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POSITIVE EFFECTS OF CULTIVATION TECHNOLOGIES BASED ON GEOREFERENCED DATA ON THE ECONOMIC SUSTAINABILITY OF WINTER WHEAT PRODUCTION

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Abstract: *Elements of precision farming, such as auto-steer navigation, section control and variable rate application, can have a positive impact on farming performance, yet the uptake of these technologies has been slow and farmers are not convinced that they can achieve additional benefits by switching to them. Therefore, the authors considered it important to examine the impact of precision farming on winter wheat yields based on data from Hungarian farms. Yield data from farms with a yield map in the MyJohnDeere database from 2018-2022 and yield and cost data from 48 farms with Variable Rate Application (VRA) from 2018-2022 were evaluated and compared to the national average. MyJohnDeere and VRA farms had significantly higher yields in all years. Despite the cost saving from the introduction of precision farming, such as non-overlapping input application, the total costs of the examined VRA farms were higher, which can be explained by more intensive production beyond precision farming. It can also be argued that the additional inputs of the VRA farms were outweighed by the additional production value, with their specific incomes being higher than the national average in all years. In conclusion, the profitability of winter wheat production - and thus its resilience to a changing economic environment - can be increased at farm scale by adapting precision farming. Technological change by farmers, in particular the widespread adoption of variable rate application, could also increase the sustainability of winter wheat production at the farm scale.*

Keywords: *farm-scale profitability; precision farming; variable rate application*
(JEL Code: Q1)

INTRODUCTION

Precision farming influences farming efficiency through both precise operation and better adaptation to production site conditions [1-5]. While the former includes the possibilities offered by the use of navigation, such as auto-steer navigation or section control, the latter involves variable rate application based on soil mapping or fertility mapping.

The use of automatic steering itself also saves money by turning the machine back next to its previous track, rather than onto the already cultivated area. In extreme cases, reduction in fuel consumption could lead to saving 25-27% of fuel costs [6], while Controlled Traffic Farming (CTF) can also increase yields by 5-10% [6-8].

The use of section control results in further significant input material savings. The simplest example is sowing as a working operation. Thanks to section control, there is noneed to worry about overlapping or skipping at the turns at the field borders and in irregularly shaped sections within the field, which reduces input material consumption by 5-7% [9]. In recent decades, precision farming has developed in a com- plex and diverse way, with variable rate application (VRA) becoming increasingly important. Today, we have the possi- bility to apply virtually all agricultural inputs in a precision and variable manner within the field, from fertilizer to seed and irrigation water [10].

Soil mapping has provided the basis for variable rate input use. While initially soil measurements based on grid sampling was the main source of information, nowadays soil sampling is typically performed by zones [11]. Zones can be delineated using satellite imagery representing the heterogeneity of the field, field sensor measurements, yield measurements, topography data, or a combination of these [12-19]. The resulting zones are correlated with yield data [19, 20] and can be used as a basis for the variable rate application of fertilization [19, 22] and even irrigation [23, 24]. In particular, topography as a soil-forming factor plays an important role in the development of heterogeneity within the field, therefore the digital elevation model (DEM), the derived topographic parameters (slope, curvature) and parameters characterizing the probability of water accumulation, such as "potential drainage density" [25-27], help to delineate soil patches more accurately in the design of zones, thus improving the nutrient use efficiency of the fertilizer.

Although variable rate input application can also result in input savings [28], the main benefits of this technology are the increase in production intensity and efficiency resulting from the distribution of inputs according to site conditions and the improvement in yield quality [1].

In the current economic environment, with strong and turbulent effects in the bulk commodity sector, including the trade in cereals, cereal farmers are increasingly exposed to the external economic environment, both at global and European level. However, the resilience of farms to changes in the mar- ket environment can be improved through the application of precision farming [1]. In addition, in the European Union, the legislative environment, such as the environmental require- ments set out in the Green Deal [29], can only be met through better input use without reducing yields. For this reason, the spread of variable rate input application would be desirable. Nevertheless, the uptake of precision farming technologies, in particular the adaptation of variable rate input application, faces barriers [1, 30, 31]. One of the typical problems is that there is little whole-farm level profitability analysis available in the literature [2], therefore the benefits of adopting the tech- nology are not proven to farmers. The aim of this paper is to investigate the impact of precision farming on the productiv- ity, cost and profitability of winter wheat production on sev- eral Hungarian farms.

