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The Analysis of Wheat Yield Variability Based on Experimental Data from 2008–2018 to Understand the Yield Gap

Elżbieta Wójcik-Gront [1,*], Marzena Iwańska [1], Agnieszka Wnuk [1] and Tadeusz Oleksiak [2]

[1] Department of Biometry, Institute of Agriculture, Warsaw University of Life Science-SGGW, Nowoursynowska 159, 02-787 Warszawa, Poland; marzena_iwanska@sggw.edu.pl (M.I.); agnieszka_wnuk@sggw.edu.pl (A.W.)
[2] Plant Breeding and Acclimatization Institute-National Research Institute (IHAR-PIB), Radzików, 05-870 Błonie, Poland; t.oleksiak@ihar.edu.pl
* Correspondence: elzbieta_wojcik_gront@sggw.edu.pl

Abstract: Among European countries, Poland has the largest gap in the grain yield of winter wheat, and thus the greatest potential to reduce this yield gap. This paper aims to recognize the main reasons for winter wheat yield variability and shed the light on possible reasons for this gap. We used long-term datasets (2008–2018) from individual commercial farms obtained by the Laboratory of Economics of Seed and Plant Breeding of Plant Breeding and Acclimatization Institute (IHAR)-National Research Institute (Poland) and the experimental fields with high, close to potential yield, in the Polish Post-Registration Variety Testing System in multi-environmental trials. We took into account environment, management and genetic variables. Environment was considered through soil class representing soil fertility. For the crop management, the rates of mineral fertilization, the use of pesticides and the type of pre-crop were considered. Genotype was represented by the independent variable year of cultivar registration or year of starting its cultivation in Poland. The analysis was performed using the CART (Classification and Regression Trees). The winter wheat yield variability was mostly dependent on the amount of nitrogen fertilization applied, soil quality, and type of pre-crop. Genetic variable was also important, which means that plant breeding has successfully increased genetic yield potential especially during the last several years. In general, changes to management practices are needed to lower the variability of winter wheat yield and possibly to close the yield gap in Poland.

Keywords: wheat; yield potential; nitrogen; crop modelling; regression trees

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1. Introduction

Wheat (*Triticum aestivum*), along with corn (*Zea mays*), rice (*Oryza sativa*) and soybean (*Glycine max*), is one of the main crops used for food and feed production around the world [1–4]. Poland is a substantial contributor to world's wheat production. However, the average yield of rain-fed winter wheat production is only 4.8 t ha^{-1} [5], which is more than two times less than the potential yield under similar cultivation conditions [6]. Polish wheat experimental farms report the average yield almost twice as high as the actual wheat yield on the commercial farms [7]. The yield gap is calculated as the difference between the potential yield of rain-fed crops and the actual yield of farmers [6,8]. Therefore, yields from high-yielding experimental plots can be a target to get closer to the potential yield and close the yield gap.

The yield of winter wheat in Poland has been steadily improving for last several years due to cultivar genetic improvement and more intensive agricultural practices, but remains very low in comparison to wheat yield obtained in western Europe [9,10]. Low values of yield gaps are mainly seen in northwestern Europe in contrary to south-western and eastern Europe [6,11]. Thus, even taking into account that the crop yields vary across regions with the same climatic zones [2], there is a room to improve Polish wheat production and unlock the yield potential. According to Schils et al. [6], the largest discrepancies between the actual grain yield and the modeled estimates of potential yield in rain-fed conditions were in eastern and south-western Europe, with half of the potential growth in Europe being found in Ukraine, Romania, and Poland. The growing global demand for cereals forces the search for opportunities to increase production in order to meet future demands of the global market [12–15]. High yields can be obtained on existing croplands with efficient use of resources and minimal environmental impact [16]. Increasing wheat production through more effective agronomic management can help to meet future food demand while minimizing the expansion of agricultural land.

Until now, the yield gap analysis has been carried out using the results obtained from the application of plant growth models [6,11]. The water available to plants during the growing season, soil properties, solar radiation, and temperature also determine the growth of crops. However, they are of primary importance when the nutrient supply from fertilizers, pests, weeds, and diseases are effectively managed [17]. Thus, the aim of this study was to identify the causes of the yield variability. Such analysis would identify possible factors influencing the yield gap. The study focused mainly on the analysis of crop management variables. It was done based on yield data collected from commercial and experimental farms scattered throughout Poland between 2008–2018. The questions were: if the yield variability can be minimized through proper crop management and if the yield can be higher when proper fertilization and plant protection are applied? The results were compared with the modelled potential yield of winter wheat.

2. Materials and Methods

To analyze the yield variability in winter wheat production in Poland, we evaluated the impact of variables related to genotype, environment, and crop management on the yield of 277 winter wheat genotypes grown on commercial and experimental farms scattered across the whole Poland during 11 growing seasons (harvest years 2008–2018). Due to the unbalance nature of the dataset, the multivariate CART analysis [18] was used to obtain the causes of yield variability.

2.1. Experimental Data

The data used in this study contained observations from low-input to high input crop management. Yield data of winter wheat were gathered from two sources: the Polish Post-Registration Variety Testing System (PRVTS) in multi-environmental trials (experimental fields) [8,19] and from individual commercial farms obtained by the Laboratory of Economics of Seed and Plant Breeding of Plant Breeding and Acclimatization Institute (IHAR)-National Research Institute (Poland) who performed surveys among farms holding agricultural accounting data [10]. Each entry in the data used refers to one field. One field is characterized by a cultivar of winter wheat, field characteristics i.e., its soil quality expressed in classes and agronomic production management. In many cases, due to privacy policy, the exact location of the field is unknown. Thus, Figure 1 indicates how many fields are examined in each one of 16 voivodeships in Poland (the highest-level administrative subdivision of Poland) during the period between 2008 and 2018. The total number of experimental observations used in the analysis was 24,797 (6561 from commercial farms and 18,236 from experimental ones).

Winter wheat was sown during the end of September and beginning of October and harvested during the end of July and in August. For each yield entry soil class, genetic and management related variables were described (Table 1). In the analysis, the winter wheat yield was the dependent variable expressed as grain yield in tons per hectare. The determinants of winter wheat yield variation applied for the construction of classification and regression trees (CART) were variables related to soil and crop management and a genetic variable (10 predictors; Table 1).

