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Profitability of smart farming technologies - Identification of economic success factors in small-scale agricultural regions

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Abstract:

Digitalization of agriculture shows positive effects on farm profitability but is also considered to be of great importance when it comes to the efficient use of limited resources and countering global problems (e.g. climate change, food security). However, since the introduction of the first precision farming technologies around 1990, high adoption rates could not be observed, especially in areas where small-scale farming is dominant. Until today, farms successfully applying smart farming technologies are mainly larger operations. Therefore, this paper is dedicated to analyze economic success factors, which favor the use of digital technologies in small-scale agricultural areas, but also to highlight the limitations of digitalization in these structures.

For this research, a calculation model has been developed, that enables a holistic view of the farm. Using empirical farm data and with the help of sensitivity analysis, the economic effect of implementing 27 different digital farming technologies is presented. The results show that very small farms (< 20 ha) are at a disadvantage with capital-intensive technologies. Furthermore, it can be shown that the success of implementing digital technologies is largely dependent on external factors (e.g. weather, soil), and is determined by initial conditions (e.g. technologies available on the farm). In summary, it can be stated that farmers in small-structured areas are by no means excluded from digitalization. For very small farms, the joint use of machines or the development of low-cost technologies can be seen as a solution.

Keywords:
Smart Farming Technologies, Economics, Small-Scale Agriculture, Case Study, Sensitivity Analysis

1. Introduction

In view of global challenges such as climate change, soil sealing and population growth, a safe and environmentally compatible food production is becoming increasingly important [1].Adaptation strategies of conventional systems lack a holistic perspective[2,3].One approach to achieving higher levels of productivity can therefore be seen in technological innovations[4].Site-specific management of fields, for example, can increase productivity and minimize environmental risks (e.g. nitrate leaching)[5].Similarly, autonomous machines can be used to address a labor shortage and provide targeted weed control without polluting the environment with herbicides[6].

Due to the high investment costs, almost only large farms have been able to use digital technologies so far[7,8]. Among farmers in small-structured agricultural regions, the opinion prevails that digital technologies cannot be used profitably[9–11]. However, large parts of Europe and Germany in particular are characterized by small-scale structures[12]. The state of Baden-Wuerttemberg was therefore selected as a model region to study the impact of digital technologies on farm profitability. The average farm size of 36,5 hectares and the high proportion of part-time farmers (65 %) are seen here as a particular challenge that needs to be addressed[13,14].

The economic impact of individual technologies in selected crops has been sufficiently investigated in previous studies[15–17]. However, investments in digital technologies are decisions that affect the entire

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farm. The demands placed on existing mechanization by digital technologies and the impact on overall farm profit of small farms have not yet been studied.

The aim of this paper is therefore (i) to identify factors that determine the economic success of a technology at the farm level, (ii) to show the limits of the profitability of different digital technologies through a sensitivity analysis of the results of the farms studied, (iii) and to identify opportunities for small farms to also participate in the digital transformation of agriculture.

2. Methods

2.1 Study area and data collection

For the calculation of the results, farm data were collected from eight farms (B1-B8, farm sizes between 11 ha and 530 ha) within the state of Baden-Wuerttemberg in spring 2021(**Figure 1**). For comparison, an average arable farm in Baden-Wuerttemberg (B0) was used, which is 65 ha in size. The selection of farms reflects the conditions in the federal state very well. With this sample, very small farms (< 20 ha) can be studied on the one hand, but also farms that are large by Baden-Wuerttemberg standards (> 150 ha).

The farms surveyed vary greatly in the design of their crop rotation. As a rule, a crop rotation with cereals, corn and another field crop predominates. Farm B1 (11 ha) is run as a sideline. Farms B2, B3 and B6 are mixed farms with livestock. Here, silage corn is grown instead of grain corn. In general, only the cultivation of arable land is considered. Other work related to animal husbandry is not included in the model calculation (e.g. harvesting of straw).

Work that occurs once a year on a small scale (e.g. harvesting) is usually performed by contractors. When implementing a digital technology on a farm in the model calculation (e.g. site-specific planting), the service is replaced by self-mechanization.

