The Role of Contractors in the Uptake of Precision Farming – A Spatial Economic Analysis

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Abstract

Contractors will play a vital role in providing farms access to new precision farming technologies, especially in small scale farming systems. We investigate the role of spatial competition among contractors in the uptake of precision farming, the distribution of farmer surplus, and the realization of policy interventions, accounting for alternative spatial pricing schedules. Conceptual analyses and case study show that a lack of spatial competition among contractors hinders uptake of precision farming technology and farmer surplus. The effectiveness of policy interventions to support precision farming among small farms is also contingent on the market structure and pricing schedules of contractors.

Keywords: precision farming, technology uptake, contractor service, market structure, spatial competition

JEL Classification: Q16, Q18, Q12

1. Introduction

Precision farming is one component towards more sustainable agriculture (Walter, Finger, Huber, & Buchmann, 2017). Inputs can be used more efficiently, reducing both farmers' variable production costs and environmental footprints of farming, e.g., by reducing losses of nitrogen and pesticides (e.g., Balafoutis et al., 2017; Finger, Swinton, El Benni, & Walter, 2019; Weersink, Fraser, Pannell, Duncan, & Rotz, 2018). Thus, the adoption and diffusion of precision farming techniques is of large political interest. However, the current adoption of precision farming techniques differs largely across technologies and countries (e.g., Barnes et al., 2019; Finger et al., 2019). Especially techniques requiring high investments such as variable rate application technologies are rarely used at small farms and/or in small scale agricultural systems due to insufficient economic return. Yet, these technologies have the largest potential for sustainable intensification (Garnett et al., 2013). In light of the misalignment between the potential public benefit of precision farming and the limited adoption among small farms due to lack of private benefit, policy instruments have been implemented to support adoption, especially in European countries where small farm systems are prevalent (Barnes et al., 2019; Finger et al., 2019). In these systems, contractor service that brings machinery to farms will play a vital role in providing access to new technologies. The combined effects of contractor service and policy interventions may further enable wide-spread adoption, and therefore aligning the public and private benefits associated with precision farming (e.g., Busse et al., 2014).

In this paper, we use a spatial competition framework to investigate the role of contractors in the uptake of precision farming and its role in the realization of policies that support precision farming. More specifically, we investigate how spatial competition between contractors providing precision farming services affects i) the uptake of precision farming, ii) the distribution of farmer surplus regarding precision farming technologies, and iii) the effects of policies such as subsidization of precision farming practices.

The spatial competition framework is highly relevant in the context of contractor service markets because due to the costs of transporting machinery to farms, the market areas of many precision farming services are localized (Erickson, Lowenberg-Deboer, & Bradford, 2017).[1] The spatial limits of precision farming services are further reinforced by the fact that with peak workloads during certain periods in the crop cycle (e.g., the vegetation or harvesting periods), the capacity of contractors often limits the services to be only available to the vicinity of the contractor. Therefore, spatial proximity to service providers has a positive correlation with farmers' access to and uptake of precision farming technologies (Khanna, 2001). Meanwhile, the transportation cost associated with contractor service may give rise to spatial market power (Hotelling, 1929), which influences the pricing strategies of contractors and therefore farmers' uptake decisions.

Previous literature has documented anecdotal evidence that contractors may facilitate precision farming uptake or make its use possible in the first place, especially in smaller scale agricultural systems prevalent in many European countries. For example, Reichardt & Jürgens (2009) show the willingness of German farmers to adopt precision farming via contractors. However, a formal economic framework that considers the spatial nature of such services is still lacking in analyzing the role of contractors in precision farming uptake and the interactions with policy interventions. Yet, knowledge in the role of contractors in precision farming can provide important gauge of the scale and viability of small farm participation in sustainable agricultural intensification, as well as how policies could effectively support such participation.

We aim to contribute to filling this gap with a conceptual investigation into the role of contractor service in the uptake of precision farming technologies in a spatial economic framework, and its interaction with policy interventions targeted at precision farming uptake. Applying established frameworks in spatial competition and spatial pricing to the context of contractor service for precision farming technologies, we investigate two potential pricing schedules by contractors: spatially non-discriminatory pricing and discriminatory (uniform) pricing. Within each pricing schedule, we analyze the uptake of a given bundle of precision farming technology, farmer welfare, and the effect of a subsidy under monopolistic and competitive markets. For competitive markets, we also consider the case of cooperative competition between contractors. We further apply results from the conceptual analysis to a case study. We perform empirically informed simulations based on an observed contractor service market of precision plant protection technology in Switzerland, taking into account farm and farmers' characteristics that lead to heterogeneous benefits and subjective beliefs about the technology, respectively. The focus on technologies to reduce pesticide use in our case study contributes to ongoing policy debates in Switzerland and Europe in general how to reduce the environmental and human health footprints of plant protection (e.g., Möhring, Ingold, et al., 2020).

Our analyses contribute to existing literature by exploring the role of policy interventions in increasing the uptake of precision farming and farmer welfare when the spatial competition of technology providers matters. Our findings underscore that the effectiveness of policy interventions is contingent on the market structure and pricing schedules of contractors, an issue that warrants more investigation in agricultural markets (Graubner, 2018; Russo, Goodhue, & Sexton, 2011).

We find theoretical evidence that higher spatial competition of contractors (vis-à-vis spatial monopolistic power and weak duopoly competition) reduces prices of precision farming services and thus facilitates overall technology uptake. Higher spatial competition also increases the extent to which subsidies on precision farming practices may enhance the uptake of the technologies and farmers' welfare. In contrast, spatial monopolistic power can largely reduce public benefits in terms of reduced environmental damages and can render public policy intervention ineffective and inefficient. This is

[1] For some precision farming technologies that only involve data analysis and are independent of machinery (e.g., Jain et al., 2019), transportation cost does not apply. In our study we consider precision farming technologies that requires machinery operation on the field.

important because transportation costs are expected to lead to spatial monopolistic power. Yet, under spatial competition, cooperative pricing between contractors would also render subsidies ineffective in increasing uptake and farmers' welfare. Additionally, under the same importance of space in the market, a spatially discriminatory pricing scheme (uniform pricing) is associated with higher uptake of precision farming technologies. In the case that policy interventions are primarily focused on increasing uptake of precision farming, a uniform pricing schedule is therefore relatively more advantageous in achieving such a policy goal. Our case study further provides estimates of the relative economic significance of a policy intervention and a change in the intensity of spatial competition in the context of a specific contractor service market.

The remainder of this paper is organized as follows. Section 2 provides backgrounds on precision farming and the spatial competition framework. Section 3 introduces formal models of non-discriminatory and discriminatory spatial pricing, and compares their effect on the uptake of precision farming technologies as well as the effect of subsidies. Section 4 presents a case study of precision plant protection contractor service markets in Switzerland, and Section 5 concludes.

2. Background and Related Literature

2.1 Background on precision farming

Precision farming incorporates a suite of technologies throughout the crop cycle that allow for management of high inter- and intra-field spatial variability. This is largely enabled by the Global Navigation Satellite System to collect spatially explicit field information and apply targeted use of inputs. The European Parliament provides descriptions of a list of precision farming technologies and their respective objectives (European Parliament, 2014). Based on their roles in forming management decision and the level of complexity, precision farming technologies can fall into several categories, including positioning, diagnostic and data management, and application (Khanna, Epouhe, & Hornbaker, 1999).[2]

Evidence from farm-level surveys has indicated that an important driver of precision farming uptake, among other factors, is economic incentives (e.g., Daberkow & McBride, 2003; Kutter et al., 2011; Paustian & Theuvsen, 2017). Farmers tend to adopt the technologies when they are affordable, and are cost effective (Pathak, Brown, & Best, 2019). As such, precision farming uptake largely depends on characteristics of the technology and the farm (e.g., Erickson et al., 2017; Khanna, Epouhe, & Hornbaker, 1999; Paustian & Theuvsen, 2017). In particular, due to the high capital intensity associated with initial investments in precision farming technologies, uptake via investment is largely limited to large farms, whereas the expected per-hectare benefits for small farms are not high enough to warrant investment (Paustian & Theuvsen, 2017; Weersink et al., 2018; Wolfert, Ge, Verdouw, & Bogaardt, 2017). Compatibility between precision farming equipment and conventional machinery and between different components of precision farming technologies is another important barrier for adoption (Barnes et al., 2019; Groher, Heitkämper, Walter, Liebisch, & Umstätter, 2020; Kutter et al., 2011). In addition, knowledge and skill gap associated with the complexity of operating some precision farming technology and analysis of data collected also hinders adoption and would require notable investments by farmers (Barnes et al., 2019; Khanna et al., 1999; Kutter et al., 2011). At the individual level, the likelihood to adopt precision farming technology also depends on a farmer's values and motivation,

[2] In a more recent review, focusing on diagnostic and applicative technologies, Finger, Swinton, El Benni, & Walter (2019) note that this typology is in line with alternative terms adopted by other related research, in which precision farming technologies are categorized into guidance, recording, and reacting groups (Balafoutis et al., 2017; Barnes et al., 2019; Evert, Been, Booij, Kempenaar, & Kessel, 2018).

which are influenced not only by subjective factors such as risk aversion, but also farm characteristics such as farm size and production conditions (Pathak et al., 2019).

Despite the barriers to access precision farming technologies, which are particularly notable to small farms and small scale agricultural systems, sustainable intensification of small farms is an important component of more sustainable agriculture (Garnett et al., 2013; Walter et al., 2017). Even though precision farming is only one out of many steps needed to make agriculture more sustainable, the uptake by small farms could contribute to create large public benefits due to reduced environmental impacts. In addition to public benefits, precision farming technologies are also desirable to small farms for the purpose of input cost reduction (e.g., Busse et al., 2014; Kutter, Tiemann, Siebert, & Fountas, 2011) and the need to comply with regulations concerning the environmental impact of farming (European Parliament, 2014). By bringing relevant machinery to the farm, contractor services of precision farming technologies allow small farms to access these technologies without investing into capital-intensive machinery and equipment. By implementing the technologies on farm and assisting with analyzing data for decision-making, contractor services can also provide means for knowledge gain, mitigating the technical barriers to precision farming uptake (Busse et al., 2014; Erickson et al., 2017; Groher et al., 2020). In other words, contractor services have the potential to mitigate the barriers for small farms to access precision farming technologies, and therefore align the public and private benefits of such technologies. A survey by Erickson et al. (2017) has suggested the viability of a market with outsourced precision farming services in the United States. The relevance of contractors is even more pronounced in European agricultural systems, usually characterized by small farms and small farm structures (e.g., Busse et al., 2014; Paustian & Theuvsen, 2017). For instance, in Switzerland, within a pilot project (called PFLOPF, which we will introduce in more detail in Section 4) that promotes optimized plant protection supported by various technologies, the use of contractor services is accepted under different incentive schemes that compensates participants for adopting precision farming technologies. Along these lines, technology sharing is also of highest relevance for beneficial technology use and diffusion in developing countries (Finger et al., 2019; Kirui & von Braun, 2018; von Braun, 2019). Furthermore, increased availability of precision farming contractor services can promote the tendency of farmers' adoption of precision farming technologies. For example, Khanna and colleagues have shown that proximity to providers of precision farming technologies play a positive and significant role in farmers' uptake decisions (Khanna et al., 1999; Khanna, 2001).

Figure 1 conceptually illustrates the relation between the spatial distribution of contractors and farm access to precision farming technologies. With sparse distribution of contractors, farms can be either too far from a contractor to be served, or face monopolistic prices (Panel (A)). High spatial accessibility of contractors not only makes services available, but can also lower the service price as the market becomes competitive (Panel (B)).