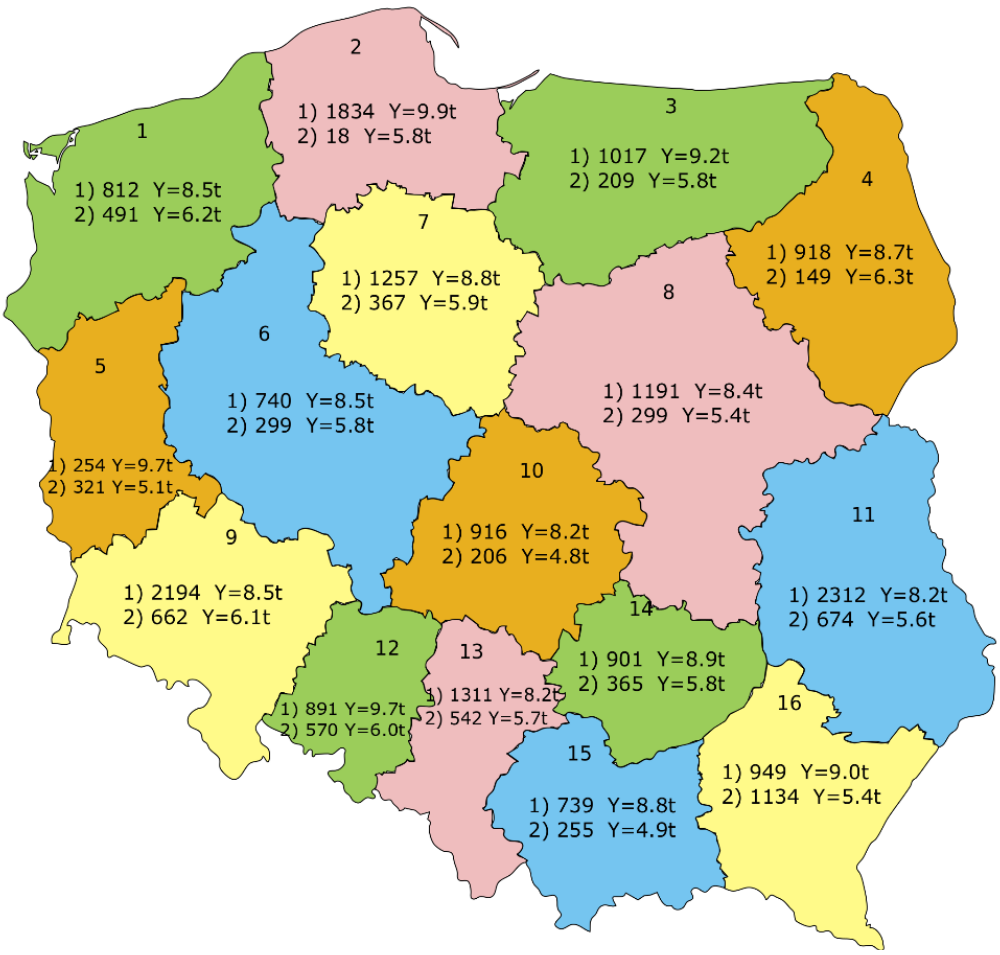

Figure 1. Number of entries from each field type (1)—PRVTS (the Polish Post-Registration Variety Testing System in multi-environmental trials, the experimental fields), (2)—IHAR (the Laboratory of Economics of Seed and Plant Breeding of Plant Breeding and Acclimatization Institute-National Research Institute, the farmers' fields) in each of 16 voivodeships in Poland with the average yield obtained at each field type. Numbers indicate voivodeships in Poland: 1 zachodniopomorskie (West Pomeranian), 2 pomorskie (Pomeranian), 3 warmińsko-mazurskie (Warmian-Masurian), 4 podlaskie (Podlaskie), 5 lubuskie (Lubusz), 6 wielkopolskie (Greater Poland), 7 kujawsko-pomorskie (Kuyavian-Pomeranian), 8 mazowieckie (Masovian), 9 dolnośląskie (Lower Silesian), 10 łódzkie (Łódź), 11 lubelskie (Lublin), 12 opolskie (Opole), 13 śląskie (Silesian), 14 świętokrzyskie (Holy Cross), 15 małopolskie (Lesser Poland), 16 podkarpackie (Subcarpathian).

2.2. Statistical Analysis and Data Visualization

All calculations and diagrams in the CART model were built using STATISTICA version 13 software and R [20–22]. The analysis of the main drivers of yield gap in Polish winter wheat production was performed using the CART model [18] with a 10-fold cross validation method to "prune" overgrowth trees created with STATISTICA software ver. 13 [20]. Classification and Regression Trees or CART is a term introduced to refer to Decision Tree algorithms that can be used for e.g., regression predictive modeling problems. The decision tree model algorithm works by splitting the data multiple times into multiple subsets, so that the results in each final subset are as uniform as possible. The produced result for regression trees consists of a set of rules used for predicting the outcome variable [23]. Here, the dependent variable was winter wheat yield and independent variables were the agricultural treatments and parameters related to growth conditions investigated within the field trials.

Table 1. Variables used in the CART analysis.

Variable	Variable Type in CART	Unit	Value
yield	dependent quantitative	mean ± SD (t/ha)	7.9 ± 2.2
nitrogen phosphorus potassium	independent quantitative	mean ± SD (kg/ha)	127.6 ± 32.4 52.7 ± 20.4 83.8 ± 28.0
fungicides		number of doses (total number of observations with this dose)	0 (6820) 1 (2772) 2 (12,356) 3 (2711) 4 (133) 5 (5)
herbicides			0 (326) 1 (18,015) 2 (5434) 3 (981) 4 (41)
insecticides			0 (9111) 1 (12,489) 2 (2883) 3 (207) 4 (106) 5 (1)
foliar fertilization			0 (9306) 1 (9497) 2 (5652) 3 (342)
pre-crop	independent qualitative (number of observations)	cereal legume rapeseed root crops	5810 6327 11,478 1182
soil quality (class reflects the agricultural value of soils, the lower the class the more fertile the soils, CM 2012)		I (best) II III IV V VI (worst)	603 4239 12,880 6632 160 283
cultivar introduction year		1965–1979 1980–1994 1995–2009 2010–2020	33 212 11,161 13,391

Numerous recursive splits are performed during the creation of the CART tree. Their goal is to search independent variables, enabling successive divisions of the yield into different but intrinsically homogeneous subsets. The CART method also made it possible to systematize the independent variables in terms of their impact on the dependent variable, i.e., the yield of winter wheat. With each split, the impact of each variable is calculated and then its importance in creating the final tree is estimated. This is how all independent variables are ranked. The independent variable that causes the greatest reduction in variance of the dependent variable wins, and it is later presented in the final CART tree [9,24,25]. There are many agronomic studies where the CART method was successfully used [8,26–30].

