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Adoption of precision agriculture technologies by German crop farmers

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Abstract In recent years, precision farming has been receiving more attention from researchers. Precision farming, which provides a holistic system approach, helps farmers to manage the spatial and temporal crop and soil variability within a field in order to increase profitability, optimize yield and quality, and reduce costs. There has been considerable research in farmers' adoption of precision agriculture technologies. However, most recent studies have considered only a few aspects, whereas in this study a wide range of farm characteristics and farmer demographics are tested to gain insight into the relevant aspects of adoption of precision farming in German crop farming. The results of a logistic regression analysis show that predictors with positive influence on the adoption of precision farming are agricultural contractor services such as an additional farming business, having under 5 years' experience in crop farming, having between 16 and 20 years' experience in crop farming, and having more than 500 ha of arable land. However, having a farm of less than 100 ha and producing barley are factors that exert a negative influence on the adoption of precision farming. The results of this study provide manifold starting points for the further proliferation of precision agriculture technologies and future research directions.

Keywords Precision farming · Technology adoption · Binary logistic regression model · Socio-demographic factors · Farm characteristics

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Introduction

Precision agriculture—also known as precision farming (PF) or site-specific crop management—is a farming management concept that provides a holistic system approach to managing the spatial and temporal crop and soil variability within a field in order to increase profitability, optimize yield and quality, and reduce costs and environmental impact (Stafford 2000; Fountas et al. 2005; Reichardt and Jürgens 2009; Aubert et al. 2012). PF technologies have been in use since the mid- to late 1980s (Zhang et al. 2002) and commercially available since the early 1990s (McBride and Daberkow 2003); meanwhile 10–30% of German farmers have adopted PF so far (Reichardt et al. 2009; Kutter et al. 2011). A wide range of tools are available, based on GPS technology, information technology, farm management and economic knowledge, and sensor and application technologies. So far, adoption and development of PF to farming operations is still in progress (Reichardt and Jürgens 2009). Employing PF provides access to a large amount of data that can be used to inform farm management decisions. The term *farming 4.0* has recently been coined to characterize this new type of information-based farming (Clasen 2016). Of course, the great amounts of data farmers have to synthesize after PF adoption may also lead to difficulties. Moreover, agricultural machinery must often be modified, and modern computer technology is needed. Furthermore, interpreting PF data correctly can be a challenge. Perhaps for these reasons, although the PF industry has spared neither effort nor expense in attempting to persuade farmers to use PF tools to professionalize their farm management, a number of surveys have shown that farmers are still hesitant to adopt PF (Stafford 2000; Batte and Arnholt 2003; Fountas et al. 2005; Daberkow and McBride 2003; Bramley, 2009; Reichardt and Jürgens 2009; Aubert et al. 2012). A lack of expected benefit due to PF is may be the reason for less adoption than it was predicted (Bramley 2009).

While farmers cite many uncertainties that prevent them from adopting PF, there are also motivations for using PF technologies pushed by economic gains from reduced agricultural inputs, strict environmental legislation, and improved farm management efficiency (Zhang et al. 2002). The advantages of PF adoption by farmers have been demonstrated by numerous ex-post studies (Khanna 2001; Daberkow and McBride 2003; Batte and Arnholt 2003; Roberts et al. 2004; Larson et al. 2008; Reichardt and Jürgens 2009; Kutter et al. 2011), in which its economic and environmental benefits have been confirmed. Similarly, key drivers of PF adoption have been identified and classified into groups of influencing factors (Daberkow and McBride 2003; Roberts et al. 2004; Pierpalo et al. 2013; Tey et al. 2014). However, most of the existing studies concentrate on only a few aspects of PF adoption tested by logit models or refer to qualitative research methods, such as case studies, and literature reviews.

It is the aim of this study to test theoretical and literature-based constructs for the first time in an empirical study of German crop farmers. The research question is this: Which operational and sociodemographic factors significantly influence the adoption of PF by German crop farmers? This study seeks to fill the existing research gap by taking a large number of factors into consideration which have been identified by other studies and testing them in a comprehensive logistic regression model. Another goal is to add to the research on PF adoption in German arable farming, which is scarce.