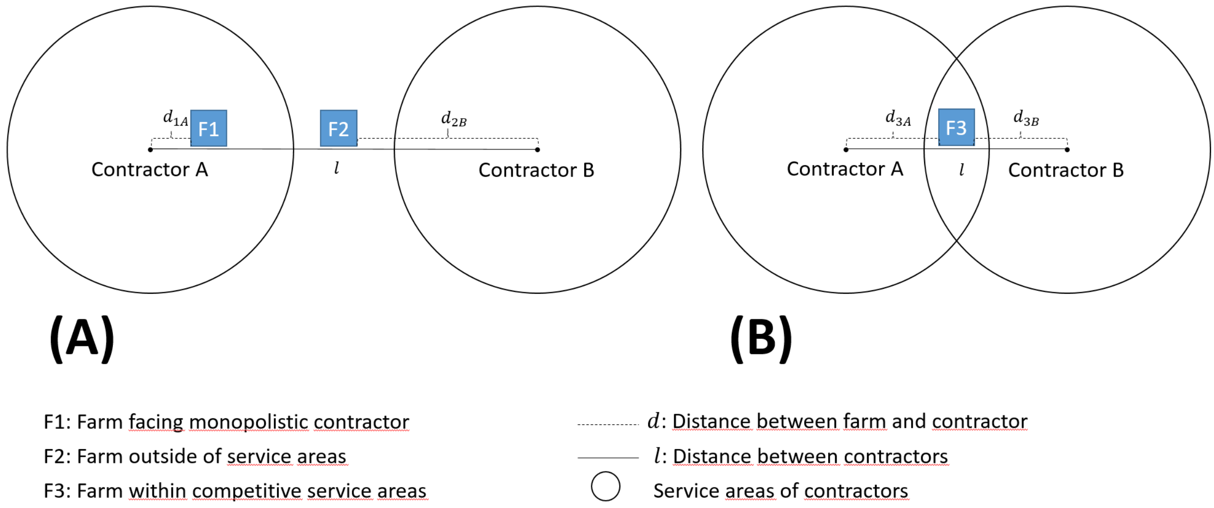


Figure 1. Conceptual background: In a spatial competition framework, the uptake of precision farming technologies will not only depend on the distance (d) from the farm to the service provider, i.e., the contractor but also of the distance between different contractors (l) which determines whether spatial competition exists (Panel (B)) or not (Panel (A)).

In addition to availability of service, public interventions can play a role in promoting the adoption of precision farming technologies. This can comprise, for example i) provision of facilitating infrastructure and legal frameworks, ii) taxation of inputs critical to the environment, and iii) subsidies (Finger et al., 2019). According to a survey on farmers and farm managers across five European countries, direct subsidy for the uptake of precision farming technologies and financial support from tax breaks are among the most effective incentives for precision farming technology adoption considered by respondents (Barnes et al., 2019). For example, through the PFLOPF project in Switzerland, participating farmers receive subsidies for adopting precision farming technologies.

Although different types of precision farming technologies are often inter-related, and can be available to farmers at the same time, previous research has shown that due to different levels of technical complexity and measurability of value-adding effects, the uptake of bundles of precision farming technologies are sequential rather than simultaneous (Griffin et al., 2017; Khanna, 2001; Khanna et al., 1999). In particular, farmers adopt relatively more simple guidance and diagnostic tools prior to more advanced applicative tools (Erickson et al., 2017; Finger et al., 2019; Groher et al., 2020; McCallum & Sargent, 2008; Weersink et al., 2018). As such, auto-guidance has been the most widely adopted type of precision farming technologies, given its directly measurable impact on farms (Balafoutis et al., 2017). In a study of farmers' sequential choices of different bundle combinations of information-intensive precision farming technologies in Kansas, United States, Griffin et al. (2017) find that as of 2016, yield monitoring tools were the most widely adopted precision farming technology bundle, followed by yield monitoring combined with soil sampling (both are diagnostic tools). In contrary, variable rate technologies (applicative tools) are the least adopted and is usually adopted in conjunction with other (diagnostic) tools.

2.2 Spatial competition and spatial pricing schedules in contractor service markets

The spatial dimension of a market is relevant whenever there exists spatial interdependence in supply and/or demand, and as a result competition is imperfect (Greenhut et al, 1987). This applies to many agricultural markets, where market power exists in the procurement market of agricultural products (e.g., Graubner, Balmann, & Sexton, 2011; Graubner, Koller, Salhofer, & Balmann, 2011; Sesmero, Balagtas, & Pratt, 2015), or agricultural inputs such as land (e.g., Graubner, 2018). In the context of contractor service of agricultural technologies, due to spatially distributed locations of contractors and the relevance of distance in farmers' considerations of acquiring service, contractors possess market power as sellers of service. For a given agricultural market, spatial competition and pricing strategies further shapes the distribution of welfare, both in terms of direct distribution of consumer (farmers in our context) and producer surplus, and interactions with market regulations and policy interventions such as subsidies (Graubner, 2018; Russo et al., 2011; Sesmero, 2016). In light of the significant environmental externalities of agricultural production and its reliance on natural resources, the spatial market structure of agricultural markets also poses indirect influence on the environment and natural resources management via farmers' choices in production such as land use and intensity of resource use (Sesmero et al., 2015; Wang, Delgado, Sesmero, & Gramig, 2020).

In terms of modeling spatial competition and spatial pricing, the strand of literature that is most relevant to our work largely stems from the model developed in Hotelling (1929) and further generalized in Smithies (1941). In the duopoly model, the market of a commodity is represented by a line segment, buyers are uniformly distributed along the line, and sellers are located at each end of the line segment. Buyers purchase the commodity from either sellers with perfectly inelastic demand, and are responsible of the cost of transportation. The transportation cost introduces differentiation of products from the two sellers, who in turn possess market power and are able to price above the marginal cost as opposed to the price game under perfect competition in Bertrand (1883). While the model in Hotelling (1929) is also extended to optimal firm location when the competitor's location is fixed, in our study we take locations of contractors as exogenous, and only examine the price competition between contractors. In the setting of Hotelling-Smithies competition, price competition takes place in the form of free-on-board or mill pricing, such that sellers choose the optimal ("mill gate") commodity price that maximize their profit, while taking into account that buyers' decisions are based on the total price composed of both the commodity price and the transportation cost. The Hotelling-Smithies competition setting also forms the premise of our conceptual analysis of spatially non-discriminatory pricing under non-cooperative competition.

In alternative to competing on "mill gate" prices, the price game in a spatial competition setting may incorporate spatial price discrimination (Greenhut & Greenhut, 1975; Hoover, 1937). Instead of choosing price at the location of the firm, sellers choose "delivered price" which includes transportation cost. Under spatial price discrimination, differences in delivered prices do not fully reflect transportation cost as in the free-on-board case, though consumers at equal distance from a firm face the same delivered price (Phlips, 1983). To demonstrate the relation between spatially non-discriminatory and discriminatory pricing, following notations in Norman (1981), let $p(r) = p + \alpha tr$ denote the delivered price faced by buyers from a given seller, where p is the commodity price net of transportation cost, r is the distance between the buyer and the seller, t is unit transportation cost, and α measures the degree of spatial price discrimination. A pricing schedule without spatial discrimination (i.e., free-on-board or mill pricing) is given by $\alpha = 1$ where transportation cost is charged in proportion to distance. A spatially discriminatory pricing occurs when $\alpha < 1$. The most commonly considered spatially discriminatory pricing is the limiting case with $\alpha = 0$, which is uniform pricing (also termed uniform delivered pricing). Under uniform pricing, transportation cost is fully embedded in delivered price and averaged over buyers (e.g., Gronberg and Meyer, 1981; Zhang and Sexton, 2001). In our conceptual analysis, we also address the case of uniform pricing in contractor service markets, with the other assumptions about the market remaining consistent with the case of non-discriminatory pricing.

For players in a spatial market, the choice of spatial pricing strategies depends on an array of factors such as the industry, market conditions such as the intensity of competition, and the magnitude of transportation cost relative to the value of product (e.g., Capozza & Van Order, 1977; Holahan, 1975, Zhang and Sexton, 2001). The equilibrium outcomes derived under spatial pricing models therefore depend on the assumptions of the model chosen. For the markets of contractor service for precision farming, since there is little empirical information on the nature of spatial competition, we are not able to speculate the exact pricing schedules in these markets. Furthermore, across the diverse range of precision farming technologies, it possible that spatial competition strategies depend on the technology (e.g., the level of machinery intensity) and the form of contracting (e.g., machinery and operation versus only machinery rental). Therefore, in this study we follow Graubner (2018) and consider the most commonly applied spatial pricing schedules, namely non-discriminatory and uniform pricing, and examine outcomes of uptake and welfare, as well as the mediating role of spatial competition on the effects of a subsidy.

3. Conceptual Analysis of Spatial Market for Precision Farming Contractors

We use the following model to conceptualize the relation between the spatial market conditions of contractor service and the uptake of precision farming technology, as well as the interaction with a policy intervention that supports precision farming. We consider two types of spatial pricing schedules extensively studied in previous literature: spatially non-discriminatory pricing (equivalent to free-on-board pricing discussed in Section 2.2) and the limiting case of spatially discriminatory pricing, i.e., uniform pricing (UP).[3] To begin with, we define the precision farming technologies to which our model is applicable. As discussed in the previous section, uptake of bundles of precision farming technologies follows a sequential pattern. The sequential adoption behavior of farmers allows us to consider precision farming technologies to be relatively homogeneous within a bundle, and distinct between different bundles, as different bundles of technology are relevant to farmers at different stages of adoption or aspects of application. As such, our model addresses adoption of standalone bundles of precision farming technologies, in the sense that individual technologies are closely related within the bundle, but are as a whole distinctive from and not substitutable with other groups of technologies. Examples of bundles of technologies include machine guidance (e.g., section or single nozzle control combined with GPS steering systems, on which we shall focus in our simulation analysis), soil sampling and testing, and variable rate technologies. As we discuss in the previous section, in terms of rental service from contractors, farmers' decision for precision farming technology uptake is whether to purchase the service, rather than a capital investment decision.[4] We therefore model farmers' adoption as a binary choice problem, i.e., whether to purchase service from a contractor that offers a particular bundle of precision farming technologies.

We investigate under a given spatial distribution of contractors, the extent to which different market structure and pricing schedules affect farmer uptake and welfare. While contractors may choose their location and service capacity strategically based on, for example, availability of farming infrastructure, it is not our focus to model the entry and expansion decisions of contractors, rather, we take location and capacity as exogenous. The exogenous service capacity also warrants constant marginal cost of

[3] While the pricing choice can also be considered as a two-stage game, with firms choosing the pricing schedule in the first stage, and the profit maximizing price in the second stage, in this study we focus on the outcomes in the subgame equilibrium under the given price schedules, and consider the cases that both contractors apply the same pricing schedule. The chosen pricing schedules can also be considered as sustained solutions in a dynamic competition framework as discussed in Espinosa (1992).

[4] For examples of studies on the capital investment decision of precision farming, see Tozer (2009) and Griffin et al. (2017).

contractor, which includes personnel and machinery maintenance cost associated with an additional unit of service (additional discussion on the assumption of constant marginal cost in Section 3.5).

