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Use of site-specific nitrogen fertilisation: Experiences of farmers from Baden-Württemberg

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Site-specific nitrogen fertilisation offers an opportunity for small-scale agriculture to meet legal requirements and future challenges (e. g., lack of resources, increased production costs, documentation requirements). Nevertheless, its use on farms is restrained; inhibiting factors here are the investment costs and the lack of knowledge of the actual added value for everyday farm work. The study therefore examines (i) the decision-making and implementation process and (ii) the changes in everyday farm work with regard to site-specific nitrogen fertilisation based on interviews with six arable farms. The results show that the farmers surveyed perceive positive effects, but that the familiarisation process is time-consuming due to technical challenges. Overall, there is a lack of skilled contact persons to provide support. In this respect, specific training courses for farmers and specialised personnel will be highly relevant in the future. The results of this study also show that it will be important in the future to establish networks for the targeted exchange of experience.

Keywords
Site-specific nitrogen fertilisation, precision farming, digitalisation

Future agriculture will inevitably have to be able to deal with numerous challenges in terms of sustainability. These include economic (e. g., increased production costs, competitive pressure and structural change), ecological (e. g., climate change, groundwater pollution, lack of resources) and social problems (e. g., shortage of skilled labour, physically demanding working conditions) (BMEL 2023a, Misaal et al. 2023, Rob and Lorenzo 2019, Weber et al. 2022). In this respect, the use of digital technologies is seen as an added value and promising tool for small and large-scale agriculture. For example, the digital technology of site-specific nitrogen fertilisation (SSNF) has increased (i) economic (e. g. saving on fertiliser inputs), (ii) ecological (e. g. saving and targeted, demand-oriented application of fertilisers, compliance with the German Fertiliser Regulation) and (iii) social (e. g. making work processes more flexible and reducing the workload through automatic documentation) potential (Blasch et al. 2021, Bongiovanni and Lowenberg-Deboer 2004, Gandorfer and Meyer-Aurich 2017, Rakun et al. 2022, Rösch et al. 2005). In practice, however, it is clear that active use is cautious in the EU in some cases (Groher et al. 2020, Rakun et al. 2022). This observation is particularly confirmed in smaller agricultural structures such as those in Bavaria and Baden-Württemberg in Germany (Gabriel and Gandorfer 2022, Gabriel and Gandorfer 2023, Pfaff et al. 2023), although these would particularly benefit from the technology due to the heterogeneity of the land (Munz and Schuele 2022).

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Taking into account the diffusion process (Rogers 2003), it can be concluded that SSNF is not yet widespread due to the lack of sufficient critical mass. In this regard, inhibiting factors can be primarily of a financial nature (Gabriel et al. 2021, Pierpaoli et al. 2013). Furthermore, the lack of availability of knowledge and expertise on the actual added value can have a negative impact on the likelihood of adoption (Cisternas et al. 2020, Kolady et al. 2021), especially since the economic added value of SSNF has not yet been comprehensively demonstrated and the ecological effects can vary depending on the method (Ebertseder et al. 2003, Gandorfer 2006, Gandorfer and Meyer-Aurich 2017, Langenberg et al. 2017, Lambert and Lowenberg-Deboer 2000, Rösch et al. 2005, Wagner 2010). There is currently a lack of impartial contacts and formats that can provide comprehensive, technology-specific information and thus support farmers in their decision-making (Cisternas et al. 2020, Shang et al. 2021). It is only possible to anticipate to a limited extent how everyday farm work will change after investing in a digital technology (e.g., SSNF) and what challenges will result from this.

It is known that the use of digital technologies can generally lead to a change in the work of a farmer and thus in everyday farm work (Reith et al. 2023). Based on the current state of research, there are assumptions as to the areas of the everyday farm work in which changes can be expected as a result of the use of digitalisation. As there are currently no comparable studies on the various areas of everyday farm work for site-specific nitrogen fertilisation on this scale, the general areas of impact of digital technologies are presented here. A selection is shown in Table 1.

Table 1: Possible areas of impact of digital technologies in everyday farm work (selection included, not a complete list)

Possible areas	Exemplary sources
Work processes and organisation, work requirements and precision	Knierim et al. (2019), Kehl et al. (2021), Prause (2021), Rolandi et al. (2021), Zscheischler et al. (2022), Reith et al. (2023)
New (digital) forms of work	Hansen et al. (2020), Goller et al. (2021), Kehl et al. (2021), Reith et al. (2023)
(Flexibility of) working day organisation	Schewe and Stuart (2015), Barrett and Rose (2020), Goller et al. (2021), Kehl et al. (2021), Sparrow and Howard (2021)
Work motivation	Schewe and Stuart (2015), Barrett and Rose (2020), Goller et al. (2021), Kehl et al. (2021), Sparrow and Howard (2021)
Family/leisure and work-life balance	Reichardt and Jürgens (2009), Frey and Osborne (2013), Carolan (2017), Pfaff et al. (2023), Reith et al. (2023)
Knowledge/skills/know-how	Reissig (2021)

Furthermore, Metta et al. (2022) differentiate the effects of digital technologies into four categories, which were applied ex-post in the qualitative content analysis in this study (see Material and Methods and Appendix II) in order to categorise the changes experienced by the farmers surveyed:

(i) boosting effects (improving the efficiency of existing activities),
(ii) depleting effects (worsening the efficiency of existing activities),
(iii) enabling effects (creating new opportunities) and
(iv) disenabling effects (reducing existing opportunities).