During the data collection, the status of the existing mechanization on the farms was surveyed. The retrofittability of the machines depends on their age (e.g. missing functions, compatibility problems, etc.). Farms B1-B3 and B5 cannot use retrofit kits in most cases due to their outdated technology. The remaining farms can partially retrofit. Some farms are already using some digital technologies (B4, B6-B8).

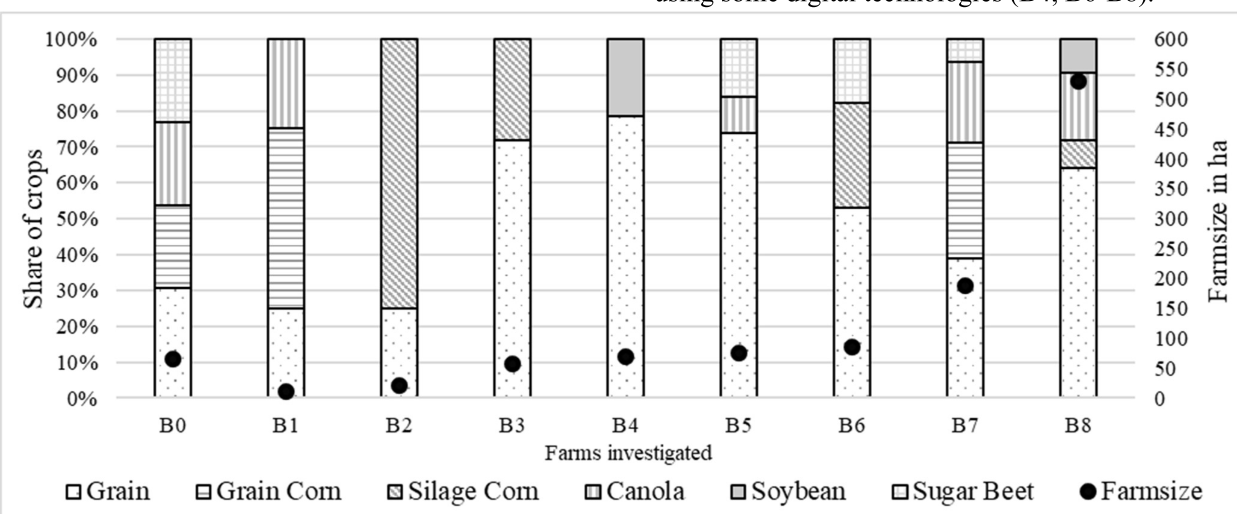


Figure 1: Investigated farms B0-B8 with shares of crops and farm size

2.2 Database and technology selection

A total of 27 technologies (T) were included in the database. For a clearer presentation, the variants of a technology were each combined into a technology group (TG). Technologies T1-T5 were combined to form the technology group TG 1 *"Automatic guidance Technologies"*, technologies T6-T9 form TG2 *"Mechanical Weeding Technologies"*, technologies T10-T13 are combined to form TG3 *"Section Control Technologies"*, T14-T17 to TG4 *"Site-Specific Soil Cultivation Technologies"*, T18-T19 to TG5 *"Site-Specific Sowing/Planting"*, T20-T24 to TG6 *"Site-Specific Fertilizing"*, T25-T26 to TG7 *"Site-Specific Spraying"* and T27 forms an independent group TG8 *"Site-Specific Manure Application"*.

Requirements for the existing mechanization were defined for each technology variant (e.g. additionally required GPS steering system, Farm Management Information Systems).

The impact of technologies on the items of the cost-benefit calculation (change in yields, price, direct costs, and impact on variable and fixed costs) was evaluated on the basis of manufacturer data and literature values.

A decision algorithm is integrated in the calculation model that takes into account the requirements of the existing technology on the part of the digital technologies (e.g. the addition of an application map for offline approaches or the retrofitting of ISOBUS devices) and differentiates whether a retrofit solution is sufficient or a replacement investment must be made.