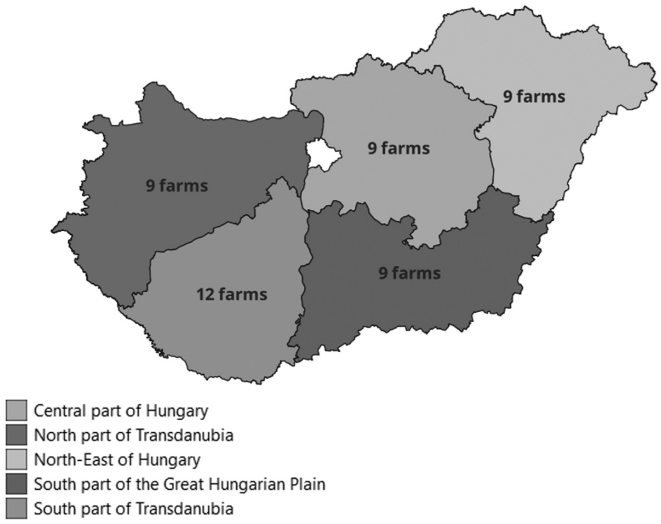
MATERIALS AND METHODS

Database

The first database is the field-level yield data available in the MyJohnDeere database. The operational data of farmers with intelligent tractor and implement connections, in particular combine harvesters for yield mapping and geo-documentation, are stored on a web-based platform (MyJohnDeere) via a wireless data link, where they are stored in a well-structured and easily understandable way for farmers. Thanks to the digitalization of agriculture, the amount of documented data is growing dynamically, providing a reliable statistical basis for data analysis at national level. Our analysis included MyJohnDeere farms that used smart harvesting tools and documented the harvesting process between 2018 and 2022. The majority of these farms do not yet use variable rate application and only benefit from navigation.

The second database contains data from 48 farms that not only practice precision winter wheat production, but also use variable rate application of inputs, thus implementing site-specific cultivation technology. The farms are located in different areas of Hungary (Figure 1) and their data were used anonymously.

Location of the 48 Hungarian farms using variable rate applications which were involved to the questionnaire research.



In addition to yield data, the targeted farms provided cost of production data for the analyses for the period 2018-2022 in a questionnaire survey. Data on the following costs were requested from farmers:

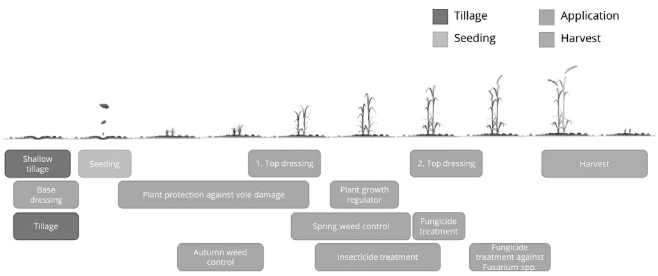
- Seed cost
- Cost of fertilizers
- Pesticide cost
- Irrigation cost
- Cleaning costs
- Drying cost
- Direct insurance cost
- Other direct variable costs
- Cost of organic manure
- Machinery costs (variable costs, fuel and lubricants, repairs, etc.)
- Cost of external mechanical services
- Wages
- Public charges on wages and salaries
- Land rent
- Depreciation and amortisation
- Other costs
- Overhead cost of the activity
- Economic overheads

Economic analysis

Investigating the economical efficiency of precision winter wheat cultivation technology is of paramount importance for the wider adoption of precision farming.

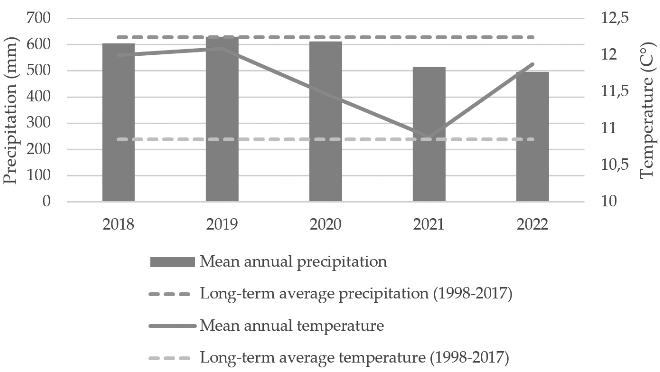
When calculating income, it is worth taking into account all the elements of the production technology in order to demonstrate the impact of precision farming on the natural and economic efficiency. The steps of winter wheat production technology are similar for both conventional and precision farmers (Figure 2), the difference lies in the design, implementation and timing of the different technological elements, which have a fundamental impact on the natural and economic efficiency of winter wheat production and the sector. Of particular importance among the costs are those of seeds, fertilizers and pesticides, which determine the intensity of the technology.