For a given time period, the profit made by a representative farmer j who is engaged in conventional or precision farming are respectively given by:

$$\pi_j^C = py_j^C - w^x x_j^C - OC_j,$$

and

$$\pi_j^{PF} = py_j^{PF} - w^x x_j^{PF} - q_j s_j - OC_j, \quad (1)$$

where p is output price, y is crop yield, w^x is a vector of input prices, x is a vector of quantities of input, q is price paid for precision farming technology, s is an indicator of precision farming adoption, and OC denotes other (fixed) costs; the output $y_j = y_j(x_j(s_j), other\ endowment)$. We assume the fixed cost for farmers to be the same regardless of whether contractor service is adopted, in that the only additional cost is the price of the service. The change in profit due to the adoption of precision farming technology is

$$\Delta\pi_j = p\Delta y_j - w^x \Delta x_j - q_j \quad (2)$$

Since precision farming technologies are expected to decrease input use and/or increase yield, holding other factors constant, adoption occurs when the perceived benefits of precision farming exceed the price of the service charged by a contractor. Expected benefits are farm-, field-, and crop-specific and can be estimated via an online savings calculator of a given technology, or based on returns achieved by other farms with similar characteristics. Let $\bar{\pi}_j = \frac{E[p\Delta y_j - w^x \Delta x_j]}{acreage_j}$ be the expected unit financial return to precision technology for farmer j, the farmer forms his or her subjective belief about the benefit of precision farming based on $\bar{\pi}_j$ as well as personal values and motivation, which establishes a reservation price, v_j. We can express the adoption decision as:

$$s_j = \begin{cases} 1 & if\ q_j \leq v_j \\ 0 & otherwise \end{cases} \quad (3)$$

At the individual level, demand is perfectly inelastic below the reservation price, and perfectly elastic above. Heterogeneous reservation price allows the aggregate demand curve to be smooth with varying price elasticities over the range of prices. In contrast, with homogeneous reservation price, the aggregate demand curve has the same discontinuity as the individual demand. We assume that contractors do not observe farmers' individual reservation price, but have knowledge about the distribution of farmers' reservation prices v which has a probability density function $f(v)$. In particular, the expected reservation price is $\bar{v}$. The distribution of the reservation price can be influenced by policy interventions. For instance, a direct subsidy to farmers for adopting precision farming can be considered as shifting the reservation price rightward.

We represent the spatial market of precision farming contractor service by applying the spatial framework presented in Hotelling (1929), using a spatial duopoly to demonstrate spatial competition among contractors, with the locations of the contractors taken as given. The market is represented by a line segment with length l, with two contractors, A and B, located at each end, and farmers who potentially could purchase the service uniformly distributed along the market.[5] The preference of farmers for service from contractor A or B is represented by only the transportation cost. Let d denote the location of a farmer in the market, we set $d_A = 0$ and $d_B = l$ (see Figure 1).

We consider two spatial pricing schedules most commonly applied to agricultural markets which we discuss in Section 2.2. Under spatially non-discriminatory (free-on-board) pricing, the transportation cost of contractor service is directly reflected in the service price. That is, farmers pay for the cost of a contractor's travel in proportion to their distance to the contractor. Alternatively, under a spatially discriminatory (uniform) pricing schedule, farmers face the same price regardless of the distance between farmers and the contractor. In this case, the contractor charges a uniform price, averaging the transportation cost across all farmers, and thus farmers located closer to a contractor assume greater transportation cost relative to farmers further away. Under each pricing schedule, we analyze the uptake of precision farming and farmer surplus under alternative market structures, as well as the effect of a subsidy that supports precision farming uptake. We consider monopolistic and duopolistic markets, and for the latter, we further consider the case of cooperative competition. To further understand the role of policy interventions under different market conditions, we investigate the interaction between contractor service markets and the effect of a direct subsidy. A direct subsidy reduces the relative cost of precision farming technologies, and thus can be considered as an increase in farmers' average reservation price, $\bar{v}$.[6] Specifically, we examine the extent to which market structure and spatial pricing strategies of contractor service affect the effectiveness of a direct subsidy in increasing precision farming uptake and farmer surplus.

3.1 Non-discriminatory spatial pricing

Formal Model

First, consider a spatially non-discriminatory strategy that a contractor charges a price for the service, and farmers bear the transportation cost of bringing the service to farm. For a farm at distance d from A, the prices of service paid to contractor A and B are $r_A + dt$ and $r_B + (l - d)t$, respectively, with r_A and r_B being the service price charged at each contractor's location, and t being the unit transportation cost.

For contractor i, the profit function is

$$\pi_i = (r_i - c)D_i - OC_i, \tag{4}$$

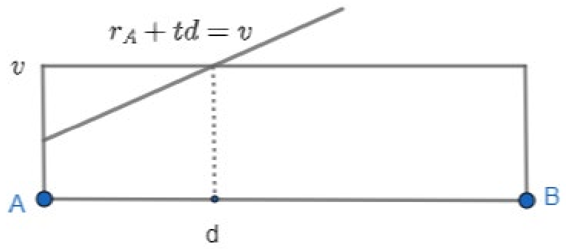
where D_i is the total demand for the service from farmers, and c is the marginal cost of the service.

For a farm j at distance d to purchase the service from contractor i, two conditions are required: (1) $r_i + dt \leq v_j$, and (2) $r_i + dt \leq r_{-i} + (l - d)t$.

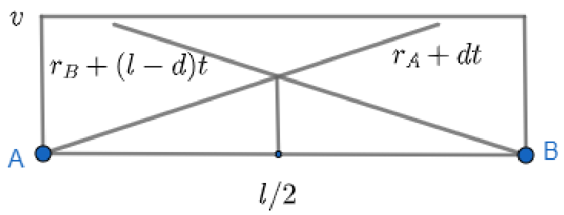
We define $\sigma = tl$ as the maximum transportation cost across the market, which represents the absolute importance of space in the market. $\frac{\sigma}{\bar{v}-c}$ represents the importance of space relative to the maximum net revenue a contractor expects to receive. Both representations of importance of space (absolute and relative) provide a measure of the intensity of spatial competition in the market: with high importance

[5] With a (continuous) uniform distribution of farmers, it is equivalent to consider that there exists a sufficiently high number of farmers at each location of the market.
[6] Direct subsidy is an example of channels through which farmers' reservation price for precision farming technologies changes relative to the net benefit of uptake. The effect of other channels, for example, technological development, can be analogous to that of a subsidy. We provide more detailed discussion in Section 3.5.

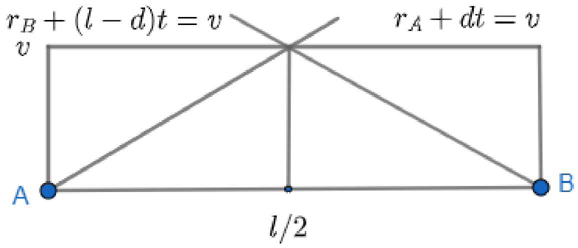
of space, markets are more likely to be separated and contractors have monopolistic power, whereas markets are more likely to be contested with low importance of space. As such, the importance of space also characterizes the thresholds between different market structures, in our case from spatial monopoly to spatial duopoly.



(a) Spatial monopoly



(b) Spatial (strict) duopoly



(c) Spatial weak duopoly

Figure 2. Prices and market covered by market structure under non-discriminatory pricing schedule

Spatial monopoly

A spatial monopoly occurs when transportation cost is too high for the entire market to be covered, such that markets are separated, and each farm can be served by at most one contractor (Figure 2). As a spatial monopolist, the contractor sets the price of service to maximize expected profit. Since the contractor does not observe farmers' individual reservation prices, the (expected) demand for service is given by condition (1) with equality held at the expected reservation price, $\bar{v}$. That is, $D_i^{mon} = \frac{\bar{v}-r_i}{t}$. Meanwhile, a monopolistic market also implies that the price from the other contractor faced by this boundary farm is expected to exceed the reservation price: $r_{-i} + (l-D)t \geq \bar{v}$, or equivalently $r_i > 2\bar{v} - \sigma - r_{-i}$.

Solution to the maximization of the contractor expected profit yields: $r_i^* = \frac{\bar{v}+c}{2}$, and therefore in equilibrium, the demand covered by one monopolist is $D_i^{mon} = \frac{\bar{v}-c}{2t}$. By definition, $D_i^{mon} \leq \frac{l}{2}$, that is, a spatial monopoly is associated with high importance of space: $\sigma > \bar{v} - c$. In other words, the relative importance of space at $\frac{\sigma}{\bar{v}-c} = 1$ marks the threshold between spatial monopoly and spatial competition.

Spatial Competition – Strict Duopoly

With spatial competition, there exists a farm that faces the same price from either contractor, and is therefore indifferent in purchasing service from either contractor: $r_i + dt = r_{-i} + (l - d)t$. When the market is entirely competitive, the demand faced by contactor i is given by $D_i^{duo} = \frac{r_{-i}-r_i+\sigma}{2t}$. Solution to the profit maximization problem yields $r_i = r_{-i} = \sigma + c$. Therefore in equilibrium, $D_i^{duo} = \frac{r_{-i}-r_i+\sigma}{2t} = \frac{l}{2}$. Condition (1) still applies, which indicates that $\sigma \leq \frac{2}{3}(\bar{v} - c)$.

Spatial Competition – Weak Duopoly

With intermediate importance of space, $\frac{2}{3}(\bar{v} - c) < \sigma \leq \bar{v} - c$, both conditions (1) and (2) determine the equilibrium prices, which corresponds to a kink point in the demand curve (shown in Figure A3). This special case is termed a "weak duopoly" following Mérel & Sexton (2010), and is characterized with an inverse relationship between equilibrium prices and transportation cost (Figure 3). Solving the profit maximization problem for a symmetric pricing strategy yields $r_i = r_{-i} = \frac{2\bar{v}-\sigma}{2}$.

Implications of non-discriminatory spatial pricing for uptake and subsidy pass-through

From the model above, the (symmetric) equilibrium prices offered by contractor i under different market structure are shown in Equation (5):

$$r_i = \begin{cases} \sigma + c, & \sigma \leq \frac{2}{3}(\bar{v} - c) \quad \text{strict duopoly} \\ \frac{(2\bar{v} - \sigma)}{2}, & \frac{2}{3}(\bar{v} - c) < \sigma \leq \bar{v} - c \quad \text{weak duopoly} \\ \frac{\bar{v} + c}{2}, & \sigma > \bar{v} - c \quad \text{monopoly} \end{cases} \qquad (5)$$

We summarize the comparison of the equilibrium prices and total market covered under different market structures into the following result.

Figure 3 (adapted from Mérel & Sexton (2010)) provides a summary of the symmetric equilibrium prices under different market structures, characterized by the relative importance of space. When spatial competition occurs over the entire market (i.e., $r_i + \sigma \leq \bar{v}$), the duopoly price is below the monopoly price. This occurs when the intensity of competition is sufficiently high ($\sigma < \frac{1}{2}(\bar{v} - c)$). Under strict duopoly ($\sigma \leq \frac{2}{3}(\bar{v} - c)$), the surplus faced by farmers increases as the relative importance of space decreases.

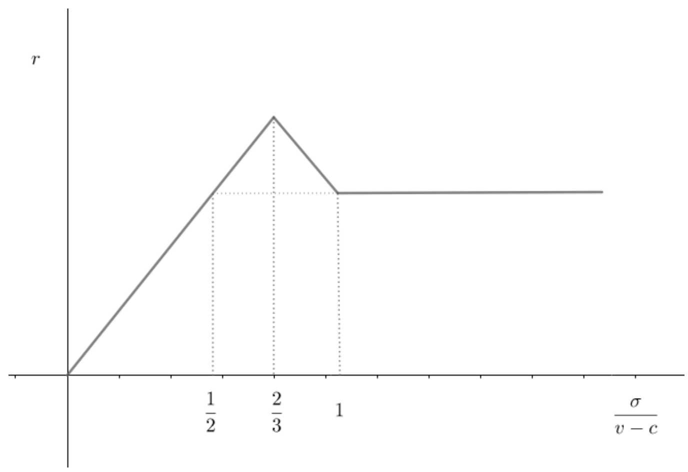


Figure 3. Equilibrium prices and transportation cost under non-discriminatory pricing

Result 1: Under spatially non-discriminatory pricing, compared to spatial monopoly, spatial competition between contractors allows for higher uptake ($D_i^{duo} = \frac{l}{2}$ while $D_i^{mon} = \frac{\bar{v}-c}{2t} < \frac{l}{2}$), and high level of spatial competition allows for greater farmer surplus (when $\sigma < \frac{1}{2}(\bar{v} - c)$, which implies $\sigma + c < \frac{\bar{v}+c}{2}$).

