

Article

Not peer-reviewed version

Soil-Based Potential/Attainable Yields of Winter Wheat on the Base of Multi-Environment Trials Conducted in Poland

[Michał Stępień](#)* and [Marzena Iwańska](#)

Posted Date: 16 April 2026

doi: 10.20944/preprints202604.1204.v1

Keywords: winter wheat; attainable yield; yield gap; arable land quality classes; arable land suitability groups



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a [Creative Commons CC BY 4.0 license](#), which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Article

Soil-Based Potential/Attainable Yields of Winter Wheat on the Base of Multi-Environment Trials Conducted in Poland

Michał Stępień ^{1,*} and Marzena Iwańska ²

¹ Independent Researcher, 02-760 Warsaw, Poland

² Institute of Agriculture, Warsaw University of Life Science, 02-787 Warszawa, Poland

* Correspondence: michal1966@gmail.com

Abstract

Attainable yields represent the yields that can be achieved under production conditions and are used to determine the exploitable yield gap. However, these yields are constrained by multiple factors, including soil properties, which vary at different spatial scales, even within a single field. Thus, the attainable yields should be adjusted to specific soil units. This study uses results from multi-environment cultivar testing trials conducted by COBORU in Poland to estimate winter wheat attainable yields depending on arable land quality classes (ALQCs) and arable land suitability groups (ALSGs). The database comprises 10 years of observations from 18 locations and 156 experiments. The results indicate a clear relationship between the scores assigned to particular ALQCs and ALSGs in 1981. In contrast, the relationship between the average scores assigned to ALQCs within ALSGs was weaker. Attainable yields were estimated directly based on experimental data, using the third quartile (Q3) of yields, for well-represented soil units, and regression analysis between Q3 yields and point scores for less-represented soil units. The results could be improved by using a more extensive dataset, particularly for underrepresented soils. The proposed method may be applied to estimate soil-adjusted attainable yields for other crops whose cultivars are tested by COBORU in multi-environment trials.

Keywords: winter wheat; attainable yield; yield gap; arable land quality classes; arable land suitability groups

1. Introduction

The yield gap is defined as the difference between actual yield and potential yield that can be achieved under optimal management and environmental conditions [Lobell et al 2009, van Ittersum et al 2013, Fischer et al. 2015, Kamkar et al. 2025]. Reducing the yield gap is crucial for achieving food security and improving the efficiency of arable land and agricultural input use [Kamkar et al. 2025, Wójcik-Gront et al 2021]. These objectives can be addressed by estimating potential yields at different spatial scales, including countries, regions, fields, and even within-field variability. The main approaches used to estimate yield potential include crop model simulations, field experiments, maximum farm yields, climate analogues, and net primary productivity of natural ecosystems [Lobell et al. 2009].

Crop yields depend on numerous natural factors, primarily soil properties and weather conditions, as well as anthropogenic factors such as water, nutrient, disease, pest and weed management, and the use of well-adapted and high-yielding species and cultivars [Miller et al. 2010, van Ittersum et al 2013, Fischer et al. 2015, Wójcik-Gront et al 2021, Senapati and Semenov 2020]. Accordingly, potential yield can be defined under optimal conditions, including sufficient water supply, or as rainfed (water-limited) potential yield when irrigation is not available or not practiced [Kamkar et al. 2025]. In addition, attainable (or exploitable) yield—typically representing

approximately 70-80 % of potential yield—can be distinguished, reflecting realistic production conditions and efficient input use. Consequently, the attainable (exploitable or manageable) yield gap can also be defined [Lobell et al. 2009, Kamkar et al 2025].

Both rainfed potential yield and attainable yield vary across spatial and temporal scales. Differences between countries and regions are mainly driven by climate variability [Lobell et al. 2009, Kamkar et al 2025], whereas within-country and within-field variability is largely related to soil heterogeneity. In addition, interannual variability results from differences in weather conditions [Gozdowski et al. 2014, Ali et al. 2014, 2021, Hennings et al. 2016, Astrauskas et al. 2022, Washmon et al. 2002]. Therefore, both potential and attainable yields are expected to differ among soils with varying properties affecting soil quality, suitability, and productivity, even under optimal crop management. Existing definitions of yield gap are typically based on ideal conditions that are rarely achieved not only across entire countries or regions but often, even within a single field due to soil variability. Thus, it is more appropriate to estimate potential and attainable yields— and the corresponding yield gap—not only at broader spatial scales but also for specific soil units characterized by relatively uniform productivity. Moreover, even within homogeneous field zones, yields vary between growing seasons; therefore, attainable yields should be considered season-dependent [Gozdowski et al. 2014, Ali et al. 2014, 2021, Hennings et al. 2016, Astrauskas et al. 2022, Washmon et al. 2002].

Soil is one of the most important natural factors determining crop yield; therefore, attainable yield is expected to vary among soil units. In Poland, agricultural land is classified into soil quality classes („klasy bonitacyjne” in Polish) and land suitability groups („kompleksy przydatności rolniczej” or „kompleksy glebowo-rolnicze” in Polish). Soil quality classes are defined based on genetic soil and their productive potential, according to the Act of 17 May 1989—Geodetic and Cartographic Law. These classes are determined separately for different land-use types (arable lands, meadows, pastures, and forests) and for different physiographic regions (lowlands, uplands, and mountains). Basic information on arable land soil quality classes (ALQC) is provided in Annex A.

Land suitability groups are defined as groups of soils that can be managed in a similar way and are primarily based on yield-limiting factors such as water conditions and erosion [Witek 1973]. This concept is closely related to later-developed concept of management zones (MZs) [Nawar et al. 2017, Abbasi et al. 2025]. As with soil quality classes, land suitability groups are defined separately for land use types and physiographic regions. Basic information on arable land suitability groups (ALSG) is presented in Annex B. Importantly, only soils belonging to specific ALQCs can be assigned to particular ALSGs.

For land valuation purposes, numerical scores were assigned to both soil quality classes and land suitability groups [Annex A and B] based on cereal yields obtained from more than 5900 experiments conducted between 1970 and 1975 [Witek in. 1981, Witek 1979]. These data reflect the technological level of that period. In a 20-years study, Niewiadomski et al. [1988] demonstrated a clear relationship between ALSGs and winter wheat yield, with the highest yields observed for ALSG 8 (56 dt ha⁻¹) and ALSG 1 (54.4 dt ha⁻¹). More recent studies by Iwańska et al. [2020, 2021] confirmed a strong relationship between the scores assigned to ALSGs Witek et al. [1981] and winter wheat yield. Based on one-year data, an increase of 10 points corresponded to a yield increase of 0.93 t ha⁻¹ [Iwańska et al. 2020], whereas in five-years data the increase was lower (0.79 t ha⁻¹ per 10 points).

Additionally, the average score assigned to ALQC and ALSG is used to calculate the soil quality and suitability index (ALQS), which is applied to characterize agricultural land in Poland alongside indices describing agroclimate, relief, and water conditions. According to Stuczyński et al. [2007], explained approximately 67 % of the variability in cereal yields in Lower Silesia.

In Germany, Hennings et al. [2016] analyzed the relationship between winter wheat and rye yields and soil quality indices, including the traditional (Bodenschätzung) Bodenschätzung and the Müncheberg Soil Quality Rating (M-SQR). They reported strong year-specific correlations, with coefficients ranging from 0.56 to 0.86 for Bodenschätzung and from 0.66 to 0.98 for M-SQR.

Despite this well-established conceptual framework, there is still limited evidence on the direct estimation of attainable yields within officially defined soil quality classes and land suitability groups under contemporary production conditions. Consequently, the quantitative translation of soil classification systems into attainable winter wheat yields remains insufficiently explored in Poland.

The aim of this study is to determine the attainable yields of winter wheat for specific arable soil quality classes and land suitability groups of lowland areas of Poland.

2. Materials and Methods

2.1. Data Source and Experimental Design

Winter wheat grain yield data used in this study was obtained from multi-environment trials conducted by the Research Centre for Cultivar Testing (COBORU). COBORU evaluates of major crop species across 49 experimental locations in Poland under standardized agronomic management conditions.

The dataset covered the period 2015-2024 and included results from 18 experimental sites (Figure 1; Table 1) representing all voivodships of Poland (https://en.wikipedia.org/wiki/Administrative_divisions_of_Poland, access: 2 December 2025). However, most experimental sites (with the exception of Tomaszów Bolesławiecki) were located on soils of higher quality and suitability than the regional averages for the respective voivodship (Table 1). Each experimental location was assigned to an arable land suitability group (ALSG) according to the official Polish soil classification system. The trials were conducted under conventional management practices typical for cultivar testing. The methodology applied by COBORU is uniform across the country and has been described in previous studies [Studnicki et al. 2017, 2019, Iwańska et al. 2021]. Grain yield was expressed in dt ha^{-1} at standard moisture content.

