

**21st Century Challenges in Arable Farming –
Essays on the Agricultural Land Market and Drone Adoption
in Germany**

Dissertation

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I Introduction

More than nearly any other economic sector, agriculture stands at the crossroads of several key global challenges (Tscharntke et al., 2012). The issues are broadly discussed in the political and social discourse. According to current projections, by the middle of this century there will be approximately nine billion people on the planet who will have to be fed with the available resources (Godfray et al., 2010). In order to meet the rising demand for food, global agricultural production needs to be increased by at least 60 % between 2012 and 2050 (Alexandratos and Bruinsma, 2012). At the same time, the amount of agricultural land available worldwide is decreasing day by day. The conversion and sealing of agricultural land is leading to a reduction in the availability of land as a production factor, which is already limited by its very nature (Ramankutty et al., 2018). As a result, the available agricultural land per capita decreases even more drastically. The major challenge of food security is made even more problematic by the other global challenges of climate change and biodiversity loss. It is estimated, for example, that global wheat production is likely to fall by an average of 6 % for every additional 1 ° Celsius rise in global temperature (Asseng et al., 2015). At the same time, the steady increase in the world's population is raising the pressure on climate and biodiversity. Resolving these three key challenges together appears yet to be more difficult. Since arable farming requires the most agricultural land, generates the largest share of the world's food, and is particularly affected by climate change, these challenges apply especially strongly (Alexandratos and Bruinsma, 2012; Tscharntke et al., 2012).

However, these challenges for arable farming are not only a problem on a global scale. German arable farmers are also confronted with related local challenges. The decline in agricultural land poses a problem in Germany. More than 142 hectares of agricultural land are converted to other land uses every day (Federal Ministry of Food and Agriculture, 2021). At the same time, Germany has experienced a drastic increase in prices on the agricultural land market in recent years (Yang et al., 2019). The average purchase price for agricultural land surged by 193 % from 8.692 €/ha to 25.485 €/ha between 2005 and 2018, whereas the average rental prices of German agricultural land have developed more moderately with a price increase of 64 % from 176 €/ha to 288 €/ha between 2005 and 2016 (Federal Statistical Office of Germany, 2005, 2006, 2018a, 2018b). One might argue that the increase in land prices has mainly negative effects,

such as rising production costs (Feichtinger and Salhofer, 2016) and stronger market entry barriers for new or expanding farms (Hüttel et al., 2013), both of which lead to a reduction in sector efficiency (Kilian et al., 2012). The active debate about the causes and effects of farmland market developments has further led to increased calls for policy intervention and regulation (van der Ploeg et al., 2015; Lehn and Bahrs, 2018). Considering the importance of land as a production factor in agriculture as well as the strong movements in the market, it is not surprising that agricultural land markets have become the subject of extensive empirical research. Various explanatory approaches to price trends have been used in recent years, such as the attractiveness of farmland as an investment portfolio choice (e.g. Baker et al., 2014), an increased market entry of non-agricultural investors (e.g. Tietz et al., 2013), the importance of farmland for renewable energies (e.g. Myrna et al., 2019), the auction design of farmland privatization (e.g. Hüttel et al., 2016; Croonenbroeck et al., 2020), and many more. Still, there are numerous unanswered questions about the agricultural land markets and the challenges they pose for arable farmers in the 21st century. In the German Farmers Association's (2017) *Agrifuture Insights* survey, over 80 % of German farmers surveyed stated that the scarcity and high prices of agricultural land were among the biggest challenges facing agriculture.

The mentioned scarcity of farmland as a production factor requires an increase in productivity on the land under cultivation from a sectoral perspective. However, productivity increases have also become more important from an individual farm enterprise point of view, as rising production costs as well as domestic competition for limited factors such as land have enhanced the value of productivity growth (Balmann and Schaft, 2008). Similarly, sustainability and resource efficiency are challenges that also affect German arable farming since agriculture is expected to contribute substantially to environmental and climate protection (EU SCAR, 2012; Valin et al., 2014). Precision agriculture (PA) is a management strategy based on the use of data from multiple sources to improve farmers' decision making (Candiago et al., 2015). In arable farming, the main goal is to tailor management practices to the need of the crop by considering spatial and temporal information concerning the crop, soil and environment (Mesas-Carrascosa et al., 2015; Gonzalez et al., 2018). With the application of precision agricultural technologies (PAT), farmers can increase farm productivity by improving yields while at the same time reducing inputs and external environmental impacts (Tey and

Brindal, 2012; Pierpaoli et al., 2013). The adoption of PAT is regarded as an important goal by the European Union to meet the challenges in agriculture. For instance, the Policy Department for Structural and Cohesion Policies of the European Union expects that digital technologies will give rise to completely new farming practices and therefore transform the agricultural sector in the European Union to a large extent (Pesce et al., 2019). However, there is a large discrepancy between the expected pace and the actual pace of PAT adoption, which is perceived to be considerably slower. Additionally, in this regard, there are major differences between the various technologies and tools that can be assigned to PA. For this reason, it is necessary to understand the adoption process of PAT in general and to examine the adoption process of individual tools of PA separately (Lowenberg-DeBoer and Erickson, 2019).