2.3. Modelling Crop Yield

The potential yield was calculated under conditions of unrestricted crop growth and excellent management that avoided yield constraints due to nutrient deficiencies and stress from weed and pest attack, and disease. Thus, the yielding potential depended mainly on the weather i.e., solar radiation and air temperature during the growing season of the crop. Moreover, the water-limited yield potential depends on the water supply, which is dictated by atmospheric precipitation and the available water in the soil.

In order to determine the potential yield of winter wheat, we used the Decision Support System for Agrotechnology Transfer (DSSAT) program V4.7.5 available at https://dssat.net, accessed on 10 September 2021 [31–33]. A simplest possible file was created to model a potential production experiment. A winter wheat cultivar was selected based on default genotype files available in DSSAT. Then, the specific environmental conditions were specified for selected fields. We used real weather data from a meteorological station not more than 15 km away from the field and default soil types defined in DSSAT, i.e., deep, medium, shallow silty clay, and deep sand. The planting information was then input: planting date, method, distribution, plant population, and planting depth. Simulation options were then set, that the plant has unlimited access to the necessary amount of nitrogen, phosphorus and potassium, and plant protection products.

3. Results

3.1. Descriptive Analysis

Yields of rain-fed winter wheat varied from 0.4 to 14.2 t ha^{-1}. Lower yields come from the commercial farms (yield from 0.4 to 9.92 t ha^{-1} with the mean 5.7 ± 1.5 t ha^{-1}) and higher from experimental ones (from 3.5 to 14.1 t ha^{-1} with the mean 8.8 ± 1.8 t ha^{-1}). The coefficient of variation (standard deviation divided by the mean) of the yields varied from 21% for experimental farms to 26% the commercial farms.

Figure 2 shows the yield changes over 11 years (medians, first and third quartiles). Average yield values changed from 5.4 t in 2009 to 9.6 t in 2014. Table 2 shows the average yields obtained in each of the studied years for each voivodeship marked in Figure 1. There were no data for a small number of combinations of voivodships and years. The lowest average yield value of 3.4 t was observed in the łódzkie voivodeship (no. 10) in 2012, and the highest 11.5 t in the pomorskie voivodeship (no. 2) in 2015.

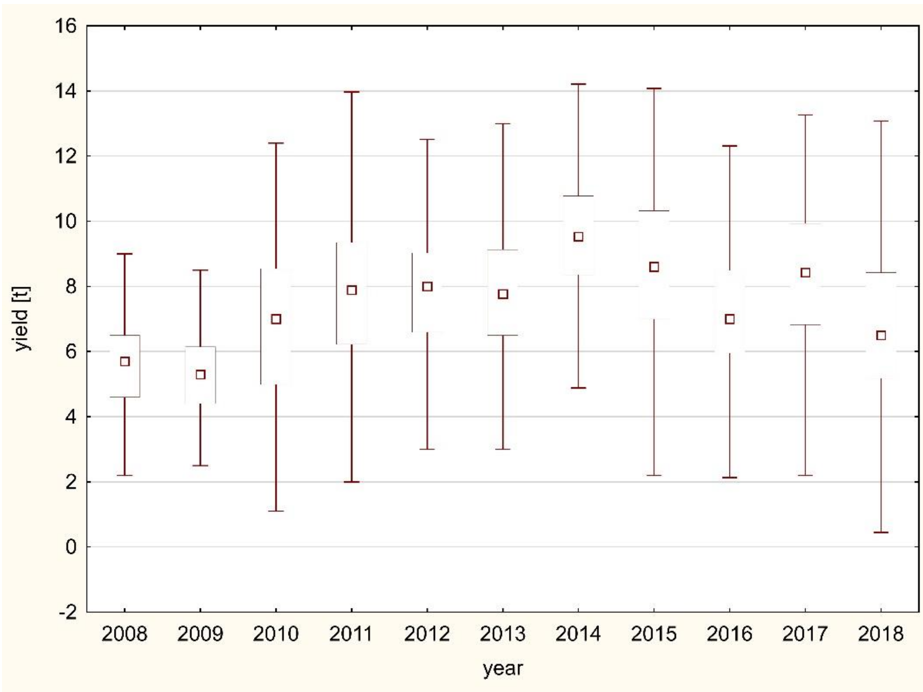

Figure 2. Temporal variability in yield within the 11 years for both commercial and experimental farms together. For each year, the middle is the median, the box is the first and third quartiles, and the whiskers are the minimum and maximum values.

Table 2. Grain yield of winter wheat [t/ha] in each voivodeship in each studied year for both commercial and experimental farms together. Numbers of voivodeships are the same as in Figure 1.

No.	Voivodeship	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
1	zachodniopomorskie	5.7	6.7	6.4	7.0	7.6	7.9	9.4	8.6	6.1	8.0	5.9
2	pomorskie	5.2	–	9.1	9.2	8.9	10.1	11.5	10.8	7.3	10.4	9.7
3	warmińsko-mazurskie	–	–	4.6	8.3	9.1	8.2	9.7	10.1	7.6	8.9	7.9
4	podlaskie	6.7	0.0	5.0	8.1	7.8	7.5	9.0	9.5	6.6	10.0	7.2
5	lubuskie	4.1	4.3	4.8	4.0	3.6	4.6	–	10.1	8.2	6.6	5.5
6	wielkopolskie	5.7	6.2	6.5	5.8	4.5	5.9	10.2	8.1	5.2	6.8	5.4
7	kujawsko-pomorskie	6.2	5.7	5.4	8.4	3.6	9.3	9.5	7.2	5.6	8.5	5.4
8	mazowieckie	3.9	–	4.6	7.5	8.1	7.9	9.8	8.2	7.0	6.9	5.3
9	dolnośląskie	–	–	6.1	8.1	8.1	7.6	10.0	8.1	7.4	7.9	6.9
10	łódzkie	–	–	5.0	7.1	3.4	7.9	8.3	7.6	6.7	9.4	6.4
11	lubelskie	6.2	4.6	7.6	7.7	7.2	7.1	8.6	9.1	6.7	8.0	7.0
12	opolskie	5.5	5.3	5.4	6.2	5.4	7.6	9.7	9.7	9.0	9.5	8.1
13	śląskie	6.2	5.2	4.7	8.0	7.7	7.1	9.6	7.7	6.2	7.5	5.4
14	świętokrzyskie	6.2	5.9	5.2	5.1	7.8	7.5	8.6	10.1	7.4	9.0	7.9
15	małopolskie	–	–	4.4	4.4	9.0	6.1	8.8	6.5	8.7	9.5	7.3
16	podkarpackie	5.1	4.4	4.1	7.1	6.8	5.1	9.0	7.9	7.7	8.4	6.9

3.2. CART

The CART analysis of winter wheat yield from eleven growing seasons revealed variables most influencing closing the yield gap. The variable giving the most yield variability reduction is soil class (Figure 3, split ID 1). Generally, higher yields are obtained on better quality soils. Wheat sown on soils of the best three classes I, II, and III gives an average of 1.7 t ha^{-1} higher yield. On lower quality soils (IV, V, VI), higher wheat yield can be obtained using doses of nitrogen higher than 97 kg ha^{-1} (Figure 3, split ID 2). When applied in doses larger than 97 kg ha^{-1}, it enables a yield of 8.2 kg ha^{-1} with legume as a pre-crop (Figure 3, subset ID 6). For other pre-crops, with doses of potassium lower than 87 kg ha^{-1}, the yield was 5.8 t ha^{-1} in comparison to 7.1 t ha^{-1} for higher doses of potassium.

