The Importance of Winter Wheat Varieties for Sustainable Cultivation under Changing Weather Conditions

Inga Morozova
Institute of Agricultural Resources and Economics
Department of Plant Breeding and Agroecology
Vilani, Latvia
inga.morozova@arei.lv

Sanita Zute
Institute of Agricultural Resources and Economics
Department of Plant Breeding and Agroecology
Stende, Latvia
sanita.zute@arei.lv

Solveiga Malecka
Institute of Agricultural Resources and Economics
Department of Plant Breeding and Agroecology
Stende, Latvia
solveiga.malecka@arei.lv

Vija Strazdina
Institute of Agricultural Resources and Economics
Department of Plant Breeding and Agroecology
Stende, Latvia
vija.starzdina@arei.lv

Veneranda Stramkale
Institute of Agricultural Resources and Economics
Department of Plant Breeding and Agroecology
Vilani, Latvia
veneranda.stramkale@arei.lv

Vita Sterna
Institute of Agricultural Resources and Economics
Department of Plant Breeding and Agroecology
Stende, Latvia
vita.strena@arei.lv

Linda Upeniece
Institute of Agricultural Resources and Economics
Department of Plant Breeding and Agroecology
Vilani, Latvia
linda.upeniece@arei.lv

Ieva Kroica
Institute of Agricultural Resources and Economics
Department of Plant Breeding and Agroecology
Vilani, Latvia
ieva.kroica@arei.lv

Abstract—The aim of this study is to assess the adaptability and productivity of winter wheat varieties under variable weather conditions by analysing grain yield, 1000-grain weight (TGW), and protein content through long-term trials, as well as evaluating the impact of nitrogen fertilisation in short-term case studies. A field trials study assesses the performance of long-established (over 13 growing seasons) and newly introduced wheat varieties (one growing season at two locations). Seven significant correlations between weather conditions and grain yield, TGW, and protein content were recorded for the varieties 'Skagen' and 'Brons' over a long-term period. 'Skagen' and 'Brons' are well-adapted to the local conditions in Latvia. Negative correlations were observed between grain yield and mean temperatures in July at Vilani ($r = -0.60$; $r = -0.73$ for both varieties), as well as between total precipitation in September ($r_{Skagen} = -0.73$) at Stende. Additionally, negative correlations were found between TGW and mean temperatures in June ($r_{Skagen} = -0.72$; $r_{Skagen} = -0.64$) at both locations, while a positive correlation was observed between total precipitation in June ($r_{Skagen} = 0.73$) at Stende. Positive correlations were also recorded between protein content and total precipitation in May and June at Vilani ($r = 0.59$; $r = 0.71$) for both varieties. Negative correlation was identified between protein contents and total precipitation in April ($r = -0.68$; $r = -0.69$) for both varieties and positive correlation mean temperatures in June ($r_{Skagen} = 0.57$) at Stende. One growing season compared the effects of nitrogen fertilisation N0, N120, N180 treatments on wheat varieties 'Bright', 'Brigens', 'KWS Ahoi', and 'KWS Imperium' at two locations. At N180, the mean values for the four varieties were significant higher at Vilani and Stende compared to the control. The highest grain yield was recorded for the variety 'Bright' at Stende and for 'KWS Ahoi' at Vilani. The variety 'Brigens' was

identified as having the high protein content and TGW at both locations. These findings provide insights into sustainable wheat cultivation, with a short-term study ongoing to further develop resilient growing systems.

Keywords— correlation, long-term and short-term trial, nitrogen fertilisation, varieties, weather.

I. INTRODUCTION

In Latvia, wheat has been cultivated for centuries, and the sown area of winter wheat is larger almost each year compared to spring wheat. In recent years, winter wheat has been sown on an average of over 400 thousand hectares per year. The average yield obtained is 4–5.5 t ha^{-1}. According to official statistics, the sown area of winter wheat in Latvia has significantly increased over the past 10 years – from 164.0 thousand hectares to 438.1 thousand hectares [1]. Global wheat yields and sown area are projected to increase by 2033, with the European Union expected to become the largest wheat producer [2].

The diversity of winter wheat varieties is dynamic and constantly evolving, driven by the introduction of new varieties each year aimed at enhancing yield and adaptability. Some varieties offer more stable yields and consistent quality, demonstrating less susceptibility to environmental fluctuations. In Latvia, there is an ongoing effort to develop new winter wheat varieties that are specifically adapted to the unique Baltic conditions, ensuring improved resilience and productivity in the region [3], [4]. In Nordic-Baltic conditions it is important to use varieties which are well adapted to marginal environments in order to reduce the influence of the environment on yield and grain quality parameters [5]. As new high-yielding varieties have been developed over the last few decades, their nutrient requirements have also increased [6].

Annual variations in wheat grain yield across varieties can be primarily influenced by meteorological conditions [7] – [9]. Studying the relationship between weather conditions in a specific month and crop yields is crucial due to the ongoing global warming phenomenon. Highlights that climate change leads to increased weather variability. Analysing weather patterns and their effects on yields helps predict future trends and assess the risks or benefits of global warming, enabling informed decision-making and proactive measures [10].

