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ECONOMIC AND ECOLOGICAL PERFORMANCE AND FARM-LEVEL ADOPTION OF MARKET-AVAILABLE TOOLS FOR VARIABLE-RATE NITROGEN MANAGEMENT IN A REGION OF SMALL-TO-MEDIUM-SCALE AGRICULTURE

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Abstract.

This paper assesses the economic and ecological performance as well as farm-level adoption of market-available tools for variable-rate nitrogen management (VRN) in the small- to medium-scale farming context of Bavaria, Germany. We combine three empirical data sources covering a similar region and time period: field trials with winter wheat, repeated farm surveys on digital technology use, and administrative data from a regional investment subsidy program for digital technologies. In 2023 and 2025, commercially available and research VRN systems were tested in high- and low-yield zones and compared with a uniform fertilization strategy recommended by official advisory services. Economic performance was evaluated using net return to nitrogen while environmental performance was assessed via N-balances across yield zones. The field trials show that most VRN approaches do not outperform the uniform strategy in terms of net return to nitrogen under the given agronomic and regulatory conditions. However, some VRN systems reduced N-balance surpluses. Survey results reveal low adoption of VRN, with adoption strongly increasing with farm size, and a clear preference for relatively low-cost satellite-based systems. Data from the Bavarian subsidy program BaySL Digital confirms limited demand for N sensors.

Keywords.
Variable-rate nitrogen, Site-specific nitrogen management, Precision agriculture, Adoption of digital technologies, Investment incentives

Introduction

In the field of precision agriculture, variable-rate nitrogen (VRN) management is one of the longest-standing and most extensively studied approaches regarding economic and environmental benefits (Papadopoulos et al. 2024). Nevertheless, the adoption of this approach in agricultural practice has fallen short of expectations for years. This applies particularly to small- to medium-scale agricultural areas.

The purpose of this paper is therefore to provide an overview of the current state of development regarding VRN management in Bavaria (Germany). This contribution combines the results of extensive field trials on VRN fertilization in winter wheat with results of a farmer survey series and findings drawn from a government investment subsidy program. All three data sources (field trials, surveys, investment subsidy program) cover roughly the same period and region. The field trials were conducted from 2023 to 2025, and the surveys were carried out in 2020, 2022, and 2025. The investment subsidy program became available in October 2018 (for component A). All empirical data refer to Bavaria, a federal state in southern Germany where agriculture is generally small- to medium-scale.

Materials and Methods

Field trial data

In 2023 and 2025, six commercially available digital tools for VRN management of winter wheat were tested at generally high-yielding sites in southeastern Bavaria. The tools were compared to a uniform fertilization strategy recommended by official advisory services in high-yield and low-yield zones within the same field. In addition to these variants, fixed N levels were included in the experiment for further analysis, but are not subject of the present analysis. Regarding the digital fertilization systems tested, four are based on satellite data and use the Normalized Difference Vegetation Index (NDVI). In addition, a handheld sensor and a tractor-mounted sensor were tested. Finally, a fertilization system developed at the Technical University of Munich (Maidl 2012) was evaluated. The product names are not disclosed here.

The experiments were designed as a latin rectangle with four replicates. In 2025, there were only three evaluable replications in the high-yield zone. Each plot measured 3 by 10 meters. The plots were fertilized using a modified Accord seed drill. Yield data was collected using a plot combine in the plots' central zone of 1.5 by 10 meters. Measured wheat yield was complemented by protein content analyses. To examine and compare the economic viability of the tested fertilization strategies, the net return to nitrogen was calculated by subtracting nitrogen costs from revenue. The impact of varying protein contents on the producer price was taken into account.

Farmer survey data

Since 2020, the Bavarian State Research Centre for Agriculture has been conducting a standardized online survey among farmers to analyze the adoption of digital technologies at farm level. For a detailed description of questionnaire design and survey process, please refer to Gabriel and Gandorfer (2023). The slightly modified survey was repeated in 2022 and 2025. The surveys yielded 1,820, 727, and 1,456 relevant observations in 2020, 2022, and 2025, respectively. For the purposes of this paper, only data on VRN management are used. It is important to note that the individual surveys do not represent a connected sample.