The next split (Figure 3, ID 3) for better quality soils was done based on pre-crop. For pre-crops, root crops, and cereals, the wheat yield is lower by 1.5 t (Figure 3, subset ID 10). However, with doses of potassium higher than 104 kg ha^{-1} the yield was 8.8 t ha^{-1}. For the pre-crops legumes and rapeseeds, other split is done based on the rate of nitrogen. The rate of nitrogen higher than 125 kg ha^{-1} gave the yield of 9.3 t ha^{-1}. With higher doses of nitrogen next split in CART was by soil class. The most fertile soils (class I and II) gave the yield of 10 t ha^{-1} (Figure 3, subset ID 15). For soils class III, the yield was higher when lower doses (0 or 1) of insecticides were used (Figure 3, subset ID 18). For doses of nitrogen lower than 125 kg ha^{-1}, the next split was done for variable cultivar (Figure 3, subset ID 14). Modern cultivars (registered in 2009 or later) enabled yield of 8.6 t ha^{-1}, higher by 0.7 t ha^{-1} than for the older cultivars.

In all trees created in CART, the most important variables in yield improvement were: nitrogen, pre-crop, soil-class, cultivar registration year, and fungicides (Figure 4). Coefficient of Pearson correlation between observed and predicted yield was 0.59.

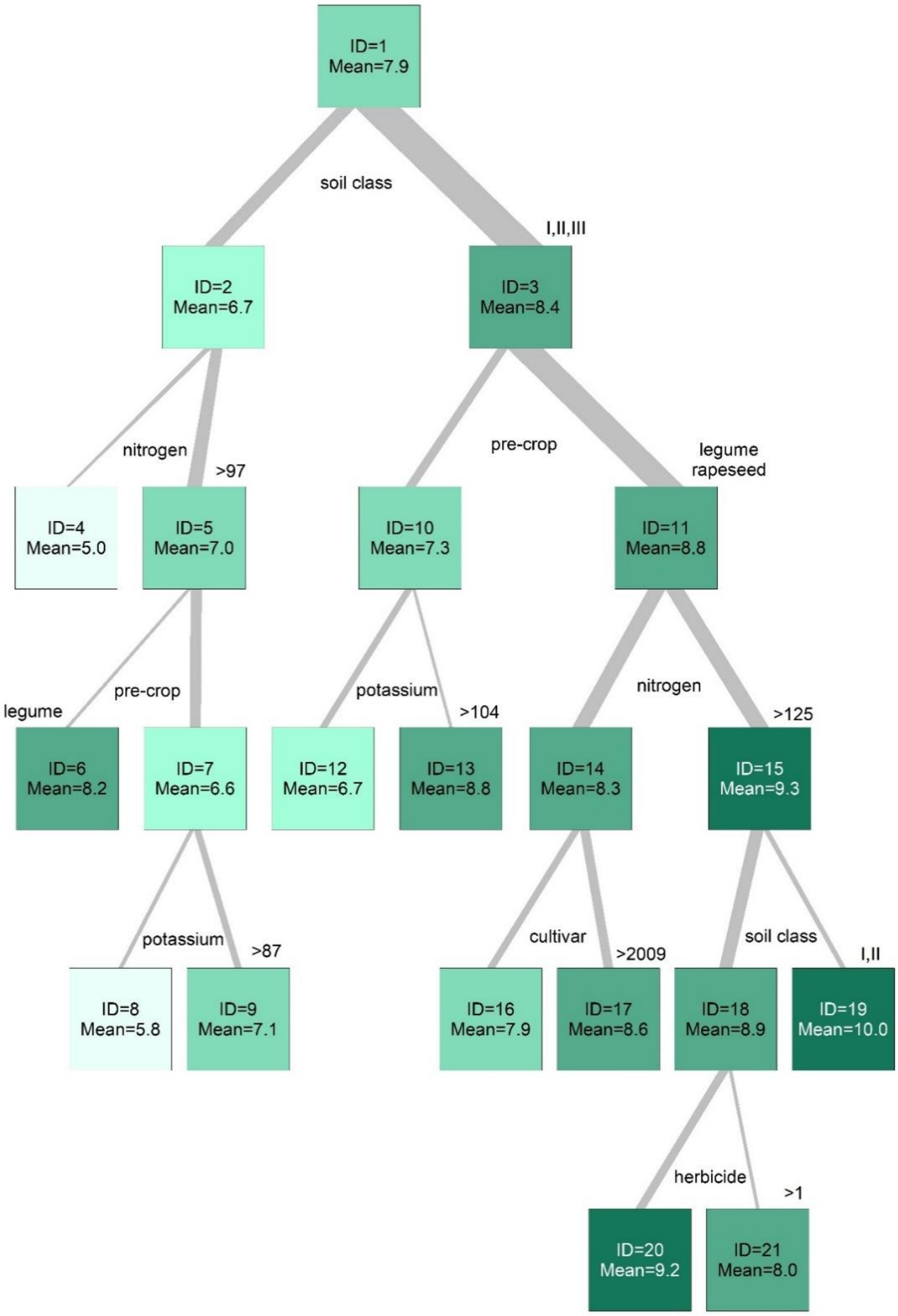

Figure 3. Regression tree for winter wheat CART analysis. Mean yield (in t/ha) is presented for each subset; the more intense the color of the subset, the higher the average yield of winter wheat. Coefficient of Pearson correlation between observed and predicted yield was 0.59.