Wheat yield is a complex trait influenced by the genetic composition of the plant, the environmental conditions, and the interaction between genotype and environment [11]. The prevailing view that winter wheat in the northeastern part of Europe will benefit from climate change is largely based on the assumption that rising average air temperatures will be accompanied by an increase in total annual precipitation [12]. However, with more variable rainfall, droughts could occur more often in Latvia. Modelling weather changes in the UK would have little impact on wheat yield, although drier years could reduce yields, particularly in soils with lower water-holding capacity, where drought-induced yield loss could exceed 50% [13]. Increasing heat stress around anthesis is expected to cause significant yield losses in heat-sensitive wheat cultivars in Northern Europe. The crop scientists and breeders should focus on developing wheat varieties resistant to high temperatures during flowering [14]. However, due to climate warming, favourable factors such as warmer winters are also influencing yields. Nonetheless, the potential benefits of a longer thermal growing season in Northern Europe are often limited by the risk of late frosts and early spring and summer heatwaves [15].

The effect of mineral fertilizers also depends on weather conditions [10]. The fertile soils with high water retention enable nitrogen to play a key role in maintaining wheat yields, even under dry conditions. Model simulations suggest that under low or moderate input, nitrogen will remain a major limiting factor for increasing winter wheat yield potential in the coming decades [12]. Therefore, efforts should focus on improving nitrogen efficiency, considering both nitrogen and climatic factors [16].

Overall, the study in Latvia suggests that winter wheat yield was influenced by 34% by cultivar, 33% by weather conditions, and 13% by the crop-year cultivar, with a small effect of nitrogen fertiliser at 3% [17].

This field study focuses on the most widely grown varieties over the long-term, as well as those with the greatest potential in recent years. The aim is to evaluate the adaptability of winter wheat varieties under variable meteorological conditions by analysing grain yield, 1000-grain weight, and protein content through a long-term trial. Additionally, a short-term case study assesses the productivity of different varieties and the impact of nitrogen fertilisation, contributing to the development of resilient and sustainable wheat cultivation practices.

II. MATERIALS AND METHODS

A. Experimental place

Field trials were conducted over 13 growing seasons (from September 2011 to August 2024) at the Agricultural Scientific Centre of Latgale, Vilani and the Institute of Agricultural Resources and Economics (AREI), Stende. This study evaluates the performance of long-term trials for the wheat varieties 'Skagen' and 'Brons'. The objective of the trial was to analyze the impact of weather conditions on the variability of grain yield, 1000-grain weight (TGW), and protein content in winter wheat. Winter wheat varieties were sown at a rate of 450–500 germinable seeds m^{-2}. The main agrochemical parameters are presented in Table 1.

Over the long term, complex mineral fertiliser NPK was applied annually at various ratios, with a rate of 300 kg ha^{-1}. Additional fertilisation was carried out with ammonium nitrate (34N + S) at an N rate of 150 kg ha^{-1} at Vilani. At Stende, either ammonium nitrate (34N + S) or N27-S4 was applied at an N rate of 120–150 kg ha^{-1}, depending on spring climatic conditions. Nitrogen fertilisers were applied twice during the wheat growing season: in spring (BBCH 22–23) and a second during stem elongation (BBCH 32).

Additional results from the 2023/2024 season compare the performance of prospective wheat varieties 'Bright', 'Brigens', 'KWS Ahoi', and 'KWS Imperium' at two locations: AREI in Vilani and Stende. This study examines the effects of nitrogen fertilisation treatments (control - N0, N120, N180) on grain yield, TGW, and protein content in winter wheat varieties. Both locations applied N at rates of 120 kg ha⁻¹ and 180 kg ha⁻¹, with ammonium nitrate (34N + S) used at Vilani and N27-S4 at Stende. Nitrogen fertilisers were applied three times during the wheat growing season: in spring (BBCH 22–23), during stem elongation (BBCH 32), and at the beginning of heading (BBCH 51).

In both long-term and short-term field trials, plant protection measures are organized taking into account the situation in the field, following the generally accepted integrated pest management practice for weed and disease control in wheat growing technologies. Except for the short-term trials, the N0 control variant was not treated with any plant protection products.

Grain yield was recalculated to 100% purity and a base moisture content of 14%. Grain quality indicators, protein content, were analysed using the express method (Infratec Nova 6). The thousand-grain weight (TGW) was determined according to the ISTA (International Seed Testing Association) methodology.

TABLE 1 THE MAIN AGROCHEMICAL PARAMETERS OF THE ARABLE SOIL LAYER DURING 13 GROWING SEASONS

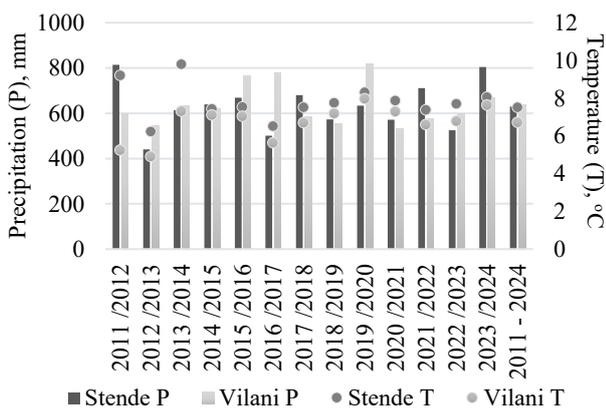| Location	Organic matter contents, %	Soil acidity (pH_{KCl})	Available P₂O₅, mg kg⁻¹	Available K₂O, mg kg⁻¹
Stende	2.0±0.3	5.7±0.1	161.0±18.4	151.2±20.8
Vilani	4.2±2.5	6.7±0.3	117.2±42.9	125.2±20.1

Fig. 1. Meteorological conditions from September 2011 to August 2024.