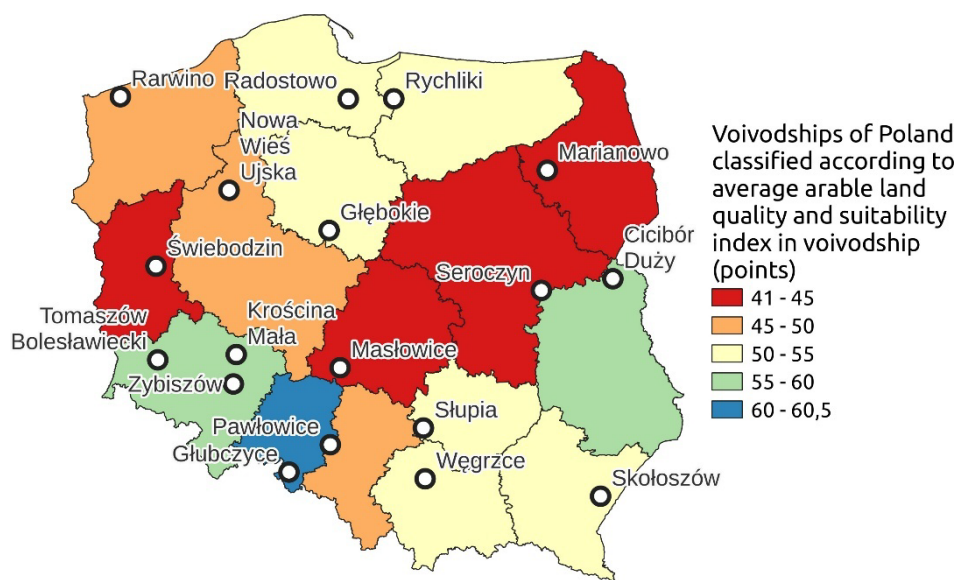


Figure 1. The winter wheat trial locations within voivodships of Poland.

Table 1. Basic characteristics of winter wheat experimental sites included in the study.

Voivodship (Polish Name)	Land Quality and Suitability Index (Voivodship Level) ¹	Experimental Site (SDOO)	Land Quality and Suitability Index (Site Level) ¹
West Pomeranian (zachodniopomorskie)	50.0	Rarwino	57.4
Pomeranian (pomorskie)	50.6	Radostowo	93.0
Warmian–Masurian (warmińsko-mazurskie)	51.1	Rychliki	75.0
Podlaskie (podlaskie)	41.0	Marianowo	67.2
Lubuskie (lubelskie)	43.6	Świebodzin	70.9
Greater Poland (wielkopolskie)	46.4	Nowa Wieś Ujska	68.8
Kuyavian–Pomeranian (kujawsko-pomorskie)	54.4	Głębokie	81.5
Mazovian (mazowieckie)	43.1	Seroczyn	66.5
Łódzkie (łódzkie)	43.2	Masłowice	67.8
Lublin (lubelskie)	55.8	Cicibór Duży	70.0
		Krościna Mała	76.6
Lower Silesian (dolnośląskie)	56.9	Tomaszów Bolesławiecki	50.9
		Zybiszów	87.2
Opolskie (opolskie)	60.5	Głubczyce	93.0
Silesian (śląskie)	46.8	Pawłowice	75.0
Świętokrzyskie (świętokrzyskie)	52.2	Słupia	81.5
Lesser Poland (małopolskie)	53.6	Węgrzce	93.4
Subcarpathian (podkarpackie)	52.7	Skołoszów	93.0
Poland (average)	49.5	-	-

¹ Land Quality and Suitability Index calculated as the arithmetic mean of weighted average agricultural land quality and suitability indices based on the scoring system for arable land quality classes (ALQCs) and arable land suitability groups (ALSGs) [Witek et al., 1981; Barabasz et al., 2015]. The index ranges from 0 to 100.

2.2. Data Preparation and Cleaning

The initial dataset comprised 19,641 winter wheat yield records from derived from 185 experiments conducted at 19 locations over 10 years. The database was constructed by integrating winter wheat yield data from COBORU multi-environment trials conducted between 2015 and 2024.

Yield records were merged into a unified dataset containing the following variables: yield, location, year, ALQC, ALSG, and corresponding soil valuation scores. The data were standardized with respect to yield units and classification codes and verified for completeness and logical consistency.

Outliers were identified and removed. Specifically, records with unrealistically low yields (0.07–0.07 dt·ha⁻¹; 74 observations) and extremely high yields (708 dt·ha⁻¹; 1 observation) were excluded. Additionally, records containing classification errors—such as non-existent ALQC categories (e.g., ALQC IIa) or inconsistencies between ALQC and ALSG that violated official classification rules—were removed (3010 observations, including one location not shown in Figure 1).

After data cleaning, the final dataset consisted of 16,556 yield observations from 156 experiments conducted at 18 locations over 10 years.

2.3. Statistical Analysis

For each site–year combination (i.e., each experiment), the empirical distribution of yields was summarized using descriptive statistics. The following parameters were calculated: minimum, 10th percentile (P10), first quartile (Q1), mean, median, third quartile (Q3), 90th percentile (P90), and maximum.

This procedure resulted in a secondary dataset comprising 156 experimental records, each representing the yield distribution for a given site–year combination.

In addition, to ensure comparability with previous studies [Witek 1979, Niewiadomski et al. 1998 and Hennings et al. 2016] a simplified dataset was constructed. This dataset included median values of selected statistical measures (mean, median, Q3, P90, and maximum) aggregated for each soil unit and soil score category. The distribution parameters were then calculated for six arable land quality classes (ALQCs), five arable land suitability groups (ALSGs), and eleven combinations of ALQCs within ALSGs.

2.4. Estimation of Attainable Yields

Based on the analysis of yield distribution and their comparison with national average winter wheat yields reported by the Statistics Poland (GUS) for the period 2015–2024, criteria for estimating attainable yields were established.

Attainable yields were defined using selected upper distribution parameters (primarily Q3), reflecting realistic high-performance production conditions. Based on these criteria, tables of attainable winter wheat yields were developed for each soil unit, including ALQC, ALSG, and combined ALQC–ALSG units (QC–LS).

2.5. Normality Testing

The distribution of yield records in the final dataset, as well as within subsets defined by ALQCs, ALSGs and their combinations, was tested for normality using the Shapiro–Wilk test. Statistical analyses were performed using appropriate statistical software (Statistica; TIBCO Software Inc., Palo Alto, CA, USA).

2.6. Software

The manuscript was prepared using open-source software Text, tables, and part of the figures were developed using LibreOffice (The Document Foundation). Data processing and figure preparation (e.g., Figure 3) were supported by scripts generated with the assistance of OpenAI tools. Image processing was performed using GNU Image Manipulation Program (GIMP), and spatial data visualization (Figure 1) was conducted using QGIS.

3. Results and Discussion

3.1. Assessment of the Representativeness

To evaluate the representativeness of the final dataset, the distribution of arable land quality classes (ALQCs) and arable land suitability groups (ALSGs) in the COBORU trials was compared with their national distribution in Poland (Figures 2a,b). This dataset comprised 16,556 yield observations from 156 experiments distributed across six ALQCs and five ALSGs (Table 2).

The trials (Table 1; Appendix A) were conducted on the best (class I), very good (II), good (IIIa and IIIb), and medium (IVa and IVb) soils belonging to land suitable for wheat cultivation (ALSG 1, 2 and 4) and, to a lesser extent, soils suitable for rye (ALSGs 3 and 5).

The best soils (ALQC I) were represented only in 2015, whereas the remaining classes were present throughout the entire study period. Most observations originated from very good (ALQC II) and good soils (ALQCs IIIa and IIIb), which together accounted for over 80% of the dataset. This distribution is consistent with agronomic recommendations for winter wheat production [Strzemski

et al. 1973, Wójcik-Gront et al. 2021, Kowalska et al. 2024] and reflects the dominant role of these soils in Poland. The relatively low share of medium-quality soils (ALQCs IVa and IVb) results from their lower suitability for winter wheat cultivation, although they are occasionally used for this purpose. Weak (class V) and very weak soils (classes VI and VIz) were not represented in the dataset. This absence is consistent with agricultural practice, as these soils are generally unsuitable for winter wheat due to severe water limitations (deficit or excess). Therefore, the distribution of ALQCs in the dataset (excluding class I) corresponds well with their share in the total arable land area in Poland and their practical use in wheat production (Figure 2a).

Table 2. Number of winter wheat yield observations and experiments (in parentheses) across arable land quality classes (ALQCs) and land suitability groups (ALSGs).

ALSG	Experimental Sites	Arable Land/Soil Quality Class (ALQC)						Total	Share of Dataset (%)
		I	II	IIIa	IIIb	IVa	IVb		
1	Głubczyce, Radostowo, Skołoszów, Węgrzce, Zybiszów	98 (1)	3953 (37)	-	-	-	-	4051 (38)	24.5
2	Głębokie, Krościna Mała, Nowa Wieś Ujska, Pawłowice, Rychliki, Słupia, Węgrzce, Zybiszów	-	-	3357 (31)	2204 (21)	-	-	5561 (52)	33.6
3	Świebodzin, Tomaszów Bolesławiecki	-	-	-	96 (1)	202 (2)	-	298 (3)	1.8
4	Cicibór Duży, Krościna Mała, Marianowo, Masłowice, Nowa Wieś Ujska, Rarwino, Seroczyn, Świebodzin, Tomaszów Bolesławiecki	-	-	364 (3)	3640 (35)	910 (9)	-	4914 (47)	29.7
5	Marianowo, Rarwino, Rychliki, Seroczyn, Masłowice, Tomaszów Bolesławiecki	-	-	-	-	992 (9)	740 (7)	1732 (16)	10.5
Total		98 (1)	3953 (37)	3721 (34)	5940 (57)	2104 (20)	740 (7)	16,556 (156)	100.1
Share of yield records (%)		0.6	23.9	22.5	35.9	12.7	4.5	100.0	-

Notes: For more information on arable soil quality classes (ALQCs) and arable lands suitability groups (ALSGs), see Appendix A and Appendix B and the references cited therein.