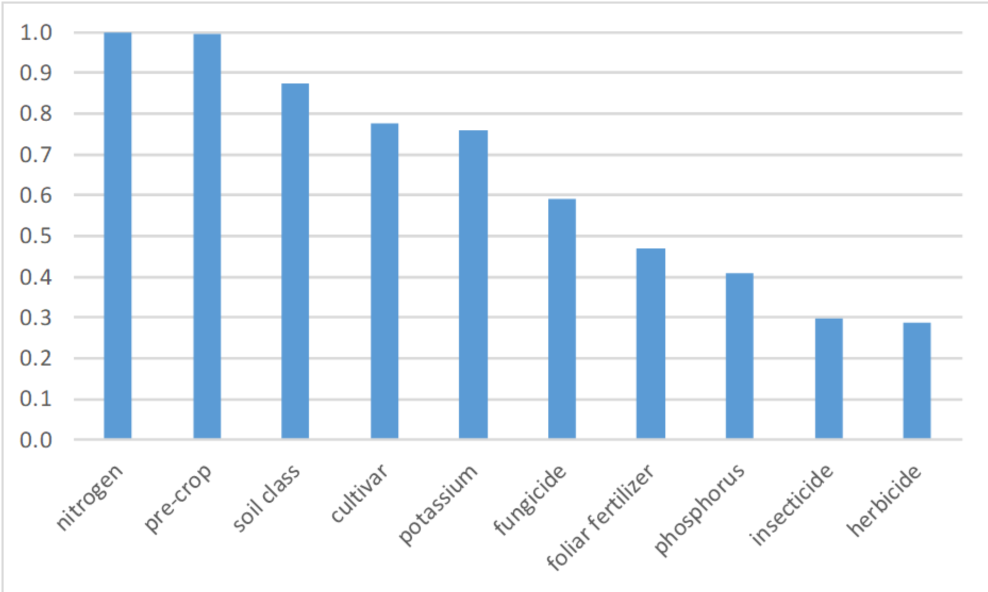

Figure 4. The most important independent variables in the CART tree construction (the closer to 1 the more important variable in the CART tree).

The modelled with DSSAT winter wheat yield was between 6.5 and 10.4 tons ha^{-1}.

3.3. Correlation and Regression Analysis

To support the CART results, we also performed an analysis of the correlation and linear regression between yield and nitrogen for each of the years studied. In all cases, the correlation was statistically significant for the significance level of 0.05 (Table 3). All Pearson's correlation coefficients were positive and ranged from 0.146 for 2016 to 0.428 for 2010. The linear regression equations shown in Table 3, presenting the effect of nitrogen dose on the yield, confirm that the average yield increase is about 0.02 tons (20 kg of grain) for each kilogram of nitrogen, but varies strongly between years (from 0.009 to 0.028 t, i.e., 9 to 28 kg of grain for kg of N) depending on weather conditions.

Table 3. Pearson correlation coefficients between wheat grain yield (t/ha) and nitrogen fertilization (kg/ha) for each studied year and linear regression equation presenting yield (Y) dependency on nitrogen (N).

Year	Correlation Coefficient	*p*-Value	Linear Regression
2008	0.395	<0.001	Y = 0.015·N + 4.128
2009	0.322	<0.001	Y = 0.010·N + 4.315
2010	0.428	<0.001	Y = 0.028·N + 3.532
2011	0.278	<0.001	Y = 0.019·N + 5.468
2012	0.381	<0.001	Y = 0.024·N + 4.936
2013	0.400	<0.001	Y = 0.026·N + 4.609
2014	0.251	<0.001	Y = 0.015·N + 7.635
2015	0.343	<0.001	Y = 0.024·N + 5.463
2016	0.146	<0.001	Y = 0.009·N + 6.054
2017	0.187	<0.001	Y = 0.013·N + 6.699
2018	0.176	<0.001	Y = 0.012·N + 5.144

4. Discussion

In this study, we analyzed winter wheat grain yield data covering a long period of time, different environmental conditions of growth in Poland, and diversified agronomic management. Data prepared in this way allow for drawing reliable conclusions about the causes of the yield variability in Poland. Thus, the data assessed in this study give a good idea of the variables most influencing the reduction of the yield gap.

Besides agricultural management, the wheat growing conditions are influenced by weather conditions [7,10,19]. The effect of weather variables were not assessed in this study, because effective management of fertilizer resources is the most important factor in yield variability and in the rain-fed conditions the effect of weather cannot be studied properly [6,17]. The weather is of primary importance when the nutrient supplies of fertilizers, pests, weeds and diseases are effectively managed [17].

The results show that the main cause of yield gap might be nitrogen deficiency for the plant to use. On one hand, farmers apply not enough nitrogen, and on the other the use of nitrogen is not efficient. As proved by many studies, nitrogen applied in excess is not a driver of yield improvement [7,34,35]. However, in the commercial farms in Poland there is still not enough nitrogen applied. For example an average nitrogen consumption per 1 ha of agricultural land was 69.2 kg in 2009/2010, 80.7 kg in 2012/2013, 71.7 kg in 2015/2016 and 78.7 kg in 2016/2017 [5]. Based on the results, the amount necessary for the proper growth and development of the wheat is at least 98 kg ha^{-1}. Thus, there might be a potential to improve site-specific nitrogen management. In work by Wójcik-Gront [7] on winter wheat yield variability, nitrogen was not the most important variable, but in that study, the average dose was 125 kg ha^{-1}.

Another important variable contributing to winter wheat yield variability was soil class which represents environmental conditions which affect grain yield potential. The wheat growing environment has a significant impact on the yield. The production of wheat requires high-quality soil; thus, the best available soil should be selected when growing wheat [36–40]. Farmers who do not have access to valuable soils may consider growing other agricultural crops to increase production efficiency. However, Deepak et al. [41] showed that on lower quality soils higher yield can be obtained by proper fertilization and pests management.

It is no surprise that, in the study, it turned out that the modern cultivars give higher yield in winter wheat production. There are still farms which use old cultivars because they use the seeds that come from their own production which is easy available and cheaper. In the experimental fields, modern cultivars are used, as they provide a high stable yield [8,42].

When there is sufficient nitrogen to meet the plant demand, other factors become limiting like fungicides [8]. Here, it is moderately important in explaining winter wheat yield variability, as it is more visible in the tree construction when nitrogen deficiency is mitigated. After supplementing nitrogen deficiencies, it will be possible to further increase the yield by using the right amount of plant protection products. Consumption data show that the trends in sales of plant protection products in Poland is still growing (insecticides 905 t of active substance in 2010 to 1809 in 2017, fungicides and seed treatments 5755 in 2010 to 7213 in 2017, herbicides 10,489 in 2010 to 13,655 in 2017 and plant growth regulators 1522 in 2010 to 2144 in 2017) (GUS, 2020). Of course, all plant protection products should be applied in the recommended growth stages and weather conditions and should be matched to the crop requirements.