Adoption of precision agriculture

Research in PF adoption focuses mainly on the farmer as the main decision maker (Mackrell et al. 2009). Nevertheless, farm characteristics such as farm size, farmed crops, and full-time farming are also influencing factors in PF adoption (Daberkow and McBride 2003). In the past, education, technical skills, familiarity with computers, and the age of farmers were often considered decisive factors in PF adoption (McBride and Daberkow 2003). In their literature review, Pierpaoli et al. (2013) analyzed several ex-post PF adoption studies and identified key drivers: competitive and other factors, financial resources, and socio-demographic factors. Supplemented by further operational and socio-demographic factors, these key factors serve as a basis for this study. In the following, we describe all the factors of farm characteristics and farmer demographics considered in the study.

Farm characteristics

All crop farms face different competitive conditions that shape the individual farm characteristics that distinguish them from other crop farms. These farm characteristics describe the range of PF-related factors that can influence PF adoption. The aspects we consider can be categorized as competitive factors and farm resources.

The impact of the farm management system, such as conventional or ecological farming, is not much discussed with regard to PF adoption. Nevertheless, the intensity of the farming system influences a farm's cost structure, and Jensen et al. (2012) confirmed that adopting PF has economic benefits for conventional crop farmers, such as yield increases, fuel savings, and reduction of herbicide use. Conventional farming is the traditional form of farming and is not certified as ecological or organic. It has also been shown that full-time (as opposed to part-time) farming has a positive impact on PF adoption (Daberkow and McBride 2003).

H1: Conventional farming has a positive effect on PF adoption.

H2: Full-time farming has a positive effect on PF adoption.

There are still various barriers regarding PF; in this regard, the high costs of the technologies involved are often cited by farmers (Reichardt and Jürgens 2009). Thus, capital expenditure on PF technology is dependent on a farm's future sustainability as well as on a secured farm succession. Further management attributes, such as computer literacy, job satisfaction, management know-how, and success in crop production could be worth considering as factors in PF adoption. Fountas et al. (2005) found that PF adoption was the result of a change in management decisions. However, PF adoption is dependent on the farm manager's management knowledge. Roberts et al. (2004) found that PF adoption depends on a manager's level of informedness about the costs and benefits of PF, which is a part of an individual's management knowledge.

H3: Secured farm succession positively impacts PF adoption.

H4: Management knowledge about PF positively impacts PF adoption.

McBride and Daberkow (2003) found that computer literacy positively affects PF adoption. However, Roberts et al. (2004) stated that computer skills had no significant influence. Nowadays, though, farmers can be assumed to be highly computer literate, and such issues as data misuse and software compatibility are increasingly discussed as reasons for non-adoption (Kutter et al. 2011).

H5: Computer literacy positively impacts PF adoption.

Satisfaction with crop farming and success in crop production are additional management attributes that contribute to PF adoption (Batte and Arnholt 2003). Farmers who have adopted PF credit it with informing a wide range of their decision types, whereby farmers are more likely to adopt PF technologies that increase results in crop production.

H6: Satisfaction with and success in crop production positively impact PF adoption.

Following considerations of economies of scale, it was found that farm size positively impacts PF adoption. The larger the farm, the greater is the likelihood of PF adoption (Daberkow and McBride 2003; Roberts et al. 2004; Reichardt et al. 2009; Lambert et al. 2014). This can also be transferred to the size of arable land and leased land. However, owning more land exerts a greater positive influence on PF adoption (Roberts et al. 2004; Lambert et al. 2014). Thus, large commercial farms are more likely to benefit economically from adopting PF on their farms (Jensen et al. 2012). These large farms are not necessarily family-owned. Farms with increasing numbers of external employees are more likely to adopt PF (Reichardt and Jürgens 2009), whereas small-scale family-owned farms with several family employees are less likely to adopt PF. On the other hand, having additional farm businesses in addition to crop farming also impacts PF adoption. For example, livestock production negatively impacts PF adoption (Walton et al. 2008), whereas offering contractor services as an additional farming business often drives PF adoption (Kutter et al. 2011).

H7: Farm size positively impacts PF adoption.

H8: Ownership of additional farm businesses impacts PF adoption.

Land quality characteristics such as soil quality influence decisions regarding PF adoption (Schoengold and Sunding 2014). The benefits of PF adoption are higher for soils with high slope, heterogeneity, or permeability.

H9: Soil quality impacts PF adoption.

