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Characteristics of cost-efficient fertilization plans at the farm level

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ABSTRACT

Fertilization accounts for a significant share of the costs of crop production. Farmers therefore aim to find cost-efficient fertilization plans, which is a complex and recurring optimization problem. This study analyses whole-farm fertilization plans to generate a deeper economic understanding of cost-efficient fertilization plans on farm level. Various fertilizer plans, obtained by a choice experiment, were grouped into "cost-efficient", "average" and "cost-inefficient" solutions, using cluster analysis. Group differences were analysed by t-test to reveal the characteristics of cost-efficient solutions. In addition, the fertilizer optimization system IoFarm was used to simulate the effects of extreme changes in farm constellations on the fertilizer plan. Our results show that certain fertilizers are significantly more common in cost-efficient fertilizer plans: diammonium phosphate covers 81.8% of the phosphorus and 21.7% of the nitrogen supply; granular potash covers 100% of the potash supply. Compared to cost-efficient fertilizer plans, inefficient ones have higher annual surpluses of sulphur (+45.4 kg ha^{-1}) and potash (+9.8 kg ha^{-1}), incurring costs and impacting sustainability. Application costs represent a proportion of 5.2% of total costs, but play a minor role compared to other factors. Fertilizer prices were identified as the largest factor influencing the fertilizer plan. The results show that cost-efficient fertilizer plans are at the same time more sustainable, which also demonstrates the societal benefit of this study. The study provides a new and important contribution to the understanding of cost-efficient fertilizer plans at the farm level. Farmers benefit significantly from this contribution, as it shows opportunities to increase cost-efficiency.

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KEYWORD IoFarm; cost-efficiency; profit maximization; fertilization plan; fertilizer application; sustainable intensification

1. Introduction

Economic efficiency is an objective that is generally pursued by rational actors. This objective requires technical efficiency and allocative efficiency. In the context of agricultural production, both the available production technology and the production programme must be considered fixed when making short-

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term production decisions. Therefore, the most cost-efficient production possible is of great importance. Cost-efficiency means that the combination and intensity of production factors and means of production are chosen in such a way that the resulting marginal profit does not become negative.

Since the fertilization of crops accounts for a significant proportion of variable production costs, a cost-efficient fertilization plan contributes significantly to the economic efficiency of the farm. The isolated consideration of a cost-efficient fertilization plan is already a complex optimization problem in itself, which in summary consists of two questions: Which fertilizer intensity (related to all relevant nutrients) promises the economically optimal, technical input/output ratio? Which combination of available fertilizers is able to provide the optimal fertilizer intensity at minimum cost? To answer these questions, all price information is relevant. In addition, growth conditions, as well as legal, operational and crop production requirements must be considered in order to develop the most cost-efficient fertilizer plan. Fertilizer plan in this study is understood to be a farm-by-farm plan that includes, for each combination of farm field and crop, over the period of a crop rotation: (i) "right" fertilizer selection; (ii) "right" fertilizer application rate; (iii) "right" timing of fertilizer application. Contrary to the well-known "4 R approach of fertilizer planning", a specification of the "right" fertilizer placement is not considered in this study. The fertilizer plan would have to be adjusted several times over the course of a planning period (e.g. crop rotation cycle) to account for changes in prices, for example. In summary, this results in innumerable possible combinations of potential fertilizer plans that differ significantly in terms of their cost-efficiency. To limit the planning effort, farmers usually only deal with fertilizer planning at certain times during the year. For a broader understanding, the current practice of fertilizer planning in Germany will be outlined below: It is common for farmers to make pre-purchases of fertilizer for the following season at the end of the current season. At this time, the purchasing conditions are usually favourable, but the required fertilizer quantities are not yet fixed, which is why partial quantities are often ordered. This means that part of the fertilizer planning has already been done, namely the selection of fertilizers. The necessary information for determining fertilizer requirements is not available until the start of the fertilizer season. This includes, for example, the mineral nitrogen content in the soil. Once the fertilizer requirement has been determined, a decision is made on the application rate, the division into dressings and the timing of the fertilizer application. The decision on the placement of the fertilizer depends to some extent on the fertilizer, the site conditions, and the available technology. During the season, the farmer will meet any remaining nutrient requirements by purchasing suitable fertilizer and adjusting the initial fertilizer plan as necessary. However, regardless of the frequency with which a farmer, or advisor, deals with fertilizer planning, the complexity of the optimization problem remains. The characteristics of cost-efficient fertilizer plans and their differences from inefficient fertilizer plans are therefore of particular interest. Based on this, it may be possible to derive recommendations for one's own fertilizer planning. The differentiation between efficient and inefficient measures can be found in numerous scientific studies: Wimmer and Sauer (2020) analyse accounting data to identify efficient farm diversification strategies; Mollenhorst et al. (2020) train a machine-learning algorithm with organic fertilization management data to derive efficient organic fertilization decisions; Grassini et al. (2011) studied the effect of various management practices on corn production efficiency in the Western US corn belt. The topic of "fertilizer plans" per se, is also heavily represented in the literature: Studies by Gil-Ortiz et al. (2020), Dimkpa et al. (2020), Mi et al. (2019), and Noellsch et al. (2009) look at the differences in fertilization plans with conventional and slow release nitrogen fertilizers; Kozlovský et al. (2009) compare CULTAN (controlled uptake long term ammonium nutrition) with conventional fertilization plans; Song et al. (2021) and Koch et al. (2004) examine variable rate control as a possible fertilization plan. These are primarily studies of technical efficiency. Studies that focus on cost-efficient fertilizer plans often specifically consider the optimal intensity of nutrient supply (Chuan et al., 2013; LI et al., 2021; Sihvonen et al., 2018; Tabak et al., 2020; Xu et al., 2017) and, in rare cases, the least-cost combination of fertilizers (Babcock, 1984; Bueno-Delgado et al., 2016; Mínguez et al., 1988; Pagán et al., 2015; Villalobos et al., 2020). Instead of a very broad definition of "fertilizer plan", the studies mentioned focus on a specific aspect in each case and examine it mostly on the basis of trials in single crops. The situation is similar with production technology trials in the fertilizer industry, where in-house fertilizers are compared with competing products. Due to a lack of representativeness and validity, these competitive comparisons have no scientific value and are therefore not published accordingly

It should be noted that the literature provides a great amount of information on specific fertilization issues. This information can be used to draw conclusions about the benefits of different technologies or to derive suitable fertilizer intensities. Farmers or consultants need to convert this knowledge into a cost-efficient fertilizer plan tailored to the farm. This requires defining the choice of fertilizers, including organic fertilizers and manure, as well as the amount and timing of fertilization. To this end, there are currently no studies in the literature that specifically refer to the characteristics of cost-efficient and inefficient fertilizer plans at farm level. Since fertilizer plans in practice are influenced by the capabilities of decision makers and by respective farm constellations, two research questions arise: (i) How do cost-efficient fertilizer plans differ from inefficient ones in terms of fertilizer selection, dosage, timing and resource use? (ii) What is the influence of varying farm constellations on a cost-efficient fertilizer plan?

To answer the first question, we refer back to a fertilizer survey in which we had asked the participants to create a fertilizer plan. In this experiment, the farm constellations were fixed. Despite uniform specifications and information, fertilizer plans differed considerably in terms of design and cost-efficiency. These differences can be useful to improve cost-efficiency without using or having access to optimization tools, avoiding associated transfer costs. We address the second question using the decision support system (DSS) IoFarm (Tröster & Sauer, 2021b). IoFarm generates fertilizer plans with optimal cost-efficiency on farm level, also considering application costs. Using IoFarm, the main aim is to clarify whether different fertilization plans arise for different farm constellations and what these potential deviations ultimately look like in concrete terms. Previous studies (Tröster et al., 2019; Tröster & Sauer, 2021b) have already pointed out relevant influencing factors in this context. Thus, we assume that the following factors will have an influence on the fertilization plan: Farm size (hectares), internal infrastructure, organic fertilizer accumulation and heterogeneity of soil fertility.

This article is closely related to two earlier articles concerning cost-efficient fertilization and partly refers to their contents and concepts. Part 1 of the series (Tröster & Sauer, 2021b) takes the complexity of fertilizer planning as an opportunity to develop a DSS called IoFarm, which calculates cost-efficient fertilizer plans at farm level. IoFarm is presented in detail in the corresponding article and its economic performance is tested with the help of a choice experiment. In part 2 of the series (Tröster & Sauer, 2021a), the DSS IoFarm is compared with standard farm fertilization plans in a field trial over several years to check its agronomic performance. According to the main results of both studies, IoFarm had no significant effect on yield or quality in crop production, with lower costs for fertilizers and their application at the same time. Despite the same fertilizer intensity, the cost advantage in the choice experiment was €66 per hectare per year (providing full price transparency and full flexibility in the purchase and application of fertilizers). The present study is intended to close another important gap: It is about the characteristics in which cost-efficient and inefficient fertilization plans differ and what influence varying farm constellations exert in this respect. This article thus contributes to a better understanding of cost-efficient fertilization plans, especially among farmers and extension workers. Furthermore, it is clarified whether general recommendations for a cost-efficient fertilizer plan can be derived from this information or whether the support of a DSS is indispensable. The results of this study are particularly relevant for farmers and consultants who want to implement more economically efficient, fertilization plans. In addition, the fertilizer industry benefits from the results, e.g. in developing new products, or in connection with strategic decisions in the company.