Bavarian investment subsidy program for digital technologies

Through the Bavarian Special Program for Digital Agriculture (BaySL Digital), the Bavarian state government supports farmers' investments in specific digital farming tools. The goal is to optimize farm management, improve environmental sustainability, enhance animal welfare, and boost competitiveness (StMELF 2026). The program originally launched in 2018 and consists of four components (A through D), of which only Component B is relevant for the present analysis. It supports sensor technology and digital control systems in crop production, focusing on fertilizer sensors, drone technology, and improvements in the efficiency of field irrigation. The grant covers 40 % of eligible expenses within the investment sum range of € 500 to € 40,000, depending on the technology to be purchased. In the case of nitrogen sensors, 40 % of a maximum acquisition cost of € 30,000 is subsidized. For the purposes of this analysis, funding data from the start of the program until May 29, 2026 for Component B of the funding program are examined. BaySL Digital was paused from January 1, 2023 until June 30, 2023.

Results and discussion

Environmental and Economic performance of digital tools for VRN

An analysis of the field trials shows that none of the VRN approaches tested achieved a higher net return to nitrogen than the uniform fertilization strategy recommended by the official advisory service (see Table 1). System 1 corresponds to the German *Fertilizer Ordinance*. Furthermore, it is important to note that the economic target (net return to nitrogen) does not represent a full-cost approach. This means that the additional costs associated with the VRN approaches – such as those for sensors or prescription maps – are not taken into account in the values presented in Table 1. Even in the case of the uniform fertilization system (System 1), the information costs incurred for soil sampling are not included.

To assess the environmental impacts of VRN management compared to uniform fertilization, the N-balances in the high- and low-yield zones are examined in greater detail. They provide a somewhat different impression than the economic assessment. Some of the VRN approaches tested have succeeded in reducing N-balance surpluses, particularly in the low-yielding zones, which have a higher risk for nitrogen leaching. For example, System 6 successfully reduced N-balance surpluses in both trial years and in both yield zones compared to uniform fertilization.

To test for differences in mean values between the fertilization systems, a one-way analysis of variance (ANOVA) was conducted. In addition, pairwise comparisons of the variants were performed using the Tukey HSD method. In both trial years (2023 and 2025), there were no significant differences between the fertilization systems for N-balance and net return to nitrogen in the high-yield zone, in the low-yield zone, or in the overall field ($\alpha = 0.05$). In practical terms, based on these two years of trials, none of the fertilization systems tested is clearly superior or inferior to the others.

Although the ecological effects observed in the experiment described here are not significant, other studies from southern Germany on various crops show that VRN management can reduce nitrogen input and minimize nitrogen surpluses (Mittermayer et al. 2024).

Table 1: **Descriptive results of field trials testing various fertilization systems in winter wheat**

			2023				2025			
			N-Balance [kg N ha^{-1}]		net return to N [€ ha^{-1}]		N-Balance [kg N ha^{-1}]		net return to N [€ ha^{-1}]	
System	Characteristics	Yield Zone	Mean	SD	Mean	SD	Mean	SD	Mean	SD
System 1	URN[1], official advisory service	low	56	15	1705	133	67	1	1148	41
		high	45	29	1847	236	45	17	1324	96
		average	50	22	1776	190	56	14	1236	120
System 2	VRN[2], satellite[3], NDVI, market available	low	43	10	1676	128	47	6	1027	60
		high	24	18	1577	319	38	16	1362	75
		average	34	14	1626	222	42	11	1194	67
System 3	VRN, satellite[3], NDVI[4], market available	low	61	11	1646	63	75	15	1109	137
		high	38	20	1873	330	55	17	1220	174
		average	49	16	1759	199	65	16	1164	155
System 4	VRN, satellite[3], NDVI[4], market available	low	56	22	1621	165	69	9	945	125
		high	45	24	1802	335	56	9	1340	41
		average	51	23	1711	264	63	9	1142	83
System 5	VRN, satellite[3], NDVI[4], market available	low	52	13	1735	82	67	14	1031	160
		high	42	28	1815	346	39	9	1215	98
		average	47	21	1775	214	53	11	1123	129
System 6	VRN, handheld spectrometer for research, REIP[5]; academic	low	13	12	1531	232	62	11	904	74
		high	18	5	1949	71	15	11	1376	66
		average	16	9	1740	151	38	11	1140	70
System 7	VRN, handheld sensor, NDVI[4], market available	low	34	6	1208	87	39	8	1066	114
		high	20	24	1814	312	19	25	1350	106
		average	27	15	1511	199	29	16	1208	110
System 8	VRN, tractor mounted sensor, proprietary system[6], (market available)	low					63	6	883	81
		high					30	14	1244	137
		average					47	10	1063	109