Farmed crops can also affect PF adoption. Due to the fact that farmers adopt PF with the aim of reducing costs or increasing revenues, they are more likely to adopt PF for crops from which they can acquire the most benefit. For example, cereals and special crops are more valuable than cotton (Kitchen et al. 2002; Walton et al. 2008). Therefore, differences in PF adoption can be traced back to differences in crops produced (Jensen et al. 2012).

H10: The types of crops farmed can impact PF adoption.

Communication has an important role in PF adoption by farmers. PF-relevant information is spread by various stakeholders, such as other farmers, technology firms, research centers, private consultants, and farmer unions. However, use of consulting services has been reported as positively impacting PF adoption by crop farmers (Kutter et al. 2011). Access to information via consulting services makes it more likely that a farmer will innovate and adopt PF (König et al. 2012).

H11: Use of consulting services can impact PF adoption.

Farmer demographics

As adopters, demanders, co-developers, and impulse providers, farmers play an important role in PF adoption and innovation mechanisms (Busse et al. 2014). For that reason, farmer demographics are important factors in PF adoption.

With respect to gender it has to be recognized that most farmers are male (Kutter et al. 2011; Reichardt und Jürgens 2009). Therefore, gender has not been treated as an important factor in PF adoption so far. At the same time, in this context, it is worth mentioning that some studies on the use of computer technologies indicate that older women above 60 years are still somewhat more reluctant to use IT technologies than are men in similar age groups (Forschungsgruppe Wahlen 2014).

H12: Gender has an impact on PF adoption.

How age impacts PF adoption is unclear (Tey and Brindal 2012). On the one hand, some researchers have reported that younger farmers are more likely to adopt PF (Walton et al. 2008; Kutter et al. 2011); similarly, Daberkow and McBride (2003) found that increasing age reduces the likelihood of PF adoption. On the other hand, Torbett et al. (2007) reported that farmers' being older correlates positively with PF adoption.

H13: Age has an impact on PF adoption.

A higher education level is often reported in the literature to have a positive impact on PF adoption (Auernhammer 2001; Cox 2002; McBride and Daberkow 2003; Roberts et al. 2004). A high education level provides knowledge and skills that are needed to understand PF technology, make farmers want to experiment with PF, and enable them to adopt it. Similar effects can be due to agricultural education level although earlier studies have revealed that attending agricultural schools and centers has no impact on PF adoption (Kutter et al. 2011). Reichardt and Jürgens (2009) found that PF is not included in exams; therefore, it is not featured in instruction even though teachers are aware of it.

H14: Higher education levels have a positive impact on PF adoption.

H15: Agricultural education level has an impact on PF adoption.

Farm location has also been reported as having an impact on PF adoption. This has been explained by higher vendor concentrations in some regions and federal states (McBride and Daberkow 2003). Reichardt and Jürgens (2009) pointed out that most Germans farms that are employ PF are located in eastern Germany.

H16: Farm location has an impact on PF adoption.

Experience in crop farming is usually related to respondents' age. Although it has been found to be an important factor in PF adoption (Lambert et al. 2014), its exact impact is still unclear. Reichardt et al. (2009) found that knowledge of PF can best lead to its adoption and that experienced crop farmers are better informed about PF. However, Aubert et al. (2012) stated that younger farmers with less experience in crop farming have a longer planning horizon, and that, in combination with a higher education level, they have the skills required for PF adoption.

H17: Experience in crop farming has an impact on PF adoption.

Conceptual framework for PF adoption

As discussed above, adopting PF can be influenced by farm characteristics and farmer demographics, as illustrated in Fig. 1. This conceptual framework forms the basis for the following empirical analysis.

Data and methods

Data were provided by an empirical study of German crop farmers which collected data on their use of strategies, performance indicators, and advisory and management tools (e.g., precision farming) as well as information on farm characteristics and farmer demographics. Data were collected in August 2014 using a standardized online questionnaire provided by the platform EFS Questback. The link to the questionnaire was widely distributed to German crop farmers through agricultural online portals, and email newsletters from local farmer associations and social networks. Altogether, data from 227 farmers were collected through the questionnaire and used in the analysis. The data were analyzed using the statistics software package IBM SPSS 23 on the basis of the conceptual framework of factors that potentially influence PF adoption developed from the literature. (See Fig. 1 above.) First, univariate methods were used to describe the sample and represent frequencies. The next step was to analyze which farm characteristics and sociodemographic factors characterizing farmers are relevant for PF adoption by German crop farmers. For this analysis, we used a binary logistic regression with forward selection and a likelihood ratio test to test the theoretical construct and identify the significant influencing variables (Backhaus et al. 2011).