Studies in innovation research indicate that negative effects and experiences in the implementation process of innovations have an inhibiting effect on the (further) adoption of digital technologies (e.g., Rogers 2003). This can, for example, lead to farmers returning to traditional working methods and techniques (Driessen and Heutinck 2015, Lundström and Lindblom 2021). A discrepancy between the expected benefits of digital technologies after their implementation (Barrett and Rose 2020, Duncan et al. 2021) and their actual added value compared to traditional ways of working (Klerkx and Rose 2020, Regan 2019) can also have the effect of inhibiting uptake due to a lack of clarity about the added value in everyday farm work (Cisternas et al. 2020, Kolady et al. 2021). It is therefore necessary to better understand the technology-specific (decision-making and) implementation process and the associated effects experienced. This can create transparency for farmers as to whether and to what extent the expected technology-specific added value can be realised compared to the original way of working. It can also help to draw further conclusions for more needs-based support measures through information, education and advice.

In the context of this study, the term 'everyday farm work' is used to describe the activities involved in crop production on the farm in relation to the nitrogen fertilisation process. This study deals with SSNF at the level of the everyday farm work, as changes in this area are relevant for the (daily) workflow and the operational success of the activities. With reference to the innovation decision-making process according to Rogers (2003), the focus is on the implementation phase of innovations (in this case SSNF) and the individual application in day-to-day work. Although purely economic effects are also primarily relevant for the decision-making process, once digital technologies have been acquired, they do not play a sole role in the perceived success of implementation during active use on the farm (Munz 2024, Pfaff et al. 2023). Based on the problem and research gap described above, the following research questions arise, which are to be answered qualitatively and descriptively with the help of the study on SSNF:

(i) What is the course of the decision-making and implementation process on the farms surveyed? and

(ii) What changes do the farms surveyed perceive in their everyday farm work as a result of using SSNF?

Basics of site-specific nitrogen fertilisation (SSNF)

Site-specific farming, one of the first applications of precision farming in the early 1990s, is based on the division of areas into zones with the same characteristics (sub-areas) and the corresponding adaptation of the farming strategy. From soil cultivation to plant protection, all work steps can be carried out on a site-specific basis (Balafoutis et al. 2017, Gandorfer and Meyer-Aurich 2017).

There are basically two SSNF strategies: The first strategy involves applying more fertiliser in areas with high yield potential. The aim of this strategy is to reduce costs and environmental losses on unproductive areas with poorer fertiliser utilisation and to promote areas with high yield potential in order to increase yields and quality. The variable application rate therefore aims to provide the plants with an optimum supply by promoting high-yield zones with a higher fertiliser quantity and reducing fertilisation of low-yield zones (differentiation strategy). The second strategy aims to supply low-yielding areas with more fertiliser and fertilise high-yielding areas correspondingly less in order to achieve a more homogeneous crop and uniform ripening. This should enable higher yields with the same total amount of nitrogen (N) or the same yield level with reduced nitrogen input. Further advantages of SSNF are less stored grain, uniform and better product qualities such as protein content and a lower environmental impact (Heege 2013). Figure 1 shows different ways of applying SSNF: the map approach, the sensor approach and the map overlay (Heege 2013).

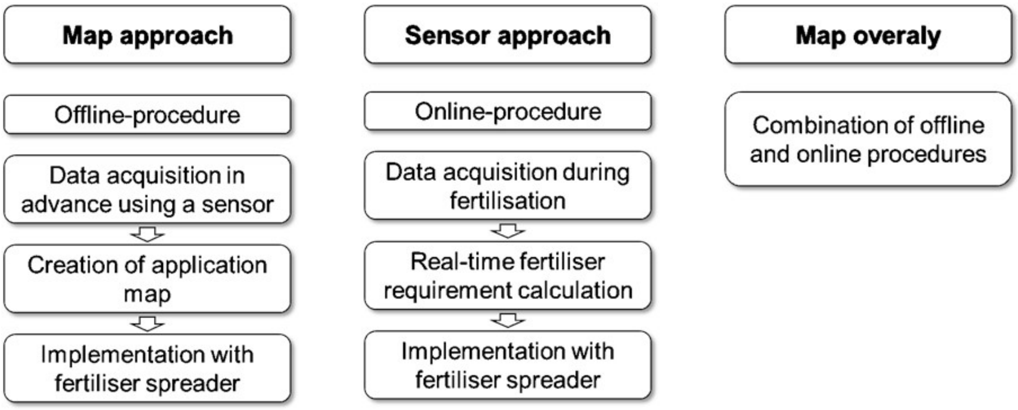

Figure 1: Possible applications of site-specific nitrogen fertilisation

In practice, the map approach is also known as the offline method. Data is recorded in advance using a sensor, which captures remote sensing data, drone images and yield maps in order to derive the nitrogen requirements of the crop based on the biomass or green colouration of the plants. Soil maps can also be used to derive spreading rates. A corresponding spreading rate map (application map) is created and implemented with the fertiliser spreader.

Alternatively, application maps can also be generated by using sensors that provide real-time data (so-called 'online method'), for example in sensor-based nitrogen fertilisation. In the sensor approach, the development and green colouration of the crop during fertilisation is recorded directly using a nitrogen sensor (N sensor) in order to draw conclusions about the fertilisation requirement. With some sensor systems, sufficient plant development is a prerequisite, which is why the first fertiliser application must be carried out without a sensor.

It is also possible to combine both methods by using a sensor-based approach with the overlay of yield potential maps. This combination enables more precise and efficient management of areas in agriculture. The use of application maps and sensors thus plays a decisive role in the implementation of site-specific management strategies and contributes to optimising the use of resources and increasing the quantity and quality of yields. The fertilisation process itself is documented accordingly and can be transferred to a digital field record or a Farm Management Information System (FMIS).

Certain technical components are required to be able to use SSNF to its full extent. First of all, ISOBUS functionalities should be available and activated for the fertiliser spreader. The tractor requires a job computer, ISOBUS equipment and a GPS receiver. The N-sensor is essential when using the online method. Appropriate software is required to create the application maps for the offline method. The additional equipment of the tractor with a steering system/steering assistant can further support the working precision.