This result is directly associated with general findings from the literature on spatial competition.

In terms of subsidies that support precision farming uptake, the effect of subsidy on uptake and adopters' welfare also varies across market structures. We derive the following result based on analyses of $\frac{\partial r_i}{\partial \bar{v}}$ under different market structures, and a detailed discussion is available in the Appendix.

Result 2: Under non-discriminatory pricing, 50 and 0 percent of subsidy is passed to price under spatial monopoly ($\frac{\partial r_i}{\partial \bar{v}} = \frac{1}{2}$) and duopoly ($\frac{\partial r_i}{\partial \bar{v}} = 0$), respectively, whereas under weak duopoly the subsidy is fully reflected in the price of the service paid to the contractor ($\frac{\partial r_i}{\partial \bar{v}} = 1$).

Under spatial monopoly, a subsidy may increase precision farming uptake within the monopolist's service area. This effect increases as transportation cost decreases: $\frac{\partial D_i^{mon}}{\partial \bar{v}} = \frac{1}{2t}$. That is, the more difficult to deliver the service in terms of transportation costs, the less effective the subsidy.

3.2 Spatial price discrimination (uniform pricing)

Formal model

With uniform pricing (UP), all farms face the same price w_i from contractor i regardless of the distance to the contractor, and the contractor embeds the average transportation cost in the total price (that is, farms close to the contractor are discriminated against). From a farmer at location d, the net price received by contractor i is $w_i - td$.

Spatial monopoly

With monopolistic power, the farthest location that the contractor would serve is determined by where it breaks even: $w_i - td = c$. That is, the maximum demand that the contractor can accommodate is $D_i^{UP} = \frac{w_i - c}{t}$.

The expected profit for the contractor depends on the price set by the contractor and the fraction of farmers with reservation price above the price: $E(\pi_i) = E\left[\int_{w_i} f(v)\mathrm{d}v \int_0^{\frac{w_i - c}{t}} (w_i - td - c)\ \mathrm{d}d\right] = E[1 - F(w_i)]\frac{(w_i-c)^2}{2t} = \frac{(w_i-c)^2}{4t}$. Since monopoly profit is monotonically increasing over the feasible region, $w_i \geq c$, the contractor would set the price as high as possible. Assuming a symmetric distribution of the reservation price, the monopolist would price at the expected farmers' reservation price, $\bar{v}$.[7] Local monopoly power implies that the markets are separated: $D_i^{UP} \leq \frac{l}{2}$, i.e., $\sigma \geq 2(\bar{v} - c)$.

Spatial competition

When the service areas of two contractors are contested, each contractor's profit depends on own price and competitor's price. A contractor with a lower price w_i^- will capture all of the demand to the extent that the contractor still receives a positive net price, and earn an expected profit $E(\pi_i^-) = \frac{(w_i^- - c)^2}{4t}$. When transportation cost does not allow the contractor to serve the entire market, i.e., when $w - \sigma \leq c$, there is a residual demand $l - D_i^{UP-}$ that can be captured by the competing contractor as a local monopolist, with expected profit given in Equation (6):

$$
\begin{aligned}
E(\pi_i^+) &= \mathrm{E}\left[\int_{w_i} f(v)\mathrm{d}v \int_0^{\frac{\sigma-(w_{-i}-c)}{t}} (w_i - td - c)\ \mathrm{d}d\right] \\
&= \frac{[\sigma - (w_{-i} - c)]\,(2w_i^+ + w_{-i} - \sigma - 3c)}{4t}
\end{aligned} \tag{6}
$$

As discussed in the literature on non-cooperative games under uniform pricing, when the two contractors set the same price, one has an incentive to overbid the competitor, and thus matching the competitor's price is not an optimal strategy (e.g., Beckmann, 1973). Since the expected profit for $w_i > w_{-i}$ and $w_i < w_{-i}$ are $E(\pi_i^+)$ and $E(\pi_i^-)$, respectively, the discontinuity of the profit function in price implies that there is not an equilibrium solution with pure strategies (e.g., Schuler & Hobbs, 1982; Shilony, 1981; Zhang & Sexton, 2001). We follow the literature and consider a mixed strategy game (Graubner, 2018; Zhang & Sexton, 2001).[8] The (symmetric) mixed strategy is described by the cumulative distribution function $\Psi(\mathrm{w_i})$ according to which contractor i plays the mixed strategy: $\Psi(\mathrm{w_i}) = \mathrm{P}(\mathrm{w_i} \leq \mathrm{w_{-i}})$. Let w^1 and w^0 denote the upper and lower price limits that support the optimal mixed strategy, respectively. In the Appendix we derive w^1 and w^0, and we present the results here. When contractor i charges a higher price than the competitor and capture the residual demand, it is optimal to set the monopoly price, that is, $w_i^1 = \bar{v}$. When contractor i charges a lower price than the competitor, we can obtain the limit of the lower price by equating the profit of contractor i from capturing the residual demand as a monopolist (while contractor $-i$ prices at the lower limit) to the profit from pricing at the lower limit. The resulting upper and lower price limits are:

[7] The monopoly profit implies a tradeoff between a higher price (and thus larger service area) and a lower probability of adoption. With a symmetric distribution of reservation price, the expected value satisfies that $F(\bar{v}) = E[F(v)] = \frac{1}{2}$. For the most generic case that allows for skewed distribution, the monopolist sets a price that solves the implicit function $f(v)(w_i - c) = 2[1 - F(w_i)]$.

[8] Alternative strategies to address the nonexistence of pure strategy equilibrium solution are also possible, for example, by incorporating an additional dimension of horizontal product differentiation (e.g., Anderson, Palma, & Thisse, 1989). We follow Graubner (2018) who also applied the mixed strategy game in an agricultural setting.

$$w_i^1 = \bar{v}$$

and

$$w_i^0 = \frac{1}{2}\left[3c - \bar{v} + \sigma + \sqrt{(\bar{v} - c)^2 + \sigma(2\bar{v} - 2c - \sigma)}\right]. \qquad (7)$$

Note that this lower price limit that supports the optimal mixed strategy decreases with the total transportation cost σ. We will next investigate the implications for uptake and subsidy pass-through at the price limits.

When a contractor who plays a lower price strategy w^- and set the price at w^0, the fraction of total demand he would capture is given by $D_i^{UP^0} = \frac{w^0 - c}{t} = \frac{\sigma - (\bar{v}-c) + \sqrt{(\bar{v}-c)^2 + 2\sigma(\bar{v}-c) - \sigma^2}}{2\sigma} l$. Since the fraction of the total market served by the contractor with the lower price increases with the price w^-, $D_i^{UP^0}$ represents the lower limit of the market that a contractor with w^- could cover. In other words, when a contractor plays a strategy w^- and sets a price higher than w^0, all else equal, the fraction of total demand covered by the contractor would be greater than that under w^0. In the Appendix we show that $\frac{\partial D_i^{UP^0}}{\partial\left(\frac{\sigma}{\bar{v}-c}\right)} < 0$. That is, when one contractor prices at the lower price limit w^0, the fraction of the market that faces this lower price increases as transportation cost decreases.

Implications of discriminatory spatial pricing for uptake and subsidy pass-through

As we discuss above, w^0 is the lower price limit that supports the optimal mixed strategy. Farmers achieve positive surplus whenever they acquire service from the contractor offering a lower price w^-, and the surplus is greatest when they are served by a contractor that charges at the lower limit w^0. Since the mixed strategy is played when the service areas of the two contractors are contested, the contractor that plays the lower price would cover more than half of the entire market, under which famers achieve positive surplus.

Result 3: Under uniform pricing, with spatial monopoly, a farmer with an average reservation price achieves zero surplus ($w_i = \bar{v}$), whereas with spatial competition, a fraction of adopters obtain positive surplus ($w_i^- < \bar{v}$). Spatial competition allows the entire market to be covered and therefore greater uptake of precision farming technologies than spatial monopoly.

Like Result 1 under spatially non-discriminatory pricing, the result on uptake and farmer surplus here is directly associated with findings in previous literature on spatial competition. We also note that under spatial monopoly, the maximum potential uptake decreases as transportation cost increases: $\frac{\partial D_i}{\partial t} < 0$.

With a subsidy, whenever the contractor act as a monopolist, either because of market power from high transportation cost, or when it takes the residual demand in a duopolistic market and sets a monopoly price, $\frac{\partial w_i}{\partial \bar{v}} = 1$. In this case a change in the reservation price of farmers (e.g., due to a subsidy) would be fully reflected in the price. When a contractor sets a lower price in a duopolistic market, we show in the Appendix that, when a contractor prices at the lower price limit w^0, the proportion of a subsidy that is passed onto the price is positive and is an increasing convex function of $\frac{\sigma}{\bar{v}-c}$. As $\frac{\sigma}{\bar{v}-c}$ increases from 0 to 2, the proportion of a subsidy passed to the price increases at an increasing rate till 100%. We provide detailed derivations in the Appendix, and summarize the findings in the following result:

Result 4: Under uniform pricing, with spatial monopoly, a subsidy is fully passed to price charged to farmers ($\frac{\partial w_i}{\partial \bar{v}} = 1$); with spatial competition, the proportion of subsidy that is passed to the lower price limit increases at an increasing rate with transportation cost ($\frac{\partial w_i^0}{\partial \bar{v}\, \partial(\frac{\sigma}{\bar{v}-c})} > 0$).

Within the service area of a spatial monopolist, the effect of a subsidy on uptake increases as transportation cost decreases: $\frac{\partial D_i^{mon}}{\partial \bar{v}} = \frac{1}{t}$.

3.3 Comparison between two (non-cooperative) pricing schedules

Comparing prices under the two pricing schedules, we can show that at the competitive segment of the market under both pricing schedules i.e., $\sigma \leq \frac{2}{3}(\bar{v} - c)$, $w^0 < \sigma + c < \sigma + c + \frac{\sigma}{2} < w^1 = \bar{v}$, where w^0 and w^1 are the lower and higher price limits charged under uniform pricing, respectively, and $\sigma + c$ and $\sigma + c + \frac{\sigma}{2}$ are the lower and upper bound of the competitive price paid by the farmer under the pricing schedule without discrimination. Over the monopolistic segment of the market under both pricing schedules, $\frac{\bar{v}+c}{2} < \bar{v}$, where $\frac{\bar{v}+c}{2}$ is the lower bound of the price paid by a farmer under the pricing schedule without spatial discrimination.

Result 5: Over the competitive segment of the market (i.e., $\sigma \leq \frac{2}{3}(\bar{v} - c)$), prices paid under the spatially non-discriminatory pricing schedule are between the lower and higher prices paid uniform pricing ($w^0 < \sigma + c < \sigma + c + \frac{\sigma}{2} < w^1$).

Result 6: Over the monopolistic segment of the market (i.e., $\sigma > 2(\bar{v} - c)$), the price under uniform pricing is greater than or equal to the prices paid under spatially non-discriminatory pricing ($\frac{\bar{v}+c}{2} < \bar{v}$).