The logistic regression model also provides information about the classification of farmers to the group of PF adopters by testing the probability of the classification's success

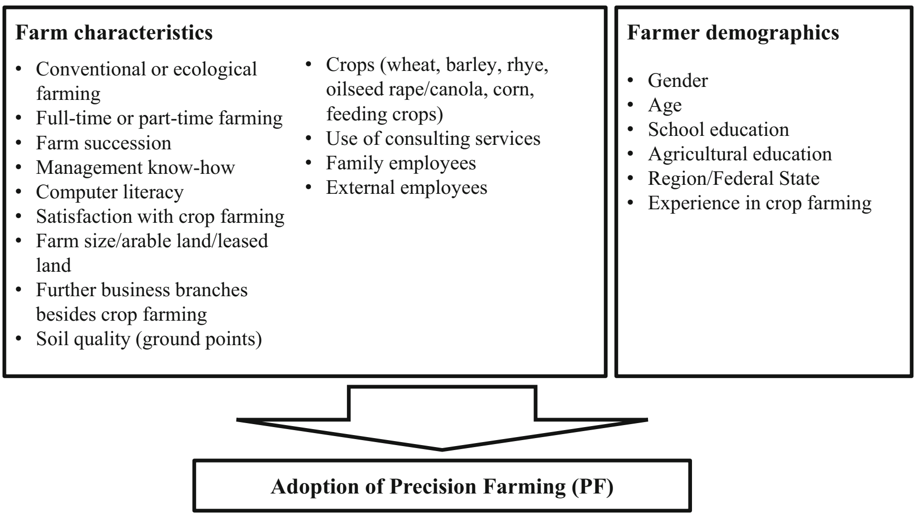

Fig. 1 Drivers of PF adoption (authors' representation derived from findings in Daberkow and McBride 2003; Roberts et al. 2004; Larson et al. 2008; Reichardt and Jürgens 2009; Pierpaoli et al. 2013; Lambert et al. 2014)

over the probability of its failure. In the questionnaire, the dependent variable "precision farming" was treated as a categorical variable; farmers stated whether they use precision farming daily, weekly, monthly, yearly, or do not use it. For use in the binary logistic regression model, the variable was transformed into the dichotomous variable "precision farming", where 0 stands for "no adoption" and 1 for "adoption of precision farming". For the dummy variable "adoption of precision farming", all respondents are counted who use PF daily, weekly, monthly, or yearly. Precision farming was asked in a general way and not further divided into specific PF applications. However, a pre-test demonstrated that the meaning of this variable was clear to farmers and researchers.

Stepwise forward selection using the maximum likelihood function was used in the regression analysis to find the best fitting model to answer the research question. It starts with the constant-only null model and adds variables stepwise one at a time in the order that best fits the model until the cutoff level of significance greater than 0.05 is reached, whereby the score of the variable is the entry criterion for adding the variable to the model (Field 2009). Independent variables that were tested as potential predictor variables were sociodemographic in nature: age, gender, school education, agricultural education, location, and experience in crop farming. Farm characteristics were also included: cultivated crops, farm size, arable land, leased land, conventional or ecological farming, full-time farming, secured farm succession, satisfaction with crop farming, management knowledge, success of crop production, family employees, external employees, and quality of soil.

Adoption of precision farming

Sample description and results of contingency tables for PF adopters and non-adopters

The analysis considered data from 227 farmers, of whom are 68 PF adopters and 159 non-adopters. Table 1 presents the distribution of the sample farmer demographics, separated into PF adopters and non-adopters. Of the respondents, 90.7% are male and 9.3% female. Most respondents are under 25 or between 25 and 34 years of age. There are more PF adopters in the age groups of 35–44 and 45–54 than in the groups of younger farmers. The educational level of school education is pretty high: 63.9% of respondents have a general matriculation standard school education, whereas only 4% do not have a secondary school education. The same pattern held true with regard to agricultural education: 48.5% have a university degree in agricultural sciences, 12.8% completed agricultural technical school, and 11.5% finished agricultural masters' certificate. Only 5.7% of the respondents have no agrarian qualification.