Material and Methods

In order to analyse the farmers' experiences with SSNF, qualitative interviews were conducted. As a result, the focus of the analysis is on the subjective perception of the individual farms, as they are the main users of the technology and therefore have to deal with the respective effects. A total of six conventional farms in Baden-Württemberg were surveyed, which were acquired and selected based on a targeted sampling. Baden-Württemberg is characterised by a small-scale agricultural sector (Statistisches Landesamt Baden-Württemberg 2021), which is why this framework is suitable for examining the SSNF with regard to the possible potential in such regions. The decisive factor was that farms were selected that actively use SSNF and are located in small-scale agriculture in Baden-Württemberg. Table 2 below summarises the farm and personal characteristics of the surveyed farm managers (B1–B6). The farms surveyed in this study all have small(er) structured areas, but with a range of 75 to 660 ha, they are above the Baden-Württemberg average for the total area (in arable farming). Of the approx. 39,000 farms in Baden-Württemberg, only 25% manage more than 50 ha and 9% more than 100 ha (Statistisches Landesamt Baden-Württemberg 2021). This is in line with the assumption that larger farms are more likely to use digital technologies (Gabriel and Gandorfer 2023, Shang et al. 2021). The data saturation required to make reliable statements can be ensured by the fact that a theoretical saturation (Strauss 1991, Glaser and Strauss 1998) exists within the surveyed farms. This is because all the farms surveyed had individual starting positions and circumstances, which meant that a broad spectrum of perspectives and experiences could be included. Nevertheless, it was possible to draw similar conclusions about the content of the surveyed farm managers' assessments.

The interviews with the farm managers were conducted using a guideline based on open questions (Meuser and Nagel 2009). The guideline is based on the research questions explained at the beginning and deals with the decision-making process, the implementation phase on the farm and the perceived changes in everyday farm work. Accordingly, the guide (see also Appendix I) is divided into the following sections:

(A) Recording of farm and socio-demographic characteristics,
(B) Description of decision-making and expectations,
(C) Description of the first phase of implementation, time required and problems and
(D) Changes in everyday farm work due to the use of digital technologies.

In the first quarter of 2024, the qualitative interviews took place in the form of both on-site farm visits and/or video interviews. The interviews were recorded, anonymised and uniformly transcribed according to the specifications of Kuckartz (2018) and Dresing and Pehl (2017). A qualitative content analysis according to Mayring (2015) was then carried out using MAXQDA software. The principle of deductive categorisation and structural content analysis according to Mayring (2015) was applied. Firstly, theory-led deductive super- and subcategories as well as structural dimensions were developed. On this basis, the respective characteristics were determined and the category system was created (see Appendix II). For this purpose, definitions and coding rules were formulated for each category. Once the category system had been finalised, the interview transcripts were analysed, including the extraction of relevant references, paraphrasing and summarising the findings. As the questions to the farmers were formulated openly, the results presented below were derived from the interview material. On this basis, the following results could be compiled from the analysed interview material.

Table 2: Personal, farm and technical characteristics of the farms surveyed for site-specific nitrogen fertilisation (SSNF) B1–6

		B1	B2	B3	B4	B5	B6
Personal characteristics	**Gender**	male	male	male	male	male	male
	Age (in years)	25	39	44	54	24	38
	Work experience (in years)	10	16	24	28	6	22
	Highest level of agricultural training	B.Sc. in Agriculture	Diploma in Agriculture	Agricultural & equine technician	Agricultural Engineer, B.Sc. in Agricultural Sciences	Agricultural apprentice–ship, B.Sc. in Agricultural Sciences	Agricultural machinery mechanic, training as a part-time farmer
	Experience with digital technologies	high, very affine	high, very affine	high, very affine	not very affine	medium affinity	medium affinity
Farm characteristics	**Legal form**	Sole proprietorship	Limited partnership (KG)	Civil law partnership GbR	Sole proprietorship	Sole proprietorship	Sole proprietorship
	Type of business	Part-time farming	Full-time farming	Full-time farming	Full-time farming	Part-time farming	Full-time farming
	Farm size (in ha)	75	660	154	115	97	82
Technological characteristics	**Previous mechanisation/ digitalisation status before investment**	Steering system	GPS steering assistant & fertiliser spreader was already there	Track guidance installed, 1 tractor with ISOBUS	There was nothing before, upgrade with GPS and ISOBUS, new tractor for site-specific sprayer, digital field records.	No new tractor since 2013, RTK steering system installed on 2 tractors in 2018 1 older tractor made ISO-BUS-capable	New purchases were planned anyway, so the ferti-liser spreader was already compatible with SSNF
	Currently used techno-logies for fertilisation process	SSNF online with map overlay, in use for 4 years	SSNF online in use for 7 years	SSNF offline based on satellite images in use for 3 years	SSNF online with map overlay, in use for 1 year	SSNF online with map overlay, in use for 6 years	SSNF (online, offline, or combined with map overlay), in use for 3 years
		Steering system	Steering assistant	Steering assistant and track guidance		Steering system	Steering system

Results

Decision to invest in SSNF: motivation and sources of information

From the perspective of the farmers surveyed, there were various reasons in favour of investing in SSNF. Due to the field conditions (heterogeneous fields, slopes, irregularly shaped fields) as well as the various investment funding opportunities and the significant financial incentives (agricultural investment programme, funding programme for agri-environment, climate protection and animal welfare (FAKT II)) as well as their own enjoyment of digitalisation, the farm managers surveyed were increasingly concerned with the possibilities of SSNF and ultimately invested. In addition, it is not possible to apply fertiliser as manually controlled as a data-based technology, because 'every sensor is better than the human eye', according to B2. This also means that fertiliser regulations can be better observed. Expectations associated with the investment in the SSNF were described as follows: In addition to improved work efficiency and possibly time savings, farm managers hope for better fertiliser utilisation and distribution through more precise application of the fertiliser.