With respect to ALSGs, the dataset shows a higher proportion of groups most suitable for wheat cultivation (ALSGs 1, 2 and 4) compared with their share in the total arable land area in Poland (Table 2; Figure 2b). In contrast, ALSGs 3 and 5 are underrepresented.

Soils belonging to ALSG 3 (imperfect wheat complex) are relatively rare and characterized by limitations such as erosion risk or susceptibility to drought, making them less suitable for wheat than ALSG 4 (very good rye or wheat-rye complex). This is also reflected in their valuation scores (Appendix B). Similarly, ALSG 5 (good rye complex) is less represented in the dataset, as it is generally recommended for cereals more tolerant to drought than wheat.

ALSGs 6-9 were not represented in the dataset. Weak and very weak rye complexes (ALSG 6 and 7) are unsuitable for wheat due to severe limitations by drought, whereas cereal-fodder complexes (ALSGs 8 and 9) are limited by excessive soil moisture (Appendix B). However, fine-

textured soils within ALSG 8 may be suitable for wheat cultivation [Strzemski et al. 1973;Niewiadomski et al. 1998]; therefore, the absence of this I group — representing approximately 4.5% of arable land in Poland — constitutes a limitation of the dataset.

When individual years are considered (Table 3 or Figure XMI), the ALSGs most suitable for wheat (1, 2 and 4) were represented in all ten years (2015-2024). ALSG 5 was present in nine years (absent only in 2019), whereas ALSG 3 occurred only in two years (2015 and 2017), indicating limited representation of less suitable soil groups.

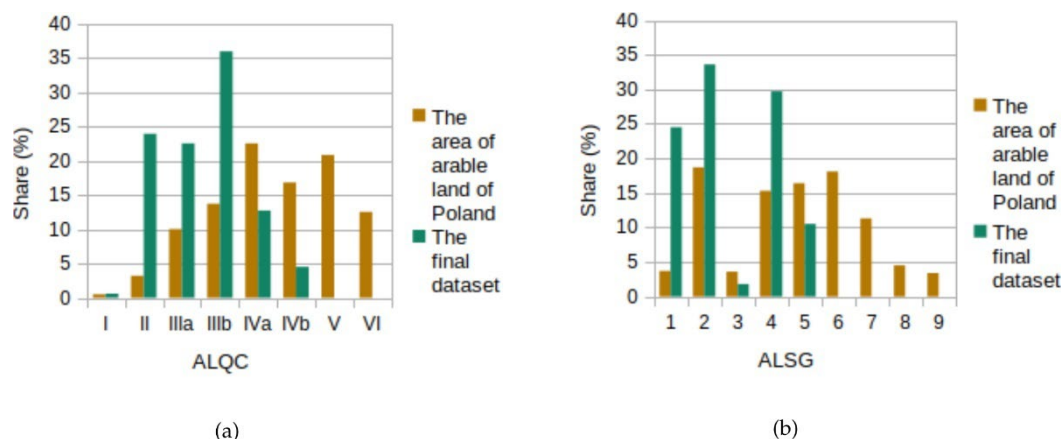


Figure 2. The representativeness of particular ALQCs and ALSGs in final field dataset and the area of arable land of Poland.

The dataset provides full temporal coverage for the most common ALQC–ALSG combinations in Poland, particularly ALQCs IIIb, (mainly within ALSGs 2 and 4), ALQC IIIa (ALSG 2), and ALQC II (ALSG 1) (Table 3). In contrast, classes IVa (ALSGs 4 and 5) and IVb (ALSG 5) were represented in 6–7 years, while other combinations (e.g., IIIa–ALSG 4, IVa–ALSG 3, IIIb–ALSG 3, and I–ALSG 1) appeared only sporadically (1–3 years). Notably, ALQC IVb within ALSG 3 was not represented.

Table 3. Number of winter wheat yield observations and experiments (in parentheses) by year across arable land quality classes (ALQCs) and arable land suitability groups (ALSGs).

Year	ALSGs and ALQCs												Total
	1		2		3		4		5				
	I	II	IIIa	IIIb	IIIb	IVa	IVb	IIIa	IIIb	IVa		IVa	
2015	98 (1)	307 (3)	396 (4)	198 (2)	96 (1)	-	-	-	402 (4)	104 (1)	98 (1)	100 (1)	1799 (18)
2016		444 (5)	164 (2)	194 (2)	-	-	-	-	286 (3)	196 (2)	-	96 (1)	1380 (15)
2017		424 (4)	212 (2)	112 (1)	-	108 (1)	-	-	208 (2)	104 (1)	100 (1)	-	1268 (12)
2018		146 (2)	218 (3)	146 (2)	-	-	-	-	274 (4)	74 (1)	-	76 (1)	934 (13)
2019		250 (3)	272 (3)	262 (3)	-	94 (1)	-	90 (1)	334 (4)	82 (1)	-	-	1384 (16)
2020		578 (5)	455 (4)	198 (2)	-	-	-	-	408 (4)	-	206 (2)	106 (1)	1951 (18)
2021		550 (5)	220 (2)	330 (3)	-	-	-	-	330 (3)	220 (2)	220 (2)	110 (1)	1980 (18)
2022		432 (4)	324 (3)	216 (2)	-	-	-	-	432 (4)	-	108 (1)	108 (1)	1620 (15)
2023		390 (3)	520 (4)	260 (2)	-	-	-	130 (1)	390 (3)	130 (1)	260 (2)	-	2080 (16)

2024	432 (3)	576 (4)	288 (2)	-	-	144 (1)	576 (4)	-	-	144 (1)	2160 (15)		
Total	98 (1)	3953 (37)	3357 (31)	2204 (21)	96 (1)	202 (2)	-	364 (3)	3640 (35)	910 (9)	992 (9)	740 (7)	16,556 (156)

In summary, although not all arable land quality classes (ALQCs) and arable land suitability groups (ALSGs) were represented throughout the entire study period, the dataset adequately covers the soil units most relevant for winter wheat production in Poland. The ALQCs and ALSGs most recommended [Strzemski et al., 1973; Kowalska et al., 2024] and most commonly used for winter wheat cultivation are well represented. Despite some temporal and structural imbalances, the dominance of key soil groups ensures that the dataset is representative of major wheat production environments.

3.2. Parameters of Yield Distribution

The final yield dataset, as well as almost all subsets defined by arable land quality classes (ALQC), arable land suitability groups (ALSGs), and their combinations (ALQC within ALSG), exhibited an approximately normal distribution. The only exception was ALQC I, which was poorly represented and did not meet the normality assumption (Tables S1- S3).

Almost all yield distribution parameters, except for minimum values, exceeded the national average winter wheat yields in Poland for the period 2015-2024, which ranged from $\text{dt}\cdot\text{ha}^{-1}$ (2018) to $54.8 \text{ dt}\cdot\text{ha}^{-1}$ (2023), according to Statistics Poland (GUS). Even on medium-quality soils (ALQC IVb) with suitability for rye (ALSG 5), which are generally not recommended for wheat cultivation [Strzemski et al., 1973; Kowalska et al., 2024], the 10th percentile (P10) and higher distribution parameters exceeded the national average. Moreover, the highest national average winter wheat yield ($54.8 \text{ dt}\cdot\text{ha}^{-1}$ in 2023) remained below the first quartile (Q1) observed in the COBORU trials. (Tables S1-S3) This confirms the existence of a substantial exploitable yield gap, even on soils with limited suitability for wheat cultivation.

The winter wheat yields differed systematically across ALQCs (Table S1; Figure 3a) decreasing from class II to IVb, in agreement with the soil quality scores assigned to these classes [Witek et al., 1981]. An was observed for ALQC I, where relatively low average and median yields ($73 \text{ dt}\cdot\text{ha}^{-1}$) were recorded, along with lower distribution parameters compared with ALQCs II–IVa. This inconsistency results from the very limited representation of this class in the dataset (one experiment, 98 observations; Table 3). Independent data indicate that winter wheat yields on ALQC I soils may reach $100\text{--}140 \text{ dt}\cdot\text{ha}^{-1}$ under favorable conditions. Therefore, the observed values for ALQC I should be considered unreliable, and this class was excluded from further regression analyses.

Yields obtained on ALQCs II and IIIa were very similar, with median values of 101 and $99 \text{ dt}\cdot\text{ha}^{-1}$, Q3 values of 109 and $108 \text{ dt}\cdot\text{ha}^{-1}$, 90th percentiles of 114 and $109 \text{ dt}\cdot\text{ha}^{-1}$, and median maximum values of 122 and $120 \text{ dt}\cdot\text{ha}^{-1}$, respectively. Yields observed for ALQC IIIb were only slightly lower and still substantially exceeded the national average yields for the study period (Table S1). A similar decreasing trend was observed across ALSGs (Table S2; Figure 3b) generally consistent with the soil valuation scores assigned by Witek et al. [1981]. However, ALSG 5 (good rye suitability, 52 points) showed slightly higher productivity than ALSG 3 (imperfect wheat suitability, 61 points), which may be attributed to the limited representation of ALSG 3 in the dataset (298 observations from 3 experiments).

Previous long-term studies [Witek, 1979; Niewiadomski et al., 1988] reported similar trends, although exceptionally high yields were observed for ALSG 8 (strong cereal–fodder complex), exceeding those of ALSG 1. ALSG 8 is characterized by fine-textured soils prone to excess moisture, which increases the risk of winter damage but may allow high yields under favorable conditions. When combined ALQC–ALSG units were analyzed (Table S3; Figure 3c), the general trend of decreasing yields with decreasing soil quality and suitability was maintained. However, deviations from this trend were observed, primarily for combinations with limited representation. Lower-than-

expected median yields were observed for ALQC I within ALSG 1 (96 observations), ALQC IIIa within ALSG 4 (364 observations), and ALQC IVa within ALSG 3 (202 observations). Conversely, higher-than-expected values were observed for ALQC IIIb within ALSG 3 (96 observations from one experiment).