Table 1 shows the sample distribution and descriptive results for the demographics of the two groups—PF adopters and non-adopters. The distribution of PF adopters and non-adopters is very close to the distribution found in a study of US farmers (Daberkow and McBride 2003), whereas Reichardt et al. (2009) found an adoption rate of less than 10% among German farmers.

The average experience in crop production amounts only 12.65 years. This is related to the high proportion of young farmers in the sample. The majority of respondents are under 34 years of age, and, for this reason, most of the farmers have had fewer than 10 years of experience in crop farming. To analyze the frequencies of non-adopters and PF adopters,

Table 1 Distribution of the sample of farmer demographics by PF adoption

	Not adopting (N)	Adopting [N (%)]	Total (N)
Sample	159	68 (30)	227
Farmer demographics			
Age			
<25 years	22	8 (27)	30
25–34 years	85	36 (30)	121
35–44 years	21	11 (34)	32
45–54 years	18	11 (40)	29
>55 years	13	2 (13)	15
Gender			
Male	146	60 (29)	206
Female	13	8 (38)	21
School education			
Secondary school	8	1 (11)	9
Secondary school (+1 year)	23	7 (23)	30
Advanced technical college certificate	28	14 (33)	42
General matriculation standard	99	46 (32)	145
Polytechnic secondary school	1	0 (0)	1
Agricultural education			
No agricultural education	12	1 (8)	13
Full agricultural training	14	3 (18)	17
Agricultural technical school	21	8 (28)	29
Agricultural master	16	10 (38)	26
Agricultural technical college (B.Sc./M.Sc.)	16	7 (30)	23
Agricultural college (B.Sc./M.Sc.)	74	36 (33)	110
Ph.D./D.Agr.	6	3 (33)	9
Experience in crop farming			
<5 years farming experience	43	26 (38)	69
6–10 years farming experience	59	17 (22)	76
11–15 years farming experience	23	2** (8)	25
16–20 years farming experience	11	10 (48)	21
>20 years farming experience	23	13 (36)	36
Region/federal state			
Baden-Wuerttemberg	6	1 (14)	7
Bavaria	34	8 (19)	42
Brandenburg	0	2 (100)	2
Hesse	4	2 (33)	6
Mecklenburg-Western Pomerania	5	4 (44)	9
Lower Saxony	78	32 (29)	110
North Rhine-Westphalia	16	8 (33)	24
Rhineland Palatinate	2	0 (0)	2
Saxony	1	1 (50)	2
Saxony-Anhalt	2	5* (71)	7
Schleswig-Holstein	9	4 (31)	13

Table 1 continued

	Not adopting (N)	Adopting [N (%)]	Total (N)
Thuringia	2	1 (33)	3

Asterisks (*) indicate items that are significantly different from the not adopting group at the following levels: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, not significant (n.s.) $p > 0.05$

contingency tables were used for frequency distribution of the examined variables. We used Pearson's Chi squared test to identify interactions between variables and PF adoption.

For farmer demographics, we found only two significant interactions between PF adoption and the variables examined. First of all, farmers with 11–15 years of experience in crop farming are significantly less likely to be PF adopters, more than half of the farmers with under 5 years of experience in crop farming are PF adopters, and the group of farmers with 16–20 years of experience is split between relatively equal numbers of PF adopters and non-adopters. The second significant interaction related to farm location. Most of the farmers in the sample are in Lower Saxony (48.5%), Bavaria (18.5%) and North Rhine-Westphalia (10.6%). Also named were Schleswig-Holstein (5.7%), Mecklenburg-West Pomerania (4.0%) and Saxony-Anhalt (3.1%). It was apparent that significantly more PF adopters are located in Saxony-Anhalt than non-adopters.

Table 2 describes the distributions of farm characteristics. Most of the farmers surveyed farm conventionally (96.5%) on professional farms (81.5%). In addition to crop farming, they engage in the following agricultural business branches: fattening pigs (17.2%), piglet production (6.2%), cattle (20.3%) and dairy production (16.3%), renewable energy production (22%), agricultural contractor services (11.9%) and cultivation of special crops (14.5%). The average farm size of all farms is 316 ha, with a standard deviation of 624 ha and a minimum farm size of 5 ha (smallest farm) and maximum of 5000 ha (largest farm). The average numbers of employees on the crop farms are 1.5 family workers and 1.7 non-family workers.