2. Material and methods

2.1. The IoFarm decision support system

IoFarm is a novel decision support system for identifying cost-efficient fertilizer plans at the farm level (Tröster & Sauer, 2021b). In the context of this study, IoFarm is used, on the one hand, as a cost-efficient benchmark for comparing different fertilization plans. On the other hand, IoFarm is based on a clear mathematical structure and is therefore well suited for scenario analyses in which a consistent solution path is important. Over an entire crop rotation cycle, the DSS IoFarm makes concrete specifications for selecting fertilizers, application rate and application time for each farm field. By regularly updating fertilizer and product prices, yield expectations, soil test results and weather information, IoFarm can dynamically adjust the fertilizer plan. The objective function is designed to find the most cost-efficient combination of fertilizers to meet crop requirements. In addition to the market prices of the fertilizers, the application costs of the fertilizers are also considered. Within the model, marginal revenues and marginal costs are also taken into account, which may limit the intensity of fertilization if it is economically reasonable. For detailed information on the DSS IoFarm, the interested reader is referred to the original publication (Tröster & Sauer, 2021b).

2.2. An experiment as data source

To assess the economic performance of IoFarm, a fertilizer survey was conducted as part of a previous study (Tröster & Sauer, 2021b). Participants were mainly reached via "mailing lists of alumni associations of higher agricultural education institutions and universities". Participants were asked to define their experience level according to the following description: Expert = person possessing either scientific experience in plant nutrition or economic optimization models; Farmer = person with at least five years of professional experience in agriculture and plant nutrition; Student = student with advanced knowledge in economic optimization models and plant nutrition; "Others". For further analysis, the last group was excluded.

The task was to define a complete fertilizer plan for a 150-hectare farm, with three equal-sized fields over a period of three years. For methodological reasons, complete flexibility in fertilizer selection and complete price transparency were assumed for this experiment. This is the only way to exclude distortions due to a different opinion of the participants regarding the price development of fertilizers. To highlight differences in fertilizer selection and timing, we ensured that the participants and the IoFarm DSS followed identical guidelines for fertilizer intensity within reasonable timeframes. These guidelines implement EU directives (e.g. Nitrates directive, NEC-directive) and build the fertilization standards valid in Bavaria (Sothern Germany; Wendland et al., 2018), but are comparable to other state-specific standards in Germany (Zorn et al., 2007): N and S are allocated according to the yield expectation within a season. For N, soil test results are considered. The basic nutrients (P, K, and Mg) are applied according to the nutrient removal of the crop rotation, whereby soil nutrient content leads to additional increases or decreases as required. Seasonal requirements for basic fertilization only arise if the soil nutrient content falls below a critical level; otherwise, these nutrients are freely allocable within a crop rotation. To keep up with these guidelines, the participants were provided with a planning tool that contained requirement specifications for the individual nutrients (N, P, K, Mg, S) as well as a selection of 25 fertilizers commonly available on the market. In addition, information on the fertilizers was provided, such as: Prices, nutrient contents, nitrogen form, acidification potential and density. This allowed the participants to concentrate on selecting, dosing and timing the fertilization measures. The objective for the participants was to identify the most cost-efficient fertilizer plan, and to help with this, a complete listing of all fertilizer prices covering the entire period was handed out along with the survey. The relevance of usage-dependent application costs (labour, fuel, repairs, contractors) was also pointed out (The survey is available online[1]). In some cases, the participants fell significantly short of the nutrient quantities specified in the survey. Presumably, it was too time-consuming or too complicated for these participants to comply with all the guidelines of the survey. For comparability reasons, these participants had to be excluded from further analysis. Thus, the data set for analysis contains only fertilizer plans that meet uniform guidelines. Through these uniform guidelines, important yield-determining factors such as fertilizer intensity, sensible time windows for fertilization and a pre-selection of fertilizers are defined. It is therefore expected that there would be no significant differences in the output of crop production, which is supported by the results of a multi-year field trail (Tröster & Sauer, 2021a). The cost-efficiency of the fertilizer plans can therefore be assessed based on total costs alone.

On average, it took the participants 81 minutes to complete the task. The best participant's total cost for fertilizer and application is about €10 per hectare per year more expensive than IoFarm's fertilizer plan. On average, this difference is as high as €66 per hectare per year (Tröster & Sauer, 2021b). The data submitted by the survey participants contain much more information than just the total costs: each data set represents a separate fertilization plan that was more or less successful from a cost perspective. This allows a detailed characterization of the fertilization plans.

2.3. Classification of similar fertilizers

The participants could choose from 25 fertilizers on the fertilizer survey, which is why the participants' fertilizer plans differed considerably. To transparently compare the fertilizer plans, it is therefore necessary to group similar fertilizers together in order to make potential solution patterns visible, which is why we distinguish between fertilizers with low (xL) and high (xH) nutrient content, e.g. 31% nutrient content is a high nutrient content. This limit was purposely chosen so as not to distort the group balance between these two categories too much. As a second characteristic, we distinguish between single-nutrient fertilizers (Sx) and compound fertilizers (Cx). A fertilizer is considered to be a single-nutrient fertilizer if it contains only N, P or K and, in parallel, no more than 20% of its total nutrient content comprises the nutrients S and Mg. The combination of these differentiation criteria results in the groups SL, SH, CL, and CH. Special lime fertilizers form their own group (CA). The fertilizers and their group allocation can be found in the appendix (Table A 1). Based on this grouping, our primary focus is to determine what proportion of the applied nutrient quantity a participant drew from each of the five fertilizer groups. This should allow conclusions to be drawn about the fertilizer plan as well as the total costs of fertilization (including application).

2.4. Data preparation and comparison of fertilization plans

Several steps were necessary to form an informative data set from the fertilization plans of the individual survey participants. First, the raw data that could be derived directly from the individual fertilization plans was listed. This included, for example, the amount of fertilizer used, number of fertilizer applications, as well as the application rate of each nutrient. Based on this information, further variables were generated that are important for analysing the fertilization plan. These variables include costs for purchasing fertilizers and their application costs, nutrient losses or nutrient balances. A large number of the variables describe the total proportion that fertilizers contribute to the total supply of each nutrient. In total, 675 variables comprise each fertilizer plan. Relevant excerpts of these data can be found in the appendix (Table A2, Table A3). Statistical calculations were performed using STATA SE 13 software (StataCorp, 2017). The total cost of fertilizer and application was used as a cluster variable to divide the fertilization plans into clusters with different cost-efficiencies. The median-linkage clustering method in combination with the Euclidean option as a continuous dissimilarity measure led, as desired, to a differentiation into three clusters: Cluster 1 with the most cost-efficient fertilization plans includes the optimal IoFarm solution and fertilization plans from one expert and two farmers. We assign this cluster to the economically "efficient" fertilization plans. The remaining two clusters can be described as “average” and economically “inefficient” fertilization plans (cluster 2, with average cost-efficiency, includes plans from two experts, fourteen farmers and four students; cluster 3 includes plans from one expert, two farmers and two students). This provided the opportunity to perform mean comparisons between clusters using t-tests in further analysis. Since more than two groups (efficient, average, and inefficient clusters) were compared, the Tukey test was used (Tukey, 1949). This post-hoc test is a multiple comparison of means that corrects for alpha error accumulation and is therefore considered to be conservative.

2.5. Scenario analysis using the DSS IoFarm

The DSS IoFarm was applied under different farm constellations to identify potential impacts on cost-efficient fertilization planning, including: Farm area; farm-to-field distance; soil fertility; organic fertilizer availability; fertilizer prices. As a starting point for this study, data from an existing farm (“original farm”) was used. The “original farm” (see Table 4, column 1) cultivates 63 hectares, of which one third each is winter barley, winter wheat and silage maize. The acreage and cropping structure correspond to an average Bavarian farm where, according to the Bavarian Agricultural Report (StMELF, 2020), cereals and fodder crops are cultivated on 60.4 hectares. No organic fertilizers are available. In order to be able to consider field-to-field distances, the total time required to reach all farm fields (in a circuit) was used according to Tröster et al. (2019). This amounts to 65 minutes. The field pieces were grouped into three management units (f1 to f3). This greatly facilitates the clarity and comparability of the results. Based on the size and the farm-to-field distances of the individual field pieces, a weighted average farm-to-field distance in minutes was determined for the three management units. The third of the fields close to the farm (f1) has a farm-field distance of only 0.75 minutes. Management unit f2 and f3 are 2.55 and 10.74 minutes away, respectively. Soil nutrient content (P, K, and Mg) of the management units was determined using representative farm fields and classified into categories “A” (very low) to “E” (very high) according to the guideline of the Bavarian State Institute of Agriculture (Wendland et al., 2018). Accordingly, a classification in categories “A” and “B” results in an increase in the respective nutrient requirement. Classification in categories “D” and “E” results in the respective nutrient requirement being halved or cancelled.