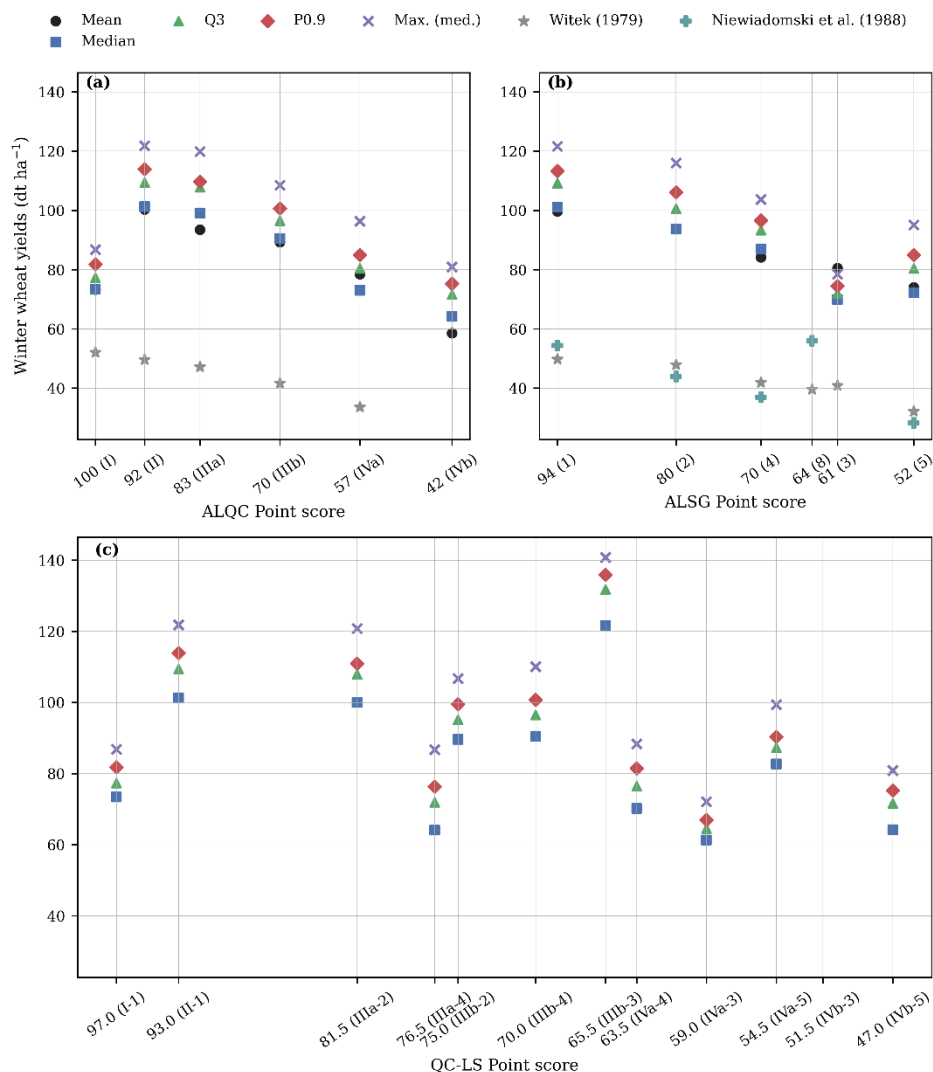


Figure 3. Relationships between selected statistical measures of winter wheat yield and soil valuation scores assigned to arable land quality classes (ALQCs) and arable land suitability groups (ALSGs) [Witek et al., 1981]: (a) ALQCs, (b) ALSGs, and (c) combined ALQC–ALSG index (quality and suitability index). Source: own elaboration based on the study data.

3.3. Relationships Between Soil Scores and Winter Wheat Yields

Scatterplots illustrating the relationship between winter wheat yield parameters and the point scores assigned to ALQCs, ALSGs and their combinations ALQCs in ALSGs (quality and suitability index) are presented in Figure 3. These plots were developed based on the data summarized in Tables S1–S3 and allow comparison with previous studies [Witek, 1979; Niewiadomski et al., 1988; Stuczyński et al., 2007].

Overall, winter wheat yield parameters (mean, medians, Q3, P90 and maximum) showed a strong relationship with ALQC point scores (excluding the poorly represented ALQC I), and a slightly weaker relationship with ALSG scores. The main deviation from this pattern was observed for ALSG 3 (61 points), which was underrepresented in the dataset.

The relationship between winter wheat yields the combined soil quality and suitability index (mean score of ALQC and ALSG) was less consistent. Deviations were observed particularly for combinations with limited representation, including ALQC I within ALSG 1, ALQC IIIa within ALSG 4, ALQC IIIb within ALSG 3, and ALQC IVa within ALSG 3. Similar relationships reported by Stuczynski et al. [2007] for cereal yields at the district level in Lower Silesia were more pronounced. Prior to regression analysis, outlying soil units were excluded. Both linear and quadratic regression models were fitted, as yield increments tended to decrease at higher soil scores (Figure 3). This was reflected in slightly higher coefficients of determination (R^2) for quadratic models (Tables 4–6). A similar pattern was previously reported by Witek [1979], who noted that soils classified as ALQCs I–IIIb exhibit relatively small differences in cereal yields and may be treated as a homogeneous group of high-quality soils. Regression equations describing the relationship between ALQC scores and winter wheat yields (Table 4) indicate an increase in yield levels compared with earlier studies [Witek, 1979; Witek et al., 1981], reflecting technological progress in agriculture. In the experimental dataset (155 records, excluding ALQC I), the models explained a relatively small proportion of yield variability ($R^2 = 0.21$ – 0.27 , depending on the parameter). For the full dataset (16,556 observations), R^2 values were 0.169 for linear and 0.185 for quadratic regression. In Germany, Hennings et al. [2016] reported correlations between soil quality indices and winter wheat yields ranging from 0.56 to 0.86 ($R^2 \approx 0.31$ – 0.74), depending on the season. These values are lower than those obtained in this study for aggregated datasets but comparable to those derived from experimental data. The German Müncheberg Soil Quality Rating (M-SQR) is based on multiple soil properties and environmental factors, whereas the Polish system is directly derived from crop yields [Witek, 1979; Witek et al., 1981]. This explains the stronger relationships observed for ALQCs in Poland.

Table 4. The regression equations of relationships of several wheat yield statistic measures and the points attributed to particular ALQCs by Witek et al. (1981).

Source or Distribution Parameter of Winter Wheat Yield	Type of Equatio n	Experiment Dataset (Without Class I)			Simple Dataset		
		n	Equation	R^2	n	Equation	R^2
Witek 1979 []	Linear		n.d.	n.d.		$Y=0.422X+10.9$	0.97
	Square		n.d.	n.d.	5	$Y=-0.00564X^2+1.31X-22.4$	0.99
Mean	Linear	155	$Y=0.683X+37.8$	0.22	5	$Y=0.791X+29.6$	0.94
	Square		$Y=-0.00869X^2+1.93-5.34$	0.23		$Y=-0.012X^2+2.39X-20.1$	0.99
Median	Linear		$Y=0.698X+37.1$	0.23		$Y=0.803X+30.4$	0.96
	Square	155	$Y=-0.00871X^2+1.95X-6.15$	0.24	5	$Y=-0.00456X^2+1.41X+11.3$	0.97
Q3	Linear		$Y=0.760X+38.5$	0.26		$Y=0.824X+36.5$	0.97
	Square	155	$Y=0.00775X^2+1.87-0.0081$	0.27	5	$Y=-0.00289X^2+1.21X+24.4$	0.97
90th percentile	Linear		$Y=0.740X+44.1$	0.24		$Y=0.814X+40.8$	0.99
	Square	155	$Y=-0.00859X^2+1.97X+1.44$	0.25	5	$Y=-0.00286X^2+1.20X+1.20$	0.99
Maximum (median)	Linear		$Y=0.723X+53.4$	0.21		$Y=0.846X+47.3$	0.98
	Square	155	$Y=-0.00933X^2+2.06X+7.10$	0.22	5	$Y=-0.00766X^2+1.873X+15.3$	0.99

Note: The outlying data regarding ALQC I was excluded from this regression analysis.

Regression models for ALSGs (Table 5) showed lower coefficients of determination than those for ALQCs, likely due to greater heterogeneity within ALSGs, which may include multiple soil classes. In the experimental dataset, these models explained up to 20% of yield variability. The slope of linear regressions indicated that an increase of one point corresponded to a yield increase of

approximately 62–88 kg·ha⁻¹, depending on the parameter. These values are consistent with previous estimates reported by Iwańska et al. [2020, 2021].

Table 5. Regression equations describing relationships between selected winter wheat yield parameters and point scores assigned to ALSGs [Witek et al., 1981].