In order to find the best solution for each farm, the farm managers used various sources of information in parallel to make their investment decision (Figure 2). In particular, advice from manufacturing companies and the exchange of experiences among colleagues are used equally intensively by all farms in order to obtain the best possible product information and a realistic assessment of the advantages and disadvantages. Experience at training farms from the education (B6) and exchanges with universities (B3) are used in some cases as well to decide on the most suitable product.

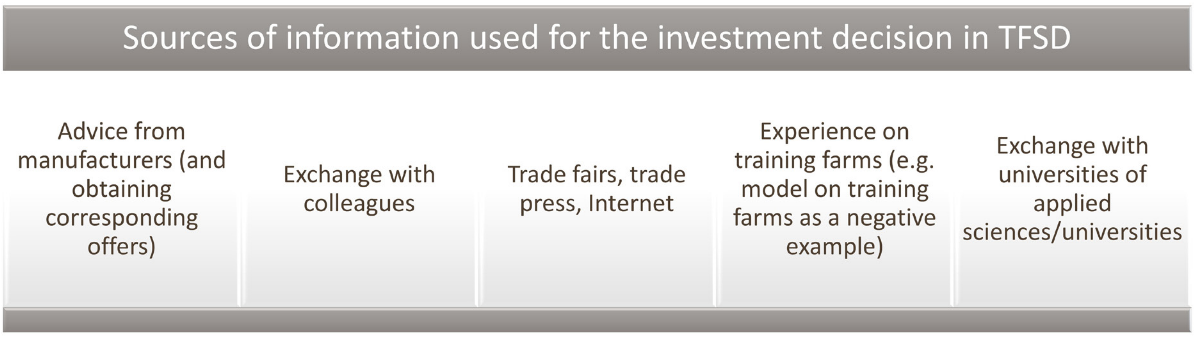

Figure 2: Sources of information used by B1–6 prior to the investment decision in SSNF

The farm managers surveyed therefore used a wide range of information to find the most suitable offer for their own farm. One farm manager (B3) mentioned that the agricultural office was no longer a useful point of contact and another (B2) that he had changed the manufacturer despite the trial device, as follow-up investments would have been necessary. Nevertheless, all the farm managers interviewed emphasised that in the end it was a very short-term decision based on 'having a gut feeling'.

Perception of the implementation phase on the farm

The conversion or retrofitting of the existing vehicle fleet to SSNF was partly carried out completely by the farmers themselves (B1, B6), partly by manufacturers or dealers (B2, B3) and partly by both in combination (B4, B5). The phase following the investment decision, in which the SSNF was actively introduced on the farms, was reflected very similarly by the farmers surveyed: On five out of six farms, a guidance or steering system was already in place when they started using SSNF. At the beginning of the SSNF implementation phase, the initial euphoria was often very high. Then, according to the farm managers interviewed, the first problems arose and the farm had to keep at it and get the appropriate support. Both time and patience were required before the basic settings were finalised. However, this was generally categorised as something that could be solved independently. After a short briefing from the manufacturers, some farms continued to work with the manual and intuitively tried out various aspects. However, all farms emphasised that the instruction provided by the dealer or the factory representative was insufficient and/or too short. The support provided by the manufacturers themselves was rated better, but the waiting times were not insignificant. For this reason, the farmers surveyed increasingly rely on help from family and private contacts to people with an affinity for technology (e. g., programmers). B1 and B5 also work together with university-led research projects, which enables them to obtain additional specialist input. Overall, it was difficult for beginners to familiarise themselves independently with the subject matter of SSNF.

During implementation and use, incorrect entries, e. g., when specifying fertiliser quantities, were unavoidable for the majority of the farm managers surveyed due to a lack of knowledge. Although these input errors were undesirable, they served as important learning opportunities and helped to improve the technology adoption process. Difficulties were also encountered, particularly in the creation of PDF documents for documentation as part of FAKT funding (B2, B4, B5, B6). As a result, additional support had to be sought. The documentation in the field works without errors, but there is a problem with the transfer to the digital field records. Based on experience with such malfunctions in the automatic documentation, one farm (B6) specifically generated screenshots of the processed application maps to ensure adequate documentation. Furthermore, he changed the FMIS. The new FMIS offered extended functions and enabled simplified importing and conversion of processed prescription maps into PDF format. According to the interviewed farm managers, this is particularly advantageous with regard to applying for subsidies through the agricultural investment subsidy programme (FAKT), as it ensures efficient documentation and archiving of work processes.

The perceptions described above are the same for all farm managers, regardless of whether they use the online method or the offline method. In the following, experiences are reported that relate only to the use of the N-Sensor and thus the online procedure. This is because the initial phase of implementation on individual farms was characterised by a number of other challenges, particularly among the farmers surveyed who combine steering systems and N-sensors. One solution approach (B5) was to initially rely on offline application maps due to malfunctions with the N sensor. In the subsequent process, the original sensor was used repeatedly, but it continued to exhibit connection problems and thus impaired operating efficiency. An additional terminal was purchased as a solution. However, it turned out that this device was only 50% functional. This farm (B5) is therefore considering selling the N-sensor again, as it was too often the case that it did not work despite repeated attempts. However, such malfunctions, such as connection difficulties, actually occurred at the majority of farms using N-sensors (B1, B4, B5, B6). In such cases, the already established offline application cards were used, the N-sensor was no longer used but kept and, if necessary, tried again in the following year. The farm managers interviewed also emphasised that it was sometimes not transparent how the N-Sensor worked, forcing them to trust the technology completely.

The time required until the SSNF is fully integrated into the nitrogen fertilisation process is described as individual to the farm and person, regardless of the method chosen. According to the farmers interviewed, it is particularly high at the beginning, but this gradually evens out with the automated documentation after fertilisation has taken place. The first year or the first season is described as the 'learning year', in which the correct settings, how to deal with faults (e. g., on the N-sensor) and the automated documentation must be learnt. Furthermore, this year is needed in order to be able to work through the fertilisation process in more detail, e. g., with the various fertiliser applications and plant stages.