As far as possible, the purchase prices were differentiated into three classes. In this way, the different demand for machine sizes can be adapted to the respective farm size and an under- or overestimation of the investment costs can be avoided (Class 1: <20 ha; Class 2: 20-70 ha; Class 3: >70 ha). This classification is based on the farm size structure in Baden-Wuerttemberg, with Class 1 primarily representing part-time farmers, Class 2 containing the farm sizes most commonly found in Baden-Wuerttemberg and Class 3 reflecting the larger farms by Baden-Wuerttemberg standards.

2.3 Economic modeling of a farm

The calculation is based on the cost-benefit calculation (1), where the direct-, variable operating-and fixed operating-costs per crop are subtracted from the revenue of each crop on the farm to obtain the profit per crop and year. The profit of each crop is then added to the total profit of the farm. Direct costs (DC) include input materials such as seed, fertilizer and crop protection products. Variable operating costs (VC) include the variable costs of machine use and costs of services. Fixed operating costs (FC) include the fixed costs of machinery use (depreciation) and labor costs for family labor.

$$(1) P = R - DC - VC - FC$$

On the output side, digital technologies can increase the yield or the product price (e.g. through improvements of protein content)[8,18]. On the direct cost side, technologically induced reductions in input quantities can lead to savings[19,20]. The price of inputs is not changed by digital technologies. A change in the variable operating costs per hour can be caused by the changed cost structure of digital technologies or the self-mechanization of work steps that were previously performed as a service. Digital technologies can also lead to savings in working time or to additional steps (e.g. calibration of sensors) and thus to a change in working time overall[21]. Fixed operating costs can be affected by the purchase of new machines (change in depreciation), when working time gets affected by the use of digital technologies (change in labor costs, family worker) or other fixed costs arise (application map, learning costs/year etc.)[8].

2.4 Comparison and evaluation of technologies at the whole farm level

The calculation and selection of technologies is based on the assumption that the farmer makes the decision to implement a technology as soon as the additional benefits exceed the additional costs. For this purpose, the profit is first calculated for the status quo at farm level (P_{SQ}) and then compared to the profit with the inclusion of the implemented digital technology (P_{DTx}).

The change in profit (PC) shows how profit develops at the overall farm level when a digital technology is added (2). This comparison can be made with all technologies or combinations of technologies.

$$(2)\ PC = P_{DTx} - P_{SQ}$$

From an economic point of view, investments should be made if condition (3) is met.

$$(3)\ P_{SQ} \leq P_{DTx} or\ PC \geq 0\ € \ ha^{-1}a^{-1}$$

2.5 Sensitivity Analysis – Marginal farm size

To show the limits of profitability of a technology, the marginal farm size can be calculated. For the calculation, the condition shown in (3) applies, i.e. implementation is assumed as soon as the additional annual costs equal the additional annual benefits.

3 Results

The effects on the items of the cost-benefit calculation are shown in **Figure 2** and **Figure 3**. All changes are presented in the unit € $ha^{-1}a^{-1}$and indicate the change compared to the status quo (whole farm level). The farms B0-B8 are sorted according to their size per technology group (starting with the smallest farm size B1). Gaps indicate that the corresponding farm already uses the technology (TG1_B8) or cannot use it (TG8 for arable farms without animal husbandry). All items on the positive side are summed up to the additional benefit. Accordingly, the additional costs that arise with the implementation are on the negative side. Through the formation of technology groups and the presentation of the overall farm differences in technologies within a group and between crops are no longer visible. Therefore, it cannot be excluded that individual variants within a technology group can be used economically on a farm or that the use in some crops would make sense.