Many farm characteristics yielded significant differences between PF adopters and non-adopters when tested using Pearson's Chi squared test. For management options, there is a contingency between full-time farming and PF adoption: 34% of full-time farmers but only 11% of part-time farmers are PF adopters. The mean comparison for farm size reveals two significant differences: one in the group of small farms and the other in the group of the largest farms. In the group of small farms (1–99 ha), only 9% are PF adopters, whereas, in the group of the largest farms (>500 ha), 69% are PF adopters. A similar picture appeared for the arable land size, where the group with small arable land holdings (1–99 ha) has significantly fewer PF adopters and the group with large arable land holdings (>500 ha) significantly more PF adopters. It was the same for leased land.

For family and external employees on the farms, there are also significant differences between PF adopters and non-adopters. Farms with no family employees are significantly more likely to be PF adopters than non-adopters; 60% of the farms without any family employees are PF adopters. Conversely, farms with 1.1–2 family employees are significantly more likely to be non-adopters, as 78% are non-adopters. For external employees, the same picture can be drawn. Those farms with no external employees have many more non-adopters than adopters, to a highly significant degree. In contrast, farms employing

Table 2 Distributions of farm characteristics by PF adoption

	Not adopting (N)	Adopting [N (%)]	Total (N)
Sample	159	68 (30)	227
Farm characteristics			
Management options			
Full-time farming	122	63** (34)	185
Part-time farming	37	5** (12)	42
Conventional farming	152	67 (31)	219
Ecological farming	5	1 (17)	6
In conversion to ecological	2	0 (0)	2
Farm size			
1–99 ha	76	8*** (10)	84
100–199 ha	39	17 (30)	56
200–299 ha	23	10 (30)	33
300–499 ha	11	10 (48)	21
>500 ha	10	23*** (70)	33
Arable land			
No arable land	2	0 (0)	2
1–99 ha	79	10*** (11)	89
100–199 ha	41	19 (32)	60
200–299 ha	21	8 (28)	29
300–499 ha	8	8 (50)	16
>500 ha	8	23*** (74)	31
Leased land			
No leased land	23	4 (15)	27
1–99 ha	93	29* (24)	122
100–199 ha	26	8 (24)	34
200–299 ha	5	2 (29)	7
300–499 ha	8	10* (56)	18
>500 ha	4	15*** (79)	19
Soil quality			
<25 ground points	8	3 (27)	11
26–50 ground points	58	25 (30)	83
51–75 ground points	71	27 (28)	98
76–100 ground points	22	13 (37)	35
Crops			
Wheat	136	62 (31)	198
Barley	101	35 (26)	136
Rye	43	19 (31)	62
Oilseed rape/canola	88	42 (32)	130
Sugar beet	86	44 (34)	130
Corn	98	48 (33)	146
Potato	28	13 (32)	41
Feeding crops	32	10 (24)	42
Family employees[a]			

Table 2 continued

	Not adopting (N)	Adopting [N (%)]	Total (N)
No family employees	8	12** (60)	20
0.1–1 family employee	55	22 (28)	77
1.1–2 family employees	76	22* (22)	98
2.1–3 family employees	16	9 (36)	25
>3 family employees	4	3 (43)	7
External employees[a]			
No external employees	92	18*** (16)	110
0.1–1 employee	36	13 (49)	49
1.1–2 employees	15	11 (42)	26
2.1–3 employees	7	7 (50)	14
3.1–5 employees	6	8* (57)	14
>5 employees	3	11*** (79)	14
Agricultural business branches			
Crop farming	153	67 (30)	220
Livestock production	74	27 (27)	101
Renewable energy	32	18 (36)	50
Contractor service	13	14** (52)	27
Special crops	20	13 (39)	33
Use of consulting services			
Business consulting	94	50* (35)	144
Organizations (farmers' association, etc.)	138	57 (29)	195
Tax consultancy	132	63 (32)	195
Management attributes			
Computer use	157	68 (30)	225
Job satisfaction	132	54 (29)	186
Farm succession	99	38 (28)	137
Management knowledge	137	63 (32)	200
Success of crop production	104	53 (34)	157

Asterisks (*) indicate items that are significantly different from the not adopting group at the following levels: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, not significant (n.s.) $p > 0.05$

[a] (1 employee = 2.200 working hours)

several external employees, there are significantly more PF adopters than non-adopters, and, in those cases where there are more than five external employees, the difference is highly significant.