All the farmers interviewed emphasised very clearly that a major problem was the lack of know-how among potential contact partners. In retrospect, they would have liked the following: workshops, dealers and manufacturers should have more skilled personnel for better (prompt) support and faster response times. In addition, customer service should be able to react more quickly, as otherwise the possible time window for fertilisation has often already elapsed. Furthermore, from the point of view of the farm managers surveyed, it would be helpful if the dealers or manufacturers could also address possible sources of error during the briefing, for example, in order to avoid certain input errors or input-specific aspects. Assistance on how to enter field boundaries correctly (e. g., areas with slopes) would also be an advantage. None of the farm managers surveyed mentioned the role of advisory services, citing a lack of expertise and experience on the part of the advisors.

From expectations to experience: Change in everyday farm work

When the surveyed farm managers reflect on whether their expectations of SSNF have materialised in reality, clear trends emerge. Firstly, the automated documentation of the fertilisation process generally works well, although a majority of the farmers surveyed regularly encounter problems with this. Furthermore, the fundamental question is whether farm managers have more expectations in terms of fertiliser savings, increased yields or better fertiliser distribution. The farm managers surveyed mainly expected better fertiliser distribution. So far, according to the farmers surveyed, the areas look more homogeneous, the distribution is more in line with requirements and the quality appears to be even across the fields. Whether the yield is actually higher as a result of SSNF remains unclear for the farm managers surveyed and is more of an intuitive assumption: 'I don't have anything directly measurable, but I do think that it makes a difference,' says B6. The reason for this is that the farmers surveyed do not, for example, record yield maps and the associated data for yield evaluation on a field- and section-specific basis or have done so in the past. Therefore, subjective assessment variables such as areas that appear more homogeneous are used. For example, the yield of B6 has increased since the use of SSNF, but according to the farm manager this could also depend on many other factors (e. g., weather). Possible fertiliser savings were only measured to a limited extent for individual farm managers (B1, B3). However, according to B3, this is so low that it would not pay off with the current prices for technology and the market sales prices for grain.

Overall, according to the surveyed farm managers, farmers can deal more intensively with the fertilisation process and assess high and low yield areas, sometimes achieve higher yields or make savings. Based on Metta et al. (2022), the changes in everyday farm work mentioned by the farmers surveyed can be categorised as shown in Figure 3: The positive perception is that automated documentation with SSNF can save working time in the office, equalise work peaks and thus lead to more flexibility if it works smoothly, as 'documentation is simply 100%' (B1). Work efficiency can also be increased through needs-based fertilisation because the working time per crop can be used more effectively, according to B1 and B3. As B2, B5 and B4 point out, work peaks can be handled by automatic documentation and precise field- and sub-zone-specific fertiliser evaluation in the winter months. According to B5, this allows you to 'push work peaks into the area where you have more time'. One empowering effect is that the areas and their subzones become more transparent for the farmer and 'you can visualise the areas better' (B2). This enables the farmer to develop a deeper understanding of these areas and to act in line with requirements. Furthermore, according to B1 and B2, the allocation of work can be simplified, for example, as the pre-planning of the fertilisation process means that field specifics are stored on the tractor. When using SSNF with a steering system, this results in a largely automated work process that can also be carried out by workers with less experience in nitrogen fertilisation.

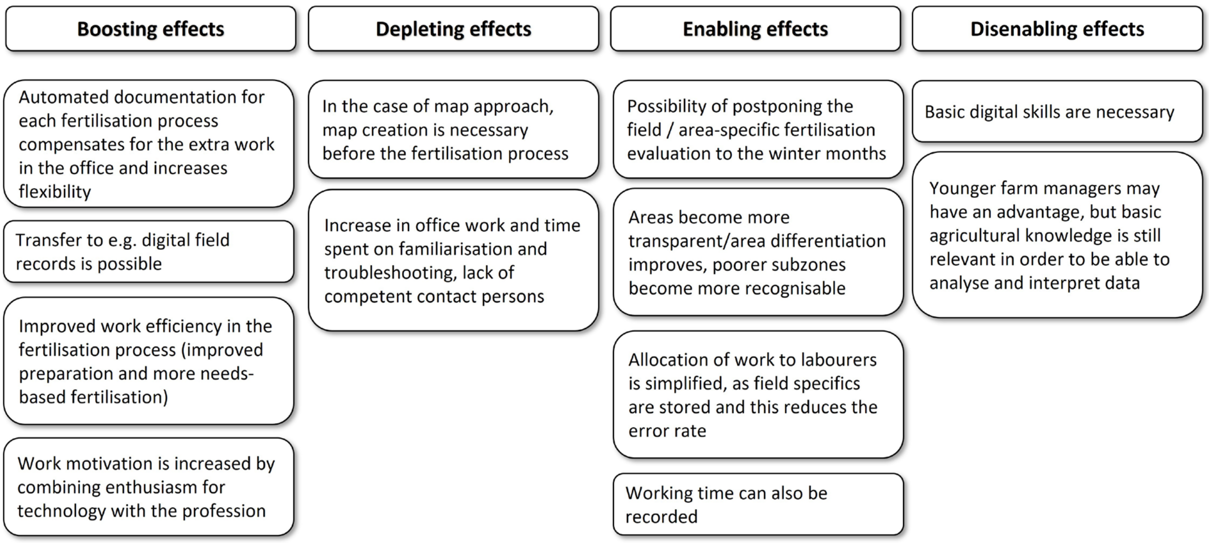

Figure 3: Perceived changes in everyday farm work through the use of SSNF, illustration based on Metta et al. (2022)

When using the map approach, 'relatively extensive advance planning is necessary, you can't just say you're going to fertilise', says B5. If there are disruptions, B2 states that 'you have to want to deal with them, because then it is no longer a purely agricultural activity, but goes beyond that and you have to pick up your mobile phone and email or wait on hold until you get support'. Overall, all farm managers also emphasise that the experience gained over time is very important and that this makes it easier to operate. Nevertheless, it is important to always keep in mind how the SSNF technology works and whether the SSNF working method is similar to or differs greatly from the conventional working experience without a site-specific application.