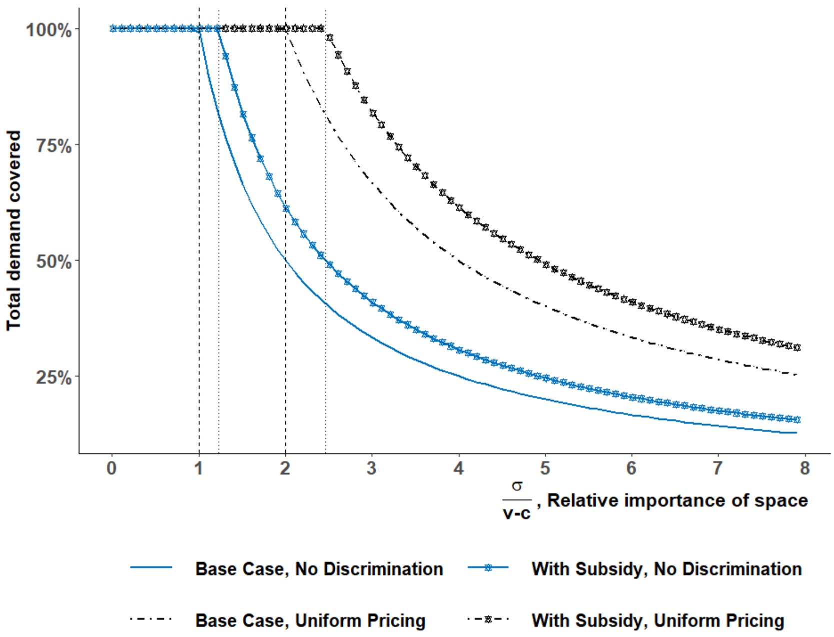


Figure 4. Total demand covered under different pricing schedules

In terms of the proportion of market covered by both contractors, when transportation cost is low and spatial competition exists ($\sigma \leq \bar{v} - c$), the entire market is covered under both pricing schedules. When $\sigma > \bar{v} - c$, without spatial discrimination, the market is separated between two monopolists, and not fully covered; under uniform pricing, the market is fully covered till $\sigma = 2(\bar{v} - c)$. At a transportation cost of $\sigma > 2(\bar{v} - c)$, the proportion of market covered under uniform pricing is twice as large as that under non-discrimination. Figure 4 shows the aggregate demand covered under both pricing schedules, with and without subsidy. Holding the relative importance of space constant, a subsidy allows a greater proportion of the market to be covered.

Result 7: Uniform pricing is associated with higher uptake rate: market covered by a spatial monopolist under uniform pricing is twice of the market covered by a spatial monopolist under non-discriminatory pricing; the transportation cost that precludes competition under uniform pricing ($\sigma > 2(\bar{v} - c)$) is twice as large as that under non-discriminatory pricing ($\sigma > \bar{v} - c$) (Figure 4).

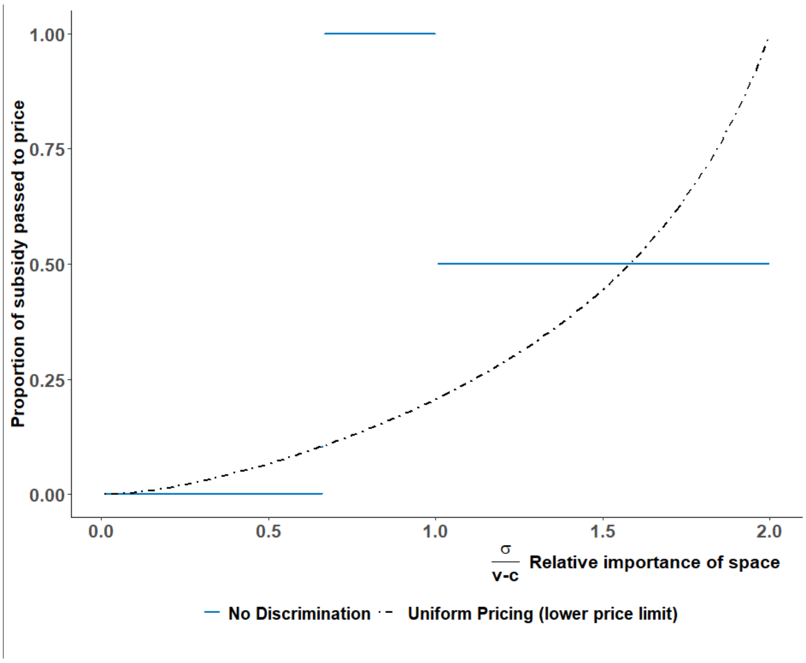


Figure 5. Proportion of subsidy passed to price under different pricing schedules

Figure 5 shows the proportion of subsidy passed to price under both pricing schedules. Overall, spatial competition decreases the proportion of subsidy passed to price: under both pricing schedules, with competition, a smaller proportion of a subsidy is passed to the price (excluding the special case of the weak duopoly) than in a monopoly market. In other words, adopters' surplus increases as the intensity of spatial competition increases.

Result 8: Spatial competition increases the extent to which a farmer benefits from a subsidy under both pricing schedules; the proportion of subsidy passed to farmers is higher under the spatially non-discriminatory pricing schedule except for under weak duopoly (Figure 5).

3.4 The case of cooperative competition

So far, we have assumed there is no cooperation between contractors in their pricing strategies. Especially when located close to each other, contractors may have incentives to cooperatively set their service price and service area in order to increase profit. We next discuss how our previous results stand in the case of cooperative competition, where the contractors match their prices to maximize joint profit (Gronberg & Meyer, 1981).

Cooperative competition and spatially non-discriminatory pricing

With a symmetric duopoly, the contractors would still each cover half of the total demand by agreeing on equal service area and a common price r^c that maximizes profit. Since the profit for both contractors, $\pi^c = \frac{r^c l}{2}$, is monotonically increasing in price, the contractors would set the price as high as possible while still satisfy the condition $\frac{\sigma}{2} + r^C \leq \bar{v}$, so that the entire market is covered. This yields $r^C = \frac{2\bar{v}-\sigma}{2}$, which is the weak duopoly price under the spatially non-discriminatory pricing with non-cooperative competition. Therefore the implications for weak duopoly also apply. In particular, a subsidy is fully passed to service price ($\frac{\partial r^c}{\partial \bar{v}} = 1$), and thus would not increase farmer welfare and would not increase the uptake of precision farming.

Cooperative competition and spatial price discrimination

Under uniform pricing and cooperative competition, the two contractors agree on a common price and service area rather than playing a mixed strategy game. With equal capacity, one way to split the market is again that each contractor covers half of the total demand over the market while maximizing profit. The profit function under this pricing strategy is $\pi^c = \int_0^{\frac{l}{2}} (w^c - td - c) \mathrm{d}d = \frac{l}{8}(4w^c - 4c - \sigma)$, which is monotonically increasing in w^c. Thus, the contractors will set the price as high as possible, at the expected reservation price: $w^c = \bar{v}$. This is the same result as the monopolistic price under non-cooperative competition, with all implications apply. As is under non-discriminatory pricing, a subsidy is fully passed to price ($\frac{\partial w^c}{\partial \bar{v}} = 1$).

In summary, in the case of cooperation between contractors in price setting and market allocation, farmers are worst off in terms of welfare, while the entire market is covered. Under spatially non-discriminatory pricing, farmers face the weak duopoly price, the highest among all price categories under non-cooperative pricing, and the price increases as the level of spatial competition increases. Under uniform pricing, a farmer with the average reservation price achieves zero surplus from purchasing the contractor service. Under both pricing schedules, a subsidy does not increase farmer welfare, as the subsidy is fully passed to the price of service.

3.5 Discussion of conceptual analysis

Table 1 provides a summary of uptake of precision farming technology and farmers' benefit from subsidy under different pricing schedules and levels of spatial competition. Since results under cooperative competition coincides with certain cases under non-cooperative pricing, we only report cases under non-cooperative pricing. The results shed light on the role of spatial competition between contractors in the uptake of precision farming by small farms, as well as the effectiveness and efficiency of policies that promote sustainable agricultural intensification via precision farming operations.[9] Due to the transportation cost of delivering precision farming technologies, the markets of contractor services are localized. Monopolistic power restricts the demand for precision farming technologies to be fulfilled due to higher prices than under perfect competition. Monopolistic power also hampers the pass-through of subsidies aimed at increasing uptake to farmers. With increased availability of contractor services, spatial competition facilitates the uptake of precision farming technologies and associated environmental benefits. It also allows farmers to reap greater benefits from both uptake and related policies.

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[9] While precision farming technologies enhance the sustainability of agriculture by improving the efficiency of input use, as is raised by one reviewer, it is possible for changes in agricultural practices to lead to greater total input use through rebound effects. In this case, policy measures are needed to steer technology use so that the positive effects from efficiency increase is not offset by rebound effects.

Table 1. Comparison of uptake and benefit distributed to farmer under scenarios of pricing and competition intensity

	Uptake		Subsidy benefit	
Spatial discrimination	No	Yes	No	Yes
Competition				
Low	Lower	Higher	Higher	Lower
Moderate	Lower	Higher	Lower*	Higher
Very high	Highest*	Highest*	Highest	Lower*

* Equivalent cases under cooperative competition.

Under non-cooperative pricing, unless the market is fully competitive, the pricing schedule offered by contractors also matters to the uptake of precision farming technologies and the efficiency of policy interventions. With high level of competition, uptake is high under both pricing schedules, while only the non-discriminatory pricing schedule allows farmers to reap all the benefits from a subsidy (Figure 5, the segment $\sigma < \frac{2}{3}(\bar{v} - c)$). With low levels of market competition, however, there exist tradeoffs between uptake and the extent to which farmers benefit from a subsidy - uptake is higher under uniform pricing, while a smaller proportion of subsidy is transferred to farmers (Figure 5, the segment where $\frac{\partial w}{\partial \bar{v}}$ is greater under uniform pricing). With moderate level of competition, uniform pricing is associated with both higher uptake and higher subsidy pass-through to farmers. Under cooperative competition, although the market is fully covered, farmers are not able to achieve additional surplus from a subsidy regardless of whether the pricing schedule involves spatial discrimination.

From a policy perspective, the effectiveness of the pricing schedules depends on the primary goal of the policymaker: technology uptake or pass-through of subsidies. In light of the ultimate goal of sustainable agricultural intensification, diffusion of precision farming technology is currently of particular priority. In this case, precision farming technologies are relatively more accessible under uniform pricing, which could therefore imply higher uptake. Moreover, under this pricing schedule, the extent to which farmers benefit from a subsidy increases with the level of competition. As we will show in Section 4, this pricing schedule is more consistent with the market in our case study. Moreover, with spatially non-discriminatory pricing, the weak duopoly case (i.e., both contractors' price at a kinked equilibrium, and price decreases as transportation cost increases) is not likely for the observed contractor service market in our case study.

As we discuss in the previous section, subsidy is one means that could change farmers' reservation price relative to the cost of uptake, which facilitates uptake of precision farming technologies. Other means, such as technological development, may also result in either a change in farmers' reservation price, or in the marginal cost of service relative to marginal value product. For contractors, technological advancement can lower the cost of machinery and equipment, and/or increase the efficiency of operations, which is particularly important during periods of peak workload. Increased degree of automation can reduce human resources cost associated with operations of precision farming services. All of such development can result in changes in the relation between the marginal value product and the unit cost of precision farming technology, c. Technological development may also improve the quality of service, which increases the expected return to adopting precision farming, or equivalently increases farmers' reservation price for the service.

Our conceptual analysis is conducted with contractor location and capacity exogenously determined. In the long run, dynamic interactions may occur between market conditions and contractor service. For instance, a lack of contractor service in the local area may motivate larger farms to invest into machineries and enter the contractor service market. Lowered machinery investment and operational cost due to technological advancement may also encourage entry of new contractors. Entries of new contractors would increase local spatial competition, and facilitate uptake of precision farming. Improved market conditions may also lead to expansions of existing contractors. In the case that contractors achieve economies of scale via expansion, marginal cost would become decreasing instead of constant. While constant marginal cost is a common assumption in previous literature on spatial pricing for model tractability (e.g., Greenhut & Norman, 1986), exceptions to constant marginal cost under monopolistic markets has been discussed in Graubner (2020). In particular, with variable marginal cost, monopolistic prices are no longer independent of transportation cost (see the equilibrium monopolistic prices in subsections 3.1 and 3.2). In the case of economies of scale, the optimal monopolistic prices would increase with transportation cost, which implies further reduction in farmer welfare in the context of our study.