The initial situation of the original farm was now changed selectively in order to be able to represent the following scenarios: “small farm”, “big farm”, “nearby fields”, “faraway fields”, “homogeneous soil fertility”, “medium slurry accumulation” and “high slurry accumulation”. In addition, to test the influence of relative price changes on fertilizer plan, fertilizer prices collected between August 2015 and October 2018 were artificially manipulated. The fertilizer prices can be viewed in conjunction with the fertilizer survey online (link provided in footnote [1]). Using binary random numbers, a decision was made for each fertilizer at the beginning of each year whether to raise or lower the original prices by 10%. This results in a data set with annually changing price relations. Price trends of the individual fertilizers within the period under consideration, however, remain. The associated scenario is labelled "artificial price shift". More detailed information on the scenarios, as well as an overview of the results, can be found in Table 4.

3. Results

The results show that cost-efficient fertilizer plans are primarily influenced by relative changes in fertilizer prices. The investigated farm-specific constellations only partially influence the fertilizer plan.

3.1. Differences between cost-efficient and inefficient fertilization plans

In order to find out how cost-efficient fertilizer plans differ from inefficient ones, a detailed analysis of the data from the fertilizer survey is carried out in this point. The most cost-efficient fertilizer plan of IoFarm is also shown separately in the group mean comparisons to enable cross-comparisons.

3.1.1. Fertilizer decision

Particularly relevant is identifying fertilizers with a high or low economic advantage. In order to be able to assess the importance of the fertilizers separated by nutrients, it is first calculated which share of a nutrient a fertilizer covers in total within the framework of the present fertilizer plan. If, for example, the potash supply is covered exclusively by gr. potash, this fertilizer has a share of 100% in the potash supply. This shows what contribution each fertilizer has made to the respective quantities of nutrients applied. A multiple mean comparison between the clusters formed in advance (cost-efficient, average, and inefficient fertilizer plans) provides insights into different frequencies of fertilizer use (see, Table 1).

Only a few of the combinations of nutrient source (e.g. N%) and fertilizer (e.g. DAP) differ significantly in their frequency of use between cluster 1 (cost-efficient fertilizer plans) to cluster 3 (inefficient fertilizer plans). Table 1 only shows combinations of nutrient and fertilizer for which significant differences in use frequency can be detected, at least when comparing clusters 1 and 3 (see right part of table). Significant differences in use frequency between clusters 1 and 2 are particularly relevant. Although AHL1to3 contributes only slightly (with

Table 1. Fertilizers with significant differences between group means of clusters.

Fertilizer	Io- Farm	Cluster 1	←versus→		Cluster 2	←versus→		Cluster 3	←versus→		Cluster 1
	Ø %	Ø %	SE	P>|t|	Ø %	SE	P>|t|	Ø %	SE	P>|t|	Ø %
N%AHL1to3	4.0	6.5	0.01	0.001	0.8	0.01	0.773	0.0	0.01	0.001	6.5
N%DAP	21.3	21.7	0.04	0.018	9.3	0.02	0.133	1.5	0.04	0.002	21.7
P%DAP	80.0	81.8	0.14	0.015	34.0	0.07	0.143	5.7	0.13	0.002	81.8
P%TSP	20.0	18.2	0.16	0.355	42.0	0.07	0.185	70.2	0.14	0.049	18.2
K%gr. potash	100	100	0.19	0.063	51.1	0.08	0.700	35.9	0.17	0.044	100
Mg%gr. potash	10.4	9.4	0.02	0.130	5.2	0.01	0.415	2.8	0.02	0.039	9.4
S%gr. potash	16.7	17.5	0.03	0.002	6.8	0.01	0.248	2.6	0.02	0.000	17.5
S%Kieserit	33.3	63.0	0.08	0.240	49.1	0.03	0.165	34.7	0.07	0.028	63.0

Notes: The optimal solution "IoFarm" is shown separately as a benchmark; Cluster 1 = cost-efficient fertilization plans; Cluster 2 = average fertilization plans; Cluster 3 = inefficient fertilization plans; SE = standard error; N%AHL1to3 = contribution of AHL1to3 to total nitrogen fertilization; P%_DAP = contribution of DAP to total phosphorus fertilization, etc.

6.5%) to the nitrogen supply in cluster 1, it is still considered a success-determining factor for a cost-efficient fertilization plan. Also relevant is DAP as a source of N and phosphorus, respectively, and gr. potash as a source of cost-efficient sulphur supply. In looking at the raw data, we also notice some patterns that were not detectable, or not sufficiently detectable, using the statistical methods: Fertilizers with a combination of N, P and K, as well as stabilized nitrogen fertilizers are rarely used in cost-efficient solutions; gr. potash plays an important role for the supply of S, but the time of application must then be within the growing season; by far the greater part of the sulphur supply is via SSA in the context of the fertilizer survey. The importance of SSA depends on its price, but also strongly on the pH value, as well as the K and Mg supply of the soil. Here is an example: A high pH value and a low Mg supply favour SSA, because due to the strong acidifying effect of this fertilizer, more Lime+Mg can be used to compensate for the acidifying effect. Lime+Mg is also the most economical source to ensure Mg supply. In contrast, at a low K supply and low pH, SSA becomes less relevant. In this case, larger portions of the S requirement are usually covered within the framework of potash fertilization via gr. potash.

3.1.2. Timing of basic fertilization with K and P

P and K are nutrients that do not necessarily need to be spread every season (here: 2016 to 2018), which presents the option of using potential low price periods to purchase these nutrients in order to save on costs. The comparison of means (not shown) provides a significant difference only for the use of P in 2016. In cluster 1, significantly ($P>|t| = 0.019$) less P was used in this year compared to cluster 3. For the timing of potash fertilization, the t-tests (due to high standard errors) did not reveal any verified differences between the clusters. Still, a look at the raw data reveals that gr. potash was preferably used in cost-efficient solutions to some extent in 2016 and 2017, but then in reduced amounts and specifically in the spring to satisfy a proportion of the sulphur requirements in parallel. This confirms the importance of gr. potash and its dual function as a source of K and S.

3.1.3. Application costs and number of fertilization measures

On average, the application costs of all survey participants account for 5.2% of the total costs. The comparison of the cluster means (Table 2) shows the differences in application costs (*A_Cost*) together with the closely related number of fertilization measures (*Measures*).

Significant differences are only found when comparing the application costs of cluster 1 and cluster 3. It is notable that the optimal solution of IoFarm, which was only presented here as a reference, also stands out with high costs for application and many fertilization measures. This in turn indicates the subordinate relevance of the two variables (*A_Cost* and *Measures*) for cost-efficient fertilization plans.

Table 2. Statistical comparison of means for application costs and number of measures.

Test-Variable	IoFarm	Cluster1	←versus→		Cluster2	←versus→		Cluster3	←versus→		Cluster1
	Ø	Ø	SE	P>|t|	Ø	SE	P>|t|	Ø	SE	P>|t|	Ø
A_Cost [€]	8323	7189	385	0.207	7926	172	0.272	8535	344	0.039	7189
Measures [No]	37	26.3	3.43	0.666	29.5	1.53	0.322	33.0	3.07	0.570	26.3

Cluster 1 = cost-efficient fertilization plans; Cluster 2 = average fertilization plans; Cluster 3 = inefficient fertilization plans; SE = standard error; A_Cost = application cost; Measures = number of fertilization measures within 3 years.

3.1.4. Nutrient losses and balances

Another factor that affects both the fertilization costs and the evaluation of the sustainability of this measure is a nutrient supply that is as close as possible to the requirements. For the basic nutrients P, K and Mg, balances were shown to the survey participants during the processing of the experiment. In these balances, the nutrient requirements resulting from the withdrawals of the crop rotation were compared with the applied nutrients (taking into account the nutrient content of the soils). The corresponding names of the variables are "*P_Bil*", "*K_Bil*" and "*Mg_Bil*". For nutrients N and S, this balancing approach is not suitable due to the high potential for leaching. However, information on potential S losses could be derived indirectly from the data by matching S supply, S demand, and sensible timing of S fertilization: For the required S supply, crop-specific target values were considered as demand. In addition, it was defined that effective sulphur fertilization can only take place in the time window from February to May. Sulphur applications above the demand, or outside this time window were summarized in the variable "*S_loss*" as sulphur loss. Unfortunately, N leaching losses cannot be derived with the available data from the experiment. However, since nitrogen fertilization was only allowed within reasonable time windows during the experiment and the fertilizer requirement was predefined, it is assumed that leaching losses do not differ significantly. However, theoretical conversion losses of the different nitrogen forms were considered during the course of the fertilizer survey. The sum of these conversion losses is summarized in the variable *N_loss*. In Table 3, a statistical mean comparison is provided to show the differences between clusters 1 to 3.

Despite the relatively high pure nutrient costs in the purchase of N and P, the associated variables (*N_loss* and *P_bil*) have no significant influence on cost-efficiency. This can be explained by the fact that the survey participants fertilized largely according to demand in this respect. In addition, there are the surprisingly high nitrogen losses in the optimal solution (IoFarm) and in cluster 1. The main reason for this is the somewhat greater use of urea as a nitrogen source. Urea fertilization is associated with higher ammonia losses compared to the use of CAN (Hutchings et al., 2019; Kreuter et al., 2014). From

Table 3. Statistical comparison of means with regard to demand-based fertilization.