B. Meteorological conditions

Agro-meteorological conditions for Vilani were characterised using data from the Rezekne station, and for Stende, data from the Stende hydrometeorological station (Fig. 1).

C. Statistical analysis

Software JASP was used for data statistical analysis. The difference between the yields properties were determined using analysis of variance (ANOVA). Significant differences among the measured characteristics of wheat varieties were compared by Fisher's protected least significant difference (LSD) tests (p ≤ 0.05). The Pearson correlation coefficient was used to analyse the relationships between grain yield, TGW, and protein content with daily mean temperature and precipitation during the vegetation period with significant difference p < 0.05 and p < 0.01.

III. RESULTS AND DISCUSSION

The results indicate variations in yield, protein content, and 1000-grain weight (TGW) over a 13-year period. The average yield exhibited a wider range, varying from 5.61 to 12.78 t ha⁻¹ for the variety 'Skagen' at Vilani and from 6.01 to 12.84 t ha⁻¹ for 'Brons' at Stende (Table 2). The variety 'Skagen' has been cultivated in Latvia for a longer period, whereas 'Brons' was introduced in later years. The varieties at both locations demonstrate the potential to achieve yields exceeding 12 t ha⁻¹. These results suggest that both 'Skagen' and 'Brons' are adaptable to local growing conditions and can achieve high yields under favourable conditions. Yield variation reflects the influence of factors such as weather, soil quality, and agronomic practices, highlighting the need for further research to optimise and ensure stable yield performance.

TABLE 2 WINTER WHEAT YIELD BY VARIETY AND LOCATION OVER MULTIPLE YEARS

Variety	Location (Years)	Yield, t ha⁻¹		
		mean ± SD	min.	max.
Skagen	Vilani (2012-2024)	9.38 ± 1.93	5.61	12.78
	Stende (2012-2024)	9.25 ± 2.18	6.23	12.28
Brons	Vilani (2013 – 2023)	10.03 ± 1.24	8.78	12.40
	Stende (2015-2024)	8.59 ± 2.21	6.02	12.84

The average 1000-grain weight of winter wheat was higher for the variety 'Skagen' at both locations, with a range from 29.03 to 58.90 g (Table 3). TGW was determined primarily by the variety.

TABLE 3 WINTER WHEAT 1000-GRAIN WEIGHT BY VARIETY AND LOCATION OVER MULTIPLE YEARS

Variety	Location (Years)	TGW, g		
		mean ± SD	min.	max.
Skagen	Vilani (2012-2024)	44.73 ± 6.83	29.03	53.20
	Stende (2012-2024)	47.39 ± 6.20	38.55	58.90
Brons	Vilani (2013 – 2023)	41.26 ± 5.48	31.06	47.70
	Stende (2015-2024)	39.79 ± 5.32	32.11	45.80

The protein content was higher for 'Skagen' at both locations, with a wider range from 10.54% to 15.33% at Stende (Table 4). The variety 'Skagen' is more suitable in certain years for food quality, reaching 12%.

TABLE 4 WINTER WHEAT PROTEIN CONTENT BY VARIETY AND LOCATION OVER MULTIPLE YEARS

Variety	*Location* *(Years)*	*Protein content, %*		
		mean ± SD	*min.*	*max.*
Skagen	Vilani (2012-2024)	13.03 ± 1.01	11.40	15.20
	Stende (2012-2024)	12.93 ± 1.71	10.54	15.33
Brons	Vilani (2013 – 2023)	12.36 ± 0.71	11.30	13.70
	Stende (2015-2024)	11.97 ± 1.08	10.39	13.23

A correlation analysis was conducted to assess the relationship between weather conditions in specific months and yield, 1000-grain weight (TGW), and protein content. Seven relationships were found to be statistically significant.
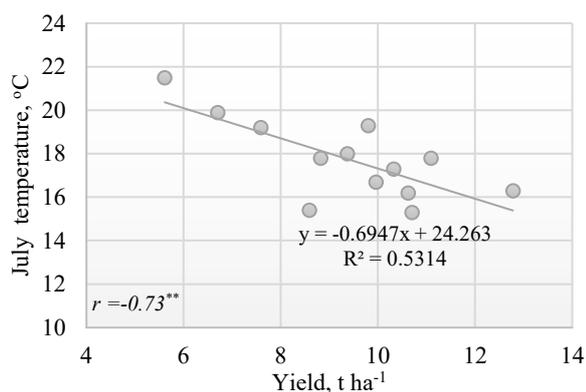

Fig. 2. Correlation of winter wheat 'Skagen' yield with July average temperature at Vilani.