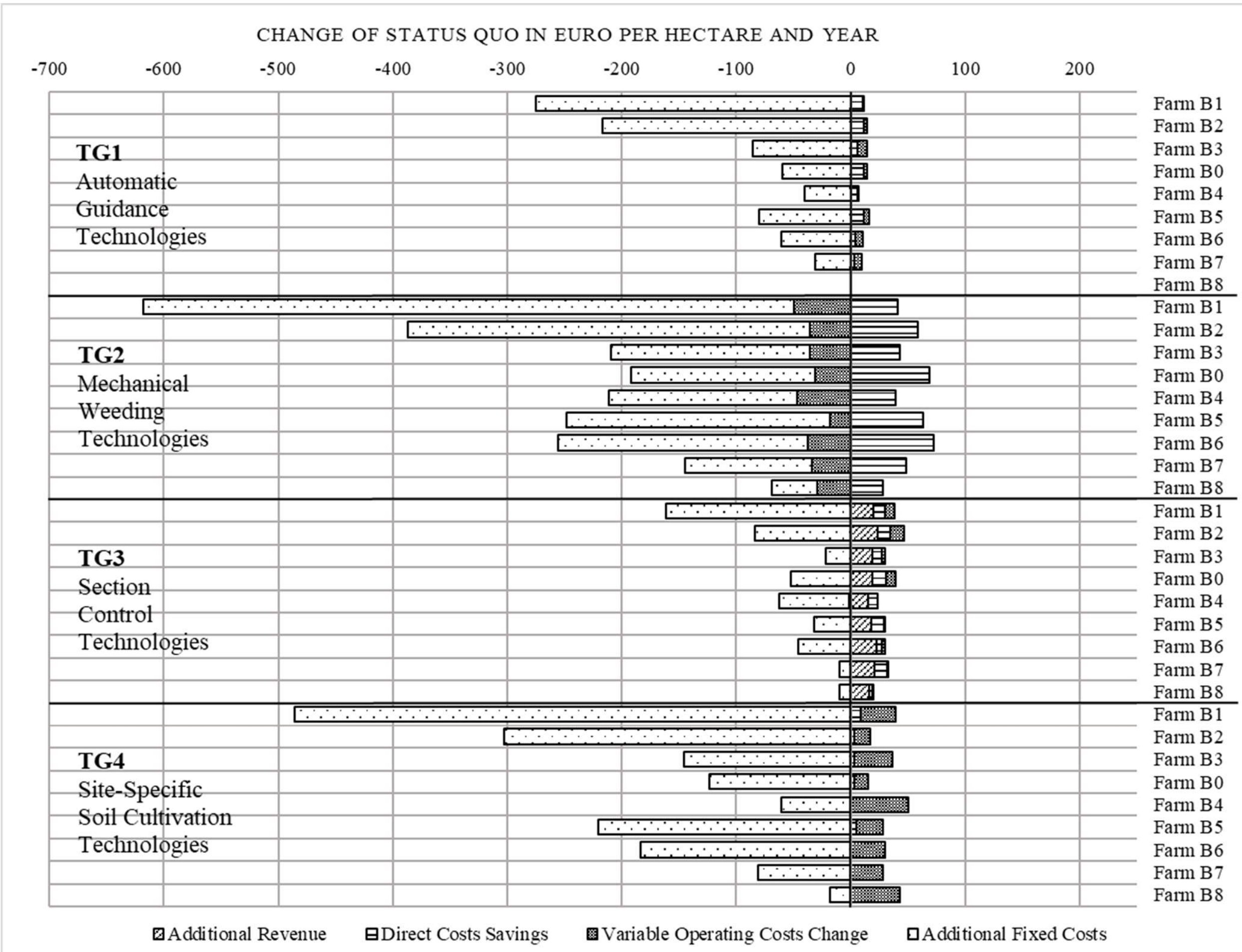


Figure 2: Technology groups 1-4 with their impact on revenue, direct costs, variable operating costs and fixed costs of farms B0-B8, each technology group is sorted by farm size. Additional costs are added on the negative side, additional benefits correspondingly on the positive side.

The technology groups shown in Figure 2 are characterized by a low level of additional benefits. On the revenue side, TG1, TG2 and TG4 cannot contribute to the additional benefit. Minor improvements (up to50 € $ha^{-1}a^{-1}$on B8, TG4) can be achieved on the variable cost side, especially for labor-intensive operations (TG4 - tillage) and the use of automatic guidance systems. The savings in direct costs from the use of automated steering systems are insignificant. The comparatively high savings in direct costs for TG2(up to72€ $ha^{-1}a^{-1}$onB6) result from the substitution of herbicides by mechanical weed control. The greatest savings can be achieved here the more intensively a farm uses herbicides. The low economic impact of the section control technologies is caused by the comparatively low investment costs and the small influence on direct costs. The average arable farm B0 is not characterized by unusually high changes in additional benefits and costs when comparing to farms B1-B8. The desired profitability constraint (3) is only met by B3, B7 and B8 in TG3, and by B8 in TG4.