Influence of digital technologies on the perception of strain and stress

All six farm managers were asked to compare the perceived relief and stress caused by the use of SSNF. The results show that the above-mentioned changes are predominantly perceived as a relief. Furthermore, the relief is only noticeable if you have familiarised yourself with the system and know how to use it. When using offline maps, the workload is reduced as soon as the corresponding application maps have been developed for the first time, as this step is still necessary in subsequent years, but can be carried out much more quickly and easily thanks to the knowledge already gained from the previous year.

According to B1, in retrospect he should have taken this investment step towards SSNF much earlier. The farm managers emphasise that, as a user, you should have a corresponding enthusiasm and affinity for technology, as otherwise disruptions or challenges could be too much of a burden, according to B6: 'If you don't enjoy it, then perhaps the negative side is sometimes even higher than the positive side' and B2: 'You also have to have fun with it´.

Figure 4 shows the perception of stress among the farmers surveyed after the introduction of SSNF. These subjective experiences were explicitly mentioned in the context of using SSNF; other influencing factors were not specifically considered. According to this, (negative) stress is triggered in the short term when operational or technical problems occur in certain situations that can be attributed to SSNF. Finally, the time required can increase and cause stress if certain SSNF functions do not work as expected, for example due to an incorrectly set tick. It can then take some time before the error is found and corrected.

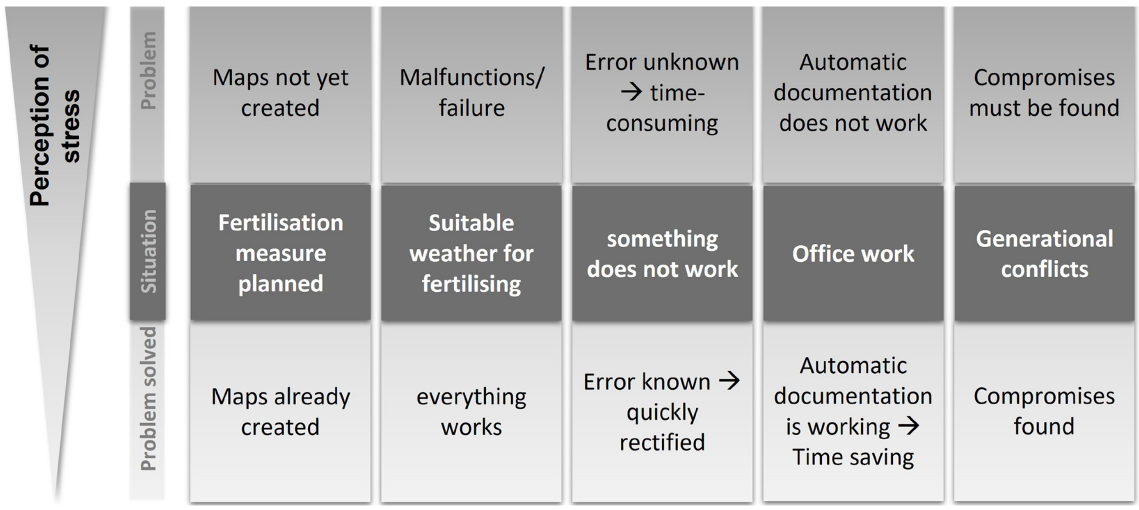

Figure 4: Stress perception of the interviewed farm managers after the introduction of SSNF in exemplary situation

The technology affinity of the farmers surveyed in this study compensates for the above-mentioned stressful situations, as it enables them to react more quickly and effectively to such breakdowns and malfunctions than those with a lower technology affinity and less digital-specific know-how. According to the farmers interviewed, differences in affinity with technology can lead to generational conflicts. An example of an inter-generational compromise is that a farm manager (B1) fertilises part of the land with site-specific technology and another part without.

Furthermore, it can be seen that in the long run, especially in combination with a steering system, it is possible to work in a much more relaxed and therefore less stressful way when fertilising in plant production.

Discussion

In principle, it can be said that all of the farm managers surveyed would choose to use site-specific nitrogen fertilisation again at any time, even if they would make some adjustments to the procedure, e.g., other more specific questions during training, and change products or dealers. The challenges of implementing and using site-specific nitrogen fertilisation are discussed below and possible solutions are proposed on this basis.

It is important to note that the results are based on the subjective perceptions of the six farm managers surveyed. Each farm is individual, e.g., in terms of site conditions, land availability and structure, labour resources, level of education, condition and age of the tractors used or financial possibilities. Therefore, the results cannot be generalised, but they are suitable for gaining deeper insights into the introduction of site-specific nitrogen fertilisation in arable farming in Baden-Württemberg.

Decision in favour of SSNF - background and motivation?

As with other digital technologies in agriculture, the use of SSNF is only possible if farmers have the necessary motivation (Pfaff et al. 2023a) and basic digital skills (Reith et al. 2023). Four of the six farmers surveyed consider themselves to be very tech-savvy. Age, professional experience, level of education, legal or commercial form and farm size did not play a decisive role for these farmers. Nevertheless, age can have an influence if, for example, generational conflicts arise, as older people may not accept the technology and want to continue farming without SSNF. As a result, farms such as B1 may have to find compromises in order to resolve generational conflicts and continue to manage everyday farm work together, even if this means that some of the land continues to be farmed without SSNF.