Source or Distribution Parameter of Winter Wheat Yield	Type of Equatio n	Experiment Dataset (Without Class I			Simple Dataset		
		n	Equation	R ²	n	Equation	R ²
Witek 1979 []	Linear				6	Y=0.400X+14.0	0.90
	Square				6	Y=-0.00768X ² +1.52X-26.0	0.96
Niewiadomski et al. 1988 []	Linear				6	Y=0.453X+11.3	0.40
	Square				6	Y=-0.00850X ² +1.70X-32.6	0.40
Mean	Linear	155	Y=0.660X+38.2	0.18		Y=0.624X+41.9	0.98
	Square	155	Y=-0.000797X ² +0.541X+42.6	0.18	5	Y=-0.00191X ² +0.903X+32.1	0.99
Median	Linear	155	Y=0.670X+37.9	0.18		Y=0.783X+28.9	0.90
	Square	155	Y=-0.000770X ² +0.555X+42.1	0.18	5	Y=-0.00151X ² +1.00X+21.1	0.90
Q3	Linear	155	Y=0.715X+40.5	0.20		Y=0.834X+31.5	0.82
	Square	155	Y=-0.00214X ² +0.395X+52.2	0.20	5	Y=0.0041X ² +0.232X+52.7	0.83
90th percentile	Linear	155	Y=0.710X+45.1	0.19		Y=0.853X+34.2	0.79
	Square	155	Y=0.00169X ² +0.456X+54.3	0.19	5	Y=0.00499X ² +0.124X+59.8	0.79
Maximum (median)	Linear	155	Y=0.697X+54.1	0.17		Y=0.877X+40.4	0.69
	Square	155	Y=-0.000568X ² +0.613X+57.2	0.17	5	Y=0.00888X ² +0.423X+86.0	0.71

Note: Outlying data for ALQC I (within ALSG 1) were excluded from the regression analysis.

The functions describing effect of combined soil quality and suitability scores on winter wheat yield were developed using both the experimental dataset (one record per experiment) and the simplified dataset (one record per ALQC–ALSG combination), after excluding poorly represented and clearly outlying combinations (ALQC I–ALSG 1, ALQC IIIa–ALSG 4, ALQC IIIb–ALSG 3, and ALQC IVa–ALSG 3).

Regression models for selected ALQC–ALSG combinations (Table 6) showed improved predictive performance compared with models based on ALSGs alone (Table 5), explaining up to 26% of yield variability (Q3) in the experimental dataset. In the simplified dataset, however, regression models based on combined indices showed lower coefficients of determination than those based solely on ALSGs for mean ($R^2 = 0.77$ – 0.79 vs. 0.98 – 0.99), median (0.78 – 0.79 vs. 0.90), and Q3 (0.82 vs. 0.83), but higher values for P90 (0.85 vs. 0.80) and maximum yields (0.81 vs. 0.70 – 0.71).

The simplified dataset presented by Witek [1979] showed higher coefficients of determination for relationships between winter wheat yield and ALQC scores ($R^2 = 0.97$ – 0.99 ; Table 4) and ALSG scores ($R^2 = 0.90$ – 0.998) than those obtained in this study for the combined ALQC–ALSG index ($R^2 = 0.77$ – 0.85 , based on 6–7 observations).

Table 6. Regression equations describing relationships between selected winter wheat yield parameters and combined soil quality and suitability scores (ALQC–ALSG index).

Source or Distribution Parameter of Winter Wheat Yield	Type of Equation	Experiment Dataset			Simple Dataset		
		n	Equation	R ²	n	Equation	R ²
Mean	Linear	149	$Y=0.701X+36.0$	0.220	8	$Y=0.782X+30.6$	0.766
	Square	149	$Y=-0.00638X^2+1.64X+2.35$	0.225	8	$Y=-0.0103X^2+2.23X-17.5$	0.7948
Median	Linear	149	$Y=0.715X+35.4$	0.228	8	$Y=0.792X+30.7$	0.783
	Square	149	$Y=-0.00641X^2+1.66X+1.55$	0.233	8	$Y=-0.00404X^2+1.36X+11.93$	0.788
Q3	Linear	149	$Y=0.771X+37.2$	0.251	8	$Y=0.832X+34.5$	0.817
	Square	149	$Y=0.00524X^2+1.544X+9.54$	0.256	8	$Y=-0.000937X^2+0.962X+30.2$	0.817
90th percentile	Linear	149	$Y=0.754X+42.5$	0.230	8	$Y=0.845X+37.5$	0.851
	Square	149	$Y=-0.00585X^2+1.62X+11.7$	0.233	8	$Y=-0.00147X^2+1.05X+30.7$	0.852
Maximum (median)	Linear	149	$Y=0.773X+52.3$	0.201	8	$Y=0.884X+42.8$	0.808
	Square	149	$Y=-0.00692X^2+1.75X+15.9$	0.205	8	$Y=-0.00393X^2+1.43X+24.6$	0.812

Note: Outlying combinations (ALQC I–ALSG 1, ALQC IIIa–ALSG 4, ALQC IIIb–ALSG 3, and ALQC IVa–ALSG 3) were excluded from the regression analysis.

Correlation coefficients reported in Germany [Hennings et al., 2016] (0.70–0.92; corresponding to $R^2 = 0.51$ –0.81) indicate weaker relationship between winter wheat yields and soil quality indices compared with those obtained in this study for combined ALQC–ALSG scores (Table 6).

A previous Polish study by Stuczyński et al. [2007] reported a stronger relationship ($R^2 = 0.67$) between cereal yields and the soil quality and suitability index, based on regional (gmina-level) data from Lower Silesia. The regression equation was $Y = 0.3017X + 16.179$. However, these results were based on aggregated regional data with lower yield levels and likely lower variability than those observed in multi-environment COBORU trials used in this study. Additionally, detailed information on the dataset (e.g., number of observations, time period, and yield distribution parameters) was not provided.

3.4. Proposal of Attainable Yields

The results of this study indicate that winter wheat yields obtained in COBORU trials are strongly related to soil quality and suitability and can be used to estimate yields and yield gaps not only at the national level but also for specific soil units.

A key question is which distribution parameter should be used to define attainable yield. Considering that attainable yields typically correspond to 70–80% of potential yields [Lobell et al. 2009, Kamkar et al 2025], this condition is satisfied not only by the 90th percentile (P90) and the third quartile (Q3), but in many cases also by the median.

Another issue whether attainable yields should be determined directly from observed data or derived from regression relationships with soil scores. A definitive answer requires more extensive and representative datasets. However, based on the present results, Q3 values were selected as the primary estimator of attainable yields, supplemented by regression-based estimates where necessary.

Two exceptions were identified: ALQC I attainable yields were assumed to be equal to those for ALQC II, due to insufficient representation in the dataset and supporting external data indicating much higher yield potential (100–140 dt·ha⁻¹).

For ALSG 8, no experimental data were available in this study. However, previous research [Niewiadomski et al., 1988] suggests that yields may be comparable to those obtained in ALSG 1. Therefore, attainable yields for ALSG 8 were assumed to be similar to those of ALSG 1, with the caveat that production on these soils is associated with higher risk due to excess moisture conditions [Strzemeski et al., 1973].

For well-represented soil units (≥ 1000 observations, ≥ 4 locations, ≥ 9 years, ≥ 20 experiments), attainable yields were directly derived from Q3 values (Tables S1–S3). For less-represented units, linear regression models based on Q3 were applied. Regression-based estimates are indicated in parentheses in Table 8.

Attainable yields were not proposed for soil units where winter wheat cultivation is not recommended (ALQCs V and VI; ALSGs 6, 7, and 9). Although regression models allow estimation of yields for these units, such estimates should be treated with caution, as soil scores were originally derived from average cereal yields and may not adequately represent wheat productivity on marginal soils.

Table 8. Proposed attainable winter wheat yields (dt ha⁻¹) for selected arable land quality classes (ALQCs) and land suitability groups (ALSGs).

Arable Land Suitability Group (ALSG) Code	Arable Land/Soil Quality Class (ALQC)						ALSG (All ALQCs)
	I	II	IIIa	IIIb	IVa	IVb	
1	(109)a	109	-	-	-	-	109
2	-	-	107	95	-	-	100
3	-	-	-	(90)r	(84)r	?	(82)r
4	-	-	(100)r	96	(90)r	-	93
5	-	-	-	-	(80)r	(73)r	80
8	-	-	?	?	?	?	(109)a
ALQC (all ALSGs)	(109)a	109	108	96	80	(70)r	

Notes: a - based on expert judgment. r - based on regressions estimates. ? - insufficient data for reliable estimation.

3.5. Limitations, Applications, and Future Research

This study has several limitations. First, although the dataset covers most soil units recommended and used for winter wheat production in Poland, ALSG 8 was not included in the dataset, despite previous long-term studies indicating high productivity of this soil group [Niewiadomski et al., 1988]. Other poorly represented units include ALQC I and ALSG 3. However, these soil units occupy relatively small areas in Poland (Tables A1 and A2), while soil units not included in the dataset (ALQCs V and VI, ALSGs 6, 7 and 9) are generally unsuitable for wheat production [Strzemeski et al., 1973; Kowalska et al., 2024].

Another limitation arises from the experimental design of COBORU trials which are conducted on relatively small and narrow plots (approximately 10 m × 1.5 m) [Lisowski et al., 2025]. Such plot geometry enhances edge (border) effects, leading to higher yields in outer rows compared with field conditions [Rudnicki and Gałęzewski, 2006; Stawiana-Kosiorek et al., 2007]. For this reason, maximum yield values were not considered appropriate estimators of attainable yields. Despite the inclusion of multiple years and locations, interannual weather variability remains a major source of yield variation. Importantly, the effect of year is not consistent across soil units and locations. Analysis of the third quartile (Q3) used in this study as a proxy for attainable yield, demonstrates substantial variability between locations and years (Figure 4). For example, the highest Q3 values were observed in 2023 for the overall ALQC IIIb and in selected locations (Pawłowice and Ciecibórz), whereas in other locations (Rychliki and Masłowice) the highest values occurred in 2022.