Negative correlations were observed between grain yield and mean temperatures in July at Vilani (r = −0.60; r = −0.73 for both varieties), as well as between total precipitation in September during the sowing period (r = −0.73 for 'Skagen') at Stende (Figs. 2., 3., 4.). These results suggest that higher temperatures in July during the grain-filling period may negatively impact grain yield, potentially through increased evaporation or heat stress, which can limit the plant's ability to accumulate dry matter. Similar results [18] were found in another modelling study in Latvia, showing a negative correlation between July temperatures and winter wheat yield. In Stende, the negative correlation with July temperature is weaker. Observing higher average July temperatures in Vilani in certain years may indicate regional differences in variety adaptability. In this study lowest grain yield was observed at a critical average daily temperature of 21.5°C in July for both varieties at Vilani. The study by [19] indicates that the optimum temperature for wheat growth is between 15 °C and 20 °C. It is estimated that for every 1°C increase in temperature, the duration of grain filling in wheat decreases by 2.8 days [20], which results in a yield reduction of approximately 6% [21]. An increase in the average ambient temperature is not only due to rising maximum temperatures but also growing minimum temperatures [22]. In this study [23] found a stronger correlation between wheat grain yield and minimum temperature than with maximum temperature, estimating a 10% yield decrease for every 1°C rise in night temperature.
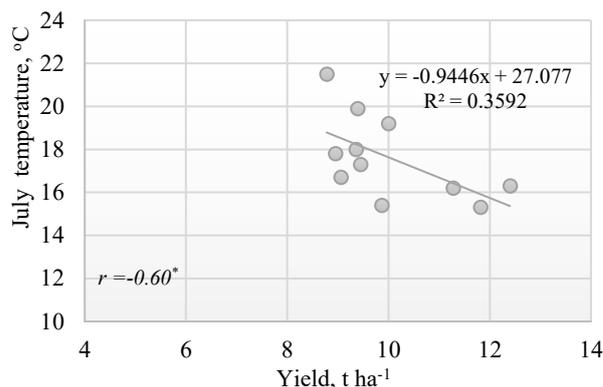

Fig. 3. Correlation of winter wheat 'Brons' yield with July average temperature at Vilani.

The strong negative correlation between September precipitation and yield in 'Skagen' at Stende suggests that excessive moisture during the sowing period can interfere with crop establishment. Lower grain yields were identified with September precipitation ranging from 134.10 to 152.40 mm, which had a negative impact over two years. This could result in poor germination, uneven emergence, or waterlogging, all of which can hinder early growth.
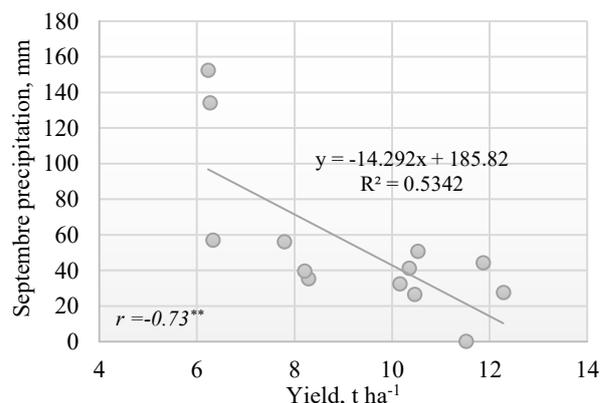

Fig. 4. Correlation of winter wheat 'Skagen' yield with September total precipitation at Stende.

Protein content and TGW interaction with weather conditions across different Latvian regions have not been extensively studied. However, the results indicate regional differences and varietal adaptability. Additionally, negative correlations were found between TGW and mean temperatures in June ($r_{Skagen} = -0.72$; $r_{Skagen} = -0.64$) at both locations, while a positive correlation was observed between total precipitation in June ($r_{Skagen} = 0.73$) at Stende (Table 5). These results indicate that higher mean temperatures in June negatively affect TGW, while increased precipitation in June positively influences TGW at Stende. This suggests that warmer conditions may reduce grain weight, possibly due to heat stress, while higher moisture availability supports grain development and yield productivity.

TABLE 5 CORRELATION OF WINTER WHEAT TGW AND PROTEIN
CONTENT WITH MONTHLY TEMPERATURE AND PRECIPITATION

Variety	*Location*	$r_{April\ P}$	$r_{May\ P}$	$r_{Jun\ P}$	$r_{Jun\ T}$
		TGW			
Skagen	Vilani			0.06	-0.71**
	Stende			0.73**	-0.64*
Brons	Vilani			0.42	-0.12
	Stende			-0.33	-0.46
		Protein content			
Skagen	Vilani	-0.16	0.47	0.59*	-0.09
	Stende	-0.68*	-0.43	-0.43	0.57*
Brons	Vilani	0.10	0.71**	0.42	-0.12
	Stende	-0.69**	-0.26	0.40	0.45

* $p < 0.05$, ** $p < 0.01$

Positive correlations were observed between protein content and total precipitation in May and June at Vilani ($r = 0.59$; $r = 0.71$) for both varieties (Table 5). Increased precipitation in May and June positively affects protein content. A negative correlation was found between protein content and total precipitation at Stende in April ($r = -0.68$; $r = -0.69$) for both varieties, while a positive correlation was identified between protein content and mean temperatures in June ($r_{Skagen} = 0.57$). This suggests that higher precipitation in April may reduce protein content, while warmer temperatures in June may have a greater impact on protein synthesis for wheats variety at Stende. According to [24], [25] protein content increases under drought and heat stress during grain formation and filling, and decreases under optimal weather conditions. Studies [26], [27] reveal that weather interactions during anthesis and mid-grain filling influence TGW and protein content, depending on the variety.