One recent tool added to farmers' PA technology tool kit is the application of unmanned aerial vehicles (UAV), also known as drones. Unlike remote sensing via satellites and aircrafts, drones are less hindered by cloud cover and atmospheric distortions, but can still be affected by severe weather conditions such as heavy rain or wind. However, they offer higher spatial and spectral resolution, as well as greater flexibility due to the ability to start at almost any time desired (Candiago et al., 2015; Moskvitch, 2015). Drones possess a high degree of multifunctionality as a form of PAT. In Europe, they are currently mostly used as a non-invasive method to collect site-specific information via cameras and sensors mounted on the drone (Usha and Singh, 2013). Due to regulatory restrictions, they are currently not widely used for spot spraying or fertilizer applications (Reger et al., 2018; Spalevic et al., 2018). However, farmers can use drones to document damage from wildlife, droughts and hailstorms for insurance claims or use them to track livestock. Furthermore, using spectral images farmers can detect plant stress due to lack of nutrients, water or drought as well as the presence of pests, weeds and diseases. In addition, information on plant growth and soil health can be collected (Candiago et al., 2015; Moskvitch, 2015; Hunt Jr and Daughtry, 2018; Sylvester, 2018; Vayssade et al., 2019; Cao et al., 2020). Collected spectral information from drones can be further processed into maps which can guide pinpoint fertilizer or pesticide application using complementary PAT (e.g. variable rate fertilizer applicators and sprayers) (Moskvitch, 2015) or to schedule irrigation procedures (Sylvester, 2018). Therefore, the capabilities and multifunctionality of drones offer several potential applications for the information collected by the drone in arable farming, providing both economic benefits

to the farmer and environmental benefits to the overall system. Nevertheless, the actual adoption rates for drones are also considerably lower than expected and there is therefore a need for research to better understand the adoption process of drones. One of the most recent studies focuses on farmers' willingness to adopt drones (Zheng et al., 2019), yet no research has investigated the actual adoption decision.

Against this background, the papers presented in this cumulative thesis address two of the identified key future challenges of arable farming in Germany. The first two papers deal with the agricultural land market in Germany, looking both at the rental market with its main price drivers as well as at the purchase market in relation to a specific policy intervention. As the implementation of PAT in arable farming can help to increase both productivity as well as profitability per hectare and to realize environmental benefits through resource savings, this second key challenge will be considered in two further papers. Specifically, these papers analyze the adoption process of drones as one of the latest tools of PAT. The four papers are further described in the following.

The first paper of the cumulative thesis (Chapter II) titled "*German farmers' perspectives on price drivers in agricultural land rental markets – A combination of a systematic literature review and survey results*" (published in *Land*) studies the status quo regarding price drivers on European farmland rental markets according to current literature and offers primary survey results of farmers' perceptions regarding those identified price drivers. While many papers look into the price drivers on the buyer's market for agricultural land, a current overview of the findings in the literature regarding the agricultural land rental market is not available. It is, however, important to study the development of land rental prices not only because there is often a high proportion of rented land under cultivation – in Germany it is over 50 % – but also because farmland operators fluctuate much more often through rent than through purchase (German Farmers Association, 2020). The rental share of agricultural land has increased dynamically in European countries with well-developed agriculture (Marks-Bielska, 2013). Another aspect why it is important to analyze farmland rental prices is that they can be objectively monitored on the market, while the purchase price often represents the subjective opinion of the owner (Takáč et al., 2020). The decision to rent land is usually made on the basis of short- to medium-term considerations, without speculation on an increase in the value of the land (Koester and Cramon-Taubadel, 2019). Previous reviews have fo-

cused on the development of rental rates in European Union member states (Ciaian et al., 2012) or on applied land reforms in 25 countries (Hartvigsen, 2014). Yet, these reviews did not focus on price drivers on agricultural land rental markets. Furthermore, current studies focusing on farmers' views on the agricultural land rental market are scarce. Specifically, only four studies have analyzed the agricultural land (rental) market and its price drivers from the perspective of farmers (Ilbery et al., 2010; Marks-Bielska, 2013; Forbord et al., 2014; Emmann et al., 2015). However, none of the studies have focused on farmers' perceptions on more than one price driver affecting the agricultural land rental market. Furthermore, farmers' expectations of the future magnitude of these price drivers have not yet been examined.

The objectives of the paper can be summarized by the following research questions:

- (1) *According to the available up-to-date literature, what are the key price drivers on European farmland rental markets?*
- (2) *And based on this, what are the current perceptions and future-related assessments of farmers themselves regarding the identified price drivers?*

In order to be able to study these research questions the paper follows a two-step approach. First, the study depicts the current findings in the literature concerning agricultural land rental markets and their price drivers by applying the “preferred reporting items for systematic reviews and meta-analysis (PRISMA)” procedure by Moher et al. (2009). This review provides an overview of 34 selected articles dealing with agricultural land rental markets, which are classified according to groups of price drivers and the methodological approaches. In a subsequent second step, an online survey was conducted among German farmers in 2020, explicitly targeting farms with rental land. A total of 156 complete questionnaires received were used and are analyzed using descriptive methods. The farmers surveyed were asked about their perceptions of the previously identified price drivers as well as their assessment of the future relevance of these price drivers.

Chapter III contains the paper “*On the effectiveness of restricted tendering as a form of policy intervention on agricultural land markets*” (published in *Land Use Policy*) and assesses the effect of a widely used intervention tool on the agricultural land market in terms of purchase price levels. In recent years, the price of agricultural land in Europe

has risen sharply, which has led to a discussion concerning the need for political intervention and stronger market regulation on agricultural land markets (van der Ploeg et al., 2015; Lehn and Bahrs, 2018). The results of the paper in the previous chapter show that farmers' perceptions of the land market can be fundamentally different from model calculations. It is concluded and recommended that policymakers incorporate the perceptions of farmers themselves into their decision making to anticipate unexpected short-term responses from farmers. Otherwise, if farmers assess the causes differently from the scientific findings, a reaction diverging from the anticipated behavior as a result of the intervention would be possible. Accordingly, it seems reasonable to examine the effectiveness of an existing policy intervention in the agricultural land market to determine whether the effect desired by policymakers is achieved.