Test-Variable	Io- Farm	Cluster 1	←versus→		Cluster 2	←versus→		Cluster 3	←versus→		Cluster 1
	Ø	Ø	SE	P>|t|	Ø	SE	P>|t|	Ø	SE	P>|t|	Ø
N_loss [kg]	6562	6388	552	0.206	5328	247	0.926	5534	494	0.492	6388
S_loss [kg]	3680	4036	2835	0.060	11,486	1268	0.001	24,486	2535	0.001	4036
P_bil [kg]	0	201	1048	0.344	1834	469	0.640	2786	937	0.177	201
K_bil [kg]	565	437	1334	0.498	2106	597	0.123	4825	1193	0.054	437
Mg_bil [kg]	1319	4456	1653	0.998	4347	739	0.243	7076	1478	0.474	4456

Cluster 1 = cost-efficient fertilization plans; Cluster 2 = average fertilization plans; Cluster 3 = inefficient fertilization plans; SE = standard error; N_loss = theoretical conversion losses of nitrogen fertilizers; S_loss = displaced or over applied sulphur fertilization; P_bil = balance of P fertilization and withdrawal, etc.

a strict economic point of view, the higher ammonia losses were tolerated due to relative price advantages of urea. From the farm's perspective, this approach may be valid, but it contradicts the goals of the farm-to-fork strategy (European Commission, 2020). This strategy clearly calls for an increase in fertilizer efficiency. The implementation of external costs in the DSS IoFarm would be a conceivable approach to solve this issue and is therefore part of the subsequent discussion. Comparing cluster 1 and cluster 3, there are highly significant differences for *S_loss* (20.450 kg in total, leading to +45.4 kg ha^{-1} annually) and almost significant differences for *K_bil* (4.388 kg in total, leading to +9.8 kg ha^{-1} annually). In both cases, over fertilization leads to higher fertilizer costs and to a deterioration in resource efficiency.

In cluster 3, the sum of nutrient surpluses is by far the highest. Cost-inefficient solutions thus also appear to be less sustainable and less resource-efficient. To test this with the help of a statistical comparison of means, a new variable (NPKMgS) was formed from the sum of the five variables N_loss to Mg_bil. The differentiation between clusters 1 and 3, or clusters 2 and 3, is highly significant ($P>|t| = 0.001$). This result is extremely relevant as it shows how cost-efficiency and sustainability have a complementary objective at this point.

3.1.5. Identification and utilization of abrupt, relative price changes

In order to be able to put the fertilizer prices into perspective, a mean pure nutrient price was first derived for N (€0.81 kg^{-1}), P (€0.86 kg^{-1}) and K (€0.69 kg^{-1}) on the basis of the average prices of CAN, TSP and gr. potash. Subsequently, pure nutrient costs for these nutrients could be derived for all fertilizers. Continuous changes in the price relations as well as abrupt price changes were analysed graphically. A particularly striking price drop was recorded for TSP from June to July 2016 (see, Figure 1). This price drop was detected and used by the IoFarm model. Only six of the survey participants also recognized this price drop and used TSP at that time. This shows that even clear price signals are often not recognized by human decision makers.

3.2. Influence of farm constellations on cost-efficient fertilizer plans

IoFarm is able to calculate cost-efficient fertilization plans. Due to the clear mathematical structure of the DSS, the solution path is consistent. IoFarm is therefore well suited for investigating the influence of farm constellations on cost-efficient fertilization plans. In the following sections, IoFarm is used to highlight changes with regard to the following farm constellations: Farm size, infrastructure, soil fertility, organic fertilizer availability, and in addition, price changes. Table 4 provides a central overview of all scenarios studied and their impact on the cost-efficient fertilizer plan. The goal of this comparison is to identify possible trends in fertilizer selection in order to locate particularly

Table 4. Differences in cost-efficient fertilization strategies under various farm constellations.

Setup		(1) Original Farm	(2) Small Farm	(3) Big Farm	(4) Nearby fields	(5) Faraway fields	(6) Homogen soil fertility	(7) Medium slurry accumulation	(8) High slurry accumulation	(9) Artificially shifted fert. price
I Farm operating data										
Farm size	ha	63	6	1500	63	63	63	63	63	63
Nitrogen from livestock	kg ha^{-1}	0	0	0	0	0	0	80	170	0
Field-field distance	min	65	65	65	6	180	65	65	65	65
II Farm unit data		f1 f2 f3	f1 f2 f3	f1 f2 f3	f1 f2 f3	f1 f2 f3	f1 f2 f3	f1 f2 f3	f1 f2 f3	f1 f2 f3
Farm-field distance	min	0.75 2.55 10.74	(as original farm)	(as original farm)	1.00 1.00 1.00	30 30 30		(as original farm)	(as original farm)	(as original farm)
Soil fertility Phosphor	Cat.	C D E	(as original farm)	(as original farm)	(as original farm)	(as original farm)	C C C	(as original farm)	(as original farm)	(as original farm)
Soil fertility Potash	Cat.	B B D	(as original farm)	(as original farm)	(as original farm)	(as original farm)	C C C	(as original farm)	(as original farm)	(as original farm)
Soil fertility Magnesium	Cat.	B C C	(as original farm)	(as original farm)	(as original farm)	(as original farm)	C C C	(as original farm)	(as original farm)	(as original farm)
III Differences in fertilization plan										
Fertilizer & application costs (F&A)	€ ha^{-1}	272.5	323.6	265.5	266.4	287.9	286.6	178.9	54.72	264.2
Application costs relative to F&A	%	7%	22%	5%	6%	12%	6%	9%	13%	8%
Application costs	€ 100 kg^{-1}	1.62	6.12	1.11	1.29	2.95	1.46	1.98	2.63	1.66
Number of measures	No	32	30	32	30	31	28	27	13	30
SL	% of nutrients	7%	6%	8%	11%	10%	11%	9%	2%	16%
SH	% of nutrients	23%	24%	23%	21%	18%	25%	7%	2%	21%
CL	% of nutrients	0%	0%	0%	0%	0%	0%	44%	78%	0%
CH	% of nutrients	61%	60%	60%	60%	64%	56%	35%	16%	56%
CA	% of nutrients	9%	10%	9%	9%	8%	8%	5%	2%	7%
Main N source	% of N	67% Urea	71% Urea	68% Urea	56% Urea	57% Urea	57% Urea	28% Slurry	69% Slurry	50% CAN+Mg
Main P source	% of P_2O_5	52% DAP	52% DAP	52% DAP	52% DAP	67% DAP	68% TSP	73% Slurry	100% Slurry	71% TSP
Main K source	% of K_2O	100% gr. potash	100% gr. potash	100% gr. potash	100% gr. potash	100% gr. potash	100% gr. potash	62% Slurry	100% Slurry	93% gr. potash
Main Mg source	% of MgO	46% gr. potash	43% gr. potash	46% gr. potash	47% gr. potash	46% gr. potash	54% gr. potash	48% Slurry	87% Slurry	46% gr. potash
Main S source	% of S	67% gr. potash	72% gr. potash	72% gr. potash	72% gr. potash	72% gr. potash	66% gr. potash	71% SSA	62% SSA	45% gr. potash

Field-field distance = time required to completely approach all fields in a circuit; Soil fertility: A = "very poor" to E = "very high"; SL = low concentrated single fertilizer; SH = high concentrated single fertilizer; CL = low concentrated compound fertilizer; CH = high concentrated compound fertilizer; CA = lime fertilizer; Nutrient composition of slurry (in kg per m^3): N: 3.9; NH4+: 1.95; P2O5: 1.7; K2O: 4.7; MgO: 1.2; S: 0.25; CaO: 1.6

relevant factors influencing a cost-efficient fertilizer plan. This contributes to a deeper understanding of cost-efficient fertilization.

3.2.1. Influence of farm size (acreage)

To examine the influence of farm size, the farm size of the "original farm" was changed from 63 hectares to 6 hectares – "small farm" – or to 1,500 hectares – "big farm" – under otherwise identical constellations. Although it can be assumed that there is a correlation between farm size and on-farm infrastructure (e.g. farm-to-field distance), both aspects are examined separately. In principle, it cannot be excluded that both, large farms with surrounding fields and small farms with distant fields occur. The change in farm size was purposely chosen drastically in order to be able to clearly highlight potential effects on fertilizer planning. Table 4, columns 1 through 3 compares the "original farm" with the two extreme variants of "small farm" and "big farm". The total costs for fertilizer and application differ significantly (small farm: €324 ha^{-1}; original farm: €272 ha^{-1}; big farm €265 ha^{-1}). The share of application costs in the total costs, as well as the application costs per 100 kg fertilizer make clear that the cost differences are almost exclusively caused by changes in application costs. The reason for this is the nonlinear composition of application costs according to Tröster et al. (2019). Included in this: setup time per fertilizer application, costs for loading the spreader, farm-to-field and field-to-field trips, costs incurred during field work. Small farms are at a cost disadvantage compared to large farms, primarily due to setup time. It should be mentioned, however, that the a priori assumptions made about setup time have a major impact on this result. By reducing the number of fertilizer measures from 32 ("original farm") to 30 ("small farm"), an attempt is made to compensate for this cost disadvantage. However, effects on the selection of fertilizers cannot be identified due to the size of the farm. For example, the ratio of nutrient proportions from the different fertilizer categories (see, section 2.3: SL, SH, CL, CH and, CA) remains almost unchanged. However, a minor adjustment response of the "small farm" should be mentioned: the share of the fertilizer category SL is reduced by 2% compared to "big farm", whereas slightly more of the higher concentrated fertilizer category SH is used. The main nutrient sources for N, P, K, Mg and S are identical for the various-sized farms: urea (N), DAP (P) and, gr. potash (K, Mg, S), each with approximately equal percentages of nutrient supply.