In similar survey-based studies carried out in Germany by Macholdt and Honermeier [43], most important variables were the choice of cultivar, pre-crop, and chemical plant protection [44–46]. Crop rotation with a higher share of cereals negatively affects the stability of the yield of winter wheat, especially wheat monocultures. Diversified crop rotation with favorable pre-crops (like legumes) positively influences the yield stability of cultivated winter wheat due to better nitrogen nutrition and lower susceptibility to pests and cereal diseases [43,47–51].

Variables less important in explaining winter wheat yield variation were: potassium and phosphorus.

The potential yield obtained in this study ranged from 6.5 to 10.4 t ha^{-1}. These values stay in agreement with other study [2] and are comparable with yield values obtained for the data gathered in experimental farms (from PRVTS). Schills et al. [2] obtained potential yield for Poland between 8.0 to 9.6 t ha^{-1}. Genetic yield gaps equal to 3.5–5.2 t ha^{-1} were estimated under rainfed conditions in Europe [52], showing that current local cultivars are far from their optimum. The Baltic states had the highest yield gaps (>4 t ha^{-1}) calculated by Boogaard et al. [11].

In the near future, improving nitrogen use efficiency (NUE) can be done by site-specific nitrogen fertilization based on remote sensing data from low-altitude (from unmanned aerial vehicles) or satellite derived imagery [53,54]. Such methods of improving NUE are very important, especially because of current circumstances including European Union Green Deal policy which assume reducing mineral nitrogen fertilization of crops in near future [55]. Various environmental issues demand changing of nitrogen fertilization form to avoid nitrogen loses, e.g., application of N-fertilizers with inhibitors [56]. Another issue which can affect nitrogen fertilization is high increase of nitrogen fertilizers prices in 2021 (https://ahdb.org.uk/GB-fertiliser-prices, accessed on 20 December 2021) which can be an economic limitation in nitrogen use by farmers. All these circumstances can affect decisions of the farmers about N-fertilizers doses which will be applied in the next years. Optimal recommendation of nitrogen fertilization should include comprehensive approach where genotype, environment, and crop management are adjusted to obtain the highest NUE [57]. It is not possible to recommend one optimal scenario for wheat nitrogen fertilization, especially because weather variability within and between seasons in quickly changing climate and more often occurred droughts which affect NUE [58]. The recommendations should include negative effect of nitrous oxide emissions to atmosphere. All these factors as well interaction of nitrogen fertilization with other agronomical and environmental factors make it difficult to limit the yield gap by optimization of nitrogen fertilization because it is very complex problem. Another problem in Poland for optimized nitrogen fertilization is agrarian structure in Poland where farms are relatively small and agronomic innovation cannot be introduced in short time [59]. We should be aware that not all factors which were important for grain yield in the study can be controlled by farmers. Soil quality is independent environmental factor which had significant effect on grain yield of wheat but is out of control. Soil quality in Poland is relatively poor, much lower in comparison to other EU countries [60], and causes lower grain yield potential of winter wheat. Higher NUE in agronomic practice can be increased by breeding progress, which is a very important factor reduction of yield gap [61].

Another factor which is difficult to control by farmers is pre-crop for winter wheat because of very high share of cereals (about 70%) in Poland in arable land [7]. Because of such large area occupied by cereals, it not always possible to cultivate winter wheat after other crops (not cereals).

In the study, we were able to obtain main drivers of winter wheat yield variability in Poland. In the future, it would be interesting to analyze geographical distribution of yield gaps across the whole Poland to identify areas with most potential for improvement. Whether yield gap reduction is desirable and feasible is a matter of farm economic objectives and country environmental targets. However, application of genetic improvements and changes to crop management practices are recommended in the Polish production of winter wheat.

Unfortunately, sowing date was not included into analysis, because we did not have access to sowing date which can be important factors which affects winter wheat yield variability.

5. Conclusions

The yield gap analysis was performed using the CART regression trees. The winter wheat yield variability was mostly dependent on the amount of nitrogen. Genetic variable was also important in winter wheat yield variability. Thus, changes to management practices, especially optimization of nitrogen fertilization, selection of pre-crop, and selection of modern cultivars are needed to decrease the winter wheat yield gap.

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References

1. Foley, J.A.; Ramankutty, N.; Brauman, K.A.; Cassidy, E.S.; Gerber, J.S.; Johnston, M.; Mueller, N.D.; O'Connell, C.; Ray, D.K.; West, P.C.; et al. Solutions for a cultivated planet. *Nature* **2011**, *478*, 337–342. [CrossRef] [PubMed]
2. Mueller, N.D.; Gerber, J.S.; Johnston, M.; Ray, D.K.; Ramankutty, N.; Foley, J.A. Closing yield gaps through nutrient and water management. *Nature* **2012**, *490*, 254–257. [CrossRef] [PubMed]
3. Shewry, P.R.; Hey, S.J. The contribution of wheat to human diet and health. *Food Energy Secur.* **2015**, *4*, 78–202. [CrossRef] [PubMed]
4. Zhao, C.; Liu, B.; Piao, S.; Wang, X.; Lobell, D.B.; Huang, Y.; Huang, M.; Yao, Y.; Bassu, S.; Ciais, P.; et al. Temperature increase reduces global yields of major crops in four independent estimates. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 9326–9331. [CrossRef] [PubMed]
5. GUS. Statistics Poland. Available online: https://bdl.stat.gov.pl/BDL/start (accessed on 23 July 2020).
6. Schils, R.; Olesen, J.E.; Kersebaum, K.C.; Rijk, B.; Oberforster, M.; Kalyada, V.; Khitrykau, M.; Gobin, A.; Kirchev, H.; Manolova, V.; et al. Cereal yield gaps across Europe. *Eur. J. Agron.* **2018**, *101*, 109–120. [CrossRef]
7. Wójcik-Gront, E. Variables influencing yield-scaled Global Warming Potential and yield of winter wheat production. *Field Crop. Res.* **2018**, *227*, 19–29. [CrossRef]
8. 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 Crop. Res.* **2013**, *143*, 4–17. [CrossRef]
9. Iwańska, M.; Oleksy, A.; Dacko, M.; Skowera, B.; Oleksiak, T.; Wójcik-Gront, E. Use of classification and regression trees (CART) for analyzing determinants of winter wheat yield variation among fields in Poland. *Biometr. Lett.* **2018**, *55*, 197–214. [CrossRef]
10. 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. [CrossRef]
11. Boogaard, H.; Wolf, J.; Supit, I.; Niemeyer, S.; van Ittersum, M. A regional implementation of WOFOST for calculating yield gaps of autumn-sown wheat across the European Union. *Field Crop. Res.* **2013**, *143*, 130–142. [CrossRef]
12. Alexandratos, N.; Bruinsma, J. *World Agriculture towards 2030/2050: The 2012 Revision*; Food and Agriculture Organization of the UN: Rome, Italy, 2012.
13. Godfray, H.C.J.; Pretty, J.; Thomas, S.M.; Warham, E.J.; Beddington, J.R. Linking policy on climate and food. *Science* **2011**, *331*, 1013–1014. [CrossRef] [PubMed]
14. Godfray, H.C.J.; Garnett, T. Food security and sustainable intensification. *Philos. Trans. R. Soc.* **2014**, *369*, 20120273. [CrossRef] [PubMed]
15. Pradhan, P.; Fischer, G.; van Velthuizen, H.; Reusser, D.E.; Kropp, J.P. Closing yield gaps: How sustainable can we be? *PLoS ONE* **2015**, *10*, e0129487.
16. Tilman, D.; Balzer, C.; Hill, J.; Befort, B.L. Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 20260–20264. [CrossRef] [PubMed]
17. Edreira, J.I.R.; Mourtzinis, S.; Conley, S.P.; Roth, A.C.; Ciampitti, I.A.; Licht, M.A.; Kandel, H.; Kyveryga, P.M.; Lindsey, L.E.; Mueller, D.S.; et al. Assessing causes of yield gaps in agricultural areas with diversity in climate and soils. *Agric. For. Meteorol.* **2017**, *247*, 170–180. [CrossRef]
18. Breiman, L.; Friedman, J.H.; Olshen, R.A.; Stone, C.G. *Classification and Regression Trees*; Wadsworth International Group: Belmont, CA, USA, 1984.
19. Studnicki, M.; Derejko, A.; Wójcik-Gront, E.; Kosma, M. Adaptation patterns of winter wheat cultivars in agro-ecological regions. *Sci. Agric.* **2019**, *76*, 148–156. [CrossRef]
20. Dell Inc. Dell Statistica (Data Analysis Software System). Version 13. 2016. Available online: software.dell.com (accessed on 30 March 2021).