In countries where agricultural land has historically not been in private ownership, such as Europe's post-communist countries, tendering procedures are being held in the course of the ongoing privatization of agricultural land (Hartvigsen, 2014). In this context, restricted tendering is discussed and used as one form of political intervention (Stacherzak et al., 2019). Only certain groups of bidders may participate in such tendering procedures in order to give them greater opportunities and to counteract effects such as land grabbing or structural change (Bunkus and Theesfeld, 2018; Stacherzak et al., 2019). The auction mechanisms on agricultural land markets have already been analyzed in many respects, for example with regard to determinants of price formation (Hüttel et al., 2013), bidder asymmetries (Croonenbroeck et al., 2020) or price-driving effects in comparison to negotiations (Visser and Spoor, 2011; Hüttel et al., 2016). The effect of restricted tendering, however, has not been studied and, accordingly, there is no scientific evidence yet on the effect of restricted tendering on the purchase price of agricultural land.

The objectives of the paper can be summarized by three research questions:

- (1) Do restricted tendering procedures lead to a statistically significant reduction in the number of bidders in agricultural land auctions?*
- (2) Is there a statistically significant difference between the purchase prices of agricultural land under open and restricted tendering procedures?*
- (3) And onward, does restricted tendering of agricultural land thus fulfill its purpose of allowing structurally disadvantaged groups of bidders to buy at lower prices?*

The paper relies on auction theory and Propensity Score Matching (PSM) introduced by Rosenbaum and Rubin (1983) as well as difference-in-means-analyses, using a data set of over 12,000 agricultural land transactions between 2005 and 2019 provided by the land privatizing agency in Eastern Germany (BVVG). The BVVG (Bodenverwertungs- und –verwaltungs GmbH) was founded in 1992 as the direct successor to the first German privatization institution (Treuhandaanstalt) with the aim of privatizing agricultural and forestry land over a long period on behalf of the German Ministry of Finance. Since then, the BVVG has been privatizing through first-price sealed-bid auctions with public tenders without binding and without reported reservation price as well as through special transactions for reparation reasons according to the privatization principles in Germany. Thereby BVVG auctions in the former East German states have a considerable local market share with regionally observed portions of up to 60 % of all transactions involving agricultural land (Croonenbroeck et al., 2020). Parts of the first-price-sealed-bid auctions are conducted as restricted tendering procedures aiming to enable groups of bidders disadvantaged by the structural change in agriculture to acquire agricultural land at lower prices (BVVG, 2019). This form of political intervention on agricultural land markets is studied for the first time in this paper with regard to its effectiveness and its effect on purchase price levels.

While the first two papers of the cumulative thesis address questions related to the agricultural land markets, the last two papers (Chapters IV and V) focus on a second identified challenge of arable farming in the 21st century – the implementation of PAT and, in this case, specifically the adoption of drones in arable farming.

Chapter IV contains the paper “*A trans-theoretical model for the adoption of drones by large-scale German farmers*” (published in *Journal of Rural Studies*). The adoption of PAT has received considerable research attention¹ and several articles have highlighted potential areas of drone application (e.g. Hunt Jr and Daughtry, 2018). Even though drones can be considered as a part of PAT, they differ in some crucial ways from other PAT since drones offer a higher multi-functionality for farmers. As shown before they can be used independently for several purposes but also as a complement to other PAT. Nevertheless, literature explicitly focusing on the adoption of drones by farmers is scarce. One of the most recent studies focuses on farmers’ willingness to adopt drones

¹ For a literature review see Pierpaoli et al. (2013) and Tey and Brindal (2012).

(Zheng et al., 2019), yet no research has investigated the actual adoption decision. Although existing studies predict a growth in the adoption of drones for agriculture (Puri et al., 2017; Hunt Jr and Daughtry, 2018; Mitchell et al., 2018) and expect that 80 % of all drones will be used in PA in the future (Moskvitch, 2015), the adoption of drones in agriculture has yet to really take off (Bramley and Ouzman, 2019). Consequently, it is worthwhile to identify key factors influencing the adoption of drones. For this purpose, it appears reasonable to focus primarily on farmer and farm characteristics in the course of an initial study and to examine which of them have a direct influence on the adoption process. Farmer and farm characteristics are objectively measurable and can therefore be directly compared with each other. This way, the characteristics of early adopters can be identified and compared with those of other PATs. Furthermore, it appears interesting whether the adoption process of drones differs from that of other PAT, which could be expected due to the high degree of multi-functionality. This is consistent with the approach of Pierpaoli et al.'s (2013) existing study regarding PAT adoption in general.

The objectives of the paper can therefore be summarized by the following research questions:

- (1) *What are the key farmer and farm characteristics influencing the adoption process of drones in arable farming?*
- (2) *Does the adoption pattern of drones correspond to the adoption patterns observed for other PAT?*

To answer these questions, the paper analyzes a data set consisting of 167 German farmers collected via an online survey in 2019. In order to study the process of adoption, the trans-theoretical model of behavioral change (TTMC) (Prochaska and Velicer, 1997) is modified to a trans-theoretical model of adoption (TTMA) for drones in agriculture, which accounts for more than two stages in the adoption process. By doing so, the paper presents a modification of the TTMC to gain deeper insights into farmers' adoption processes.