[1]uniform rate nitrogen; [2]variable rate nitrogen; [3]prescription maps are generated form satellite data, [4]variable rate nitrogen application is based on the NDVI index; [5]variable rate nitrogen application is based on the Red Edge Inflection Point (REIP); [6]variable rate nitrogen application is based on a proprietary system

Adoption of VRN in Bavarian agriculture

The percentage of surveyed Bavarian farms that report having invested in and using VRN has remained relatively constant in the mid-single digits over the surveys (Figure 1). Starting in 2022, the response option “use by external service provider” was added to the questionnaire. The results show that this is a relevant option, as the percentage of farms using this option is roughly the same as the percentage that have directly invested in the technology. Nevertheless, 76% of the farms surveyed in 2025 state that they do not plan to use VRN in the future. Given that VRN is one of the longest-standing precision farming approaches, this share seems relatively high. A more in-depth analysis of the survey data shows that the adoption of VRN depends significantly on farm size. The average farm size among adopters in 2025 was 116 ha, while it was 45 ha among those who do not plan to use VRN in the future.

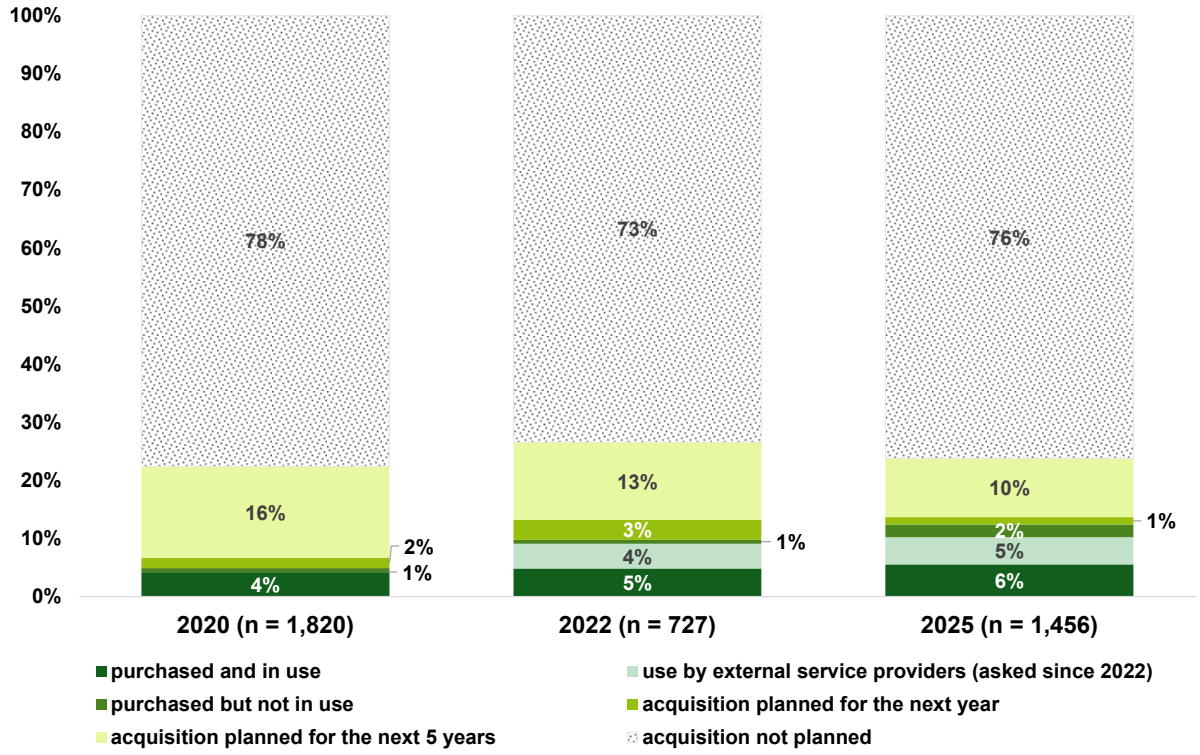

***Figure 1*: Adoption rates for VRN among Bavarian farms surveyed in 2020, 2022, and 2025.**

The farmers that reported using VRN in the 2025 survey were also asked about the used data. The results are clear: 48 % of VRN users report that they rely on satellite-based approaches, while only 18 % use tractor-mounted sensors. This result can be explained by the significant difference in cost of these approaches. While satellite-based approaches are relatively inexpensive to implement, the use of tractor mounted sensors requires a significant investment.

Demand for investment support for VRN

Table 2 provides a detailed overview of the approved grant applications under the BaySL Digital funding program until May 29, 2026. It shows that 58 applications for tractor mounted sensors were approved over the entire funding period. The mean costs for the sensor technology reported in the dealers' offers amount to €24,242, ranging between €13,440 and €34,840. This variation can be explained in part by the sensor brand. However, it is also evident that the range is relatively wide for individual brands, reflecting different equipment packages and accessories. Despite the 40% subsidy, fewer than 10 grant applications were approved each year on average. This means that even with a meaningful reduction in investment costs, the technology has not gained widespread acceptance in Bavarian agriculture. These findings are consistent with the survey results presented above, showing that farmers who use VRN overwhelmingly prefer satellite-based systems.

Table 2: **BaySL Digital funding applications approved until May 29, 2026**