The financial support provided by investment subsidies was a decisive factor for the farmers surveyed in favour of investing in SSNF. This is because it is often not possible for small, diversified farms in particular to make a (sometimes very high) investment in this relatively small area of work, nitrogen fertilisation, as it hardly pays off in terms of the overall process and the cultivated area (Sonntag et al. 2022). For an average farm in Baden-Württemberg (50–100 ha), the costs are between € 23,000 and € 33,000, depending on whether the online or offline method is used (Munz et al. 2024). Furthermore, the farmers surveyed have difficulties assessing the profitability of SSNF. This results, for example, from a lack of field- and sub-zone-specific documented fertilisation and yield data, which makes it difficult for the farmers surveyed to prove the profitability of their investment. Uncertainty about the potential for improved profitability to amortise the investment therefore often prevents farmers from making such an investment (Barnes et al. 2019). Munz and Schuele (2022) recommend a precise calculation of the financial situation in order to decide which investment can pay off under individual farm conditions. A suitable tool for this could be the WiLaDi profitability calculator (Pfaff and Munz 2024).

If the purchase of SSNF is financially feasible, the advantages of this technology can be considered. The small-structured areas in Baden-Württemberg are highly heterogeneous, which means that subzones often cannot be optimally supplied with fertiliser (Engelhardt 2004). SSNF supports more precise fertiliser distribution and utilisation (Mittermayer et al. 2020) and helps to balance out the heterogeneity of plant populations (Schmitz 2017). This is also confirmed by the subjective assessments of the farmers surveyed. In principle, all farmers surveyed stated that they were satisfied with the investment. However, satisfaction depended on whether the main expectation was fertiliser savings, a higher yield or better distribution of the fertiliser. The optimised distribution of fertiliser was particularly important to the farm managers surveyed. The answers of the surveyed farmers regarding an increased yield or more homogeneous areas are based on their subjective assessment, not on measured results. Furthermore, it is not possible to prove whether the increased yield was due to the SSNF or to specific weather conditions. Two farms show – subjectively – savings in the amount of fertiliser, but so small that this does not contribute to the amortisation of the technologies – especially in view of the current market sales prices.

This assessment is in line with the divergent assessments of previous studies on the economic and ecological savings potential of SSNF (Blasch et al. 2021, Bongiovanni and Lowenberg-Deboer 2004, Ebertseder et al. 2003, Gandorfer 2006, Langenberg et al. 2017, Rösch et al. 2005). It can therefore be said that the use of SSNF on these farms tended to lead to a subjective improvement in the homogeneity of the areas and in the quality of the crops due to a needs-based fertiliser distribution. Based on these findings and the fact that the actual (economic) added value of SSNF cannot be estimated in advance, it is not surprising that studies such as Gabriel and Gandorfer (2022, 2023) or Pfaff et al. (2023b) describe the active use of SSNF as cautious.

Entry into SSNF - facilitated by steering assistants, track guidance or steering systems?

Digital technologies such as steering systems can significantly reduce the driver's workload, allowing them to concentrate on the actual work in the field (Schmitz 2017). A steering system can also be used to drive in poor visibility conditions or allow the driver to perform other tasks on the side or make it easier for non-specialists to learn how to use the machine. This is particularly helpful when, for example, new technologies such as SSNF are implemented, as it allows the farmer to familiarise themselves with the technology while driving, which can reduce errors and stress in the long term. Steering systems are often already installed on newer tractor models (Schmitz 2017). Upgrading with SSNF is easier with steering systems, for example, as digital field records are already in use in some cases, which means that field boundaries are already recorded (Schmitz 2017).

Due to the advantages mentioned, steering assistants, guidance or steering systems are used relatively frequently in arable farming (Gabriel et al. 2021) and are well suited for beginners (Paetow 2017), as they are relatively inexpensive (Bahrs 2018) and quickly amortise due to the potential savings in operating resources (Paetow 2017). However, it should be added here that the farms in Paetow (2017) were larger in terms of area and structure. This means that the cost advantages mentioned are more likely to apply to farms with a sufficiently large cultivation area (Munz and Schuele 2022), but this can be very farm-specific. Five of the six farm managers surveyed also started using steering assistants, track guidance or steering systems. By combining steering systems with SSNF, the fertilisation process on the farm can be made considerably easier, as both the documentation and the driving process can be relieved.

Challenges in the implementation of SSNF and their practical implications

With regard to the implementation process, the farmers surveyed stated that it takes around a year ('learning year') to become familiar with the system and to deal with challenges such as malfunctions, correct settings and automated documentation, as the work steps in the fertilisation process change.

Initially, some farmers had problems with the automatic documentation when implementing SSNF in existing or older digital field records. The solution was to change the FMIS and the associated effort and additional screenshots as a safeguard in the case of system failure. This raises the question of whether better prior consultation could have avoided this transition.

One farmer mentioned that the intended more precise application did not work with N-Sensor in some cases, despite additional investments in expansion. Due to these problems, he will sell the N-Sensor and work with offline maps again, as he considers this to be reliable and more transparent. The problem here was not the technology itself but the lack of competent support. As there was no competent contact person available, this led to negative experiences with the SSNF, so that the farmer gave up this sub-technology.

The literature also confirms that negative experiences can have an inhibiting effect on the further use of innovations (here SSNF) (Rogers 2003) or lead to a return to traditional working methods (Driessen and Heutinck 2015, Lundström and Lindblom 2021). However, a premature exit from such a (partial) technology can be problematic and uncertain from an economic perspective, as the investments in this technology are often not yet fully amortised. There may also be uncertainty as to whether amortisation could have been achieved at all in the future (Munz 2024).