TABLE 6 YIELD (T HA⁻¹) OF WINTER WHEAT VARIETIES BY LOCATION
AND VARIETY DURING THE 2023/2024 GROWING PERIOD

N, kg ha⁻¹	*Bright*	*Brigens*	*Ahoi*	*Imperium*	*Mean* ^{A}
		Vilani			
0	5.23	5.27	5.23	4.37	5.02
120	6.64	6.31	6.72	4.58	**6.06**
180	7.36	7.39	7.52	5.51	**6.95**
Mean ^{B}	**6.41**	**6.32**	**6.49**	4.82	
A factor LSD₀.₀₅ = 0.30; B factor LSD₀.₀₅ = 0.35					
		Stende			
0	1.54	1.27	1.24	1.43	1.37
120	3.89	3.95	3.72	3.55	**3.78**
180	5.83	5.28	5.48	5.48	**5.51**
Mean ^{B}	3.75	3.50	3.48	3.49	
A factor LSD₀.₀₅ = 0.34; B factor LSD₀.₀₅ = 0.40					

$^{A,\ B}$ with bold significant difference ($p < 0.05$)

This study compared long-term and short-term results, indicating that the climatic conditions during the 2023/2024 growing period affected lower grain yield, protein content, and 1000-grain weight for all prospective varieties at both locations.

Grain yield was comparable across all varieties, with the exception of variety 'Imperium', which exhibited a significantly lower yield at Vilani (Table 6). The highest grain yield was recorded for the variety 'Bright' at Stende (5.25 t ha⁻¹) and for 'Ahoi' at Vilani (7.52 t ha⁻¹) under the N180 rate. Due to high soil organic matter at Vilani, relatively high yields were observed even at N0, and the

effect of nitrogen was less pronounced than at Stende. N treatment had a significant impact on yield, with the highest yield observed at N180, particularly in Stende. Several studies in Latvia have shown that grain yield increases when nitrogen rates are raised to 180 kg ha⁻¹ N. Beyond this point, further increases in nitrogen application do not result in significant yield growth, but grain quality indicators continue to improve [6].

TABLE 7 PROTEIN CONTENT (%) OF WINTER WHEAT VARIETIES BY
LOCATION AND VARIETY DURING THE 2023/2024 GROWING PERIOD

N, kg ha⁻¹	*Bright*	*Brigens*	*Ahoi*	*Imperium*	*Mean* ^{A}
		Vilani			
0	10.02	9.95	9.50	9.83	9.83
120	10.82	10.91	10.19	11.59	**10.87**
180	11.72	11.66	11.10	12.29	**11.69**
Mean ^{B}	**10.85**	**10.84**	10.26	**11.24**	
A factor LSD₀.₀₅ = 0.50; B factor LSD₀.₀₅ = 0.54					
		Stende			
0	9.18	10.18	9.18	9.13	9.41
120	10.16	10.85	10.02	10.52	**10.38**
180	12.69	13.06	12.92	12.25	**12.73**
Mean ^{B}	10.68	**11.36**	10.71	10.63	
A factor LSD₀.₀₅ = 0.26; B factor LSD₀.₀₅ = 0.31					

$^{A,\ B}$ with bold significant difference ($p < 0.05$)

Protein content was more variety-specific, with significantly higher levels for 'Brigen' at both locations, as well as for 'Imperium' and 'Bright' at Vilani (Table 7). N treatment had a significant impact at both N120 and N180 compared to the control. The highest protein content was observed with the N180 treatment at both locations, indicating a strong positive effect of higher nitrogen application on protein accumulation. The standard protein content for food-quality wheat grain is 12%. This quality was achieved by almost all varieties under the N180 rate, except for the variety 'Ahoi' at Vilani. A study in Latvia [16] and research in Germany [28] both found that an N rate of 180 kg ha⁻¹ is crucial for achieving protein content suitable for bread baking, highlighting the importance of optimal fertilisation for wheat quality.

