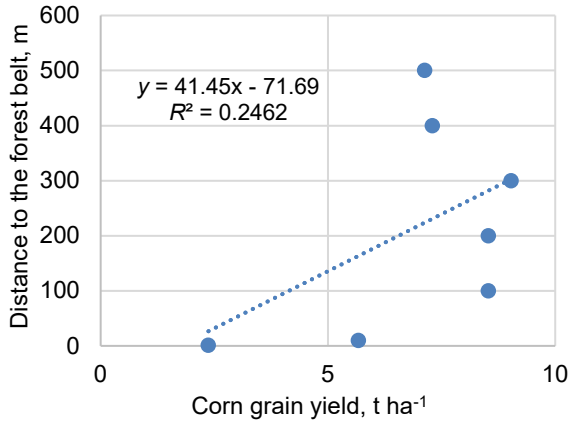

Figure 4. Correlation-regression relationship and coefficient of determination between corn grain yield and distance from the main forest shelterbelt, mid-2022–2024.

A high positive correlation was found between corn grain yield and: plant height near the auxiliary shelterbelt ($r = 0.8785$); stem length ($r = 0.8638$); medium positive correlation between corn grain yield and: stem diameter ($r = 0.5879$); thousand seed weight ($r = 0.3360$).

According to Amilia et al. (2021), the potential for increasing crop yields in the system of shelterbelts, provided they are fully functioning, can reach 20%, and the increase in pasture productivity will be 25%. According to averaged data by Demyanyuk (2019), the average increase in crop yields from the impact of shelterbelts is 15%. As Hendrawat notes, crop yields in the zone of influence of shelterbelts can increase in the range of 5-40%. The data we obtained confirm the magnitude of the increase in corn grain yields from the impact of the shelterbelt, which in our studies is 21%.

Hnatiuk et al. (2019) claims that the positive impact of the shelterbelt on increasing crop yields increases in years with unfavorable weather and climatic factors. It has been established that in dry years, when protected by forest belts, sunflower forms full grain and increases the yield by 30–45% compared to the yield in the open field. It was during the years of our observations that extreme weather conditions were detected, which manifested themselves in a 1.9 times lower amount of precipitation during 2022 compared to the norm, and in 2023–2024 – about 100 mm of precipitation fell less than the norm. And it was in such extreme weather conditions that an increase in corn grain yield by 21% was detected. The positive effect of forest belts is manifested not only in adverse conditions, but also in years with sufficient precipitation, without dry winds and dust storms. With a large amount of precipitation, the yield of winter wheat increases by up to 15%.

As Kaletnik & Lutkovska (2020) notes, forest amelioration plantations affect the microclimate, ecology and crop yield differently, depending on their type and type of structures. Yield depends on both natural and climatic conditions, the type and variety of plants, their resistance to disease, and the type of structures and the sanitary condition of forest belts. In some cases, it is lower due to the loss of the number of plants in the adjacent part of the field to the forest belt. This statement fully coincides with our studies, where the yield of corn grain at a distance of up to 10 m from the outer row of trees is very low – 3.11–5.67 t ha^{-1} and only at a greater distance begins to increase.

Mazur (2021c) found that the yield of agricultural crops, using the example of sunflower, increases with distance from the field buffer strip. The average yield increased from 2.07 t ha^{-1} to 3.10 t ha^{-1}, which is consistent with our research results, where corn grain yield increased from 1 m to 300 m from the forest belt and only decreased at a greater distance.

According to Okrushko (2022), thanks to the shelterbelts, the increase in corn yield was 3.3 t ha^{-1}. This level of yield increase is observed mainly on lands surrounded by open-cut or open-cut-blown forest belts. Forest belts of this type have small gaps, which are more or less evenly distributed throughout the entire longitudinal vertical profile of the belt and occupy approximately 15-35% of the entire area of this profile.

In our research, blown shelterbelts were studied, which allowed to obtain an increase in corn grain yield of 1.2–1.7 t ha^{-1}. Therefore, it can be concluded that blown shelterbelts contribute to a greater increase in corn grain yield than open ones.

Thus, the results of our research on increasing corn grain yield due to the presence of shelterbelts are consistent with the data of other scientists.

CONCLUSION

Studies have confirmed a significant dependence of corn grain yield on the distance from the buffer strips and their functional design. The positive meliorative effect of buffer strips was most pronounced in the range of distances of 100–300 m from crops. The maximum corn grain yield was recorded at a distance of 300 m from the main blown buffer strip, which exceeded the yield at a distance of 500 m by 21.0%. The main buffer strip demonstrated higher microclimatic efficiency compared to the auxiliary one, providing an average increase in corn yield by 22.6% due to differences in its design, width and protective capacity. It was found that the protective radius of the auxiliary buffer strip is limited, with the peak of corn yield forming at a distance closer to 100 m from the edge, after which a gradual decrease in productivity is observed.

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