This shows that there is an urgent need to establish a sufficient network of competent contact persons so that farmers can receive prompt support in problematic cases. In this way, incorrect purchases could be avoided and the time and associated (learning) costs for futile problem-solving could be used wisely. One possible approach here is direct networking between farmers, companies, advisors and other relevant stakeholders. A digital interactive map with all stakeholders could be set up for more concrete visualisation. By using it, interested parties could easily establish contacts, exchange knowledge and benefit from the experiences of others. This approach takes into account that the exchange of experience plays an essential role in decision-making and implementation (Pfaff et al. 2022, Giua et al. 2022).

The training on SSNF was also categorised as insufficient and/or too short by the farm managers surveyed. For example, there was a lack of information on possible input-specific sources of error or assistance with entering field boundaries. All farm managers would have liked better support and faster reactions, as the time window for fertilising is very short and therefore sometimes elapsed before shops, dealers, manufacturers or customer services responded. As a result, some of the farmers surveyed had to solve problems on their own or seek support elsewhere. Having a network of contacts is almost essential in agriculture, however, this should not be necessary to cover the areas of activity of dealers or manufacturers – a problem that is generally widespread in agriculture (Blasch et al. 2021). Consequently, although training for farmers themselves is also important (Pfaff et al. 2023a), there is a particularly great need to catch up on the training of specialised personnel (manufacturers, dealers, service centres). It could also be helpful to create a database (Zscheischler et al. 2022), which could be used to collect information and solutions from farms. Farms such as B6, which has changed its FMIS in the meantime, could document their reasons and experiences there and support others in their decision-making and implementation processes. A concrete approach here could be, for example, the 'FARMWISSEN' platform (https://farmwissen.de/).

Changes in everyday farm work through the use of SSNF

The introduction of SSNF has changed the nitrogen fertilisation process for the farm managers surveyed. For example, fertiliser applications should be adapted to plant stages, taking into account possible weather conditions. This can mean that skilled farmers have to spend more time in the office to prepare the fertilisation process, whereas non-specialist personnel could also sit on the machine, as the fertiliser application can be preset in advance. If a steering system is also used, for example, this makes it even easier to allocate non-professional labour. This can open up new possibilities for allocating labour during seasonal work peaks, especially in light of the shortage of skilled workers (Gindele et al. 2016, Pitson et al. 2020).

The automatic documentation not only simplifies compliance with the requirements, e.g., in the FAKT funding programme or with regard to the new fertilisation regulation, but also effectively saves working time and thus creates flexibility during seasonal work peaks. The fertilisation evaluation can be carried out in the winter months and the findings can be used for the following year. The use of SSNF leads to increased area transparency and a deeper understanding among the farm managers surveyed, which can significantly support demand-orientated, agronomic action. Against the background of declining numbers of agricultural apprenticeships (BMEL 2023b) and students (Destatis 2024), this could have a positive effect on the image of the profession and make the profession of a farmer more attractive, as farmers are thus able to work in a data-based and well-founded manner in fertilisation, in the best case with less effort.

However, the offline method requires extensive advance planning and preparatory work, which can limit spontaneous fertilisation decisions. Especially in times of climate change and rapidly fluctuating weather extremes (Misaal et al. 2023), this can make actual (stress-free) implementation more difficult. It is therefore important to develop strategies that enable foresighted planning in winter based on the fertiliser evaluation as well as fine adjustments shortly before fertiliser application based on current data. In this way, planning requirements can be harmonised with the necessary flexibility in the dynamic everyday farm work. Schleicher and Gandorfer (2018) also emphasise that the user-friendliness and compatibility of digital technologies must be increased. This assessment is also reflected among the farmers surveyed, as challenges arise in this regard both during the implementation process and after years of using SSNF, such as automatic documentation with digital field records or connection difficulties with the N-sensor. Such cases of troubleshooting can lead to additional work if the availability of in-house digital expertise or skilled contact persons is limited.

SSNF is predominantly perceived by the six operations managers as a relief. However, this positive perception is not universal and depends heavily on the quality of familiarisation, user enthusiasm and their affinity for technology. This suggests that targeted training for contact persons and/or farmers and support for farmers during the implementation phase are crucial and essential in order to overcome the initial hurdles and fully utilise the long-term positive effects of SSNF.

Conclusions

For five of the six farmers surveyed, the introduction of SSNF followed an existing investment in steering assistants, steering or guidance systems. Not only before, but also during and after the implementation of SSNF, the support provided by manufacturers, dealers, factory representatives or customer services was rated as inadequate and, above all, untimely. This sometimes resulted in misinvestments and long familiarisation periods. The feedback from the farmers surveyed in this study should be an impetus for change: practical solutions are needed so that these stakeholders can provide better support services to farmers and increase their confidence in technology.

Despite these negative aspects, the farmers surveyed stated that they predominantly perceived a reduction in workload after familiarising themselves with the technology. Nevertheless, the learning costs associated with familiarisation should not be ignored. The reasons for perceived relief are less financial and more of a social nature. The farmers surveyed stated that the SSNF enabled them, for example, to postpone the field and site-specific fertiliser evaluation to the winter months or to have easier work allocation and time recording. It was also mentioned that the automated documentation increases flexibility and compensates for the extra work in the office if the system is working properly. The combination with a steering system offers a much more relaxed and pleasant way of working in the field.

Based on the results of this study and its practical implications, concrete activities are needed to promote the use of SSNF in practice. In addition to (i) training farmers to make informed, farm-specific investment decisions and (ii) training skilled personnel to provide prompt, high-quality familiarisation and support, (iii) networks should be established in which farmers can exchange information with each other and with skilled personnel. Finally, a (iv) database with empirical values can be a helpful strategy for providing experience across the board. The basis for all of the approaches mentioned is that the various stakeholders (industry, (further) education, trade) in agriculture work together and that concrete concepts are developed for this in the future.

In addition, there is still a need for research in the area of farm-specific profitability of SSNF (offline, online, combined) on farms with small-structured areas or fundamentally small farm sizes.

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