Moreover, in a single location (Pawłowice), Q3 values ranged from 52 dt·ha⁻¹ (2018) to nearly 122 dt·ha⁻¹ (2023).

These findings indicate that weather conditions strongly influence attainable yields and vary both spatially and temporally [Iwańska and Stępień, 2019]. Therefore, year should not be treated as a uniform factor at the national scale. Instead, attainable yields—and consequently yield gaps—should be considered variable and season-dependent. Similar conclusions were reported by Hennings et al. [2016]. In practice, season-specific attainable yields can only be reliably estimated after the growing season.

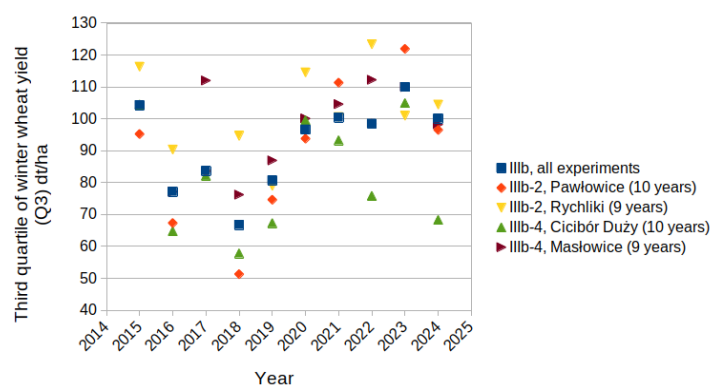


Figure 4. Interannual variability of the third quartile (Q3) of winter wheat yield for ALQC IIIb soils and selected ALQC–ALSG combinations. The attainable yields proposed in Table 8 were derived from well-controlled COBORU experiments conducted using current cultivars and agronomic practices. Ongoing progress in plant breeding and crop management may further increase yield potential in the future.

The soil-specific attainable yields presented in this have practical applications at multiple scales. At the farm level, they can be used to estimate exploitable yields for specific field zones based on soil quality class and suitability group. In Poland, such information is available from large-scale soil maps (e.g., 1:5000), which can support precision agriculture practices, including variable-rate application of inputs such as lime, fertilizers, and seeds.

At regional and national levels, soil-adjusted attainable yields may support yield gap analysis and agricultural planning. Importantly, yield gaps should not be defined relative to the most productive soils, but rather in relation to the specific soil units present. Further refinement of yield potential and yield gap estimates should account for weather variability at regional and seasonal scales, which requires additional research.

4. Conclusions

The novelty of this study lies in the integration of long-term, multi-environment yield data with officially defined soil quality classes (ALQCs) and land suitability groups (ALSGs), enabling empirical estimation of attainable winter wheat yield within these classification units under current production conditions. To the best of our knowledge, this is the first study to estimate attainable yields not only for ALQCs and ALSGs separately, but also for their combinations (ALQC–ALSG), allowing for more precise, soil-adjusted assessment of attainable yields and yield gaps.

By linking administrative soil classification systems with contemporary yield data, this study provides a quantitative, agronomically meaningful interpretation of soil units. The proposed approach enables soil-specific yield benchmarking and improves the assessment of yield gaps by accounting for inherent soil variability. The results have important practical and policy implications. Soil quality classes and land suitability groups are integral components of land valuation systems, spatial planning, and agricultural policy in Poland. The provision of empirically derived attainable yield benchmarks enhances the transparency and scientific basis of these systems and supports more

objective decision-making. From the perspective of climate change adaptation, translating soil classification units into attainable yield levels allows for the identification of soils that are more vulnerable or more resilient to weather variability. Soil-based yield benchmarks help distinguish structural (soil-related) constraints from weather-induced variability and support the development of climate-resilient cropping strategies.

Furthermore, soil-specific attainable yield enable improved monitoring of yield gap at regional and farm levels. This allows assessment of whether observed yields approach their attainable potential or remain limited by technological or seasonal factors. Such an approach may enhance the targeting of advisory services, precision agriculture practices, and sustainability-oriented measures.

In the context of the Common Agricultural Policy (CAP), the proposed framework may contribute to more evidence-based allocation of support measures, refinement of environmental conditionality, and improved monitoring of agricultural productivity. Finally, the methodology developed in this study can be extended to other crops evaluated in COBORU multi-environment trials and may be applicable in other countries with comparable soil classification systems and experimental data infrastructure.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/doi/s1>, Tables S1–S3.

Author Contributions: Conceptualization, M.S. and M.I.; methodology, M.S.; software, M.S.; validation, M.S.; formal analysis, M.S.; data curation, M.S. and M.I.; writing—original draft preparation, M.S. and M.I.; writing—review and editing, M.S. and M.I.; visualization, M.S. All authors have read and agreed to the published version of the manuscript. **Funding:** This research received no external funding.

Data Availability Statement: The experimental and simplified datasets are available upon request. The final yield dataset is available from the corresponding author upon reasonable request.

Acknowledgments: The authors acknowledge the Research Centre for Cultivar Testing (COBORU) for providing the data used in this study. The authors also thank Dariusz Gozdowski and Jan Stępień for their valuable comments on the preparation of figures.

Use of Artificial Intelligence Tools: During the preparation of this manuscript, the authors used ChatGPT to assist in data summarization and code generation for figure preparation. All outputs were critically reviewed and edited by the authors, who take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ALQC Arable Land Quality Class
ALSG Arable Land Suitability Group
ALQS Arable Land Quality and Suitability Index
COBORU Research Centre for Cultivar Testing
GUS Statistics Poland
Q1 First Quartile
Q3 Third Quartile
P10 10th Percentile
P90 90th Percentile
CAP Common Agricultural Policy

Appendix A. Soil Classification System in Poland

Appendix A.1

This appendix provides an overview of arable land quality classes (ALQCs) and arable land suitability groups (ALSGs) used in Poland, including their characteristics, point scores, and associated yield levels.

Table A1. Arable land soil quality classes (ASQCs) defined in Poland.

Code	Name	Points*	Yields** (t ha ⁻¹)		Short Description	Percentage of Arable Land Area in Poland	
			Winter Wheat	4 Cereals***		****	Percentage of Dataset
I	The best arable soils	100	5.21	5.01	These soils are located in good physiographic conditions, with good natural structure and proper air-water properties, they are easy to till and suitable for cultivation of all crops. They permit to achieve good production even without great inputs.	0.5	0.5
II	Very good arable soils	92	4.96	4.82	These soils are similar to the soils of the I class, but they are located in worse physiographic conditions, with slightly worse physical properties, and quite more difficult to till.	3.2	21.7
IIIa	Good arable soils	83	4.72	4.68	These soils have worse physical or chemical properties and located in worse physiographic conditions than soil of I and II class. These soils are characterised by less adequate air-water properties and frequently they are more difficult to till. The yields vary in broader ranges and depend on soil culture****, abilities of the farmer and atmospheric conditions.	10.0	26.1
IIIb	Moderately good arable soils	70	4.17	4.13	Generally these soils are similar to those belonging to IIIa class, but they have worse physical or chemical properties or they are located in worse physiographic conditions. The yields depend even more on weather conditions, sometimes these soils temporarily too dry or too wet or exposed to erosion.	13.7	31.5
IVa	Arable soils of medium quality, better	57	3.36	3.64	These soils are suitable for production of smaller number of plant species. The yields are usually medium even if these soils present good culture and they depend on amount and distribution of rainfall during vegetation period. These soils often are located in worse physiographic conditions.	22.5	13.4
IVb	Arable soils of medium quality, worse	42	-	2.96	These soils are generally similar, in terms of their properties, to soils of IVa class, however they are more deficient - too dry or too wet. The yields vary in broad ranges and are strongly affected by weather conditions.	16.8	6.7

V	Weak arable soils	30	-	2.55	These soils are characterised by low fertility and productivity generally too dry or too wet.	20.8	-
VI	The weakest arable soils				These soils are very weak and defective and characterised by low and unreliable yields due to almost permanent shortage or excess of water.		-
	The weakest arable soils,	18	-	1.80		12.5	
VIz	permanently dry or wet				These soil are unsuitable for agriculture and they should be converted to forest use.		-

Based on UTKG 2012, Witek 1973 and 1979, Witek et al. 1981, Witek. * According to Witek et al. 1981. ** According to [Witek 1979], 1525 experiments on winter wheat and totally 5900 experiments on cereals. *** winter wheat, winter rye, spring barley and oats, 5900 experiments [Witek 1979]. **** Gleboznawstwo 1999 []. ***** the soil culture was defined by Strzemeski et al., 1973 [] as the totality of its agricultural properties, acquired under both natural and agronomic conditions. This applies in particular to the accumulation of humic substances and nutrients, as well as biological activity.