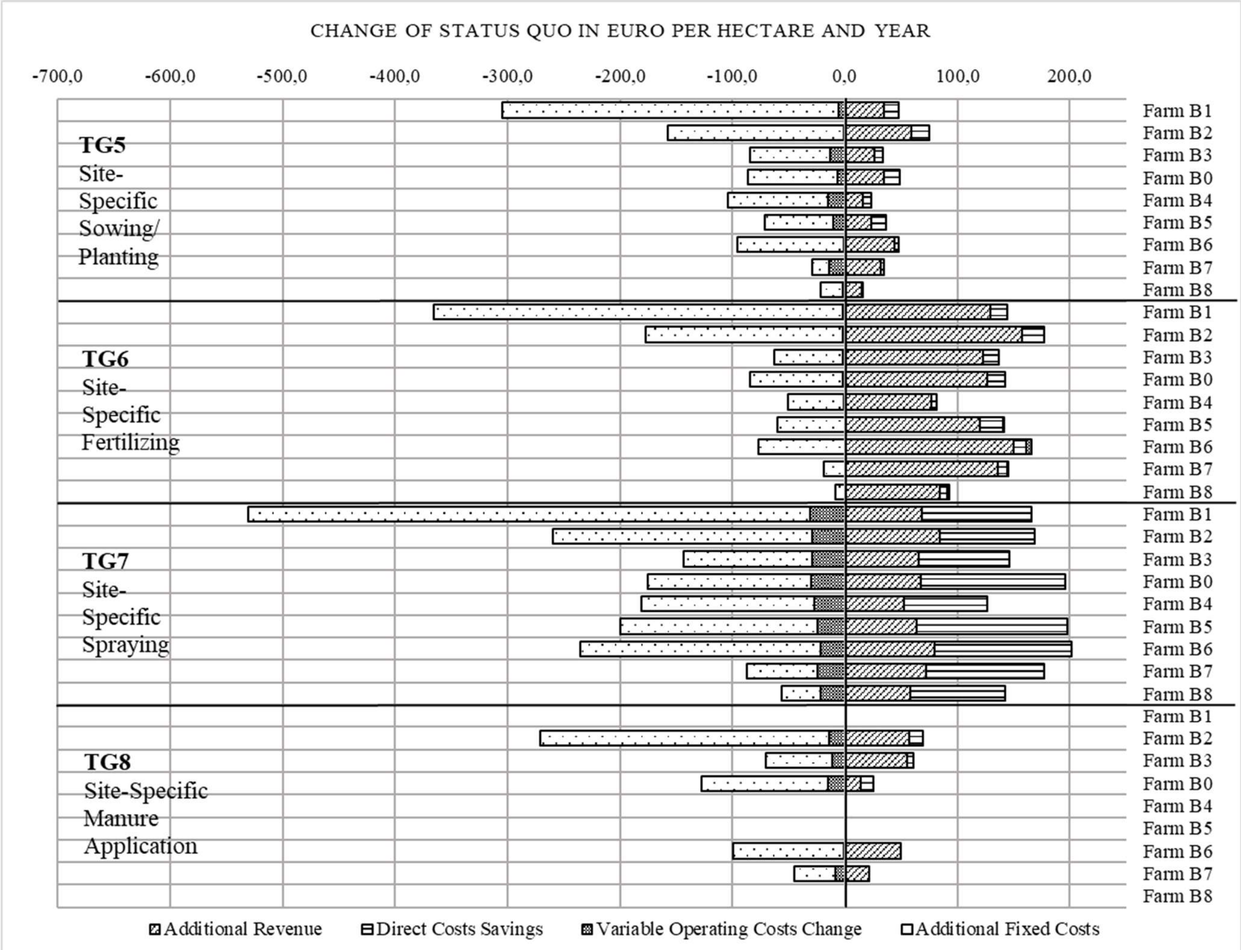
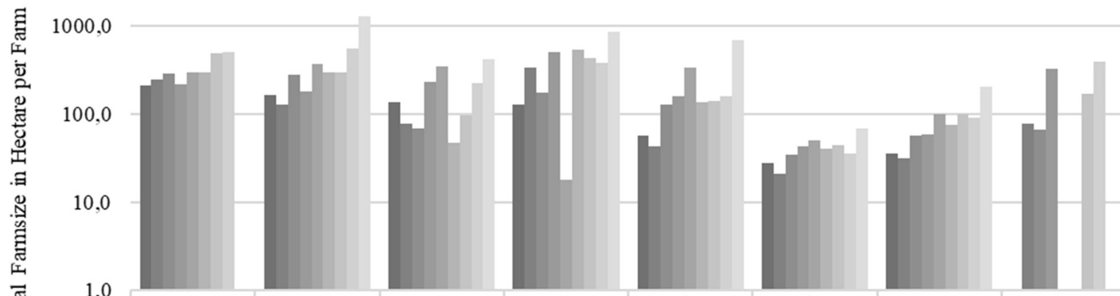