The fourth paper of this cumulative thesis (Chapter V) titled "*The adoption of drones in German agriculture: A structural equation model*" (published in *Precision Agriculture*) builds on the content of the previous chapter. However, while the third paper focuses on farmer and farm characteristics that influence the adoption process, the fourth paper

expands the scope of research to include latent factors influencing the adoption decision. In contrast to directly observable variables (e.g. individuals' age), a latent variable (e.g. individuals' perception or beliefs) cannot be directly measured but has to be estimated based on other directly observable variables (Kaplan, 2004). Understanding farmers' perceptions and beliefs towards a technology is essential for several reasons. Bearing in mind that farmers' utility does not depend solely on profit maximization, the utility they derive from a particular technology will vary between individuals. On top of that, especially with new technologies, an objective assessment of the associated economic benefits is limited, so the farmer's perception of these benefits will influence his or her adoption behavior. If the farmers' adoption of new technologies was purely based on objectively measurable (economic) benefits that would imply that all farmers are equal and adopt a technology simultaneously (Diederer et al., 2003). Thus, ultimately, it is the farmers' perception of the utility of a new technology that drives the adoption process (Barnes et al., 2019). Moreover, farmers are not fully rational in their decision making (Musshoff and Hirschauer, 2011) and may also be influenced by a status quo bias, such as a preference to preserve the current state (Kahneman et al., 1991). To disentangle such cognitive reasoning that cannot be observed directly, literature has shown that assessing farmers' perceptions and beliefs can contribute to the understanding of farmers' decision making (e.g. Schaak and Mußhoff, 2018). Unsurprisingly, literature has also shown that farmers' perceptions and beliefs towards the technology play a major role in decision making with respect to PAT (e.g. Adrian et al., 2005; Rose et al., 2016). Consequently, it is reasonable to suggest that farmers' perceptions and beliefs about the benefits and expenses of using a drone can play a major role in the decision-making process. This holds especially true since drones are not widespread yet and therefore farmers' first perceptions about drones may be of great importance in the adoption process. In consequence, delivering programs and marketing activities that addresses farmers' perceptions and beliefs will be more likely to succeed (Gaffney et al., 2019).

A theoretical framework which explicitly focuses on individuals' perceptions and beliefs is the Technology Acceptance Model (TAM) (Davis, 1989) which aims to explain an individuals' intention to adopt a new technology with latent variables (e.g. perceptions and beliefs). The TAM consists of the key latent variables perceived usefulness and perceived ease of use which are expected to affect an individuals' intention to use a

new technology or practice and ultimately the actual adoption decision (Davis, 1989). Pierpaoli et al. (2013) concluded based on their literature review that both perceived usefulness and perceived ease of use are important latent factors in determining the success of a PAT. With respect to drones, Zheng et al. (2019) already included both latent variables as factors explaining Chinese farmers' intention to use drones in a binary probit model. However, both latent variables have not been used in a structural equation model as proposed by the framework of the TAM to explain farmers' intention to use drones and also the actual adoption of drones. More specifically, they have not been used to identify causal relationships in the adoption process as it is possible using structural equation modelling.

The objectives of the paper can be summarized by the following research questions:

- (1) *What are the key latent factors influencing farmers' intention to adopt a drone and the adoption process of drones in arable farming?*
- (2) *Can the TAM framework contribute to the understanding of arable farmers' decision making with respect to the adoption of drones?*

In order to answer these questions, the paper analyzes the same sample of 167 German arable farmers as the paper from the previous chapter, which was collected through an online survey using a standardized questionnaire in 2019². The methodical approach to estimate the TAM and analyze the causal relationships between the latent variables is partial least squares structural equation modelling (PLS-SEM). Furthermore, a logit model to test the relationship between the intention to use a drone and the actual adoption of drones stated by the farmers in the sample is applied. Thus, by first applying the TAM for drone technology, the paper extends the insights gained in Chapter IV regarding the adoption process of drones in arable farming.

Accordingly, this cumulative thesis is composed of four papers, two of which address questions related to agricultural land markets, while the other two focus on questions revolving around drone adoption by German arable farmers. The results of this cumulative thesis are primarily of interest to agricultural policymakers who are involved in the

² In order to maintain full transparency in the publication process, the editor of the journal *Precision Agriculture* was informed from the beginning that the evaluated data set had already been analyzed using a different model in regards to an alternative research question and that the corresponding article had been published in the *Journal of Rural Studies*.

active debate on agricultural land market interventions as well as those who wish to politically promote the dissemination of PAT. Furthermore, the results are of interest to farmers, (potential) buyers in the farmland market and agricultural expansion services. Developers and providers of drones and farm equipment that integrates drone technology could also benefit from this research. Lastly researchers on agricultural land markets as well as PAT could profit from the several impulses for further research provided throughout this thesis. In the following chapters, the four papers are presented consecutively before the thesis closes in Chapter VI with a summary and the conclusions.

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II German farmers' perspectives on price drivers in agricultural land rental markets – A combination of a systematic literature review and survey results

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Abstract

Despite the popularity of agricultural land markets as a research topic, a current literature review on price drivers on agricultural land rental markets is missing, which is crucial in order to gain an overview of the status quo. Furthermore, farmers' perceptions of price drivers on agricultural land rental markets have not been considered sufficiently. Therefore, this study combines descriptive results from a survey with 156 German farmers conducted during 2019–2020 using purposive sampling and a systematic literature review. The systematic literature review reveals four important areas acting as price drivers in agricultural land rental markets: policy/Common Agricultural Policy (CAP), bioenergy, climate change, and market prices/competition. Based on the overview, several points of departure for further research are provided. Furthermore, results from the survey show that farmers' perceptions of the relative importance of the price drivers differ from the results of scientific literature. Therefore, perceptions of farmers should be considered for possible policy interventions derived from scientific evidence.