21. R. Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2020.
22. Therneau, T.; Atkinson, B. rpart: Recursive Partitioning and Regression Trees. R Package Version 4.1-15. 2019. Available online: https://CRAN.R-project.org/package=rpart (accessed on 20 July 2021).
23. Strobl, C.; Malley, J.; Tutz, G. An introduction to recursive partitioning: Rationale, application, and characteristics of classification and regression trees, bagging, and random forests. *Psychol. Methods* **2009**, *14*, 323–348. [CrossRef] [PubMed]
24. Wójcik-Gront, E.; Studnicki, M. Long-Term Yield Variability of Triticale (× Triticosecale Wittmack) Tested Using a CART Model. *Agriculture* **2021**, *11*, 92. [CrossRef]
25. Dacko, M.; Zając, T.; Synowiec, A.; Oleksy, A.; Klimek-Kopyra, A.; Kulig, B. New approach to determine biological and environmental factors influencing mass of a single pea (*Pisum sativum* L.) seed in Silesia region in Poland using a CART model. *Eur. J. Agron.* **2016**, *74*, 29–37. [CrossRef]
26. Krupnik, T.J.; Ahmed, Z.U.; Timsina, J.; Yasmina, S.; Hossain, F.; Mamun, A.A.; Mridha, A.I.; McDonald, A.J. Untangling crop management and environmental influences on wheat yield variability in Bangladesh: An application of non-parametric approaches. *Agric. Syst.* **2015**, *139*, 166–179. [CrossRef]
27. Mézière, D.; Colbach, N.; Dessaint, F.; Granger, S. Which cropping systems to reconcile weed-related biodiversity and crop production in arable crops? An approach with simulation-based indicators. *Eur. J. Agron.* **2015**, *68*, 22–37. [CrossRef]
28. Aman, M.N.; Bhatti, A.U. Comparison of regression models to predict potential yield of wheat from some measured soil properties. *Pak. J. Agric. Sci.* **2015**, *52*, 239–256.
29. Aouadia, N.; Aubertotb, J.N.; Caneillc, J.; Munier-Jolaina, N. Analyzing the impact of the farming context and environmental factors on cropping systems: A regional case study in Burgundy. *Eur. J. Agron.* **2015**, *66*, 21–29. [CrossRef]
30. Andrianasolo, F.N.; Casadebaig, P.; Maza, E.; Champolivier, L.; Maury, P.; Debaeke, P. Prediction of sunflower grain oil concentration as a function of variety, crop management and environment using statistical models. *Eur. J. Agron.* **2014**, *54*, 84–96. [CrossRef]
31. Hoogenboom, G.; Porter, C.H.; Boote, K.J.; Shelia, V.; Wilkens, P.W.; Singh, U.; White, J.W.; Asseng, S.; Lizaso, J.I.; Moreno, L.P.; et al. The DSSAT crop modeling ecosystem. In *Advances in Crop Modeling for a Sustainable Agriculture*; Boote, K.J., Ed.; Burleigh Dodds Science Publishing: Cambridge, UK, 2019; pp. 173–216.
32. Hoogenboom, G.; Porter, C.H.; Shelia, V.; Boote, K.J.; Singh, U.; White, J.W.; Hunt, L.A.; Ogoshi, R.; Lizaso, J.I.; Koo, J.; et al. *Decision Support System for Agrotechnology Transfer (DSSAT)*; Version 4.7.5; DSSAT Foundation: Gainesville, FL, USA, 2019.
33. Jones, J.W.; Hoogenboom, G.; Porter, C.H.; Boote, K.J.; Batchelor, W.D.; Hunt, L.A.; Wilkens, P.W.; Singh, U.; Gijsman, A.J.; Ritchie, J.T. The DSSAT cropping system model. *Eur. J. Agron.* **2003**, *18*, 235–265. [CrossRef]
34. Hawkesford, M.J. Reducing the reliance on nitrogen fertilizer for wheat production. *J. Cereal Sci.* **2014**, *59*, 276–283. [CrossRef]
35. Zhou, M.; Butterbach-Bahl, K. Assessment of nitrate leaching loss on a yield-scaled basis from maize and wheat cropping systems. *Plant Soil* **2014**, *374*, 977. [CrossRef]
36. Mohammadi, R.; Roustaii, M.; Haghparast, R.; Roohi, E.; Solimani, K.; Ahmadi, M.; Abedi, R.; Amri, A. Genotype × environment interactions for grain yield in rainfed winter multi-environment trials in Iran. *Agron. J.* **2010**, *102*, 1500–1510. [CrossRef]
37. Tapley, M.; Ortiz, B.V.; van Santen, E.; Balkcom, K.S.; Mask, P.; Weaver, D.B. Location, seeding date, and variety interactions on winter wheat yield in South-eastern United States. *Agron. J.* **2013**, *105*, 509–518. [CrossRef]
38. Slafer, G.A.; Savin, R.; Sadras, V.O. Coarse and fine regulation of wheat yield components in response to genotype and environment. *Field Crop. Res.* **2014**, *157*, 71–83. [CrossRef]
39. Derejko, A.; Studnicki, M.; Mądry, W.; Gacek, E. A Comparison of Winter Wheat Cultivar Rankings in Groups of Polish Locations. *Cereal Res. Commun.* **2016**, *44*, 628–638. [CrossRef]
40. Rozbicki, J.; Ceglinska, A.; Gozdowski, D.; Jakubczak, M.; Cacak-Pietrzak, G.; Mądry, W.; Golba, J.; Sobczynski, G.; Studnicki, M.; Drzaga, T. Influence of the cultivar, environment and management on the grain yield and bread-making quality in winter wheat. *J. Cereal Sci.* **2015**, *61*, 126–132. [CrossRef]
41. Panpatte, D.G.; Jhala, Y.K. (Eds.) *Soil Fertility Management for Sustainable Development*; Springer: Singapore, 2019.
42. Studnicki, M.; Mądry, W.; Noras, K.; Wójcik-Gront, E.; Gacek, E. Yield response of winter wheat cultivars to environments modeled by different variance-covariance structures in linear mixed models. *Span. J. Agric. Res.* **2016**, *14*, 10. [CrossRef]
43. Macholdt, J.; Honermeier, B. Yield Stability in Winter Wheat Production: A Survey on German Farmers' and Advisors' Views. *Agronomy* **2017**, *7*, 45. [CrossRef]
44. Bertelsen, J.R.; de Neergaard, E.; Smedegaard-Petersen, V. Fungicidal effects of azoxystrobin and epoxiconazole on phylloshere fungi, senescence and yield of winter wheat. *Plant Pathol.* **2001**, *50*, 190–205. [CrossRef]
45. Mercer, P.C.; Ruddock, A. Disease management of winter wheat with reduced doses of fungicides in Northern Ireland. *Crop Prot.* **2005**, *24*, 221–228. [CrossRef]
46. Loyce, C.; Meynard, J.M.; Bouchard, C.; Rolland, B.; Lonnet, P.; Bataillon, P.; Bernicot, M.H.; Bonnefoy, M.; Charrier, X.; Debote, B.; et al. Interaction between cultivar and crop management effects on winter wheat diseases, lodging, and yield. *Crop Prot.* **2008**, *27*, 1131–1142. [CrossRef]
47. Berzsenyi, Z.; Győrffy, B.; Lap, D. Effect of crop rotation and fertilisation on maize and wheat yields and yield stability in a long-term experiment. *Eur. J. Agron.* **2000**, *13*, 225–244. [CrossRef]