TABLE 8 1000-GRAIN WEIGHT (G) OF WINTER WHEAT VARIETIES BY
LOCATION AND VARIETY DURING THE 2023/2024 GROWING PERIOD

N	*Bright*	*Brigens*	*Ahoi*	*Imperium*	*Mean* ^{A}
		Vilani			
0	39.28	35.27	35.69	36.59	36.71
120	39.79	35.49	33.93	35.25	36.11
180	43.18	40.68	37.83	39.64	**40.33**
Mean ^{B}	**40.75**	**37.15**	35.81	**37.16**	
A factor LSD₀.₀₅ = 1.08; B factor LSD₀.₀₅ = 0.94					
		Stende			
0	27.44	30.61	28.14	28.83	28.75
120	28.91	29.23	27.92	30.11	29.04
180	33.15	34.56	29.79	34.07	**32.89**
Mean ^{B}	29.84	**31.47**	28.62	**31.00**	
A factor LSD₀.₀₅ = 1.26; B factor LSD₀.₀₅ = 1.09					

$^{A,\ B}$ with bold significant difference ($p < 0.05$)

The results for the 1000-grain weight of winter wheat varieties showed that 'Brigens' and 'Imperium' had higher potential at both locations, while 'Bright' also had a higher weight at Vilani. Coarser grains were observed at Vilani (Table 8). The N180 treatment had a higher impact on

thousand-grain weight for all varieties and locations compared to the control, highlighting the positive effect of higher nitrogen application on grain size. Effect of N-rate on TGW is also shown by [16], [17].

At N180, the mean values for the four varieties were higher at Vilani, with yield increasing average by 130%, protein content by 16%, and TGW by 6% and at Stende, yield increased by 241%, protein content by 23%, and TGW by 8% compared to the control (Fig. 5). These results confirm that higher N treatment significantly impacted grain yield across all varieties. The findings suggest that the effect of nitrogen is more pronounced at Stende, likely due to differing soil and environmental conditions between the two locations.
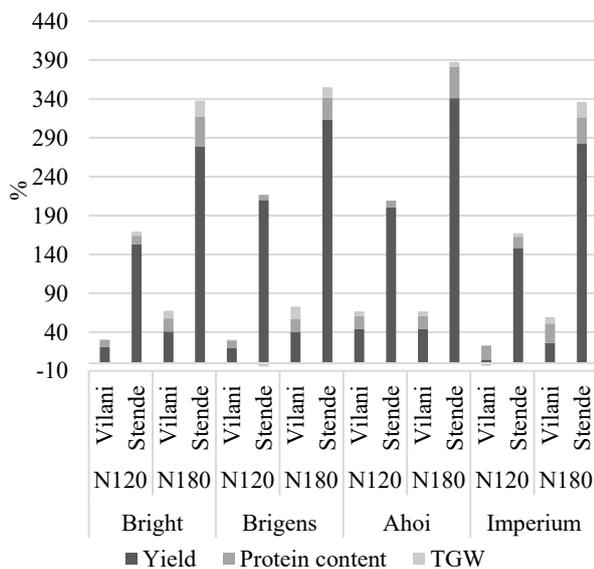

Fig. 5. Yield, protein, and TGW changes by N treatment compared to control during the 2023/2024 growing period.

IV. Conclusions

'Skagen' and 'Brons' are well-adapted to local conditions and can achieve yields exceeding 12 t ha⁻¹, with protein content ranging from 10.54% to 15.33% and TGW ranging from 29.03 to 58.90 g under Latvian climatic conditions.

Analysis of the interaction with weather conditions identified seven significant correlations, providing further insights due to future climatic and agronomic challenges. Negative correlations were observed between grain yield and mean temperatures in July at Vilani ($r = -0.60$; $r = -0.73$ for both varieties), as well as between total precipitation in September ($r_{Skagen} = -0.73$) at Stende. Additionally, negative correlations were found between TGW and mean temperatures in June ($r_{Skagen} = -0.72$; $r_{Skagen} = -0.64$) at both locations, while a positive correlation was observed between total precipitation in June ($r_{Skagen} = 0.73$) at Stende. Positive correlations were also recorded between protein content and total precipitation in May and June at Vilani ($r = 0.59$; $r = 0.71$) for both varieties. Negative correlation was identified between protein contents and

total precipitation in April ($r = -0.68$; $r = -0.69$) for both varieties and positive correlation mean temperatures in June ($r_{Skagen} = 0.57$) at Stende.

One growing season compared the effects of nitrogen fertilisation treatments on wheat varieties 'Bright', 'Brigens', 'KWS Ahoi', and 'KWS Imperium' at two locations. The application of N180 significantly increased yield, protein content, and TGW at both Vilani and Stende. Results highlight the positive effects of N180 on crop performance, with particularly strong benefits observed at Stende. The highest grain yield was recorded for the variety 'Bright' at Stende (5.25 t ha⁻¹) and for 'KWS Ahoi' at Vilani (7.52 t ha⁻¹). The variety 'Brigens' was identified as having the highest protein content and TGW at both locations. These findings provide insights into sustainable wheat cultivation, with a short-term study ongoing to further develop resilient growing systems.