Keywords: Agricultural land rental markets; price drivers; German farmers; PRISMA procedure; agricultural policy

III On the effectiveness of restricted tendering as a form of policy intervention on agricultural land markets

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Abstract

The ongoing sharp rise in farmland prices in Europe has led to a discussion concerning the need for political intervention and stronger market regulation on agricultural land markets. In this context, restricted tendering for the privatization of agricultural land in post-communist countries is discussed and used as one form of political intervention. Only certain groups of bidders may participate in such tendering procedures in order to give them greater opportunities and to counteract effects such as land grabbing or structural change. Against this background this paper aims to answer the question, whether restricted tendering procedures allow structurally disadvantaged groups of bidders to buy at lower prices as is intended by the assessed policy intervention. A rich data set of over 12,000 first-price-sealed-bit auctions of agricultural land between 2005 and 2019 from Eastern Germany is analyzed using an auction theory individual private value framework and Propensity Score Matching. Results show that restricted tendering on agricultural land markets does not fulfill its intended purpose. Although the policy's intermediate aim of considerably reducing the number of bidders is achieved, the ultimate goal of lower purchase prices is missed. On the contrary, the findings indicate that restricted tendering actually leads to higher purchase prices for comparable farmland plots.

Keywords: Agricultural land markets, farmland auctions, restricted tendering, propensity score matching

IV A trans-theoretical model for the adoption of drones by large-scale German farmers

Authors: Marius Michels, Cord-Friedrich von Hobe and Oliver Musshoff

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Abstract

To analyse the adoption of drones in agriculture as the latest tool added to the set of precision agriculture technologies, this paper makes use of a novel application of the trans-theoretical model of behavioural change by analysing a sample of 167 large-scale German farmers collected in 2019. The model provides a gradual measure of farmers' decision making with respect to the adoption of drones, which gives more detailed insight into farmers' adoption processes than the more common approach of applied binary classifications. Ordinal logit regression results show that, among other factors, farmers' age, precision agriculture technology literacy and farm size affect farmers' adoption process. Thus, this paper contributes to the literature by identifying key determinants of the drone adoption process in agriculture. Furthermore, this study provides information about the fields of drone application as well as reasons that oppose the usage of drones by farmers. The results are of interest for policy makers and suppliers of drones.

Keywords: Drones; German farmers; ordinal logit regression; precision agriculture; technology adoption; unmanned aerial vehicle

V The adoption of drones in German agriculture: A structural equation model

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Abstract

Drones are one of the latest tools to have been added to farmers' precision agriculture technology tool kit. Despite the proclaimed benefits, adoption rates of drones are low and literature regarding the adoption of drones in agriculture is scarce. Therefore, this study investigates whether an extended Technology Acceptance Model (TAM) can contribute to the understanding of latent factors influencing farmers' intention to adopt a drone. The sample of 167 German farmers was collected in 2019 via an online survey. Using partial least squares structural equation modelling and a binary model, the TAM explains 69 % of the variance in the intention to use a drone by German farmers. According to the results, raising farmers' awareness of farm-specific areas of drone application and the confidence level of using a drone can increase farmers' intention to adopt a drone. The results are of interest for agribusinesses developing drones as well as selling or providing drones. Furthermore, the results are of interest for researchers in precision agriculture technologies.

Keywords: Drones; precision agriculture; Technology Acceptance Model; partial least squares structural equation modelling; unmanned aerial vehicle

VI Summary and conclusions

This cumulative thesis addresses two specific challenges that German arable farmers face in the 21st century. The first two papers focus on the agricultural land market in Germany. In this context, the first paper (Chapter II) studies price drivers on European farmland rental markets, as stated in the current academic literature, and contrasts them with the perceptions of German arable farmers. The second paper (Chapter III) assesses the purchase market in relation to a specific policy intervention. The last two papers focus on a second identified challenge – the implementation of PAT and, in this case, specifically the adoption of drones in arable farming. In this regard, the third paper (Chapter IV) examines which farmer and farm characteristics have a direct influence on the adoption process. Building on this, the fourth paper (Chapter V) studies the key latent factors influencing farmers' intention to adopt a drone and the adoption process of drones in arable farming. In the following, the results and conclusions are summarized for the individual papers consecutively. Additionally, political implications are provided and potential starting points for future research are given.

In the first paper, the status quo regarding price drivers on European farmland rental markets according to current literature was studied and primary survey results of German farmers' perceptions regarding those identified price drivers were offered. The systematic literature review was conducted through the “preferred reporting items for systematic reviews and meta-analysis (PRISMA)” procedure by Moher et al. (2009). It resulted in 38 scientific papers, which were included in the final literature analysis and, thus, in the subsequent development of the questionnaire. The results of the systematic literature review show that the drivers of farmland rental prices in Europe can be divided thematically into the four categories “policy/CAP”, “bioenergy”, “climate change”, and “market prices/competition/various” whereby causal and interdependent relationships exist in between the categories. In this regard, price drivers due to political interventions, incentives and subsidies clearly play the main role in research on factors influencing farmland rental markets in Europe. Methodologically, the majority of the literature examined used historical time series data as the basis for the calculations (“historical data/ex-post assessment”) or simulated the influence of various price drivers on rental prices using model assumptions (“simulation/ex-ante assessment”). However, surveys to gain insights into farmers' perceptions as well as literature reviews are

scarce. The descriptive results of the survey among German arable farmers, which was based on the findings of the literature review, show that competition among farmers is by far perceived as the strongest influencing factor on the agricultural land rental market. This finding supports previous results in the literature (Marks-Bielska, 2013; Forbord et al., 2014). Additionally, non-agricultural investors were recognized as the second-strongest factor. The literature confirms this perception of farmers (Emmann et al., 2015), while empirical studies show little or no evidence of such a significant impact (e.g. Odening and Hüttel, 2018; Balmann and Odening, 2021). The effect of agricultural policy was perceived as the third strongest factor, contrary to the results of the literature review. Bioenergy was hardly recognized by farmers as a major price driver. Looking at future developments, however, the surveyed farmers considered agricultural policy price drivers and non-agricultural investors most relevant. In contrast, the strongest decrease in strength of influence is observed for bioenergy. Ultimately, particularly with regard to the influence of non-agricultural investors, the findings of existing studies and the perception of farmers contradict each other.