48. Christen, O. Yield, yield structure and yield stability of wheat, barley and oilseed rape in different crop rotations. *Pflanzenbauwissenschaften* **2001**, *5*, 33–39.
49. Sieling, K.; Christen, O. Crop rotation effects on yield of oilseed rape, wheat and barley and residual effects on the subsequent wheat. *Arch. Agron. Soil Sci.* **2015**, *61*, 1531–1549. [CrossRef]
50. Coromaldi, M.; Pallante, G.; Savastano, S. Adoption of modern varieties, farmers' welfare and crop biodiversity: Evidence from Uganda. *Ecol. Econ.* **2015**, *119*, 346–358. [CrossRef]
51. Gaudin, A.C.; Tolhurst, T.N.; Ker, A.P.; Janovicek, K.; Tortora, C.; Martin, R.C.; Deen, W. Increasing crop diversity mitigates weather variations and improves yield stability. *PLoS ONE* **2015**, *10*, e0113261. [CrossRef]
52. Senapati, N.; Semenov, M.A. Large genetic yield potential and genetic yield gap estimated for wheat in Europe. *Glob. Food Secur.* **2020**, *24*, 100340. [CrossRef]
53. Sozzi, M.; Kayad, A.; Gobbo, S.; Cogato, A.; Sartori, L.; Marinello, F. Economic Comparison of Satellite, Plane and UAV-Acquired NDVI Images for Site-Specific Nitrogen Application: Observations from Italy. *Agronomy* **2021**, *11*, 2098. [CrossRef]
54. Argento, F.; Anken, T.; Abt, F.; Vogelsanger, E.; Walter, A.; Liebisch, F. Site-Specific Nitrogen Management in Winter Wheat Supported by Low-Altitude Remote Sensing and Soil Data. *Precis. Agric.* **2021**, *22*, 364–386. [CrossRef]
55. Schulte-Uebbing, L.; de Vries, W. Reconciling Food Production and Environmental Boundaries for Nitrogen in the European Union. *Sci. Total Environ.* **2021**, *786*, 147427. [CrossRef]
56. Folina, A.; Tataridas, A.; Mavroeidis, A.; Kousta, A.; Katsenios, N.; Efthimiadou, A.; Travlos, I.S.; Roussis, I.; Darawsheh, M.K.; Papastylianou, P.; et al. Evaluation of Various Nitrogen Indices in N-Fertilizers with Inhibitors in Field Crops: A Review. *Agronomy* **2021**, *11*, 418. [CrossRef]
57. Hawkesford, M.J.; Riche, A.B. Impacts of G $\times$ E $\times$ M on Nitrogen Use Efficiency in Wheat and Future Prospects. *Front. Plant Sci.* **2020**, *11*, 1157. [CrossRef] [PubMed]
58. Thilakarathna, S.K.; Hernandez-Ramirez, G.; Puurveen, D.; Kryzanowski, L.; Lohstraeter, G.; Powers, L.; Quan, N.; Tenuta, M. Nitrous Oxide Emissions and Nitrogen Use Efficiency in Wheat: Nitrogen Fertilization Timing and Formulation, Soil Nitrogen, and Weather Effects. *Soil Sci. Soc. Am. J.* **2020**, *84*, 1910–1927. [CrossRef]
59. Bański, J.; Mazur, M. Farms' Agrarian Structure and the Market for Land. In *Transformation of Agricultural Sector in the Central and Eastern Europe after 1989*; Springer International Publishing: Cham, Switzerland, 2021; pp. 53–65. ISBN 9783030737658.
60. Jones, R.J.; Houšková, B.; Bullock, P.; Montanarella, L. (Eds.) *Soil Resources of Europe*; European Soil Bureau, Joint Research Centre: Ispra, Italy, 2005.
61. Zetzsche, H.; Friedt, W.; Ordon, F. Breeding progress for pathogen resistance is a second major driver for yield increase in German winter wheat at contrasting N levels. *Sci. Rep.* **2020**, *10*, 1–17. [CrossRef]