References

[1] Central Statistical Bureau of Latvia (2025). Central Statistical Bureau of Latvia database. February, 2025. [Online]. Avalaible: https://data.stat.gov.lv/pxweb/lv/OSP_PUB/START__NOZ__LA__LAG/LAG020/table/tableViewLayout1/ [Accessed February 11, 2025]

[2] OECD-FAO Agricultural Outlook 2024-2033, Paris and Rome, p. 331. October 2024. [Online]. Available: OECD-FAO Agricultural Outlook, https://www.oecd.org/ [Accessed March 11, 2025], https://doi.org/10.1787/4c5d2cfb-en

[3] V. Strazdiņa, "Development of new winter and spring wheat varieties in Latvia" Proceedings of the Latvian Academy of Sciences Section B Natural Exact and Applied Sciences, vol. 66, p. 48–53. January 2012 . [Online]. Available: Sciendo https://sciendo.com/ [Accessed February 11, 2025], https://doi.org/10.2478/v10046-011-0046-9

[4] V. Strazdiņa, L. Vilmane, V. Fetere and L. Šalkovska "Suitability of Latvian origin rye and wheat genetic resources for a niche products", Scientific-Practical Conference "Sustainable Agriculture 2023", Jelgava, Latvia 2023, pp. 19.

[5] R. Koppel, A. Ingver, P. Ardel, T. Kangor, H. J. Kennedy and M. Koppel, "The variability of yield and baking quality of wheat and suitability for export from Nordic–Baltic conditions", Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, vol. 70, no. 8, p. 628–639. October 2020. [Online]. Available: Taylor & Francis https://www.tandfonline.com/ [Accessed February 11, 2025], https://doi.org/10.1080/09064710.2020.1829025

[6] V. Guberac, S. Marić, G. Drezner, S. Petrović, K. Dvojković, and V. Brandić, Interrelationships of important agronomic traits and kernel yield in winter wheat. 11th International Wheat Genetics Symposium: Australia, 2008, pp. 681–684.

[7] I. Skudra and A. Linina, "The influence of meteorological conditions and nitrogen fertilizer on wheat grain yield and quality. In Innovation for food science and production" presented at 6th Baltic Conference on Food Science and Technology, pp. 23–26. Jelgava, Latvia, 2011.

[8] A. Karklins and A. Ruza, 2015 "Nitrogen apparent recovery can be used as the indicator of soil nitrogen supply", Zemdirbyste-Agriculture, vol. 102, no. 2, p. 133–140. June 2015. [Online].

Available: ResearchGate https://www.researchgate.net/. [Accessed January 21, 2025].

[9] H. Liu, T. Colombi, O. Jäck, T. Keller and M. Weih, "Effects of soil compaction on grain yield of wheat depend on weather conditions", Science of the Total Environment, vol. 807, e150763. October 2021. [Online]. Available: ScienceDirect, https://www.sciencedirect.com/. [Accessed January 21 2025], https://doi.org/10.1016/j.scitotenv.2021.150763

[10] L. Hlisnikovský, L. Menšík, P. Barłóg and E. Kunzová, "How weather and fertilization affected grain yield and stability of winter wheat in a long-term trial in the South Moravian region, Czech Republic", Agronomy, vol. 13, e-2293. August 2023. [Online]. Available: MDPI, https://www.mdpi.com/ . [Accessed January 21, 2025], https://doi.org/10.3390/agronomy13092293

[11] S. Lazauskas, V. Povilaitis, Š. Antanaitis, J. Sakalauskaitė, S. Sakalauskienė, G. Pšibišauskienė, O. Auškalnienė, S. Raudonius and P. Duchovskis, "Winter wheat leaf area index under low and moderate input management and climate change", Journal of Food, Agriculture & Environment, vol.10, no. 1, p. 588–593. January 2012.

[12] G. M. Richter and M.A. Semenov, "Modelling impacts of climate change on wheat yields in England and Wales: assessing drought risks", Agricultural Systems, vol. 84, no. 1, p. 77–97. April 2005. [Online]. Available: ScienceDirect, https://www.sciencedirect.com/ . [Accessed February 02, 2025], https://doi.org/10.1016/j.agsy.2004.06.011

[13] V. O. Sadras and D. Rodriguez, "Modelling the nitrogen-driven trade-off between nitrogen utilisation efficiency and water use efficiency of wheat in eastern Australia", Field Crops Research, vol. 118, no. 3, p. 297–305. September 2010. [Online]. Available: ScienceDirect, https://www.sciencedirect.com/ . [Accessed February 06, 2025], https://doi.org/10.1016/j.fcr.2010.06.010

[14] M. A. Semenov, M. A., and P. R. Shewry, "Modelling predicts that heat stress, not drought, will increase vulnerability of wheat in Europe", Scientific Reports, vol. 1, no. 1, p. e66. August 2011. [Online]. Available: ResearchGate https://www.researchgate.net/. [Accessed February 07, 2025].