Several implications for research and policy could be derived from the study. On the one hand, the individual price drivers should be broken down more precisely than was done in this fundamental research approach. On the other hand, it appears worthwhile to investigate whether (and to what extent) the discrepancy between existing literature and farmers' perceptions also applies to purchase prices. Against the background of a considerable discrepancy between survey results and model calculations, a combined approach of both methods appears to be advantageous. Studies based on this fundamental research should therefore also consider a combined approach to cover a wider range of findings. Regarding policy impact assessments, an inclusion of the perceptions of farmers themselves is also suggested. Along this line it is recommended that policymakers derive procedures from combined methodological approaches to anticipate unexpected short-term reactions of farmers. Particularly, the perception of farmers should be considered for possible policy interventions that could be derived from scientific evidence. Otherwise, if farmers assess the causes differently from the scientific findings, a reaction diverging from the anticipated behavior as a result of intervention would be possible.

Taking this conclusion regarding the first paper as a starting point, the second paper studies the effect of restricted tendering in farmland auctions as a widely used policy intervention tool on the agricultural land market. The objective is to verify whether restricted tendering of agricultural land fulfills its purpose of allowing structurally disadvantaged groups of bidders to buy at lower prices. To answer this question and to understand the mechanisms at work in restricted tendering procedures on agricultural land markets, the paper relies on auction theory and Propensity Score Matching (PSM) introduced by Rosenbaum and Rubin (1983) as well as difference-in-means-analyses, using a data set of over 12,000 agricultural land transactions between 2005 and 2019 provided by the land privatizing agency in Eastern Germany (BVVG). An independent private value (IPV) model was chosen as the assumed auction theory framework. This approach is in line with the existing literature on BVVG auctions (e.g. Hüttel et al., 2013; Croonenbroeck et al., 2020) and follows the assumptions set out by the BVVG as the responsible institution. The results of the PSM procedure showed sufficient overlap and common support of the estimated propensity scores as well as a good matching quality. For the average number of bids as well as the average purchase price per hectare, the average treatment of the treated (ATT) was calculated. Regarding the number of bids, the results reveal a highly statistically significant difference between open and restricted tendering procedures. The ATT shows that restricting the circle of potential bidders as is done by the BVVG leads on average to 1.47 fewer bids for a land plot with comparable baseline covariates. This immediate outcome of the restricted tendering procedure shows that the mechanism sought by the BVVG to reduce the number of bidders is working. In terms of average purchase prices, the results also show a statistically significant difference between open and restricted tendering procedures. However, the nature and direction of the statically significant difference is contrary to what is expected in the model used in this study and envisaged by the BVVG. The average purchase price in open tendering procedures (16,934 €/ha) is actually lower than the average purchase price of restricted tendering procedures (17,564 €/ha) for a land plot with comparable baseline covariates. Thus, the ATT shows that restricted tendering leads on average to a higher purchase price of agricultural land by 630 €/ha. Three alternative matching algorithms all qualitatively confirm the presented results as a robustness check.

The paper provides several potential explanations for this apparent paradox. If, contrary to the assumption at the auctions on the farmland market, there is a common component

in the valuation of the land plots by the individual bidders the phenomenon could be explained by the optimal bidding strategy. New findings from Seifert and Hüttel (2020) support this explanatory approach. In this case, a ‘winner’s curse’ or the so-called ‘affiliation effect’ could lead to higher prices being achieved despite fewer bidders (Pinkse and Tan, 2005). This would mean that the implementing institution might misjudge mechanisms in the auctions carried out. Other possible explanations are an anchor effect due to minimum bids, an incentive to offer more than usual for participants in restricted tendering procedures or speculation on resale to previously excluded bidders. Implications for research and policy emerge from the findings. Further scientific evidence is needed, in particular with regard to possible motivations for bidding behavior in restricted tendering on agricultural land markets as well as on the possible existence of a common component in agricultural land auctions. At the same time, policymakers are recommended to question the effectiveness of restricted tendering as an intervention tool on agricultural land markets in their existing form. They should review whether the behavior and considerations of the bidders in farmland auctions they have assumed are correct in order to avoid that the policy intervention leads to undesired results.

In the third paper, key factors influencing the adoption of drones were studied. The focus of this fundamental research was mainly on sociodemographic farm and farmer characteristics. Additionally, the status quo regarding the use of drones in German arable farming was to be evaluated. For this, the paper analyzed a data set consisting of 167 German arable farmers collected via an online survey in 2019. In order to study the process of adoption, the trans-theoretical model of behavioral change (Prochaska and Velicer, 1997) was modified to a trans-theoretical model of adoption (TTMA) for drones in agriculture, which accounts for four stages in the adoption process: “Pre-contemplation”, “contemplation”, “preparation” and “action”. Descriptive sample results show that the average farmer in the assessed sample belongs in the contemplation stage. 22 % of the surveyed farmers actually use a drone on their farm. Almost all of these adopters (92 %) use drones for the identification and documentation of damages caused by wild animals or extreme weather conditions. Approximately half of the adopters also use drones for spectral images for crop monitoring to identify the current status of the plants with respect to nutritional status, infection with diseases or ripeness of plants. Smaller shares of adopters stated that they use drones for specific crop protection purposes as well as 3D field mapping and the construction of terrain models. The