Overall, it can thus be stated that the farm size exerts only a minimal influence on the fertilization plan.

3.2.2. Influence of the internal infrastructure

The on-farm infrastructure is the distance between farm and field, as well as the position of the fields in relation to each other (field-to-field distance) in combination with the existing mechanization. Changes in this area have a significant effect on transport and application costs. In order to test possible effects on fertilizer planning, the farm-field distance of the management units (f1 to f3) was changed to one minute each for "nearby fields" and to 30 minutes each for "faraway fields". In parallel, the duration for the complete approach of all field pieces (field-to-field distance) had to be adjusted to 6 minutes for "nearby fields" and to 180 minutes for "faraway fields". Table 4, columns 4 and 5 compares the two scenarios. As expected, both scenarios differ in total fertilizer and application costs (nearby fields: €266 ha^{-1}; faraway fields: €288 ha^{-1}). Also in this case, it can be seen that the difference in total costs is mainly caused by the application costs. However, the change in the fertilizer plan itself is small: more fertilizer of the SL category is used in the "nearby fields" variant than in "original farm". This is mainly a higher proportion of CAN+Mg. Due to the short transport distances, the nutrient density in the fertilizers used is less important, so this change is comprehensible. With regard to the other fertilizer categories and the main fertilizers used, the adjustments are insignificant compared to the "original farm". It is interesting to note that even in the "faraway fields" scenario, significantly more of the lower concentrated SL fertilizers (10%) are used than in the "original farm". This initially is contrary to the logic that fertilizers with high nutrient concentrations are preferred in case of long transport distances. However, in fact, part of the urea fertilization (SH) was replaced by CAN+Mg (SL) in this scenario (compare main N source Table 4). The reason for this is probably the strong acidifying effect of urea, which in parallel also increases the need for compensatory liming. Partial replacement of urea with CAN+Mg can reduce fertilization measures and application costs. In the "faraway fields" scenario, the share of the CH fertilizer group is 3% higher than the original level. This increase is directly related to the growing importance of DAP as a P (and N) source (see main P source Table 4). Since DAP has no other disadvantages, the benefits of the enormously high nutrient density of this fertilizer are fully realized.

As a result, on-farm distances play a minor role in the fertilizer plan; the share of transport costs in the total costs of fertilization is too small to exert an influence on the fertilizer plan.

3.2.3. Influence of soil nutrient content

In the "original farm" scenario, the soil content of the nutrients P, K and Mg is relatively heterogeneous. The classifications are between "B" low and "E" very high. In order to investigate the influence of soil nutrient content on the fertilization plan, a scenario with an absolutely homogeneous soil nutrient content was created under otherwise identical constellations. For this purpose, it is assumed that the nutrients P, K and Mg are each present in optimal concentrations and can therefore be classified as "C". This setup as well as the results for this variant can be found in Table 4, column 6, "Homogeneous soil fertility". Due to the changes, slightly more P and Mg must be spread in total than in the "original farm" scenario. As a result, the total costs for fertilizer and application are higher than before (€287 ha^{-1}). Due to the homogeneous soil nutrient content of all management units, the fertilization plan can be simplified. This reduces the fertilization measures from 32 to 28 measures, which also leads to a reduction in application costs. In total, the nutrient percentage shifts from the fertilizer category CH towards SL and SH. This is due to the fact that significantly less urea is used compared to "original farm". Instead, more CAN+Mg is used. DAP (CH) is replaced by TSP (SH) as the main source of P. TSP has an advantage in homogeneous P soil conditions because it can be used simultaneously in all crops, largely independent of the season. This allows optimal use of periods of low prices and also enables fertilization measures to be combined to reduce application costs. Changes in terms of K, Mg and S fertilization are marginal. As in all previous scenarios, gr. potash is used for the most part as the fertilizer of choice for these nutrients.

It should be noted that differences in soil nutrient content affect the complexity of the optimization problem and therefore significantly influence the fertilization plan.

3.2.4. Influence of the amount of organic fertilizer

The type and availability of organic fertilizers vary in practice from farm to farm. The "original farm", in which no organic fertilizer is available, was therefore compared with two scenarios with organic fertilizer (see, Table 4): "medium slurry accumulation" with a nitrogen accumulation from livestock of 80 kg N ha^{-1} and "high slurry accumulation" with the maximum organic nitrogen fertilization currently permitted in Germany of 170 kg N ha^{-1}. Slurry fertilization covered a considerable proportion of the nutrient requirement in both variants. As a result, the cost of purchasing commercial fertilizer and the associated application costs drop drastically to €179 ha^{-1} (medium slurry accumulation), or to €55 ha^{-1}. It is assumed that the slurry is the farm's own slurry, which is why no additional purchase costs are incurred and the application costs are allocated to livestock farming in accordance with the costs-by-cause principle. The availability of organic fertilizer also has a significant effect on the number of mineral fertilization measures. In the "high slurry accumulation" scenario, the farm would manage with just 13 mineral fertilization measures in the 3-year period under consideration. Since slurry must be classified in the CL fertilizer group, the nutrient percentage of this fertilizer group increases from its original 0% to 44% or 78%. Due to this massive change, the percentages of the other fertilizer groups can no longer be directly compared with the previous scenarios. However, in both cases, a clear decrease in the SH fertilizer group is noticeable. This decrease is mainly due to a reduced use of urea and TSP. The evaluation of the main nutrient sources for the different nutrients is dominated by slurry in both scenarios.

Only the main source of S stays inorganic and has changed from gr. potash to SSA. Further adjustments to the selection of purchased commercial fertilizers can only be detected when looking at the second-most important nutrient source after slurry: For the medium slurry accumulation scenario, CAN+Mg is the most important purchased N fertilizer, accounting for 27% of the N supply. For Mg supply, Lime+Mg is mainly used. DAP remains the main commercial fertilizer for P and gr. potash remains the main commercial fertilizer for K. In the "high slurry accumulation" scenario, neither P nor K is purchased externally. The second-most important N source besides slurry is urea (12%). Lime+Mg (8%) is used as a source for Mg. S needs are primarily covered by SSA.

In summary, the availability of organic fertilizers affects several issues at once: (i) external nutrient requirements; (ii) the cost of fertilizer purchase and application; (iii) the distribution and number of fertilizer applications; (iv) the choice of fertilizers themselves.

3.2.5. Influence of relative price changes of fertilizers

So far, major changes in the fertilizer plan have only occurred in the scenarios with organic fertilizer use and with changed soil nutrient conditions. In order to test whether relative price changes on the fertilizer market have a noticeable influence on the fertilizer plan, fertilizer prices were artificially changed as described in section 2.5. The result of this analysis can be found in Table 4, column 9. Despite moderate price adjustments of ±10%, different fertilizers are now selected for N (50% CAN+Mg) and P (71% TSP) than in the "original farm". With regard to the origin of K, Mg and S, the fertilizer plan remains relatively constant. Here, too, gr. potash is mainly used, although somewhat more use is made of other fertilizers for sulphur supply than in the original situation.

Relative changes in fertilizer prices thus have a major impact on cost-efficient fertilizer plans.

4. Discussion

This study investigated the characteristics of cost-efficient fertilizer plans. For this purpose, an experiment in the form of a fertilizer survey was conducted in which the participants had to set up a fertilizer plan that was as cost-efficient as possible. On the other hand, this study also clarifies whether and how different farm constellations influence a cost-efficient fertilizer plan. This study will also help to increase knowledge about cost-efficient fertilizer plans and, if possible, derive general recommendations for farmers and advisors.