[15] D. V. Gaeva, G. M. Barinova, and Eugene V. Krasnov, "Hot and Cold Extreme Temperature Risk and Resilience in the Baltic Sea Region: Agricultural Aspects", SDGs in the European Region, Implementing the UN Sustainable Development Goals – Regional Perspectives, p. 3–23. 2023. [Online]. Available: Springer Nature Link https://link.springer.com/ . [Accessed February 06, 2025], https://doi.org/10.1007/978-3-031-17461-2_31

[16] L. Litke, Z. Gaile, A. Ruža, "Effect of nitrogen fertilization on winter wheat yield and yield quality", Agronomy Research, vol. 16, no. 2, p. 500–509. 2018. [Online]. Available: EMU DSpace https://dspace.emu.ee/ .[Accessed February 06, 2025], https://doi.org/10.15159/AR.18.064

[17] A. Linina and A. Ruza, "The influence of cultivar, weather conditions and nitrogen fertilizer on winter wheat grain yield", Agronomy Research, vol. 16, no. 1, p. 147156, 2018. [Online]. Available: EMU DSpace https://dspace.emu.ee/ . [Accessed February 16, 2025], https://doi.org/10.15159/AR.18.034

[18] A.Vannoppen, A. Gobin, L. Kotova, S. Top, L. D. Cruz, A. Vīksna, S. Aniskevich, L. Bobylev, L. Buntemeyer, S. Caluwaerts, R. D. Troch, N. Gnatiuk, R. Hamdi, R. C. Remedio, A. Sakalli, H.V. D. Vyver, B. V. Schaeybroeck and P. Termonia, "Wheat Yield Estimation from NDVI and Regional Climate Models in Latvia", Remote Sensing for Agrometeorology, vol. 12, no. 14, e2206. July 2020 [Online]. Available: MDPI, https://www.mdpi.com/ . [Accessed February 06, 2025], https://doi.org/10.3390/rs12142206

[19] B. Mueller, M. Hauser, C. Iles, R. H. Rimi, F. W. Zwiers, H. Wan, "Lengthening of the growing season in wheat and maize producing regions", Weather Clim Extrem, vol. 9, no. 2, p. 47–56. May 2015. [Online]. Available: ScienceDirect, https://www.sciencedirect.com/. [Accessed February 06, 2025], https://doi.org/10.1016/j.wace.2015.04.001

[20] N. A. Streck, "Climate change and agroecosystems: The effect of elevated CO_2 and temperature on crop growth, development, and yield", Ciência Rural, vol. 35, p. 730–740. Jun 2005. [Online]. Available: SciELO Brazil https://www.scielo.br/ . [Accessed February 01, 2025], https://doi.org/10.1590/S0103-84782005000300041

[21] S. Asseng, I. Foster and N. C. Turner, "The impact of temperature variability on wheat yields", Global Change Biology, vol. 17, p. 997–1012. 2011. [Online]. Available: Wiley https://onlinelibrary.wiley.com/ . [Accessed February 01, 2025], https://doi.org/10.1111/j.1365-2486.2010.02262.x

[22] R. S. Vose, D. R. Easterling, and B. Gleason, "Maximum and minimum temperature trends for the globe: An update through 2004", Geophysical Research Letters, p. 32. 2005. [Online]. Available: AGU Journals https://agupubs.onlinelibrary.wiley.com/. [Accessed January 21, 2025], https://doi.org/10.1029/2005GL024379

[23] D. B. Lobell, A. Sibley and J. I. Ortiz-Monasterio, (2012). Extreme heat effects on wheat senescence in India. Nature Climate Change, vol. 2, p. 186–189. 2012. [Online]. Available: ResearchGate https://www.researchgate.net/. [Accessed January 21, 2025].

[24] A. Linina and A. Ruza, "Weather conditions effect on fresh and stored winter wheat grain gluten quantity and quality", 25th Congress. Nordic View To Sustainable Rural Development: Latvia 2015, p. 148–153.

[25] M. I. Kulyk, A. O. Rozhkov, O. V. Kalinichenko, A. O. Taranenko and O. V. Onopriienko, "Effect of winter wheat variety, hydrothermal coefficient (HTC) and thousand kernel weight (TKW) on protein content, grain and protein yield", Agronomy Research, vol. 18, no. 3, p. 2103–2116, 2020. [Online]. Available: EMU DSpace https://dspace.emu.ee/ . [Accessed February 01, 2025], https://doi.org/10.15159/AR.20.187

[26] M. Mirosavljevi, S. Miki, V. Župunski, L. Abdelhakim, D. Trkulja, R. Zhou, A. K. Špika and C.-O. Ottosen, "Effects of Heat Stress during Anthesis and Grain Filling Stages on Some Physiological and Agronomic Traits in Diverse Wheat Genotypes", Plants, vol. 13, e2083. July 2024 [Online]. Available: ResearchGate https://www.researchgate.net/. [Accessed January 21, 2025].

[27] E. Sugár, Z. Berzsenyi, T. Árendás and P. Bónis, "Effect of nitrogen fertilization and genotype on the yield and yield components of winter wheat", Journal of Land Management, Food and Environment, vol. 67, no. 1, p. 25–34. 2016. [Online]. Available: Sciendo https://sciendo.com/ [Accessed January 21, 2025], https://doi.org/10.1515/boku-2016-0003

[28] E. A. Weber, S. Graeff, W. D. Koller, W. Hermann, N. Merkt, and W. Claupein, "Impact of nitrogen amount and timing on the potential of acrylamide formation in winter wheat (*Triticum aestivum* L.)", Field Crops Research, vol. 106, p. 44–52. February 2008. [Online]. Available: ScienceDirect, https://www.sciencedirect.com/. [Accessed January 21, 2025], https://doi.org/10.1016/j.fcr.2007.10.011