When another farm characteristic—engaging in other farm business branches besides crop production—was tested, the results showed that half the farms offering contractor services are PF adopters. This result was highly significant. Furthermore, the use of business consulting services was significant. On the other hand, between the groups of PF adopters and non-adopters, no further contingencies were tested for the use of other consulting services such as tax or farmers' association consultancies.

Results of binary logistic regression analysis

Identifying the drivers of PF adoption enabled us to analyze the influencing factors for PF adoption on German crop farms. We used a binary logistic regression model with PF adoption as the dependent variable to determine the strength and influence of the variables described in Fig. 1. The variables tested in the model as predictors were the farmer demographics and farm characteristics described above in "Sample description and results of contingency tables for PF adopters and non-adopters" section. The results of the binary logistic regression are presented in Table 3.

The model fits well, having fulfilled the conditions for a predictive model in the significance and classification tests. The model's goodness-of-fit is indicated by a significant model Chi square value of 66.034 and probability of $p < 0.000$, showing that the null model, which includes only the constant, has a poor fit and adding the predictors creates a better fit. The best-fitting model was created in six steps with the forward selection LR test. Nagelkerke's R^2 (0.358) indicates a moderate relationship between the predictors and the prediction. The Hosmer–Lemeshow test also shows a good fit for the model. Classifying the dependent variable indicates that 78.0% of all cases are correctly classified to *adoption of precision farming*. This is better than the classification of 70.0% in the null model—another indication that the model with predictors is significantly better. As a result of the forward selection LR test, only significant predictors appear in the full model. The influence of predictors is expressed by the values of the logistic coefficients (B).

Results show that predictors exerting positive influence on *adoption of precision farming* are agricultural contractor services as an additional farm business branch, experience in crop farming under five years, experience in crop farming from 16 to 20 years, and a farm size of more than 500 ha arable land. However, a farm size below 100 ha and barley production exert a negative influence on the adoption of PF. The Wald criterion uses p-values to demonstrate the power of significance of all predictors in the full model. The Wald criterion is a Chi squared-based test of significance. EXP (B) values indicate that, when arable land is raised to one unit, the odds ratio is 6.7 times greater and therefore farmers are 6.7 times more likely to adopt precision farming. More advanced experience in crop farming (from 16 to 20 years) has a similar effect on farmers' decisions to adopt PF.

Table 3 Results for PF adoption tested by binary logistic regression

	B	SE	Wald χ^2	p	Exp (B)
Agricultural contractor services	1.045	0.510	4.202	0.040*	2.844
Experience crop farming (<5 years)	0.842	0.386	4.761	0.029*	2.321
Experience in crop farming (16–20 years)	1.637	0.561	8.512	0.004**	5.142
Farm size (<100 ha)	−1.617	0.441	13.457	0.000***	0.198
Arable land (>500 ha)	1.910	0.493	15.019	0.000***	6.752
Barley production	−0.909	0.360	6.389	0.011*	0.403
Constant	−0.781	0.320	5.957	0.015*	0.458

Method: forward selection (likelihood ratio), dependent variable: precision farming (0 = no adoption; 1 = adoption of precision farming); null model (−2Log-Likelihood): 227.163; Full model (−2 Log-Likelihood): 211.128; Chi squared: 66.034 ***; R^2 (Cox and Snell) = 0.252; R^2 (Nagelkerke) = 0.358; Hosmer–Lemeshow test: Chi squared = 2.218, df = 5, Sign. 0818 (n.s); Classification (model): 78.0%; N = 227; * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

However, farmer demographics such as gender, age group, education and agricultural training, and region are not significant; nor are the farm characteristics management options, leased land, soil quality, family and external employees, use of consulting services, and management attributes.

Discussion

The study identified several socio-demographic and farm characteristics which tested as statistically significant in the logistic regression model for positive and negative influences on PF adoption in German crop farming. The results of the analysis showed a high relevance of farm size; more specifically, farming a large amount of arable land has a significant effect on PF adoption by German crop farmers. This finding parallels the results of earlier studies on PF adoption (Daberkow and McBride 2003; Roberts et al. 2004; Reichardt et al. 2009; Lambert et al. 2014). Due to the continuing structural change in agriculture, this indicates a growing market for PF in Germany in the future.