Figure 2. Elements of the winter wheat agrotechnology.



The econometric analysis was carried out for 5 years to reduce the bias due to the crop year effect. Precipitation and temperature conditions for the period 2018-2022 are shown in Figure 3.

Figure 3. Mean annual temperature and precipitation of Hungary from 2018 to 2022 [32].



The specific income (profitability, Pw , EUR/ha) of winter wheat (Equation (1)) was calculated on the basis of the production value (revenue, Rw) less subsidies and the total cost (TCw) less land rent.

$$P_w = R_w - TC_w \tag{1}$$

The production value (Rw) was determined on the basis of the yield (Yw) and the annual winter wheat sales prices (Table 1) provided by the Institute of Agricultural Economics, Market Price Information System [33].

Table 1. Wheat prices (EUR/t) in Hungary according to the Institute of Agricultural Economics, Market Price Information System [33].

Year	Price (EUR/t)
2018	148.78
2019	146.94
2020	151.24
2021	201.54
2022	326.28

Costs and sales prices are also collected in HUF, converted into EUR at the Hungarian Central Bank's yearly average exchange rate (Table 2).

Table 2. Yearly average exchange rate according to the Hungarian Central Bank (MNB).

Year	Yearly average exchange rate (HUF/EUR)
2018	318.87
2019	325.35
2020	351.17
2021	358.52
2022	391.33

Yield data were compared with the national winter wheat yield averages published by the Hungarian Central Statistical Office [34] (Table 3), and the costs determined from the Farm Accountancy Data Network maintained by the Institute of Agricultural Economics [35] were used as a benchmark for the cost and income analysis.

Table 3. Wheat production of Hungary from 2018 to 2022 according to the Hungarian Central Statistical Office [34] and total costs according to the Institute of Agricultural Economics, Farm Accountancy Data Network [35]

Year	Harvested area (ha)	Yield (t/ha)	Total Costs (EUR/ha)
2018	1 026 151	5.12	614.58
2019	1 015 640	5.29	637.82
2020	936 624	5.47	631.59
2021	892 794	5.93	685.78
2022	950 632	4.40	821.21

Statistical analysis

The yield, cost and income data were weighed by the field area for the MyJohnDeere farms and by the farm area for the VRA farms. Weighting, descriptive statistics and 95% confidence intervals were calculated in IBM SPSS Statistics.

Results

Evaluation of additional yield

The field level winter wheat yields of MyJohnDeere farms (Table 4) and the farm-level winter wheat yields of the 48 farms included in the questionnaire survey (Table 5) were evaluated by area weighting for the period 2018 to 2022.

It can be concluded that the two data series show similar trends over time, with the highest yield year being 2021 and the lowest yield in the extremely drought year of 2022. However, in absolute terms, the average yield of farms with variable rate input application (VRA) was significantly higher in all years at the 95% confidence interval.

Table 4. Area-weighted winter wheat yield (t/ha) of MyJohnDeere farms in Hungary from 2018 to 2022.

Year	Area (ha)	Mean yield (t/ha)	SD*	Std. Error**	95% Confidence Interval for Mean Yield (t/ha)		Minimum	Maximum
					Lower Bound	Upper Bound		
2018	20460	5.84	1.95	0.01	5.81	5.86	1.00	15.83
2019	25651	5.71	1.77	0.01	5.68	5.73	1.04	13.72
2020	35351	5.94	1.93	0.01	5.92	5.96	0.51	17.05
2021	44314	6.52	2.10	0.01	6.50	6.54	0.63	19.83
2022	59336	4.94	2.06	0.01	4.93	4.96	0.50	18.94