4. Case Study: Empirical Application on Precision Plant Protection Service in Switzerland

In this section we use a case study to place the results in our conceptual analysis in an empirical setting. We draw on observed market conditions, and farm characteristics derived from farm structural data that give rise to heterogeneous reservation prices. We simulate uptake decisions of a bundle of precision plant protection technologies under different policy and market structure scenarios. The use of empirical data on farm structures allows us to incorporate heterogeneity in reservation prices into our conceptual analysis. Thus, we are able to assess the relative economic significance of policy interventions and changes in the spatial market structure of contractors. This underscores the importance of considering spatial competition of contractor services in how policies could effectively support the uptake of precision farming technologies.

4.1 Plant protection service with precision technology and the PFLOPF Project

To assess the role of spatial competition among contractors in a real-world setting, we study the case of precision plant protection technologies via contractor service in three Swiss cantons under the PFLOPF (in German 'Pflanzenschutzoptimierung mit Precision Farming') project. This pilot project is an initiative funded by the Swiss Federal Office for Agriculture which aims for optimization and reduction of the use of pesticides with precision farming technologies for a limited number of farms. The initiative reflects current efforts made by policymakers, farmers and industry in Switzerland aiming to reduce risks caused by pesticide use for the environment and human health (e.g., Böcker et al., 2019; Huber & Finger, 2019; Möhring, Ingold, et al., 2020). The pilot project runs between 2019 and 2026 in the cantons of Aargau, Thurgau, and Zürich and comprises ca. 60 farms that are provided with different incentive schemes. Participating farmers are subsidized for the use of precision plant protection technologies that meet the project requirements (a per-hectare payment is used to compensate the implementation of specific measures). The measures considered in the project comprise: i) automatic section or single nozzle control on pesticide sprayers, ii) camera hoeing services, both combined with GPS steering system, iii) site-specific application of crop protection agents based on drone images, iv) use of warning and prediction systems in making pesticide use decisions (see Möhring, Wuepper, Musa, & Finger (2020) for an example), and v) robot-based weed control and drone-based pesticide application in orchards and vineyards. Farmers can fulfill the requirements by installing their own devices or acquiring services from contractors. Information of contractors providing services that meet the project requirement is publicly available to both current and potential participants.

Our case study focuses on the potential uptake of a section or single nozzle control on pesticide sprayers combined with GPS steering system, because this is a widely used measure and is indeed offered by contractors. We do not consider uptake via farmers purchasing their own machinery and devices as this is uncommon in Switzerland due to the small acreage for each farm (Groher et al., 2020).

As of January 2020, there are ten contractors offering plant protection agent spraying services with automatic section or single nozzle control combined with GPS steering system in the cantons of Aargau, Thurgau, and Zürich that were accepted to the PFLOPF project. Since two contractors located in Lucerne and near the Aargau-Lucerne border are likely to offer services to farms in Aargau as well (Figure 6), we include these two contractors in the analysis, though only farms in Aargau, Thurgau, and Zürich are considered. In addition to the information provided by the PFLOPF project, we surveyed the contractors and asked for their pricing and service capacity (in terms of maximum travel distance) information (Table 2). By simulating potential uptake of the technology via these contractors over the entire study area, our case study also provides an extrapolation of the coverage of the project which is currently in a pilot phase. Based on information provided by contractors in our sample, the majority charge all clients within the service area a flat rate, with one indicated that extra charges can apply if they need to travel outside of their usual service area. This suggests that the pricing schedule within a certain distance is consistent with uniform pricing. We therefore focus on the uniform pricing schedule in the case study.

Table 2. Price of service and service radius based on survey of contractors

	Mean	Minimum	Maximum	Std. dev.
Price (CHF/ha)	89	75	100	8.8
Service radius (km)	20	15	25	3.2

Note: Includes two contractors located in Lucerne near the Aargau-Lucerne border. Service radius based on information provided by six contractors.

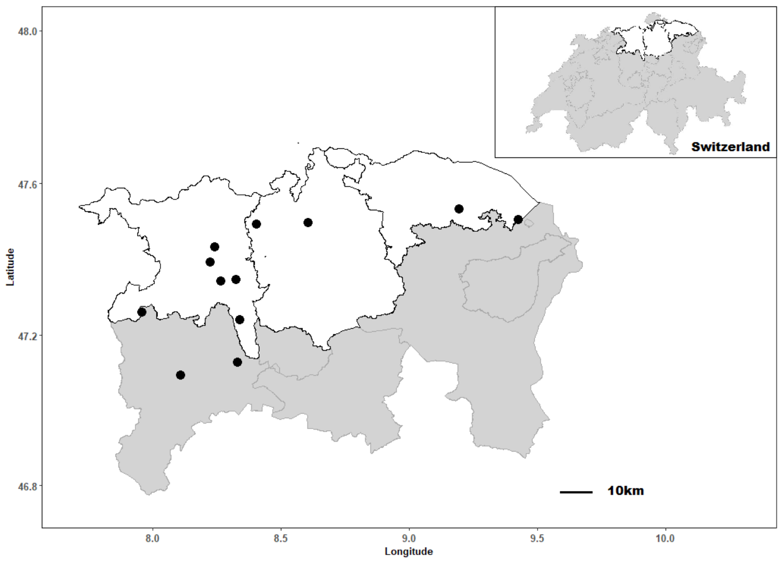

Figure 6. Spatial distribution of contractors offering spraying service with section or nozzle control

4.2 Definitions of scenarios and outcomes, and parameter calibration

Simulation scenarios

Although only a small number of farms have currently enrolled in the pilot project, the presence of the contractors allows for larger scale adoption of the technology by farmers to which contractor service can reach. In the baseline scenario of the simulation, we estimate the potential uptake from the entire study area that the current market of contractor service could facilitate. We then assess the relative economic significance of policy interventions and change in market structure under alternative scenarios.

In the baseline scenario, we consider a 20 kilometer service radius, which is the most common among all contractors (Table 2). With this service radius, approximately 86 percent of the study area has access to contractor service. The potential uptake depends on farmers' reservation price relative to the price of service. For farmer j, adoption occurs when the price of service is below the reservation price: $q_j < v_j(\theta)$, with θ being a dispersion parameter that measures the deviation of individual reservation price from the expected unit financial return to using the technology, $\bar{\pi}$. We calibrate the baseline price-to-reservation-price relationship based on observed service prices and farm characteristics (discussed in detail below). We then consider two alternative scenarios, each of which is associated with a change in one side of the inequation $q_j < v_j(\theta)$. Finally, we assess the case where both changes occur at the same time.

First, we consider a shift in the distribution of the reservation price. Such a change can be due to policy interventions that encourage efficient use of pesticides. For example, under the PFLOPF project, utilization of precision farming technology is compensated with a subsidy upon provision of billing records from a contractor. Alternatively, a tax or quota on the amount of pesticide use per unit of land would also increase farmers' willingness to pay for a technology that increases the efficiency of pesticide use. In all cases, the distribution of the reservation price would be shifted rightward.

In another scenario, we consider changes in the service prices due to a change in the intensity of spatial competition between contractors.[10] Increased intensity of competition can arise from increased service capacity and technological advancement. For instance, an increase in the efficiency of sprayers would allow contractors to shorten the time needed for a given task, and therefore serve more customers. This is especially relevant during peak seasons when the applications of pesticides need to be done within a certain time window. In the simulation, we represent such an increase in service capacity with an increase of the service radius from 20 kilometers to 30 kilometers. The larger service radius by contractors also implies that a greater proportion of each contractor's service area would be contested with others', implying higher intensity of spatial competition within the market and lower service prices.

In a final scenario, we assess the joint performance of a policy intervention along with technological advancement, where we consider a shift in the reservation price concurrently with an increase in the service radius. We summarize the four scenarios in Table 3.

[10] Other shocks can lead to uniform changes in service price, for example, subsidies to contractors offering precision farming technology service. This case would be equivalent to a change in farmers' reservation price.

Table 3. Simulation scenarios

		Policy intervention	
		No	Yes
Service radius	20 km	Scenario 1: Baseline	Scenario 2: Policy
(Competition intensity)	30 km	Scenario 3: Competition	Scenario 4: Policy & Competition

Outcome variable definition

We define uptake rate as the proportion of acreage operated by farms that specialize in crop farming and adopt contractor service, out of the total acreage of crop farming in the study area: $uptake = \frac{Acreage\ of\ crop\ farms\ with\ adoption}{Acreage\ of\ all\ crop\ farms}$. We obtain the number of crop farms (including farms specialized in crop farming solely, and in a mixture of crops and animal production), and the type and size of each farm in 2017 at the municipality level from the farm structural data by the Federal Office for Agriculture. This allows us to calculate the total crop acreage in the study area as well as the area of farms in each municipality. Farmer surplus at the individual level is defined as the proportion of the reservation price that exceeds the price paid for the technology: $surplus_j = \frac{v_j(\theta)}{q_j} - 1$, and average surplus is defined as the acreage-weighted geometric mean of individual surplus: $\overline{surplus} = \left(\prod^n \left(\frac{v_j(\theta)}{q_j}\right)^{\omega_j}\right)^{\frac{1}{\sum^n \omega_j}} - 1$, where ω_j is the acreage operated by farmer j.

Parameter calibration

As we discuss above, farmer j adopts the precision farming technology when the price of service is below the reservation price: $q_j < v_j(\theta)$. For a given set of service prices, the total uptake of the technology depends on the distribution of the reservation price. Farmers form their reservation prices based on the expected unit financial return to using the technology, $\bar{\pi}$, and individual subjective beliefs of the benefit of the technology. Deviation in a farmer's reservation price from the expected return can arise from perceived effectiveness of the technology, openness to new technologies, risk aversion, and production restrictions due to farm characteristics. In particular, as shown in Groher et al. (2020) for Switzerland, with economies of scale, larger farms are more likely to benefit from precision farming, and therefore more likely to adopt the technology (regardless of via investment or contractor service). Therefore, we explicitly account for farm size in the distribution of reservation price. Specifically, we assume farmers' reservation price follows a probability distribution such that $v(\theta_g) = \bar{\pi} \cdot (\theta_g + 0.5)$. θ_g measures the dispersion of individual belief from $\bar{\pi}$ for farm size group g, and has a Beta distribution with parameters $(\alpha, \beta, f_g, h_g)$, where (α, β) characterize the shape of the distribution, and (f_g, h_g) are the minimum and maximum values of the distribution. In other words, we assume that the distributions of reservation price of different farm size groups have the same shape but different supports. Based on farm structural data of the study area from the Swiss Federal Office for Agriculture and the results by Groher et al. (2020), we categorize farm sizes into three groups: (1) less than 20 hectare, (2) 20-50 hectare, and (3) over 50 hectare. We assume θ_g is independent and identically distributed, that is, farmers form their beliefs of the benefits of precision farming technology independently. We acknowledge that certain farm characteristics, access to extension services, as well as soil and climate conditions may give rise to spatial correlations in the reservation price. Yet, since our study area is relatively small with reasonably homogeneous conditions, we contend that such correlations do not concern the current simulation analysis. Table 4 presents the parameters and variables along with their definitions. For the baseline scenario, we assume that farm size group (2) has a mean reservation price that equals to the expected financial return to adopting the technology, $\bar{\pi}$, setting $\bar{\theta}_2 = 0.5$. We calibrate the dispersion parameter of farm size groups (1) and (3) based on the farm bookkeeping data from Swiss center of excellence for agricultural research (Hoop et al., 2020), setting $\bar{\theta}_1 = 0.4$ and $\bar{\theta}_3 = 0.55$.