According to this and further work (Kiełbasa et al., 2018; Rajsic & Weersink, 2008), a nutrient supply that is as close to demand as possible is particularly relevant for the cost-efficiency of fertilizer plans. Survey participants had the supply of the N and P nutrients largely under control. Fertilizing with N and P is strictly regulated in Germany (Bundestag, 2009; BMEL, 2017), which is why farmers pay particular attention to it. However, human decision makers find it difficult to meet all crop nutrient requirements in an equally balanced manner. As a result, inefficient solutions result in significant over-supply of S and K, which, of course, is associated with unnecessary costs. A look at the total nutrient surpluses (NPKMgS) also shows that cost-efficient fertilizer plans have significantly lower nutrient surpluses. Considered separately for N nutrient, however, this statement does not apply per se. Here owing to increased urea fertilization in cost-efficient solutions, N losses were also increased. Overall, economically efficient fertilizer plans also contribute substantially to resource efficiency and sustainable land use (see, also Expósito and Velasco (2020) and Kiełbasa et al. (2018)). However, this is not an automatism that can simply be assumed. Instead, resource efficiency and sustainability must be ensured through the model's internal consideration of external costs (air or water pollution). This case moves away from a purely economic target function towards a socially preferred target function with much higher compliance with the farm-to-fork strategy (European Commission, 2020). Although a general recommendation can be formulated at this point: "All crops should be fertilized according to nutrient demand", this requirement is not new and was also known to the survey participants. Therefore, it can be assumed that this recommendation simply cannot be fully implemented by the human decision maker. The mean time required (81 min) and the education level of the participants suggests carefully developed fertilization plans on their part and reinforces this conclusion. The same is true for the recognition of clear price signals, which we could demonstrate with the example of the abrupt price drop of TSP (see, Figure 1). Most participants missed this favourable opportunity for phosphorus fertilization. Arguably, farmers are unlikely to constantly modify their fertilizer planning. However, they regularly observe the fertilizer market to identify the most favourable timing for purchasing fertilizers. Since the survey revealed price information in advance, it is even more surprising that the price drop of TSP was either overlooked or TSP was simply ignored in fertilizer planning. Despite complete information (e.g. prices, weather, and yield expectation) gathered and a clear aim of profit maximization, participants of the experiment could hardly translate this into fertilizer plans with satisfactory cost-efficiency. Moreover, the complexity and frequency of fertilizer planning are independent of each other. Practically, fertilizer planning may only be considered twice or thrice a year, but the complexity of the optimization problem remains the same. Complex problems often cannot be fully understood by humans and limited rational behaviour occurs (Simon, 1959). On the other hand, it is also possible that the transaction costs or costs of acquiring information to solve the problem optimally are so high for the decision maker that a suboptimal solution to the problem may be rational from their perspective (Simon, 1959). IoFarm is an

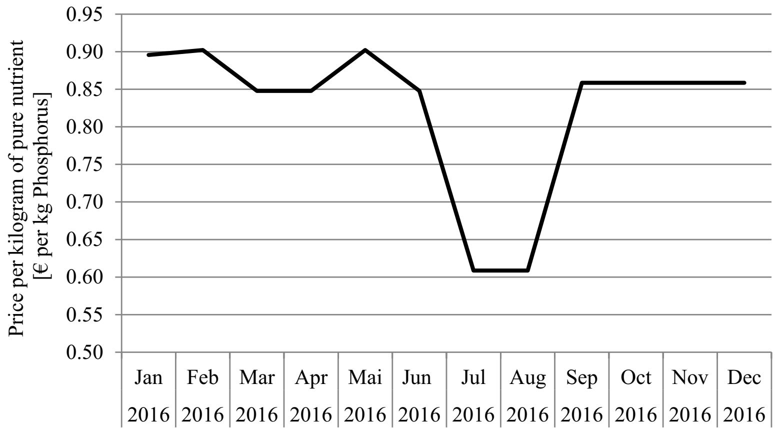

Figure 1. Pure nutrient price of P based on triple superphosphate in 2016.

important tool for overcoming these barriers. It allows cost-efficient fertilization plans to be located and updated at regular intervals.

The analysis of the fertilizers used showed that significantly more DAP, gr. potash and lime+Mg were used in cost-efficient solutions (cluster 1). Here, DAP covers about 80% of the phosphorus demand and about 22% of the nitrogen demand and was thus an economically relevant source for both nutrients. Gr. potash also fulfils a significant dual function in cost-efficient solutions: 100% of the potash supply is realized via gr. potash, and in parallel around 17% of the sulphur supply is achieved. In order to take advantage of the dual function of both fertilizers, farmers and consultants must make sure to apply these fertilizers in spring. Also significant is the use of lime+Mg to ensure magnesium supply. In addition, the studiy shows that NPK fertilizers were not used in cost-efficient solutions. Other studies, however, come to different results here: Sayegh et al. (1981) found on poorly supplied soils in the Middle East that NPK fertilizers have a positive effect on yield at many locations and should therefore be used. There was no economic evaluation of the results in this context. If NPK fertilizers are evaluated with pure nutrient costs, they are at times definitely more favourable than single-nutrient fertilizers, which can also be shown for the period of this study (D. Schiebel, personal communication, 1 August 2015 – 1 December 2018). The reason for avoiding NPK fertilizers in cost-efficient solutions lies rather in the fixed nutrient composition of these fertilizers. NPK fertilizers meet the exact farm requirements only in exceptional cases and therefore make it difficult to supply nutrients in line with requirements.

The benefits of the fertilizers mentioned at the beginning (DAP, gr. potash and lime+Mg) are clearly dependent on relative price changes in the fertilizer market. Lahmiri (2017) studied the price volatility of rock phosphate, DAP, TSP, urea, and potassium chloride before and after the global financial crisis in 2007, finding that external shocks lead to volatile fertilizer markets and are associated with relative price changes among fertilizers. External shocks are also to be expected in the future, as the current global COVID-19 pandemic, or the war against Ukraine, teaches us. For this reason, relative price changes in the fertilizer market can also be expected in the future, which is why no long-term recommendations can be derived for farmers and consultants on the basis of the fertilizers currently considered to be beneficial.

During the analysis, it became apparent that the importance of application costs for a cost-efficient fertilizer plan was often overestimated by the survey participants. While the impact of application costs on the total cost of fertilization is significant, striving for the lowest possible application costs leads to several undesirable side effects. To achieve low application costs, the number of fertilization measures must be reduced. As a consequence, the nutrient quantities per measure are increased. This is done, for example, by using NPK fertilizers or by reducing the distribution of nitrogen fertilization to a few applications. All in all, a small number of fertilization measures leads to savings in application costs, but at the same time this makes it more difficult to combine fertilizers cleverly in the sense of demand-based fertilization. In addition, it is more difficult to benefit from the relative price advantages of individual fertilizers. Fertilizer systems that are designed to minimize the number of fertilization measures are more affected by these undesirable side effects. An example of this is CULTAN fertilization. This fertilization plan is evaluated quite differently in the literature. For example, Kozlovský et al. (2009) and Sedlář et al. (2011) come to significantly higher, lower, and non-differentiable yield effects in different years compared to standard nitrogen fertilization. The effects of CULTAN fertilization or other aggregated N fertilization measures on the total fertilization costs of a crop rotation, however, remain unclear in the literature. Unfortunately, no recommendation for practice can be derived regarding prioritizing application costs. On the one hand, it has been shown that application costs have a relevant influence on the total costs of fertilization, on the other hand, a demand-based nutrient allocation is by far the most important factor to save costs. If both goals are not compatible, the demand-based nutrient allocation has to be prioritized.

To test the influence of farm size, infrastructure, soil fertility and the availability of organic fertilizers, a typical Bavarian farm was used, which was subjected to extreme changes in the respective categories according to the ceteris paribus principle. Contrary to the original assumption, the analysis showed that the factor farm size has no visible influence on the selection of a cost-efficient fertilizer plan. Only a minor influence is caused by the on-farm infrastructure. Unfavourable infrastructure does increase application costs, but even under the constellations of the “faraway fields” scenario with a 30-minute farm-to-field distance, the influence of application costs, accounting for 12% of total costs, was not large enough to cause significant changes in fertilizer plan. We therefore conclude that the factors of farm size and infrastructure (within realistic limits) do not have a significant impact on fertilizer plan. Future versions of IoFarm may therefore be able to omit the consideration of transportation costs (farm-to-field and field-to-field), thereby saving considerable computational resources. In contrast, the factors of soil fertility and the availability of organic fertilizers must be evaluated differently. Both factors directly influence the need for nutrients, choice of fertilizer, and timing of fertilization and are therefore relevant for cost-efficient fertilization plans. The effect of homogeneous soil fertility is particularly interesting: here, the number of fertilization measures can be reduced, since no field-specific requirements must be considered. In reality, these requirements differ even on a spatial level within a field. However, this study does not address the spatial variability of soil fertility. In this case, precision farming could make a significant contribution to increasing nutrient efficiency. This is also reflected in the farm-to-fork strategy (European Commission, 2020) wherein precision farming is mentioned as an important approach in this regard. Site-specific application of fertilizer is based on application maps or online sensor data. Depending on the application zone or sensor value, the quantitative allocation of fertilizer is regulated. Therefore, site-specific fertilization can, in principle, also be applied to fertilizer plans discussed here. However, a systematic homogenization of the spatial variability of soil fertility is more difficult to achieve if compound fertilizers are used in fertilizer plans.

The previous findings on cost-efficient fertilizer plans (IoFarm) suggest that a large part of the optimization potential must come from the least-cost combination of fertilizers (type, quantity and timing). This assumption could be confirmed with the "artificial price shift" scenario. Even a slight manipulation of prices led to a recognizable adjustment of the fertilizer plan. It also seems that a higher variability of fertilizer prices accommodates the optimization potential of IoFarm, because with total costs of €264 ha^{-1} the scenario "artificial price shift" was significantly cheaper than fertilization in the "original farm". Overall, relative price changes in the fertilizer market are commonplace (Lahmiri, 2017), so regular recalculation is also required for a cost-efficient fertilizer plan.