**SD: standard deviation, **Std. Error: standard error*

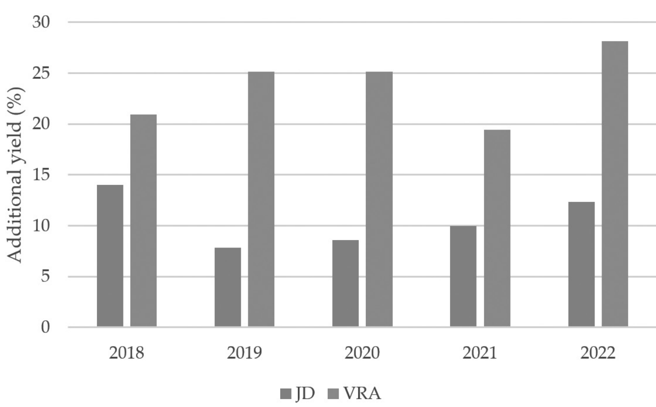
Table 5. Area-weighted winter wheat yield (t/ha) of 48 Hungarian farms using variable rate applications from 2018 to 2022.

Year	Area (ha)	Mean yield (t/ha)	SD*	Std. Error**	95% Confidence Interval for Mean Yield (t/ha)		Minimum	Maximum
					Lower Bound	Upper Bound		
2018	11732	6.19	0.81	0.01	6.18	6.21	4.50	9.00
2019	12507	6.62	0.85	0.01	6.60	6.63	4.00	8.50
2020	12499	6.85	1.18	0.01	6.83	6.87	4.50	9.55
2021	11800	7.08	1.08	0.01	7.06	7.10	4.84	9.00
2022	12528	5.64	1.81	0.02	5.61	5.67	2.63	9.11

**SD: standard deviation, **Std. Error: standard error*

The average annual winter wheat yields were also compared to the national average yield [34]. Figure 4 shows that both the winter wheat yields of farms in the MyJohnDeere system and those with variable rate input application exceeded the national average. The former by 7.9-14%, while the farms that opted for VRA by 19.5-28.1%.

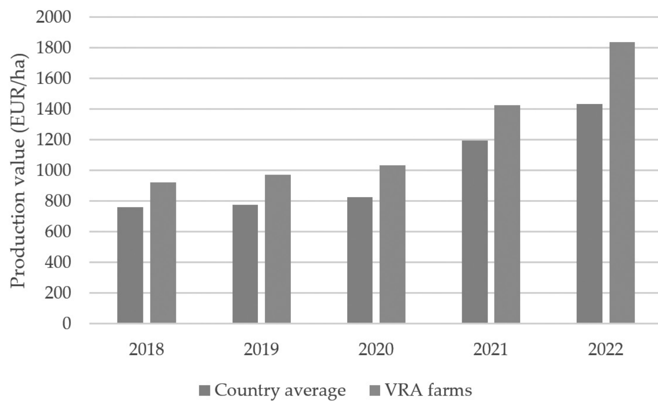
Figure 4. Additional winter wheat yield compared to the average yield of Hungary [34] (JD: MyJohnDeere farms, VRA: 48 Hungarian farms using variable rate applications.



Evaluation of additional production value

For farms that use variable rate applications, the production value was calculated and plotted on Figure 5 together with the production value based on the national average yields. The production value shows a trend increase for both data sets, reaching its highest value in 2022, the year with the lowest yield, due to high sales prices (Table 1).

Figure 5. Production value of winter wheat production (Country average: calculated from country average yield according to the Hungarian Central Statistical Office [34], and prices according to the Institute of Agricultural Economics [33], VRA: calculated from the average yield of 48 Hungarian farms using variable rate applications and prices according to the Institute of Agricultural Economics [33].



Evaluation of costs

Input costs

The technological tools of precision farming can lead to efficiency gains in the whole production cycle, as input and fuel savings, labour efficiency are all points that also lead to production cost reductions. At the same time, the introduction of precision farming on individual farms is often accompanied by intensification, which increases costs.

The annual area-weighted average of input costs (seed, fertilizer, pesticide) provided by VRA farms is presented in Table 6.

Table 6. Area-weighted winter wheat input costs of 48 Hungarian farms using variable rate applications from 2018 to 2022.