Table 4. Parameter definition

Parameter	Definition	Baseline Value
v	Reservation price, $v = \bar{\pi} \cdot (\theta_g + 0.5)$	$\bar{v} = \bar{\pi}$
$\bar{\pi}$	Expected financial return of technology uptake	
θ_g	Dispersion parameter of reservation price of farm size group g, $\theta_g \sim Beta(\alpha, \beta, f_g, h_g)$	
α, β	Shape parameters of θ_g	$\alpha = 2, \beta = 2$
f_g, h_g	Minimum and maximum values of θ_g	$f_1 = -0.1, h_1 = 0.9$ $f_2 = 0, h_2 = 1$ $f_3 = 0.05, h_3 = 1.05$
q	Price charged by contractor	$q^{Mono} = \bar{\pi}$
$\frac{q}{\bar{\pi}}$	Adoption threshold, to be compared with v	

With $v(\theta_g) = \bar{\pi} \cdot (\theta_g + 0.5)$, the decision rule for farmer j's decision to adopt can be written as $q_j < \bar{\pi} \cdot (\theta_{jg} + 0.5)$, or equivalently, $\frac{q_j}{\bar{\pi}} < \theta_{jg} + 0.5$. That is, farmer j in size group g would adopt if the re-centered dispersion parameter value exceeds the ratio of service price divided by the expected financial return to the technology. The ratio $\frac{q_j}{\bar{\pi}}$ is therefore the "adoption threshold" in the simulation. According to Result 3 of the conceptual analysis, under uniform pricing, a monopolistic contractor sets the price at the expected reservation price. For simplicity, we assume that the overall expected reservation price is the same as that of farm size group (2), that is, $q^{Mon} = \bar{\pi}$. As such, in the "Baseline" scenario, the adoption threshold under spatial monopoly is 1. Prices charged by contractors under spatial competition are lower compared to spatial monopoly, implying a lower threshold of adoption. According to the observed service prices, on average, contractors with high monopolistic power offer prices approximately 12 percent higher than prices from contractors in highly competitive markets. We therefore calibrate the baseline adoption threshold under spatial competition as 0.88 (row 1 of Table 5).

We next introduce a subsidy that amounts to 10 percent of the unit expected financial return of the precision farming technology i.e., $0.1\bar{\pi}$.[11] The subsidy increases farmers' reservation price, which leads to a rightward shift in the distribution of θ_g by 0.1 for all groups. According to Result 4, the pass-through of the subsidy to farmers vary by market structure. Under spatial monopoly, the subsidy is fully passed to the price farmers face, such that farmers will be charged $1.1\bar{\pi}$, and thus the adoption threshold under monopoly increases to 1.1 under the scenario "Policy". In a competitive market, a fraction of subsidy is passed to price. We therefore calibrate the adoption threshold under competition in this scenario as 0.94 (row 2 of Table 5). In the scenario "Competition", the intensity of spatial competition increases as the service radius increases, implying a further reduction in the competitive prices. We calibrate the competitive adoption threshold as 0.82 for this scenario, while the threshold under monopoly is again 1 (row 3 of Table 5). Finally, according to Result 4, the proportion of subsidy that is passed to price

[11] This assumption of a relative definition of the subsidy level used in the simulation implies the total subsidy depends on the specific crop and farming system, as the number of times of plant protection agent application differs.

decreases at an increasing rate as the intensity of spatial competition increases. Thus, in the scenario "Policy & Competition", we set a lower fraction of the subsidy to be passed to price compared to the scenario "Competition", with the adoption threshold under competition set as 0.86, and the threshold under monopoly as 1.1 (row 4 of Table 5).

As we discuss in Section 3, it is also possible for two closely located contractors with contested market areas to adopt a cooperative pricing strategy. The prices under cooperative competition coincides with the monopoly price under uniform pricing, where the same implications apply, and thus we do not separately examine this case.

Table 5. Adoption threshold, $\frac{q_j}{\bar{\pi}}$, under different scenarios

Scenario	Radius (km)	Subsidy	Monopolistic	Competitive
1: Baseline	20	No	1	0.88
2: Policy	20	Yes	1.1	0.94
3: Competition	30	No	1	0.82
4: Policy & Competition	30	Yes	1.1	0.86

Simulation steps

Under each scenario, we take the following steps to simulate the uptake rate and average farmer surplus. First, for each farm, we determine the corresponding market structure of contractor service. Since farm information is available at the municipality level, we assume farms have access to contractor service when the municipality centroid falls within the service area of any contractor. A farm is in a monopolistic market if it falls in the service area of one contractor, and a competitive market if it falls in the service areas of two or more contractors. We then take a random draw of the dispersion parameter θ_g from the respective distribution and compare the realized value to the corresponding adoption threshold in Table 5. Farm j is an adopter if θ_{jg} is above the adoption threshold. Based on the uptake decisions of each farm, we calculate uptake rate and adopter's surplus over both types of market structures. Total uptake rate over the study area is given by the sum of uptake rates over the monopolistic and competitive markets; average surplus is calculated separately over the two types of market structures.[12]

4.3 Simulation results and discussion

Table 6. Estimated uptake rate and farmer surplus

Scenario	% Total area covered		Uptake		Surplus	
(Radius; Subsidy)	Mono.	Comp.	Mono.	Comp.	Mono.	Comp.
1: Baseline (20 km; No)	0.39	0.47	0.19	0.31	0.18	0.26
2: Policy (20 km; Yes)	0.39	0.47	0.19	0.34	0.16	0.26
3: Competition (30 km; No)	0.14	0.83	0.06	0.64	0.18	0.32
4: Policy & Competition (30 km; Yes)	0.14	0.83	0.06	0.69	0.16	0.34

"% Total area covered" is the fraction of total study area served by contractors; "Uptake" is the share of arable land adopting contractor service ; "Surplus" is the proportion of the reservation price that exceeds the price paid for the service, weighted by farm size. The subsidy is set to $0.1\bar{\pi}$.

[12] Detailed contractor information and code for simulations are available upon request.

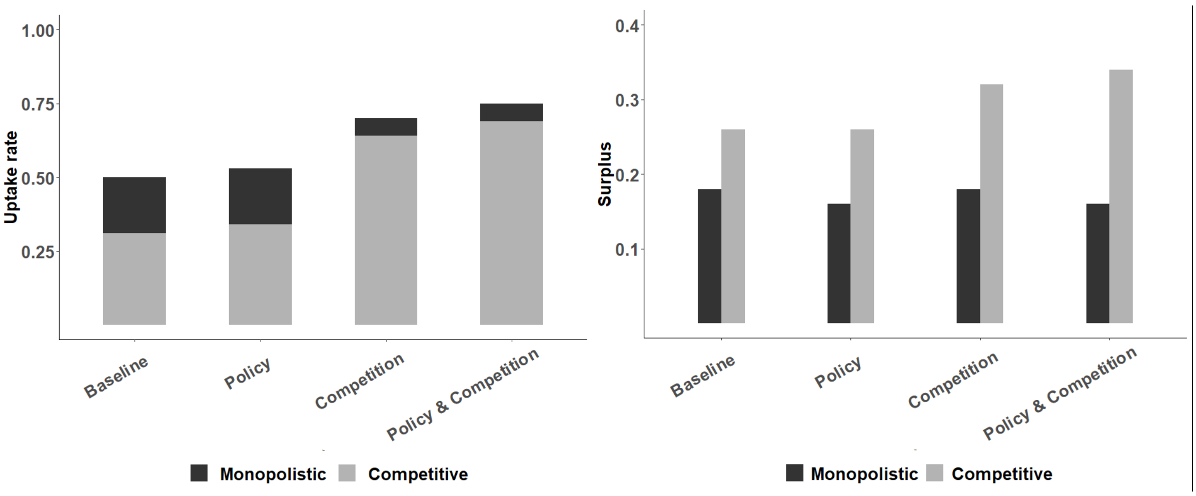

Figure 7. Comparison of estimated uptake rate and farmer surplus across scenarios

Overall, higher intensity of spatial competition is associated with higher uptake and farmer surplus. As service radius increases from 20km to 30km, a larger fraction of the study area has access to contractor service. With a service radius of 30km, almost the entire study area is covered by contractor service areas, with the majority (83 percent) being competitive markets. Total uptake rate increases by over 20 percentage points, with a lager fraction (e.g., 64 out of 70 percent in the scenario "Competition"), and farmer surplus on the competitive market increase by over six percentage points (Table 6 and Figure 7). With a policy intervention that encourages precision farming such as a subsidy (scenarios "Policy" and "Policy & Competition"), uptake from the competitive contractor service markets increases (compared to scenarios "Baseline" and "Competition", respectively), but not from the monopolistic markets. Thus, in the case that the policy shifts farmers' reservation price uniformly, the increase in farmers' willingness to pay for the service is offset by the increase in service price. Under spatial competition, a fraction of the subsidy remains with the farmers, which allows for an increase in uptake. Due to the low pass-through of subsidy to farmers, the subsidy almost does not change farmer surplus.[13] Furthermore, comparing the differences in the outcomes between scenarios "Policy" *vs.* "Baseline" and scenarios "Policy & Competition" *vs.* "Competition", with the same level of subsidy, total uptake is increased by 3 percent with a 20km service radius by contractors, and by 5 percent with a 30km service radius, and farmer surplus also sees an overall increase in the latter case. These relative differences indicate that subsidy is more effective in markets with overall higher intensity of spatial competition.

Our simulation substantiates the extent to which spatial competition among contractors may influence precision farming technology uptake and farmers' welfare, as well as the effectiveness of policies that support uptake. Apart from the scenarios considered in the simulations, here we discuss several aspects not directly addressed in the analysis that could help place our results in a broader context. Firstly, farmers may also adopt precision farming technologies (and get subsidized) via investment into machineries and devices of their own, which is not accounted for in the simulation. An estimate of precision farming technology uptake attributable to contractor service can be refined with the fraction of farmers that adopt comparable precision farming technologies via individual or joint investment. Thus, the uptake rates should be interpreted as lower bounds of the potential adoption. In this context, increased adoption rates via contractor service might also have a self-reinforcing effect by increasing peer learning among farmers that mitigates the knowledge barrier in adopting precision farming technologies, especially via investment. Secondly, and in a related manner, especially for larger-scale

[13] The slight decrease in surplus under spatial monopoly is due to sampling variability.

farms, a lack of availability of contractor service may prompt the farmers to invest in machineries on their own and become a provider of contractor service. In other words, in the long run, there may exist dynamic interactions between the level of spatial competition between contractors and uptake, and entries of new contractors may emerge, which further alters the spatial market structure. With new observations of entrants in the contractor service market over multiple periods, a future extension of our work would be to investigate into the motivations for the new entries, as well as how they could influence uptake and welfare. For our current purpose of evaluating the overall effect of spatial competition intensity change, however, we note that it is sufficient to create alternative scenarios of market structure by varying the service radius. Over the long run, the expansion of service capacity could lead to economies of scale. Another future extension of our work would therefore be to relax the constant marginal cost assumption and allow for economies of scale. As we discuss in the introduction, in this case, we expect the monopoly price to increase with transportation cost, and reduces farmer surplus. Finally, we believe that the role of contractor services may also be viable in making use of new technologies for conservation purposes (e.g., as precision conservation), so that our analysis could be expanded beyond the more efficient use of inputs.