Our study also confirmed that the likelihood of PF adoption for crop farms increases if the farmer's experience in crop farming is greater than 16 years or less than 5 years, which indicates well-educated, experienced farmers, on the one hand, and young ICT-savvy farm successors, on the other. For these two groups, economic gains may be clearly observable and may outweigh the costs of PF adoption. With regard to the PF affinity of farmers with 16–20 years of experience, this study confirmed earlier findings on the relevance of a long-term perspective due to the high investment costs of PF technologies (Reichardt and Jürgens 2009) and the relevance of farm management know-how (Roberts et al. 2004). Torbett et al. (2007) found that older farmers (>50 years) are more likely to adopt PF on their farms. Although age and experience are often closely related, this study did not confirm that age has a significant effect on PF adoption.

Having no more than 5 years of experience in crop farming was confirmed as significant. This is nothing out of the ordinary, as it was expected that the younger well-educated farmers would face a lower initial hurdle for PF adoption due to their education and habituation to rapid changes and developments in PF and ICT in general. Kitchen et al. (2002) found that the optimal value for PF is best achieved through improving agricultural knowledge and skills—mainly ICT skills—and understanding of PF as a system for increasing knowledge. Lencsés et al. (2014) stated that for Hungarian farmers two requirements have to be fulfilled for using PF technology: a farm size greater than 300 ha and a young farmer. This agrees with the results of our analysis. Younger farmers who have recently finished their agricultural education at a university are skilled, motivated, and have a long planning horizon, which make them PF adopters, looking forward to benefiting from their decision for many years to come. The results also support empirical studies that have highlighted the central role of innovativeness and entrepreneurial spirit for the adoption of innovations (e.g., Kröger et al. 2016).

Conclusions

This study has identified several drivers of PF adoption by German arable farmers. The empirical results on predictors exerting positive influence on PF adoption have manifold managerial implications for industry, consulting and farmers. For developers and manufacturers of PF technologies, this study provides insights into the characteristics of their core target group, which can be addressed through their marketing and sales activities. Furthermore, the study also identifies which farmers do not apply PF solutions so that future research and development activities can purposefully address the needs of the current non-adopters, for instance by bringing up simpler and, therefore, cheaper technological solutions which address smaller farms and less high-tech oriented farmers. Since PF is not yet a field in advisory in Germany (Reichardt und Jürgens 2009), the results are also interesting for better adapting private as well as public consulting services to an emerging technological trend and farmers' information and training needs. The backlog of farm consultants regarding use of state-of-the-art PF might be due to a lack of appropriate training and up-to-date knowledge of consultants and, thus, could indicate a need for more in-depth training in consulting companies. Finally, farmers can benchmark their own adoption behavior against adopters and non-adopters in the survey to see whether their investment decisions regarding PF are in accordance with the decisions of comparable farms. Observed discrepancies can then trigger more in-depth analyses of farmers' investment decisions.

Several limitations of this study must also be mentioned. The sample was provided by an online-questionnaire and comprised data from 227 farmers. The sample is not representative of German farmers. This has to be taken into account when interpreting the results and deriving managerial implications. Another point is that the farmers needed access to the internet by smartphone, tablet or computer when they wanted to participate in the survey. This may have led to a (presumably small) selection bias. Finally, despite carefully pre-testing the questionnaire, there is a risk that the term "PF" might have been interpreted differently by the respondents.

The study also provides starting points for future research. Zhang et al. (2002) stated that the success of PF technologies has to be measured by economic and environmental gains. This could be a focus of further research since these factors have not been tested for German crop farmers in recent years; however, the economic and ecological effects of PF have been confirmed in several studies in other countries (Robertson et al. 2009; Aubert et al. 2012; Jensen et al. 2012). PF is not advancing as it has been supposed in recent years (McBratney et al. 2005; Reichardt and Jürgens 2009; Kutter et al. 2011), even though it was shown that 30% of farmers in this sample and 69% of crop farmers with farms of more than 500 ha have adopted PF. Future research studies should analyze in greater depth why farmers in general are reluctant to invest in PF technologies and whether there are differences between the adoption rates and reasons for different technologies. Finally, since marketing activities are more likely to deliver the desired outcome if the farmers to be addressed are clearly identified it would be interesting and useful for future studies to analyze in greater detail the effect of psychographic factors on PF adoption.

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