The results from the comparison of fertilizer plans (section 3.1) are based on a low number of survey participants (n = 29). Due to the small number of participants, the data set obtained does not meet the statistical requirements for the sample size. As a result, the validity of the results must be questioned. Even with the greatest efforts, it was not possible to motivate more voluntary participants, which was also due to the large amount of time required to participate in the fertilizer survey. A further simplification of the experiment or payment for participation was purposely rejected, since only intrinsically motivated participants show a real will to optimize and can thus create realistic fertilization plans that can also serve as a reference for IoFarm (Barge & Gehlbach, 2012; Göritz, 2006; Stanley et al., 2020). Therefore, priority was given to the quality rather than the quantity of the data. The data set was analysed using standard statistical methods. The optimal solution of IoFarm itself appears only once in this data set. As part of the comparisons of means (see, Table 1, Table 2, Table 3), the optimal solution of IoFarm was additionally shown in order to be able to point out special features if necessary. However, statements made about cost-efficient fertilizer plans can also be confirmed with regard to the optimal solution of IoFarm.

The second part of the analysis (section 3.2) is based as described on a typical Bavarian farm, which was subjected to extreme changes by undergoing different scenarios. By consistently applying the ceteris paribus principle, it is possible to analyse the various farm constellations in the scenarios very precisely. This knowledge is helpful for deriving statements for farms that are subject to other constellations. For more applicability, however, it would be helpful to supplement the analysis with actual, but different types of farms. This might lead to combination effects that are suppressed in an analysis according to the ceteris paribus principle. However, due to the inaccessibility of information regarding the farm infrastructure, this consideration had to be postponed.

One aspect that should be considered is the discussion of the practicability of the results obtained: Reduction in the number of fertilization measures and the application costs is not a priority for cost-efficient fertilization plans. The preferability of certain fertilizers, or the timing of basic fertilization, is heavily dependent on the current price situation. Therefore, the corresponding results cannot be generalized. The importance of demand-based allocation of all nutrients is already known, but not easy to implement. The direct results of this study are of limited help to practitioners in developing cost-efficient fertilization plans. Instead, reference is made to DSS IoFarm.

Hence, the current focus is the possible use of IoFarm and an assessment of the potential benefits for the intended users. First, whether the intended users are focused on cost-efficiency and thus pursue an objective function that is consistent with IoFarm should be clarified. Cost-efficiency is the balance between all marginal costs and the associated marginal benefits. Therefore, it includes, for instance, the consideration of yield effects, long-term soil fertility, and scarce human resources. Conformity of the objective function can only be established under the strong assumption of an objective and a substantially rational decision-maker – *Homo oeconomicus*. Those who identify with this objective function will certainly still question the necessity and added value of a DSS such as IoFarm. Since IoFarm is not a ready-to-market program yet, no feedback from practitioners can be included at this point. However, the results of the fertilizer survey (Section 2.3) suggest that saving management time and a significant increase in farm profit are the added value for the user. On average, the participants were €66 ha^{-1} behind IoFarm's solution. Even for the best candidate, an improvement of €10 ha^{-1} would still have been possible, indicating an additional €10,000 for a 1,000 ha farm. Specifically, all costs related to the IoFarm application must be covered. Examples of these costs include service fees and transfer and opportunity costs from the user's perspective, which brings us to the discussion on the possible use of IoFarm: The DSS requires a large amount of farm data at the field level, such as nutrient levels, cropping plans, and executed fertilizer measures. In professionalized farms, digital farm management systems (FMS) are often used, which contain the necessary data. To maintain the low transfer costs for the IoFarm application, interfaces to existing FMS are therefore required. To make the development and maintenance of interfaces the responsibility of software providers, IoFarm must be used as an external application: As soon as the user requests fertilizer planning via a FMS, the necessary data are passed on to an external server, processed, and transferred back to the FMS as a fertilizer plan. The frequency of such a query depends on the user. As a DSS, IoFarm does not take any decisions, and the user remains the decision-maker. Therefore, the fertilization measures implemented may deviate from the proposed fertilization plan. The realized fertilization measures are documented in the FMS and used by IoFarm as input data for future fertilization plans. Additionally, the user has the option of adjusting the yield expectation at the field level before running the program. Therefore, unpredictable, yield-influencing effects (e.g. drought, diseases, and pests) can be considered, similar to the usual practice. Certainly, this approach relies on the objective assessment by the user.

Thus far, the impression that IoFarm and its optimization potential are dependent on a very short-term selection of fertilizers might exist. For methodological reasons, this approach was chosen in the fertilizer survey. A common practice of farmers is to buy quantities of fertilizers in advance; therefore, they might not always be affected by short-term price changes. IoFarm also supports this behaviour: Based on the proposed fertilizer plan, the user decides whether and which fertilizer quantities should be purchased in advance. Pre-purchased quantities of fertilizers are inventoried and ensured to be used in future fertilizer plans. The economic optimization potential of IoFarm is not affected by this. However, every decision for, or against, the pre-purchase of fertilizer is always a bet on future price developments with an uncertain outcome. (Further explanations on the use and benefits of IoFarm can be found in Tröster and Sauer (2021b)).

An outlook on the need for further interdisciplinary research: This study represents an intensive link between agricultural economics and plant nutrition to arrive at cost-efficient fertilizer planning. The current optimization approach relates to the selection, quantity, and temporal distribution of fertilizer use. This approach can be extended through further research.

However, there is, for example, the question of how the placement of fertilizers or the adjustment of the overall farm organization (e.g. crop rotation and livestock farming) can be integrated into the optimization system. In addition, links to other research areas emerge (e.g. agricultural engineering). For example, how cost-efficient fertilization plans, possibly containing compound fertilizers, can be implemented in a site-specific fertilization system remains unclear. Fixed nutrient ratios in compound fertilizers prevent full variability in site-specific fertilization. The exploration of technical solutions that can create compensation in real time by admixing single fertilizers is potentially interesting. From the agribusiness perspective, IoFarm is an interesting tool for deriving individual mixed fertilizers that are tailored to the needs of farms (e.g. crop rotation and accumulation of organic fertilizers). Such highly farm-specific mixed fertilizers would be a significant enhancement compared to the current practice of using more crop-specific mixed fertilizers. There is also a link to this study from a societal perspective, that is, harmful greenhouse gas emissions associated with fertilization. Therefore, IoFarm should also be used to investigate particularly greenhouse gas-efficient fertilizer plans. To this end, an adapted objective function must first be developed that allows greenhouse gas emissions to be quantified.

5. Conclusions

This study clarifies the distinguishing features between cost-efficient and inefficient fertilization plans. The influences of different farm constellations were also demonstrated. Here, it is shown that the homogeneity of soil fertility and the availability of organic fertilizers have a far greater influence on fertilization plan than a farm's size and infrastructure. Ultimately, however, the study also shows that relative price variations among fertilizers dominate cost-efficient fertilizer plan design. Prices influence the selection of fertilizers and the timing of fertilizer application. Nevertheless, some of the results of this study remain relevant regardless of the fertilizer market and farmers and consultants should therefore consider them when thinking about cost-efficient fertilizer planning: nutrient surpluses should be avoided; application costs are not the primary issue in fertilizer planning; due to fixed nutrient composition, standard NPK fertilizers are difficult to integrate into a farm-specific fertilizer plan. Generally, people find it difficult to optimally solve complex problems . In addition to the cognitive challenge, another reason for suboptimal solutions could be due to transfer costs incurred in the context of finding the best possible solution. DSS IoFarm is a potentially suitable tool to accomplish this task. The overall conclusion of this study and the two predecessor studies is that, in its current form, IoFarm can help increase farm profits and facilitate decisions regarding optimal fertilizer planning. Increased profits and efficient nutrient use go together to a large extent. Nevertheless, conflicting goals cannot be eliminated. To ensure the control of unnecessary nutrient use, external costs for nutrient surpluses must be integrated in the future. With this expansion, the goals of resource efficiency and sustainability can be further promoted in addition to economic objectives.

Note

[1] https://drive.google.com/file/d/14rBHNKKDuBq8oyeeVUXuek2id1B9z_Dw/view?usp=sharing

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Appendix

Table A1. Allocation of fertilizers to fertilizer categories.

		Content/Effect in kg per 100 kg					
Abbreviation	Name	N	P_2O_5	K_2O	MgO	S	CaO
Category SL (single low)							
AHL	Ammonium nitrate urea solution	28					-28
AHL1to3	67%Water + 33%AHL	9					-9
CAN	Calcium ammonium nitrate	27					-15
CAN+Mg	Calcium ammonium nitrate	27			4		-9
CAN+S	Calcium ammonium nitrate	24				6	-34
Category SH (single high)							
TSP	Triple superphosphate		46				-1
U+Inhib	Alzon	46					-46
Urea	Urea	46					-46
Category CL (compound low)							
Kainite	Kainite			11	5	4	0
Slurry	Liquid organic fertilizer	3,9*	1,7	4,7	1,2	0,3	1,6
Category CH (compound high)							
ASS	Ammonium sulphate nitrate	26				13	-49
DAP	Diammon phosphate	18	46				-36
ENTEC+S	ENTEC	26				13	-49
ENTEC NPK	ENTEC	15	5	20	2	8	-14
gr. potash	Granular potash			40	6	5	0
Kieserit	Kieserite				25	20	0
NP 20;20	NP	20	20			2	-31
NPK 15;15;15	NPK	15	15	15		2	-15
NPK 20;8;8	NPK	20	8	8	3	4	-21
NPK 23;5;5	NPK	24	5	5		4	-23
PK 16;16	PK		16	16	2	8	6
SSA	Sulfuric acid ammonia	21				24	-63
Urea+S	Piamon S	33				12	-54
Category CA (special lime fertilizer)[3]							
Burned Lime	Burned lime						90
Lime+Mg	Carbonic lime				14		53
Lime+S	Carbonic lime					2	50

SL and SH: Single-nutrient fertilizers containing either N, P, or K and whose content of S and Mg does not exceed 20% of its total nutrient content. Fertilizers that do not meet this definition are called compound fertilizers (CL and CH). L stands for low nutrient content (≤ 31%); H for high nutrient content (> 31%); CA = group of lime fertilizers.