5. Conclusion

Contractor service can provide farmers access to precision farming technologies without capital investment. It thus has the potential to mediate the misaligned private and public benefits of precision farming which often exist in small scale agriculture and facilitate small farms' participation in sustainable agricultural intensification. Due to costs associated with delivering contractor service, the local market power of contractors can govern the effectiveness of contractor service in promoting precision farming uptake. The local market structure of contractor service may further interact with the policy interventions aimed at promoting precision uptake. In this paper we conceptually investigate the role of contractors in the uptake and diffusion of precision farming technologies, as well as the pass-through of a subsidy from a spatial competition perspective. Informed with results from the conceptual analysis, we further use a case study of precision plant protection technology contractor service in Switzerland to empirically assess the extent to which changes in spatial market structure and policy interventions can influence precision farming uptake and welfare distribution. Overall, our analyses provide evidence that high local market power may hinder the diffusion of precision farming technologies, as well as the pass-through of a subsidy for precision farming uptake to farmers. Conversely, spatial competition between contractors is associated with lower prices and higher pass-through of a subsidy. Our simulation further shows the relative economic significance of policy interventions and changes in the intensity of spatial competition, as well as the interaction between policy interventions and spatial market structure. As such, we conclude that increased intensity of spatial competition in the contractor service market can enhance both farmers' uptake of precision farming technologies and the extent to which they benefit from a subsidy. Considering alternative pricing schedules by contractors which differ in whether spatial price discrimination is present, our analyses reveal an overall higher uptake supported by the uniform pricing schedule under imperfect competition, yet farmers achieve lower surplus under uniform pricing. We also conceptually show that when competing contractors cooperate in the form of price and market area matching, farmers face high service prices and therefore are less likely to adopt the technology, and are worst off in terms of subsidy pass-through, though we do not observe such a case in the contractor service market we study.

From a policy point of view, our results show that the lack of spatial competition among contractors can largely reduce possible public benefits due to reduced environmental damages arising from the use of precision farming technologies, e.g., by reducing losses of nitrogen and pesticides to the environment.

Moreover, policy intervention such as subsidies to foster the uptake of precision farming technologies in order to contribute to sustainable agricultural intensification can be rendered highly inefficient due to the lack of spatial competition of contractors. Thus, the optimal choice of policy instruments also needs to account for the availability and structure of contracting services. We conclude that for the primary goal of increasing uptake, a uniform pricing strategy by the contractors is advantageous from a policy perspective, and cooperative pricing between contractors is undesirable in this regard.

Our analyses provide an avenue for further research on the interaction of contractors, policies and precision farming adoption of small farms. This is highly relevant as the vast majority of farms globally is too small to directly invest in new technologies but rely on purchasing services or joint investments. Effects of spatial competition and dynamic effects shall be tested empirically and a broad spectrum of policies (subsidies, taxes on inputs, interventions on contractor markets) shall be tested.

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Appendix

Effect of subsidy and technological change under non-discriminatory pricing

Given the equilibrium prices and demand functions derived above, we can show that in the monopoly case, $\frac{\partial r_i}{\partial \bar{v}} = \frac{1}{2}$, i.e., half of the subsidy would be passed to the contractor. In the duopoly case, $\frac{\partial r_i}{\partial \bar{v}} = 0$, the subsidy entirely remains with the farmer. However, in the weak duopoly case, $\frac{\partial r_i}{\partial \bar{v}} = 1$, the entire subsidy would be passed to the contractor. In terms of the effect on demand, with spatial competition, each contractor serves half of the market, and $\frac{\partial D_i}{\partial \bar{v}} = 0$; under spatial monopoly, $\frac{\partial D_i}{\partial \bar{v}} = \frac{1}{2t}$.

Duopoly pricing strategies under uniform pricing

As we discuss in section 3.2, with non-cooperative uniform pricing, a solution with pure strategies does not exist, and we consider a symmetric mixed strategy game described with a cumulative density function that applies to both contractors: $\Psi(w)$. For contractor i, the optimal mixed strategy is $\Psi(w_i)$, where he has the options of setting a lower price than the competitor with probability $\Psi(w_i) = \int_{w_i}^{w^1} \mathrm{d}\Psi(w_{-i}) = P(w_i \le w_{-i})$, or setting a higher price and capturing the residual demand. We have shown that the expected profit from charging at a lower price is given by $E(\pi_i^-) = \frac{(w_i^- - c)^2}{4t}$, and the expected profit from charging at a higher price and capture the residual demand is $E(\pi_i^+) = \frac{[\sigma-(w_{-i}-c)]\,(2w_i^+ + w_{-i} - \sigma - 3c)}{4t}$. Suppose the competitor plays the pricing strategy w_{-i} with probability $\Psi(w_{-i})$. Let w_i^1 and w_i^0 denote the upper and lower price limits that support the optimal mixed strategy (we later drop the subscripts given the symmetry of the game), the expected profit of contractor i under his own strategy is

$$E[\pi_i(w_i, w_{-i})] = \int_{w^0}^{w^1} \pi_i \mathrm{d}\Psi(w_{-i}) = \pi_i^- \Psi(w_i) + \pi_i^+ \big(1 - \Psi(w_i)\big) \qquad \text{(A1)}$$

Following Zhang & Sexton (2001) and Graubner (2018), as the optimal mixed strategy, $\Psi(w_i)$ must satisfy that for every price over the support (w^0, w^1), the expected profit equals to the value of the game for contractor i : $E[\pi_i(w_i, w_{-i})] = \pi_i^- \Psi(w_i) + \pi_i^+ \big(1 - \Psi(w_i)\big) = V$. The optimal strategy can therefore be represented as

$$\Psi(w_i) = \frac{V - \pi_i^+}{\pi_i^- - \pi_i^+} \quad \text{(A2)}$$

Since at the upper price limit that support the mixed strategy game, $\Psi(w^1) = 0$. From Equation (A2), we get $V = \pi_i^+(w^1) = \frac{[\sigma-(w_{-i}-c)](2w^1+w_{-i}-\sigma-3c)}{2t}$. Maximizing V with respect to w^1, we get $w^1 = \bar{v}$, and $V^* = \frac{[\sigma-(w_{-i}-c)](2\bar{v}+w_{-i}-\sigma-3c)}{2t}$. At the lower price limit for the mixed strategy, $\Psi(w^0) = 1$, which gives $V = \pi_i^-(w^0)$. As such, when $\pi_i^+(\bar{v}) = \pi_i^-(w^0)$, the contractor is indifferent between pricing at the lower price limit and setting a monopoly price to capture the residual demand (while the competitor prices at the lower price limit,$w_{-i} = w^0$). We can then equate the two profit functions and find w^0:

$$w^0 = \frac{1}{2}\left[3c - \bar{v} + \sigma + \sqrt{(\bar{v} - c)^2 + \sigma(2\bar{v} - 2c - \sigma)}\right] \quad \text{(A3)}$$

Given the lower price limit that supports the optimal mixed strategy, w^0, the fraction of total demand captured by the contractor pricing at w^0 is given by $D_i^{UP^0} = \frac{w^0-c}{t} = \frac{\sigma-(\bar{v}-c)+\sqrt{(\bar{v}-c)^2+2\sigma(\bar{v}-c)-\sigma^2}}{2\sigma} l$. Since the fraction of the total market served by the contractor charging the lower price increases with w^-, $D_i^{UP^0}$ represents the lower limit of the market that a contractor with w^- could cover. When one contractor prices at w^0, how the market is divided between the two competitors depends on the magnitude of transportation cost: Let $\gamma = \frac{\bar{v}-c}{\sigma}$, which is the inverse of the relative importance of space, then $D_i^{UP^0}$ can be rewritten as $D_i^{UP^0} = \frac{1-\gamma+\sqrt{\gamma^2+2\gamma-1}}{2} l$. It can be easily shown that $\frac{\partial D_i^{UP^0}}{\partial \gamma} > 0$, and thus $\frac{\partial D_i^{UP^0}}{\partial\left(\frac{\sigma}{\bar{v}-c}\right)} < 0$. That is, the fraction of the market that faces w^0 increases as transportation cost decreases. In Figure A1 we plot the total demand covered against $\frac{1}{\gamma} = \frac{\sigma}{\bar{v}-c}$. The segment to the left of the vertical line $\frac{\sigma}{\bar{v}-c} = 2$ shows the potential demand covered by a duopolist pricing at the lower price limit: $D_i^{UP^0}$. Over this segment, the competing contractor acts as a monopolist, covering up to the residual demand. The segment to the right of the vertical line represents the market covered by one of the two monopolists when the markets are separated.

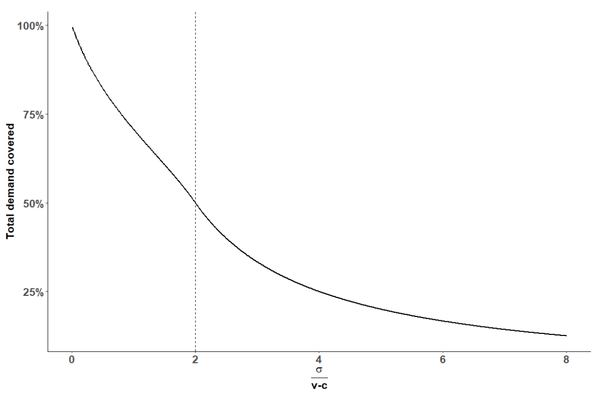

Figure A1. Demand captured by duopolist pricing at the lower price limit in a competitive market, and one monopolist in a monopoly market

As we discuss above, in a competitive market, $D_i^{UP^0}$ represents the lower limit of the fraction of total demand that a contractor charging the lower price w^- could cover. In other words, when a contractor plays a strategy w^- which is higher than w^0, all else equal, the fraction of total demand covered by the contractor with w^- would be greater than that under w^0. In the extreme case that transportation cost is zero, the contractor with the lower price capture the entire market. As the importance of space increases, the demand that the contractor with w^0 can capture decreases till half of the market: at $\frac{\sigma}{\bar{v}-c} = 2$, pricing at w^0 would cover half of the market, which is equivalent to acting as a monopolist.

Effect of subsidy under uniform pricing

When a contractor prices at the lower price limit in a duopoly market, the proportion that is passed onto the price is positive: $\frac{\partial w^0}{\partial \bar{v}} = \frac{1}{2}\left[-1 + [(\bar{v}-c)^2 + \sigma(2\bar{v} - 2c - \sigma)]^{-\frac{1}{2}}(\bar{v} - c + \sigma)\right] \geq 0$, which is an increasing convex function of $\frac{\sigma}{\bar{v}-c}$ (shown below in Figure A2). As the importance of space relative to maximum net revenue increases, the portion of a subsidy is passed to the price increases with an increasing rate till 100%. In the two extreme cases, when $\sigma = 0, \frac{\partial w^0}{\partial \bar{v}} = 0$, the effect of a subsidy would entirely remain with the farmer; when $\sigma = 2(v-c), \frac{\partial w^0}{\partial \bar{v}} = 1$, the subsidy is entirely passed to the price.

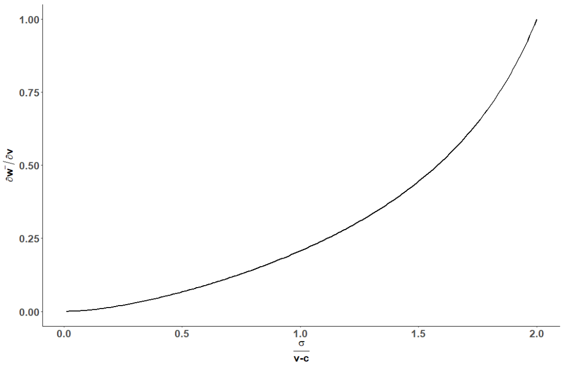

Figure A2. Proportion of subsidy passed onto price ($\frac{\partial w^0}{\partial \bar{v}}$) as a function of $\frac{\sigma}{\bar{v}-c}$