Code	Name	Points ¹	Winter Wheat ² (t·ha ⁻¹)	Cereals ³ (t·ha ⁻¹)	Short Description	Share of Arable Land in Poland (%) ⁴	Share in Dataset (%)
I	The best arable soils	100	5.21	5.01	Soils occurring under favorable physiographic conditions, with good structure and optimal air-water properties. Easy to cultivate and suitable for all crops.	0.5	0.5
II	Very good arable soils	92	4.96	4.82	Similar to class I, but located in slightly less favorable conditions and somewhat more difficult to cultivate.	3.2	21.7
IIIa	Good arable soils	83	4.72	4.68	Soils with less favorable physical or chemical properties. Yield variability depends on soil management, farmer practices, and weather conditions.	10.0	26.1
IIIb	Moderately good arable soils	70	4.17	4.13	Similar to IIIa, but with poorer properties or location. Yields strongly depend on weather and may be affected by temporary drought, excess water, or erosion.	13.7	31.5
IVa	Medium-quality arable soils (better)	57	3.36	3.64	Suitable for a limited number of crops. Yields are moderate and depend on rainfall distribution and soil management.	22.5	13.4

IVb	Medium-quality arable soils (worse)	42	–	2.96	Similar to IVa, but with stronger limitations (too dry or too wet). Yields are highly variable and weather-dependent.	16.8	6.7
V	Weak arable soils	30	–	2.55	Soils of low fertility and productivity, often limited by water deficit or excess.	20.8	–
VI	Very weak arable soils	18	–	1.80	Soils with very low productivity and unstable yields due to persistent water limitations.	12.5	–
VIz	Very weak soils (permanently dry or wet)	–	–	–	Soils unsuitable for agriculture; recommended for afforestation.	–	–

Notes (Table A1): ¹ Point scores according to Witek et al. (1981). ² Based on Witek (1979), derived from 1525 winter wheat experiments. ³ Includes winter wheat, winter rye, spring barley, and oats (~5900 experiments; Witek, 1979). ⁴ Based on national data (Gleboznawstwo, 1999).

Table B. Arable lands suitability groups (ALSGs) of lowland and upland soils defined in Poland and their relationship with arable land quality classes.

Code	Name	Yields** (t/ha)			Short Description	Main Factors.	Limiting	Soil Quality Classes (ASQCs)	Percentage of Arable Land in Poland *****	Percentage of Dataset
		Points*	Winter Wheat	4 Cereals***						
1	Very good wheat complex	94	4.98	5.00	Mainly medium textured soils, sometimes fine soils and rarely coarse soils	No limiting factors, or slight limitation by erosion	I and II	3.7	22.3	
2	Good wheat complex	80	4.79	4.80	As above, sometimes quite finer soils	Slight limitation by excess of water, erosion or relief	IIIa and IIIb	18.7	36.5	
3	Imperfect wheat complex	61	4.09	3.92	Similar to ALSG 2, but underlaid by more permeable materials Similar to ALSG 2, but located on slopes	Medium limitation of shortage of water	IIIb, IVa and IVb	3.6	1.6	
4	Very good rye complex (wheat-rye complex)	70	4.19	4.24	Coarse (light) soils underlaid shallowly by finer materials, or, deeper (more than 75 cm), by coarser materials	Slight but notable limitation by shortage or excess of water	IIIa, IIIb, sometimes IVa	15.3	29.6	
5	Good rye complex	52	3.22	3.70	Similar to ALSG 4, but the finer subsoil is found deeper, or the the coarser	Medium limitation by shortage of water	IVa and IVb	16.4	10.0	

6	Weak rye complex	30	-	2.80	subsoil is located at smaller depth Very coarse soils (sands), sometimes coarse soils (loamy sands), sometimes fine and very fine soils underlaid shallowly by sands or gravels	Significant limitation by shortage of water	IVb and V	18.1	-
7	Very weak rye complex	18	-	2.33	Very coarse-textured soils, or other, but underlaid very shallowly by sands or gravels	Constant and severe limitation by shortage of water	V and VI	11.3	-
8	Strong cereal and fodder complex	64	3.96	4.00	Fine and very fine soils, exceptionally coarse, but on subsoil of low permeability or/and with shallow groundwater level, sometimes organic soils	Medium or even severe limitation with excess of water	(IIIa), IIIb, IVa, IVb (V)	4.5	-
9	Weak cereal and fodder complex	33	-	2.72	Coarse and very coarse soils located at low relative altitudes or underlaid by impermeable subsoil	Medium or even severe limitation with excess of water	IVa, IVb, V and VI	3.4	-

Based on Witek 1973 [1] and 1979 [2], Witek et al. 1981 [3]. * According to [Witek et al. 1981]. ** According to [Witek 1979], 1525 experiments on winter wheat and totally 5900 experiments on cereals. *** winter wheat, winter rye, spring barley and oats, 5900 experiments [Witek 1979]. **** Stępień and ??? #podręcznik 2018. ***** Gleboznawstwo 1999 [4].

Table A2. Arable land suitability groups (ALSGs) and their relationship with ALQCs in Poland.

Code	Name	Points ¹	Winter Wheat ² (t·ha ⁻¹)	4 Cereals ³ (t·ha ⁻¹)	Short Description	Main Limiting Factors	ALQCs Included	Share of Arable Land in Poland (%) ⁵	Share in Dataset (%)
1	Very good wheat complex	94	4.98	5.00	Mainly medium-textured soils, sometimes fine soils	None or slight erosion	I, II	3.7	22.3
2	Good wheat complex	80	4.79	4.80	Similar to ALSG 1, sometimes finer soils	Slight limitations: excess water, erosion, relief	IIIa, IIIb	18.7	36.5
3	Imperfect wheat complex	61	4.09	3.92	Soils similar to ALSG 2 but with less favorable subsoil or slope conditions	Water deficit or erosion	IIIb, IVa, IVb	3.6	1.6
4	Very good rye (wheat-	70	4.19	4.24	Coarse soils with finer subsoil or	Moderate water limitations	IIIa, IIIb (IVa)	15.3	29.6

	rye complex				deeper soil profiles				
5	Good rye complex	52	3.22	3.70	Similar to ALSG 4 but with less favorable subsoil conditions	Water deficit	IVa, IVb	16.4	10.0
6	Weak rye complex	30	–	2.80	Very coarse soils or soils with shallow sandy layers	Severe drought limitation	IVb, V	18.1	–
7	Very weak rye complex	18	–	2.33	Very coarse soils or shallow sandy subsoil	Persistent drought limitation	V, VI	11.3	–
8	Strong cereal–fodder complex	64	3.96	4.00	Fine-textured soils, often with shallow groundwater	Excess water	(IIIa), IIIb, IVa, IVb (V)	4.5	–
9	Weak cereal–fodder complex	33	–	2.72	Coarse soils in low positions or with impermeable subsoil	Excess water	IVa, IVb, V, VI	3.4	–

Notes (Table A2): ¹ Point scores according to Witek et al. (1981). ² Based on Witek (1979), derived from 1525 winter wheat experiments. ³ Includes winter wheat, winter rye, spring barley, and oats (~5900 experiments). ⁵ Based on national data (Gleboznawstwo, 1999).

References

- Abbasi, D.; Ashworth, A.J.; Owens, P.R.; Winzeler, H.E.; Kharel, T.; Zhou, Y. Leveraging Digital Soil Maps and Clustering Techniques to Enhance Soil Management Zone Delineation. *Agronomy Journal* **2025**, *117*, e70210. <https://doi.org/10.1002/agj2.70210>.
- Ali, A.; Martelli, R.; Lupia, F.; Barbanti, L. Assessing Multiple Years' Spatial Variability of Crop Yields Using Satellite Vegetation Indices. *Remote Sensing* **2019**, *11*, 2384. <https://doi.org/10.3390/rs11202384>.
- Ali, A.; Martelli, R.; Scudiero, E.; Lupia, F.; Falsone, G.; Rondelli, V.; Barbanti, L. Soil and Climate Factors Drive Spatio-Temporal Variability of Arable Crop Yields under Uniform Management in Northern Italy. *Archives of Agronomy and Soil Science* **2023**, *69*, 75–89. <https://doi.org/10.1080/03650340.2021.1958320>.
- Astrauskas, P.; Staugaitis, G.; Masevičienė, A.; Žičkienė, L. Variation of Winter Wheat Grain Yield and Its Quality in Fields with Different Soil Cover. *Zemdirbyste-Agriculture* **2022**, *109*, 297–304. <https://doi.org/10.13080/z-a.2022.109.038>.
- Barabasz, W.; Bednarek, R.; Gonet, S.S.; Baran, S.; Weber, J.; Kucharski, J.; Kabała, C.; Wyszowska, J.; Marcinek, J.; et al. *Gleboznawstwo*; Wydanie I; PWN: Warszawa, 2015; ISBN 978-83-01-17994-6.
- COBORU. Information available online: <https://coboru.gov.pl/pl/struktura%20organizacyjna/oddzialy> (accessed: 21.02.2026)
- Fischer, R.A. Definitions and Determination of Crop Yield, Yield Gaps, and of Rates of Change. *Field Crops Research* **2015**, *182*, 9–18. <https://doi.org/10.1016/j.fcr.2014.12.006>.
- Gleboznawstwo: Podręcznik Dla Studentów: Praca Zbiorowa*; Zawadzki, S., Walczak, R.T., Stępniewski, W., Smyk, B., Skawina, T., Prusinkiewicz, Z., Bednarek, R., Białousz, S., Dobrzański, B., Gliński, J., Kossowski, J., Gonet, S.S., Konecka-Betley, K., Kuźnicki, F., Kowaliński, S., Eds.; Wydanie IV poprawione i uzupełnione.; Państwowe Wydawnictwo Rolnicze i Leśne: Warszawa, 1999; ISBN 978-83-09-01703-5.
- Gozdowski, D.; Stępień, M.; Samborski, S.; Dobers, E.S.; Szatyłowicz, J.; Chormański, J. Determination of the Most Relevant Soil Properties for the Delineation of Management Zones in Production Fields.