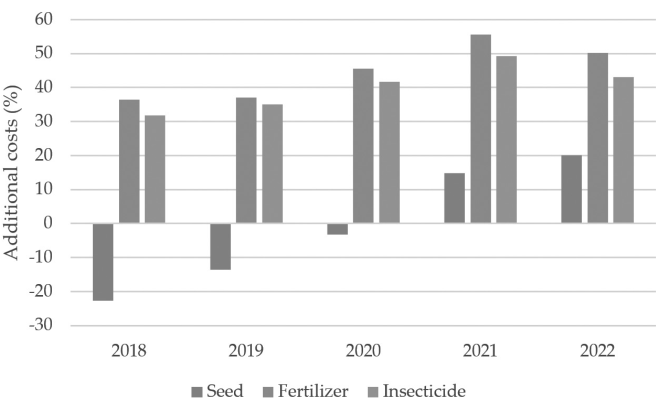
Year	Area (ha)	Mean yield (t/ha)	SD*	Std. Error**	95% Confidence Interval for Mean Yield (t/ha)		Minimum	Maximum
					Lower Bound	Upper Bound		
Seed cost (EUR/ha)								
2018	49.08	19.24	0.18	48.73	49.43	7.84	94.08	9.00
2019	56.00	18.77	0.17	55.67	56.33	30.18	93.78	8.50
2020	61.99	21.65	0.19	61.61	62.37	31.47	128.14	9.55
2021	75.37	26.80	0.25	74.89	75.86	39.29	167.35	9.00
2022	87.30	48.61	0.43	86.45	88.15	22.51	195.49	9.11

Fertilizer cost (EUR/ha)								
2018	183.15	64.31	0.59	181.99	184.32	81.54	313.61	9.00
2019	180.69	65.92	0.59	179.53	181.85	89.13	431.84	8.50
2020	196.53	88.64	0.79	194.98	198.09	56.95	427.14	9.55
2021	229.07	97.99	0.90	227.30	230.83	73.36	502.06	9.00
2022	357.03	131.19	1.17	354.73	359.33	102.22	638.85	9.11
Pesticide cost (EUR/ha)								
2018	96.47	36.27	0.33	95.81	97.12	0.00	219.53	9.00
2019	102.87	43.43	0.39	102.10	103.63	0.00	233.59	8.50
2020	108.30	39.93	0.36	107.60	109.00	0.00	227.81	9.55
2021	122.97	45.02	0.41	122.15	123.78	0.00	251.03	9.00
2022	122.17	50.39	0.45	121.29	123.06	0.00	255.54	9.11

**SD: standard deviation, **Std. Error: standard error*

Calculated input costs were compared to national averages based on the Farm Accountancy Data Network maintained by the Institute of Agricultural Economics [35]. The percentage difference in seed, fertilizer and pesticide costs for VRA farms is shown in Figure 6. It can be seen that for winter wheat, seed costs were lower in three years and higher in two years on VRA farms, and in none of the years was the difference as significant as for fertilizer and pesticide. Fertilizer costs were 36-55% higher, while pesticide costs were 31-49% higher on VRA farms.

Figure 6. Additional input costs of winter wheat production of 48 Hungarian farms using variable rate applications compared to the country average [35



Input costs

Total costs less land rent for VRA farms (Table 7) were calculated and annual data was compared with national averages based on the Farm Accountancy Data Network maintained by the Institute of Agricultural Economics [35]. The additional costs for VRA farms are shown in Figure 7.

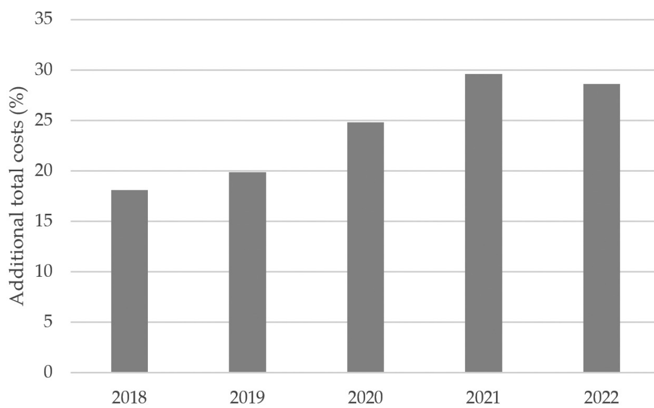
It can be seen that the total production costs of winter wheat are 18.1-29.6% higher than the national average. The ratio of the production costs of VRA farms to the national average increased dynamically until 2021 and then declined slightly.

Table 7. Area-weighted winter wheat total costs (EUR/ha) of 48 Hungarian farms using variable rate applications from 2018 to 2022.