non-adopters were asked about their reasons for not using drones in agriculture. Almost half of the non-adopters indicated they were not using drones because they perceive their application as too expensive. This finding is in line with existing literature regarding the adoption of PAT (Tey and Brindal, 2012). To a similar extent, the second most cited reasons were legal hurdles as well as a perception that the application is not practical. Reasons stated to a lesser extent were a possible non-acceptance by the public as well as missing providers, contact persons or system compatibility. The regression results show that increasing farm size positively influences the adoption process, whereas farmers' age has a negative influence on the adoption process of drones. Moreover, attitudinal factors as well as farmers' PAT literacy and gender affect the farmers' adoption process. No statistically significant effect was found for farmers' education and participation in livestock farming beyond the arable operations of the farm. The results are in line with the existing literature on the adoption of other PAT. Thus, this study provides proof of the anecdotal evidence that the adoption of drones corresponds to a certain extent to the observed patterns in the adoption of PAT.

Several implications could be drawn from these insights. For policymakers, there is a need for clarifying the legal status of drone applications for farmers. Policymakers who aim to increase uptake in the near future with educational programs and extension services can be given the advice to consider that older farmers and female farmers face barriers in the adoption process. For developers and providers of drones, better communication as well as demonstration of the technology's benefits poses an opportunity. Such practical demonstrations might increase the trust of non-adopters in the use of drones for agricultural purposes. Furthermore, a target group of drone adopters which could be addressed with marketing activities by the providers and suppliers was identified. These activities should focus on younger, male farmers from larger farms who have already implemented other PAT on the farm. Additionally, an investigation of the complementary use of drones with other PAT could be fruitful for developers and providers. For researchers in the field of PAT, future studies should take the perceptions of smaller farms into account since it can be expected that as adoption increases, costs for drones will decrease and drones may also become of interest to smaller farmers. To further expand the understanding of the adoption process of drones in arable farming, it appears promising to include latent factors influencing the adoption decision in future studies.

Building on the findings of the third paper, the fourth paper extends the scope of research towards the latent factors influencing the adoption process of drones in arable farming. For this purpose, the same data set of 167 German arable farmers was analyzed that was already assessed in the third paper. In the paper, an extended Technology Acceptance Model (TAM) (Davis, 1989) was utilized using partial least squares structural equation modelling (PLS-SEM) and a binary model. The TAM studies behavioral adoption drivers and consists of the key latent variables “perceived usefulness” and “perceived ease of use” which are expected to affect an individuals’ “intention to use” a new technology or practice and ultimately the actual adoption decision. In addition to the original TAM, the latent variables “attitude of confidence” and “job relevance” were included in the model. The results show that 69 % of the variation in the intention to use a drone decision was explained by the model. Seven of eight hypotheses of the extended TAM could be supported by the model. Merely the effect of “perceived ease of use” on “perceived usefulness” was found not statistically significant. Thus, the paper provides empirical evidence that the TAM framework can also be applied to the adoption process of drones in agriculture and is also able to capture a large amount of information about the latent features in the process. The paper’s results especially indicate that raising farmers’ awareness of farm-specific areas of drone application and the confidence level of using a drone can increase farmers’ intention to adopt a drone. This confirms suggestions from literature to extend the original TAM by further contextualized motivational influences beside its core latent factors and that it can therefore maintain its relevance (Lim, 2018).

The findings lead to several implications. In summary, the results suggest that besides the communication of economic benefits explaining and demonstrating drones and their benefits in an individual meaningful way to the farmers, it is necessary to change farmers’ perceptions as well as beliefs about drones to ultimately increase their intention to use drones. This is of relevance to policymakers who aim to increase drone usage with educational programs and extension services as well as developers and providers of drones. The latter are recommended to individualize their marketing activities and guided applications to farmers’ needs and relevant areas of drone application on the specific farm. Regarding potential future research it could be useful to investigate farmers’ perceptions with respect to drones in several other potential areas of drone application like precise input application to validate the results. Additionally, the study should be re-

peated in other countries. In this, by using panel data and a larger more representative sample, further evidence for the predictive strength of the TAM by assessing the link between farmers' intention to use a drone and the actual adoption of a drone at a later point of time could be provided. Lastly, combining structural equation modeling with multivariate regression techniques might be a promising area for future research. For instance, the model used in this paper could be paired with categorical regression approaches to study the adoption probability of drones in arable farming with different levels of complexity.

The first two papers of the thesis provide valuable insights with regard to agricultural land markets. The conjecture elaborated in the first paper that if farmers' own perceptions of causes and effects in the agricultural land market deviate from empirical evaluations and research model assumptions, interventions may lead to undesirable consequences was anecdotally analyzed and confirmed in the second paper. This phenomenon should be studied scientifically in relation to other policy interventions in the agricultural land market, especially since further policy interventions are currently under high discussion. Additionally, it seems worthwhile to analyze the relationship between purchase and rental markets for agricultural land in more detail, especially with regard to agricultural land as an alternative investment object. Since empirical results on land market auctions are almost exclusively available on purchase auctions, future research should increasingly turn to auctions for rental land.