- Communications in Soil Science and Plant Analysis* **2014**, *45*, 2289–2304. <https://doi.org/10.1080/00103624.2014.912289>.
- GUS <https://new.stat.gov.pl/> (accessed on 11.03.2026)
- Hennings, V.; Höper, H.; Mueller, L. Small-Scale Soil Functional Mapping of Crop Yield Potentials in Germany. In *Novel Methods for Monitoring and Managing Land and Water Resources in Siberia*; Mueller, L., Sheudshen, A.K., Eulenstein, F., Eds.; Springer Water; Springer International Publishing: Cham, 2016; pp. 597–617 ISBN 978-3-319-24407-5.
- Iwańska, M.; Paderewski, J.; Stępień, M.; Rodrigues, P.C. Adaptation of Winter Wheat Cultivars to Different Environments: A Case Study in Poland. *Agronomy* **2020**, *10*, 632. <http://doi.org/10.3390/agronomy10050632>
- Iwańska, M.; Paderewski, J.; Stępień, M.; Rodrigues, P.C. Winter Wheat Cultivar Recommendation Based on Expected Environment Productivity. *Agriculture* **2021**, *11*, 522. <https://doi.org/10.3390/agriculture11060522>
- Iwańska, M.; Stępień, M. The Effect of Soil and Weather Conditions on Yields of Winter Wheat in Multi-Environmental Trials. *Biometrical Letters* **2019**, *56*, 263–279. <https://doi.org/10.2478/bile-2019-0016>.
- Kamkar, B.; Hoogenboom, G.; Alizadeh-Dehkordi, P.; Bazkiaee, P.A.; Nehbandani, A. Comprehensive Insights into Modeling Yield Gap in Agroecosystems: Definitions, Theoretical Framework, and Multidimensional Perspectives (a Review). *Agricultural Systems* **2025**, *228*, 104392. <https://doi.org/10.1016/j.agsy.2025.104392>.
- J. Kowalska; K. Jończyk; M. Holka. Instrukcja uprawy pszenicy ozimej ze szczególnym uwzględnieniem ochrony roślin w systemie ekologicznym **2024**. <https://www.ior.poznan.pl/plik,4778,instrukcja-uprawy-pszenicy-ozimej-ze-szczegolnym-uwzglednieniem-ochrony-roslin-w-systemie-ekologicznym-pdf.pdf> (accessed on 18.02.2026)
- Lisowski, J.; Żochowski, Ł.; Konarzewski, P. PORÓWNANIE PLONOWANIA ŻYTA HYBRYDOWEGO I POPULACYJNEGO W DWÓCH OKRESACH WEGETACYJNYCH. *SJIAAS* **2025**, *94*, 116–132. <https://doi.org/10.58246/4fvdg578>.
- Lobell, D.B.; Cassman, K.G.; Field, C.B. Crop Yield Gaps: Their Importance, Magnitudes, and Causes. *Annu. Rev. Environ. Resour.* **2009**, *34*, 179–204. <https://doi.org/10.1146/annurev.enviro.041008.093740>.
- Mueller, L.; Schindler, U.; Mirschel, W.; Shepherd, T.G.; Ball, B.C.; Helming, K.; Rogasik, J.; Eulenstein, F.; Wiggering, H. Assessing the Productivity Function of Soils. A Review. *Agron. Sustain. Dev.* **2010**, *30*, 601–614. <https://doi.org/10.1051/agro/2009057>.
- Nawar, S.; Corstanje, R.; Halcro, G.; Mulla, D.; Mouazen, A.M. Delineation of Soil Management Zones for Variable-Rate Fertilization. In *Advances in Agronomy*; Elsevier, 2017; Vol. 143, pp. 175–245 ISBN 978-0-12-812421-5.
- Niewiadomski, W.; Zawisłak, K.; Boreńska, Ł.; Krześlak, S.; Adamiak, J.; Hruszka, M.; Kasprzykowski, W.; Nożyński, A. Plonowanie Pszenicy Ozimej w Specjalistycznych Zmianowaniach i Monokulturach w Zróżnicowanych Warunkach Glebowych (Synteza 20-Letnich, Ścisłych Doświadczeń Polowych). *Zesz. Probl. Post. Nauk Rol.* **1988**, *1988*, 77–91. <https://bibliotekanauki.pl/articles/804637.pdf> accessed 08.10.2025
- Rudnicki, F.; Gałęzewski, L. Efekty Oddziaływań Brzegowych w Doświadczeniach z Owsem Wysiewanym w Różnych Gęstościach. *Biuletyn IHAR* **2006**, 73–83. <https://doi.org/10.37317/biul-2006-0076>.
- Samborski S. (ed.) *Rolnictwo Precyzyjne*; Wydawnictwo Naukowe PWN S.A.: Warsaw, Poland; Vol. 2018;
- Stawiana-Kosiorek, A.; Gołaszewski, J.; Załuski, D. Efekty Konkurencyjności Roślin Pszenżyta Ozimego w Doświadczeniach Polowych. *Biuletyn IHAR* **2007**, 97–107. <https://doi.org/10.37317/biul-2007-0074>.
- Senapati, N.; Semenov, M.A. Large Genetic Yield Potential and Genetic Yield Gap Estimated for Wheat in Europe. *Global Food Security* **2020**, *24*, 100340. <https://doi.org/10.1016/j.gfs.2019.100340>.
- Studnicki, M.; Derejko, A.; Wójcik-Gront, E.; Kosma, M. Adaptation Patterns of Winter Wheat Cultivars in Agro-Ecological Regions. *Sci. agric. (Piracicaba, Braz.)* **2019**, *76*, 148–156. <https://doi.org/10.1590/1678-992x-2017-0183>.
- Studnicki, M.; Kang, M.S.; Iwańska, M.; Oleksiak, T.; Wójcik-Gront, E.; Mądry, W. Consistency of Yield Ranking and Adaptability Patterns of Winter Wheat Cultivars between Multi-Environmental Trials and Farmer Surveys. *Agronomy* **2019**, *9*, 245. <https://doi.org/10.3390/agronomy9050245>.
- T. Stuczyński; J. Kozyra; A. Łopatka; G. Siebielec; J. Jadczyzyn; P. Koza; A. Doroszewski; R. Wawer; E. Nowocień Przyrodnicze uwarunkowania produkcji rolniczej w Polsce. *Studia i Raporty IUNG-PIB* **2007**,

- 2007, 77–115. <https://www.iung.pl/studia-i-raporty-pib/> accessed 22.02.2026 #do zależności wsk. jakości i przydatności a plon
- UTKG. Urzędowa Tabela Klas Gruntów, załącznik do Rozporządzenia Rady Ministrów z dnia 12 września 2012 r. w sprawie gleboznawczej klasyfikacji gruntów (Dz.U. z 2012 r., poz. 1246) (*Official Table of Land Classes (in Polish)*); attachment to a Regulation of the Council of Ministers on soil classification Poland, 2012, available at <https://eli.sejm.gov.pl/eli/DU/2012/1246/ogl> accessed 07.08.2025
- Ustawa z dnia 17 maja 1989 r. – Prawo geodezyjne i kartograficzne (Dz. U. 1989 Nr 30 poz. 163). Act of 17 May 1989 – Geodetic and Cartographic Law (in Polish). Available online <https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU19890300163> (accessed on 19 Feb 2026)
- Washmon, C.N.; Solie, J.B.; Raun, W.R.; Itenfisu, D.D. Within-Field Variability in Wheat Grain Yields over Nine Years in Oklahoma. *J. Plant Nutr.* 2002, 25, 2655–2662. <https://doi.org/10.1081/PLN-120015529>
- Witek, T.; Górski, T.; Kern, H.; Bartoszewski, Z.; Biesiadzki, A.; Budzyńska, K.; Demidowicz, G.; Deputat, T.; Flaczyk, Z.; Gałęcki, Z.; et al. Waloryzacja rolniczej przestrzeni produkcyjnej Polski wg gmin (Valorization of Productive Agricultural Area of Poland in Districts, in Polish); IUNiG: Puławy, Poland, 1981; pp. 1–416.
- Witek, T. Wpływ jakości gleby na plonowanie roślin uprawnych (Influence of the quality of soils on yielding of crops, in Polish). *Zesz. Probl. Postęp. Nauk Rol.* 1979, 224, 35–47.
- Witek, T. Mapy Glebowo-Rolnicze Oraz Kierunki ich Wykorzystania; Instytut Uprawy, Nawożenia i Gleboznawstwa: Puławy, Poland; PWRiL: Warszawa, Poland, 1973; pp. 1–75. Available online: <https://www.gov.pl/web/gugik/materialy-dotyczace-map-glebowo-rolniczych> (accessed on 30 October 2024).
- Wójcik-Gront, E.; Iwańska, M.; Wnuk, A.; Oleksiak, T. The Analysis of Wheat Yield Variability Based on Experimental Data from 2008–2018 to Understand the Yield Gap. *Agriculture* 2021, 12, 32. <https://doi.org/10.3390/agriculture12010032>.
- Wyniki PDO -SDOO Cicibór Duży. Available online: <https://cicibor.coboru.gov.pl/wyniki> (accessed 11.03.2026)
- Van Ittersum, M.K.; Cassman, K.G.; Grassini, P.; Wolf, J.; Tittonell, P.; Hochman, Z. Yield Gap Analysis with Local to Global Relevance—A Review. *Field Crops Research* 2013, 143, 4–17. <https://doi.org/10.1016/j.fcr.2012.09.009>.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.