Figure 3: Technology groups 5-8 with their impact on revenue, direct costs, variable operating costs and fixed costs of farms B0-B8,each technology group is sorted by farm size. Additional costs are added on the negative side, additional benefits correspondingly on the positive side.

All technology groups shown in Figure 3 are able to positively influence the revenue side. Technology group 6*"Site-Specific Fertilizing"* stands out in particular. Here, an increase in revenue of up to177€ $ha^{-1}a^{-1}$ (B2) can be achieved. The amount is linked to the previous yield expectation and the intensity of management. Farms with a high yield expectation and a high production intensity also tend to achieve higher yield increases or quality improvements. The direct cost position is most strongly influenced by technology group 7. Savings of up to 134€ $ha^{-1}a^{-1}$ (B5) are caused by potentially high reductions in pesticide use (up to 80% of fungicides and 61% of herbicides).The variable operating costs are most strongly influenced by technology group 7, since in some cases time consuming aerial inspections of the fields (with drones) are necessary in advance of the operation. These operations are included in the calculation as a service with about 40 € $ha^{-1}a^{-1}$. In terms of fixed costs change, technology group 7, and in particular farm 1, is the most noticeable with an increase of 500 € $ha^{-1}a^{-1}$.The profitability threshold (3) is reached by B7 in TG5, by B2-B8 in TG6, by B3, B4, B7 and B8 in TG7 and by none of the investigated farms in TG8.

Across all technology groups, a scale dependency emerges on the side of the additional fixed costs, which leads to the fact that the technologies can only be used economically with increasing farm size. The low overall benefit for most small farms in relation to the additional costs makes the use of the examined digital technologies uneconomical if the farms want to be self-mechanized. In general, it can be observed that technologies that lead to an increase on the revenue side tend to be of economic interest for more farms, as well as technologies that lead to savings in cost-intensive inputs.



	Auto Guidance	Mechanical Weeding	Section Control	Site-Specific Soil Cultivation	Site-Specific Sowing /Planting	Site-Specific Fertilizer Application	Site-Specific Spraying	Site-Specific Manure application
Farm B1 (11 ha)	212,4	163,9	135,9	127,2	55,8	28,0	35,5	
Farm B2 (20 ha)	244,8	127,4	78,4	335,5	43,2	21,0	31,7	78,4
Farm B3 (57 ha)	285,8	275,6	68,5	176,1	128,8	34,5	55,9	65,4
Farm B0 (65 ha)	217,9	180,1	229,1	500,2	157,7	43,0	58,2	323,4
Farm B4 (70 ha)	298,3	370,8	343,2	17,9	333,9	50,1	98,8	
Farm B5 (76 ha)	298,6	293,3	46,5	526,1	134,1	40,4	76,0	
Farm B6 (85 ha)	479,1	298,7	96,0	429,3	141,0	44,0	99,0	169,2
Farm B7 (187 ha)	504,6	552,0	222,4	373,2	158,7	35,1	91,2	384,6
Farm B8 (530 ha)		1288,9	420,5	841,1	675,9	68,7	205,5	