Year	Area (ha)	Mean yield (t/ha)	SD*	Std. Error**	95% Confidence Interval for Mean Yield (t/ha)		Minimum	Maximum
					Lower Bound	Upper Bound		
2018	725.80	220.99	2.04	721.80	729.80	401.42	1274.72	9.00
2019	764.56	232.31	2.08	760.49	768.63	424.16	1892.03	8.50
2020	788.26	231.60	2.07	784.20	792.32	423.05	1331.26	9.55
2021	888.66	263.25	2.42	883.91	893.41	439.48	1515.82	9.00
2022	1056.00	279.58	2.50	1051.10	1060.89	611.48	1916.04	9.11

**SD: standard deviation, **Std. Error: standard error*

Figure 7. Additional total costs of winter wheat production of 48 Hungarian farms using variable rate applications compared to the country average.



Evaluation of profitability

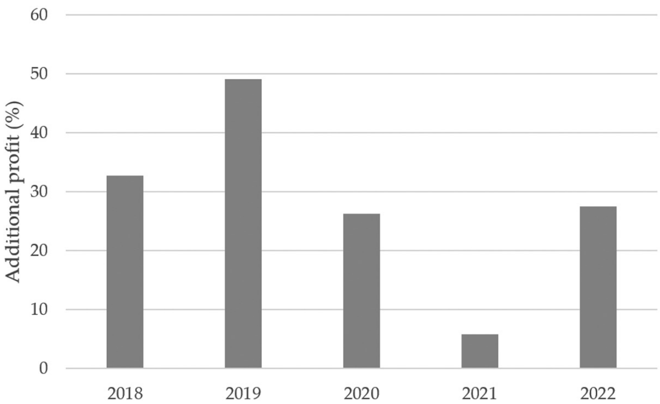
Based on the production value and total costs, the area-weighted annual specific income of VRA farms was calculated (Table 8) and compared with the national average (Figure 8). The obtained results show that the average income of farms using variable rate application in winter wheat exceeded the national average by 28.3% during the examined period. The smallest difference was in 2021 (5.8%), while the additional income rate was particularly high in 2019 (49.1%).

Table 8. Area-weighted winter wheat annual specific income (EUR/ha) of 48 Hungarian farms using variable rate applications from 2018 to 2022.

Year	Area (ha)	Mean yield (t/ha)	SD*	Std. Error**	95% Confidence Interval for Mean Yield (t/ha)		Minimum	Maximum
					Lower Bound	Upper Bound		
2018	195.36	222.58	2.05	191.33	199.39	-327.30	732.18	9.00
2019	208.03	216.67	1.94	204.24	211.83	-874.73	636.53	8.50
2020	247.15	258.24	2.31	242.62	251.68	-225.19	723.25	9.55
2021	539.04	251.56	2.32	534.50	543.58	-267.72	1025.93	9.00
2022	783.60	473.15	4.23	775.31	791.88	-215.03	2080.30	9.11

**SD: standard deviation, **Std. Error: standard error*

Figure 8. Additional profit of winter wheat production of 47 Hungarian farms using variable rate applications compared to the country average



DISCUSSION

The average winter wheat yields of MyJohnDeere farms, which primarily benefit from navigation, exceeded the national average by 7.9-14% over the five examined years, while the yields of VRA farms were 19.5-28.1% higher. In both cases, the yield surplus exceeds the values reported in the literature [6-8], which is presumably explained by the fact that farmers open to the introduction of precision technologies are not only more technologically advanced in the field of GIS technology, but also in other areas of crop technology. This is supported by the ratio of input costs of VRA farms compared to the national average, which was 36-55% for fertilizer and 31-49% for pesticide, despite the fact that losses are reduced due to non-overlapping and variable rate application [9]. No similar difference was found for seed costs, because the variable rate application of seed is not widespread in winter wheat and more intensive technology is not clearly associated with higher number of plants.

The total cost of VRA farms also exceeded the national average by 18.1-29.6%. The additional cost rose steadily between 2018 and 2021, before declining slightly in 2022, presumably as farmers cut back slightly on costs due to the dry year and low maize yields in 2021.

Therefore, the farms included in these studies with variable rate application produce more intensively at higher cost levels, i.e. the aim of the authors was to determine whether the additional production value exceeds the additional input. The obtained results show that the specific income from winter wheat production was higher than the national average in all examined years and 28.3% higher than the national average over five years on VRA farms. The results of these studies suggest that the examined VRA farms realized additional income from winter wheat production compared to the national average and are therefore presumably more resilient to changes in the economic environment than conventional farms.

The authors feel it is necessary to extend the studies carried out for winter wheat to other major arable crops in the future to obtain a more complete picture of the economic sustainability of production on VRA farms.

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