Technology in Component B of BaySL Digital	Number of approved applications	Costs as per the dealer's submitted offering [€]
Near-infrared sensors (NIR sensors) for determining the nutrient content in manure	23	29,228[1] (18,023-39,525)[2]
Sensor systems for determining the nutrient supply of crops (N sensors)	58	24,242 (13,440 – 34,840)
Drone-mounted sensors and actuators (analysis of plant stocks, application of beneficial organisms/seeds)[3]	9	9,026 (4,150-15,000)

[1)] mean across all submitted applications; [2)] min and max

Conclusions

Although VRN management has been the subject of research for a long time and the technologies required for its practical implementation have been commercially available for some time, the number of farms using VRN in Bavaria remains low. However, based on the presented results, we conclude that VRN adoption rates in Bavaria are rising slightly among larger farms. Based on the survey data, it appears that service providers play a certain role in the context of VRN in Bavarian agriculture.

One reason for the hesitant development is likely the still unclear economic impact of products currently available. This is also evident from the field trials described. To further increase adoption, especially among small and medium-sized farms that constitute the majority in Bavaria, additional external incentives that reward environmental benefits beyond investment subsidy programs are needed. Otherwise, it will not be possible to roll out complex, environmentally-friendly technologies whose economic viability is limited for small- to medium scale farms.

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References

Bavarian State Ministry of Food, Agriculture, Forestry, and Tourism (StMELF), 2026. Bavarian Special Program for Digital Agriculture (BaySL Digital). www.stmelf.bayern.de/foerderung/bayerisches-sonderprogramm-landwirtschaft-digital-baysl/index.html (last accessed 07.06.2026)

Gabriel, A., Gandorfer, M., 2023. Adoption of digital technologies in agriculture—an inventory in a european small-scale farming region. Precision Agriculture 24:68–91. doi.org/10.1007/s11119-022-09931-1

Maidl, F.-X., 2012. Method for Ascertaining the Fertilizer Requirement, in particular the Nitrogen Fertilizer Requirement, and Apparatus for carrying out the Method. US-Patent Specification US 10 007 640.

Papadopoulos, G., Arduini, S., Uyar, H., Psiroukis, V., Kasimati, A., Fountas, S., 2024. Economic and environmental benefits of digital agricultural technologies in crop production: A review. Smart Agricultural Technology 8:100441. doi.org/10.1016/j.atech.2024.100441

Mittermayer, M., Donauer, J, Kimmelmann, S., Maidl, F.-X. Hülsbergen, K.-J., 2024. Effects of different nitrogen fertilization systems on crop yield and nitrogen use efficiency – Results of a field experiment in southern Germany, Heliyon, Volume 10, Issue 7, https://doi.org/10.1016/j.heliyon.2024.e28065.