Figure 4: Marginal farm size for each technology group and farm

The marginal farm sizes shown in Figure 4 are based on the profitability frontier (3), where all incremental costs must be at least covered by the incremental benefits. Since the calculation of the marginal farm size of the technologies depends on the additional costs and benefits, the size varies from farm to farm based on the necessary changes of the existing mechanization (additional fixed costs), the yield level and the management intensity (potential increase of additional benefit). Larger differences can be seen in technology group 4*"Site-Specific Soil Cultivation"*. The reason for the relatively low marginal farm size on Farm 4 is the low cost of implementation and the high savings in labor time. Also noticeable is the high marginal farm size of TG2*"Mechanical Weeding"* on farm 8 compared to the rest of the farms, due to the low savings in direct costs.

The marginal farm size is smaller, the higher the additional benefit of a technology and the lower the additional costs. Technologies that have a positive influence on several items of the cost-benefit calculation, especially on the performance side (TG6 and TG7), can reduce direct costs to a greater extent (TG2 and TG7) or technologies with low investment costs (TG1 and TG3) are in an advantageous position. Technologies that only lead to small improvements on the revenue side and direct costs or which are costly to implement should not be chosen as a starting technology. A slight increase in the marginal farm size can be observed as the size of the farm increases. This is mainly due to the intensively managed small farms in the sample, which have a high yield level and input use and can therefore achieve higher potential savings per hectare. In this case, however, this does not create an advantage for small farms, since the marginal farm size is still a multiple of the actual farm area and can often only be achieved by the larger farms.

1. Discussion

The changes in the positions of the cost-benefit calculation shown in section 3 are based on literature values and substantiated assumptions. When comparing the farms B3-B5 and B0, it becomes clear that the results differ from each other due to different preconditions despite similar farm sizes. In practice, these differences can be even more apparent if the uniformly used assumptions in the calculation model are modified for each farm. In the following subsection, various factors that can influence the success of the use of digital technologies will therefore be discussed.

4.1 Revenue side

The yield of the status quo is linked to a variety of site-related factors (e.g. soil type and yield potential, weather, genetic potential of the variety) which cannot be influenced by the farmer[20].Since the production function per field is also not known and depends on a variety of influencing variables, it is not possible to make reliable predictions about the response of yield to site-specific management[21,22]. The farmer's influence on the change in yield is therefore very limited. Only the amount of fertilizer and the spatial distribution of fertilizer in the field can be controlled. However, due to the law of diminishing marginal returns, it can be assumed that farms at high yield levels and farms that meet already high quality requirements (e.g. B1, B2 and B6) cannot expect particularly large increases here[23]. The same low level of influenceability applies to the height of the product price, which is essentially determined by the market[20]. Only the qualities produced can be changed to a small degree. This change is again subject to environmental influences and can therefore only be controlled to a limited extent by the farmer and the use of technology.

4.2 Direct cost side

The input quantities could be changed almost arbitrarily by the farmer, but there are upper limits (laws and regulations) and lower limits (e.g. personal preferences, yield expectations) that restrict the flexibility of the farm manager[24]. Digital technologies can influence the use of inputs to a small extent, but in most cases only a redistribution of the input quantity is carried out, so that no saving effects can be realized with these technologies[25]. Intensively managed farms have a small advantage per hectare compared to extensively managed farms as far as savings can be achieved. The influence of unshaped fields was not taken into account in this calculation, but can be of considerable importance, especially for TG 3 "*Section Control*"[26].

4.3 Variable operating costs side

Additional variable operating costs can be influenced by the use of the examined technologies only to a small extent, since these costs are technically determined. An enormous savings potential on the variable cost side arises if a farmer can replace non-family labor on a large scale[27,28]. This replacement of labor by capital is not possible in the studied arable farms with mostly 1-2 family laborers and the small amount of time saved through the use of the studied digital technologies.