The results of the last two papers of this thesis offer first insightful findings on the adoption of drones as PAT in arable farming. In this context, the two papers complement each other in two ways. On the one hand, the papers support each other in their research questions, which examine both sociodemographic factors as well as latent behavioral patterns as an influence on drone adoption in arable farming. On the other hand, the TTMA and the TAM have complementary methodological aspects. Particularly with regard to new technologies, the combined approach of both methods appears useful, as both can play out their advantages in combination. In the first step, the TTMA enables a gradual determination in the adoption process that goes beyond the binary adoption decision and provides insights into which sociodemographic characteristics make up the first-adopters. Based on this, the extended TAM provides insights into the often crucial latent factors and enables predictions regarding adoption intention. Build-

ing on these initial findings on the adoption process of drones in arable farming, several future research approaches emerge. While the two papers in this thesis examine drone use in general, future research should look at specific drone services in more detail. Due to the high degree of multifunctionality of drones, it might be interesting to analyze the willingness to pay for specific drone services. In this way, the target groups for drones in arable farming identified in this thesis could be addressed in an even more targeted manner. Due to the fast pace of digitalization in the PAT, the results should also be continuously updated to check when and in what form the use of drones in arable farming is economically more interesting, even for smaller farms.

Summarizing, the four papers of this cumulative thesis contribute to the understanding of two specific challenges that German arable farmers face in the 21st century. The results are primarily of interest to agricultural policymakers who are involved in the active debate on agricultural land market interventions as well as those who wish to politically promote the dissemination of PAT. Furthermore, the results are of interest to farmers, (potential) buyers in the farmland market and agricultural expansion services. Developers and providers of drones and farm equipment that integrates drone technology could also benefit from this research. Each of the papers contributes to its particular body of literature and shows potential directions for future research.

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Publication list

Papers published in peer-reviewed journals

- von Hobe, C.-F.** and Musshoff, O. (2021). On the effectiveness of restricted tendering as a form of policy intervention on agricultural land markets. *Land Use Policy*, 103, 105343.
- von Hobe, C.-F.**, Michels, M. und Mußhoff, O. (2021). Präferenz deutscher Landwirte für Pachtpreisanpassungsklauseln unter Berücksichtigung des Klimawandels und der Änderung agrarpolitischer Rahmenbedingungen. *Berichte über Landwirtschaft - Zeitschrift für Agrarpolitik und Landwirtschaft*, 99(1), 1-19.
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- von Hobe, C.-F.** and Musshoff, O. (2020). On the effectiveness of restricted tendering as a form of policy intervention on agricultural land markets. 60te Jahrestagung der Gesellschaft für Wirtschafts- und Sozialwissenschaften des Landbaues (GEWISOLA), Herausforderungen für die ländliche Entwicklung - Wirtschafts- und sozialwissenschaftliche Perspektiven, Halle (Saale), 23. bis 25. September 2020.
- von Hobe, C.-F.**, Michels, M., Fecke, W., Mußhoff, O. und Weller von Ahlefeld, P. J. (2019). Wie kommunizieren Landwirte in Zeiten der Digitalisierung?. 39te Jahrestagung der Gesellschaft für Informatik in der Land-, Forst-, und Ernährungswirtschaft (GIL), Digitalisierung für landwirtschaftliche Betriebe in kleinstrukturierten Regionen-ein Widerspruch in sich?, Wien, Österreich, 23. bis 28. September 2018.
- Michels, M., **von Hobe, C.-F.**, Weller von Ahlefeld, P.J. and Mußhoff, O. (2021): An Extended Technology Acceptance Model for the Adoption of Drones in German Agriculture. Forthcoming in: 13th European Conference on Precision Agriculture (ECPA), Adoption of innovative precision agriculture technologies and solutions, Budapest, Ungarn, 19. bis 22. Juli 2021.
- Michels, M., **von Hobe, C.-F.** and Mußhoff, O. (2020): A trans-theoretical model for the adoption of drones in German agriculture. 15th Biennial Conference of the International Society of Precision Agricultural (ISPA), Minneapolis, USA, 28. Juni bis 01. Juli 2020.

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- von Hobe, C.-F.** und Mußhoff, O. (2021): On the effectiveness of restricted tenders as a form of policy intervention on agricultural land markets. Forthcoming in: Schriften der Gesellschaft für Wirtschafts- und Sozialwissenschaften des Landbaues e. V.
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Declaration of contribution

The table summarizes my contribution to each paper included in this cumulative thesis. The order of names is determined taking into account the overall input for each type of contribution.

List of authors by contribution type

	Chapter II	Chapter III	Chapter IV	Chapter V
Conceptualization	CFvH, MM	CFvH	MM	MM
Methodology	CFvH	CFvH	CFvH, MM	CFvH, MM
Data collection and preparation	CFvH	CFvH	MM	MM
Formal analysis	CFvH, MM	CFvH	MM, CFvH	MM, CFvH, PJWvA
Visualization	CFvH, MM	CFvH	CFvH, MM	CFvH, MM, PJWvA
Interpretation of results	CFvH, MM, OM	CFvH, OM	MM, CFvH, OM	CFvH, MM, OM
Writing – original draft preparation	CFvH, MM, OM	CFvH, OM	MM, CFvH, OM	CFvH, MM, OM
Writing – review and editing	CFvH, MM, OM	CFvH, OM	CFvH, MM, OM	CFvH, MM, OM

Authors: CFvH	Cord-Friedrich von Hobe
OM	Prof. Dr. Oliver Mußhoff
MM	Dr. Marius Michels
PJWvA	Paul Johann Weller von Ahlefeldt

Eidesstattliche Erklärungen

Hiermit erkläre ich eidesstattlich, dass:

1. diese Arbeit weder in gleicher noch in ähnlicher Form bereits anderen Prüfungsbehörden vorgelegen hat.
2. ich mich an keiner anderen Hochschule um einen Doktorgrad beworben habe.

Göttingen, im Juni 2021

.....

Cord-Friedrich von Hobe

Hiermit erkläre ich eidesstattlich, dass diese Dissertation selbständig und ohne unerlaubte Hilfe angefertigt wurde.

Göttingen, im Juni 2021

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Cord-Friedrich von Hobe