Table A2. Fertilizer survey data part 1 - Costs, Clusters, Quantities.

ID	FA_Cost [€]	Cluster	A_Cost [€]	Measures [No]	P2016 [kg]	K2016 [kg]	P2017 [kg]	K2017 [kg]	P2018 [kg]	K2018 [kg]	N_loss [kg]	S_loss [kg]	P_bil [kg]	K_bil [kg]	Mg_bil [kg]	NPKMgS [kg]
1	123376	1	8323	37	7531	9413	10435	0	34085	9977	6562	3680	0	565	1319	12125
2	127864	1	6776	27	12995	0	21919	9420	17158	9420	7655	4981	22	15	6555	19228
3	132756	1	7394	19	9200	0	34500	0	8625	19320	5087	2581	275	495	3736	12173
4	134985	1	6263	22	16100	0	12075	0	24380	19500	6250	4903	505	675	6215	18548
5	141114	2	7956	37	20470	8275	14720	4840	17250	6000	5720	4786	390	290	3510	14696
6	143540	2	6969	25	28750	0	16905	0	7360	19375	6357	8881	965	550	8855	25607
7	143793	2	8237	36	18170	0	28990	10000	10120	9600	5607	5976	5230	775	1655	19243
8	143828	2	7058	17	18676	12930	14973	7843	22678	0	3959	9496	4277	1948	4131	23810
9	145439	2	7988	30	16875	775	25610	14000	10015	4265	7004	15421	450	215	7165	30255
10	145631	2	8210	26	15870	4488	18630	7900	17940	6655	4747	4033	390	218	423	9811
11	145660	2	7700	32	18925	4525	17600	5550	16775	10125	4689	9861	1250	1375	7720	24895
12	146906	2	7723	24	16780	2750	8600	9735	27480	6525	6108	6701	810	185	6380	20183
13	148514	2	8957	40	17250	8000	23690	5000	11900	12600	5464	7916	790	6775	8930	29875
14	150062	2	6538	22	18545	7445	15600	1800	21530	13480	4063	8236	3625	3900	6565	26389
15	152787	2	8442	34	21575	8875	15650	4840	15575	6325	3897	10911	750	1215	700	17473
16	153753	2	7603	32	11660	7750	15425	1625	29050	18800	3720	15231	4085	9350	2850	35235
17	154487	2	7602	21	6200	0	7000	0	42500	19200	4451	18756	3650	375	3900	31132
18	155535	2	7832	32	22310	550	15220	2000	14870	19760	8638	7196	350	3485	4725	24393
19	155881	2	9629	37	15180	0	18860	13790	18630	8000	6002	19291	620	2965	1590	30468
20	156842	2	7220	25	10200	0	13000	10000	31450	10000	4302	12186	2600	1175	305	20568
21	159048	2	8902	42	17485	4325	18505	10580	17560	4200	5369	16921	1500	280	3535	27605
22	161504	2	8155	28	17250	0	18140	4800	17790	14240	5825	13386	1130	215	2205	22761
23	161825	2	7562	24	15600	6400	19600	10400	20250	8750	5650	14566	3400	6725	6400	36741
24	162500	2	8248	26	6400	6400	7425	4300	38640	8225	4981	19976	415	100	5405	30877
25	165821	3	8303	26	25300	2750	14950	9600	12650	6800	6456	37816	850	325	15235	60682
26	167323	3	8793	36	21200	500	22250	5000	18600	15400	5154	18761	10000	2075	9235	45225
27	170625	3	8843	41	28865	9000	15200	2800	8850	13500	5269	18471	865	6475	1190	32270
28	174442	3	7196	27	11385	25300	21150	0	20440	0	5282	16066	925	6475	2995	31742
29	180804	3	9539	35	22400	12300	16400	12550	14540	2750	5509	31316	1290	8775	6725	53615

ID: identification number; FA_Cost = total fertilizer and application costs; Cluster = classification according to FA_Cost; A_Cost = application costs; Measures = number of fertilizer measures; P2016 (and similar) = P fertilization in 2016; N_loss = N conversion losses; S_loss = S losses or wrong placement; P_bil (and similar) balance of P fertilization and withdrawal; NPKMgS = sum of N_loss to Mg_bil.

Table A3. Data from the fertilizer survey part 2 - Shares in nutrient supply.

ID	N% CAN +Mg	N% AHL1to3	N% DAP	P% DAP	P% TSP	K%-ENTEC NPK	K% gr. potash	Mg% gr. potash	Mg% Lime +Mg	S% gr. potash	S% Kiserit	SL	SH	CL	CH	CA
1	26%	4%	21%	80%	20%	0%	100%	10%	59%	17%	33%	8%	12%	0%	67%	12%
2	10%	0%	26%	100%	0%	0%	100%	9%	52%	16%	66%	3%	12%	0%	75%	10%
3	39%	9%	13%	47%	53%	0%	100%	10%	36%	20%	80%	16%	15%	0%	62%	7%
4	5%	13%	27%	100%	0%	0%	100%	9%	50%	17%	73%	12%	2%	0%	76%	10%
5	28%	0%	26%	100%	0%	0%	50%	5%	36%	8%	57%	15%	3%	18%	56%	8%
6	27%	0%	19%	74%	26%	0%	93%	8%	48%	12%	52%	9%	13%	2%	66%	10%
7	25%	0%	8%	28%	67%	0%	100%	10%	50%	16%	43%	12%	20%	0%	59%	10%
8	35%	0%	24%	82%	0%	0%	50%	5%	50%	5%	39%	9%	0%	0%	81%	10%
9	0%	3%	2%	7%	82%	0%	68%	6%	52%	7%	43%	4%	24%	0%	62%	10%
10	42%	6%	0%	0%	100%	0%	73%	8%	25%	13%	67%	23%	20%	10%	40%	6%
11	0%	0%	19%	71%	6%	0%	54%	5%	44%	7%	70%	13%	4%	2%	73%	9%
12	6%	0%	9%	32%	25%	0%	0%	0%	56%	0%	28%	5%	13%	32%	38%	11%
13	11%	1%	21%	80%	20%	0%	98%	11%	44%	17%	68%	11%	8%	0%	72%	9%
14	30%	0%	8%	27%	17%	0%	0%	0%	51%	0%	37%	8%	5%	0%	77%	10%
15	31%	0%	0%	0%	88%	0%	63%	7%	46%	7%	33%	24%	20%	2%	45%	9%
16	16%	0%	9%	32%	31%	0%	25%	4%	62%	4%	22%	19%	6%	0%	63%	12%
17	3%	0%	0%	0%	29%	0%	0%	0%	46%	0%	39%	15%	10%	0%	66%	9%
18	3%	4%	1%	5%	91%	9%	81%	9%	48%	14%	61%	2%	35%	1%	52%	10%
19	19%	0%	7%	28%	72%	0%	95%	11%	26%	9%	42%	9%	19%	1%	65%	6%
20	30%	0%	13%	48%	0%	0%	100%	11%	0%	12%	75%	12%	1%	0%	87%	0%
21	10%	3%	7%	25%	22%	40%	26%	2%	48%	2%	35%	7%	7%	3%	73%	10%
22	5%	0%	0%	0%	73%	32%	0%	0%	34%	0%	57%	19%	15%	0%	59%	8%
23	62%	0%	0%	0%	54%	0%	0%	0%	25%	0%	46%	17%	18%	0%	60%	5%
24	36%	0%	11%	42%	39%	0%	44%	4%	0%	4%	65%	18%	8%	7%	67%	0%
25	0%	0%	0%	0%	100%	0%	86%	6%	60%	4%	22%	9%	27%	4%	48%	12%
26	6%	0%	0%	0%	91%	4%	94%	8%	42%	9%	48%	8%	23%	0%	61%	8%
27	19%	0%	3%	12%	54%	47%	0%	0%	39%	0%	35%	8%	15%	2%	67%	8%
28	16%	0%	4%	16%	46%	100%	0%	0%	42%	0%	40%	5%	15%	0%	71%	9%
29	15%	0%	0%	0%	60%	0%	0%	0%	25%	0%	28%	6%	17%	19%	52%	6%

ID: identification number; N%CAN+Mg = share of calcium ammonium nitrate+Mg to N fertilization, etc.; SL to CA = share of fertilizer categories SL(single low), SH (single high), CL (compound low), CH (compound high), and CA (lime fertilizer) to total nutrient supply.