4.4 Fixed costside

Farmers are severely limited in their ability to reduce the position of additional fixed costs. The decisions made in the past about the purchase of machines determine the cost of implementing a digital technology (especially learning costs and investment costs). Problems related to the evaluation of these costs are diverse. On the one hand, they are linked to the competence and experience of the farmer, but on the other hand, they are also linked to factors that cannot be directly influenced by the farmer, such as compatibility problems due to different manufacturers or missing interfaces[15]. Reliable data on learning costs are lacking and could only be considered with great uncertainty even when collecting data from farmers who already use digital technologies[21].The learning costs per year account for only about 2.5-3.0 % of the annual depreciation (with up to 6 h/year TG2, i.e. 60 h over the 10 years lifetime of the equipment). The assumption made in the calculation to depreciate learning costs over the service life (see also Godwin et al.[8]) will hide the fact that more time has to be spent especially in the first year, i.e. higher costs are expected in the first year.

In the longer term, investment costs can be expected to decrease as the technologies are further developed, and thus more technologies will be available to farmers[29,30]. The service life of digital technologies remains uncertain. There is a lack of data on the robustness of these technologies. Whether investment subsidies will lead to over-mechanization, especially of small farms, needs to be investigated more closely. It is undisputed that the reduction of investment costs through subsidies will lead to a reduction of additional costs and thus the minimum input areas can be reduced.

Overall, the additional fixed labor costs put small farms at a distinct disadvantage, as they tend to use existing technology for longer and a more cost-effective retrofit solution is often not possible for their outdated technologies. Some of the operations that are outsourced to contractors cannot simply be self-mechanized because the necessary know-how or manpower is lacking, thus creating a far greater hurdle to the use of digital technologies for small farms[31].

4.5 Marginal farm size

In general, it can be assumed that the hard limits drawn for Figure 4 are probably softer in practice and that especially technology-friendly farmers and farms with advantages in terms of implementation effort (e.g. if only activations are required) might decide to implement, even though the additional costs are not fully covered by the additional benefits[32].
The consideration of soft factors (e.g. farmer's preferences) and other possible benefits of digital technologies that are difficult to quantify (e.g. positive environmental effects) was intentionally excluded. Changes in this area could lead to small farms being able to use digital technologies from an economic point of view with the help of subsidies or the compensation of environmental services[33].
In most cases (e.g. TG1-TG5), even a doubling of the farm size will not be sufficient from an economic point of view to be able to use the technologies economically. Although a progression of structural change will be inevitable, it can be assumed that small farms will still be able to hold their position in 10 years[34]. Cooperation's between several farms or performing the operation as a service could be a solution to use digital technologies and minimize fixed costs per hectare. Technologies that can be easily deployed across farms, such as TG2, TG4, TG5, and TG7, are of particular interest. For very small farms (B1/B2), it is not advisable to use the technologies across farms, because otherwise too many farms would have to coordinate the use of the machines [31]. Nevertheless, these farms are not excluded from using these technologies. In this case, it makes sense to outsource this work to a service provider[31,33]. In the case of technologies that are permanently installed in the farmer's tractor (TG1) or are usually available as additional equipment in the farmer's machinery anyway and only need to be activated (TG3), the sharing of machinery is also not attractive.

5. Conclusion

With the help of a model calculation and data of eight farms, this paper was able to substantiate the low adoption rates of digital technologies in small-structured agricultural regions from an economic point of view. Especially very small farms (< 20 ha) are at a disadvantage when it comes to the implementation of capital-intensive technologies. It could be shown that technologies that make changes on the output side or influence large direct cost positions tend to be profitable even for smaller farms. The economic success of digitization varies greatly between farms and depends on a variety of factors (e.g. existing mechanization and environmental factors). The reluctance of farmers to adopt digital technologies can be attributed to the uncertainty of the benefits that can be achieved and the difficulty of monitoring success. The decision about an implementation must therefore be made individually for each farm. The results of the model calculation also show that some technology groups (e.g. TG2 *"Mechanical Weeding Technologies"*) cannot be profitably implemented even on large farms. Due to the continuous further development of technologies, it can be expected that the digital technologies offered will become more affordable for farmers over time. If additional positive environmental benefits can be achieved with the use of digital technologies that are not rewarded by the consumer, the investment costs for the farmer should be reduced with the help of financial support from the state. Overall, however, the scale-dependent use of the technologies also gives hope for widespread use in small-structured agricultural regions with the help of service providers, who generally achieve high utilization of the machines and thus low costs per hour of use.

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