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REVIEW

Precision Agriculture: Where do We Stand? A Review of the Adoption of Precision Agriculture Technologies on Field Crops Farms in Developed Countries

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Abstract Precision agriculture is a management concept, which relies on intensive data collection and data processing for guiding targeted actions that improve the efficiency, productivity, and sustainability of agricultural operations. Several studies have assessed the adoption rate of precision agriculture technologies at regional or national scale, but the literature lacks global evaluations of the development of precision agriculture. For this paper, a review of 17 papers was conducted to provide an evaluation of the adoption rate of precision agriculture technologies on field crops farms in developed countries. This review shows a fast development of Global Navigation Satellite System-based technologies (such as guidance system and automatic section control), and yield monitor on combine harvesters, with a rate of adoption ranging from 60 to 80% in 2016. The adoption rate of these technologies is higher for North American farms than for European farms, with an average rate of adoption 17% higher in North America than in Europe. The three technologies closely correlated with variable rate application (soil mapping, variate rate fertilizing, and variable rate seeding) have seen a slower pace of growth, with only a third of the field crops farms of developed countries using automated methods of managing the spatial crop variability and spatial soil variability within a field. Three hypotheses to explain this difference are discussed: successive adoption of technologies, reject of complex technologies and preference for technologies improving working conditions.

Keywords Precision farming · Adoption rate · Diffusion of innovation · Variable rate application · Site-specific adaptation

Introduction

Precision agriculture, also called precision farming, is a holistic management concept, which relies on intensive data collection and data processing for guiding targeted actions that improve the efficiency, productivity, and sustainability of agricultural operations [12]. If some authors have argued that agriculture is undergoing a major revolution due to the ever-increasing use of information and communication technology [36], others reported a low rate of adoption of precision agriculture technologies [25, 33]. According to these studies, the number of farm precision agriculture practitioners is growing slower than expected, especially when compared to the rapid adoption of previous innovations such as hybrid corn seeds in the 1930's [8], or the rapid development of genetically modified seeds in the 1990's in Northern America [3].

While precision agriculture technologies emerged roughly at the same time as genetically modified seeds, the adoption rate of precision agriculture is generally accepted to be slower. However, although several studies have assessed the adoption rate of precision agriculture technologies at regional scale [5, 7] or national scale [32, 34], providing figures for given points in time, the literature lacks a global evaluation of the development of precision agriculture. Moreover, precision agriculture is a complex concept that covers a broad spectrum of practices, such as use of Global Navigation Satellite System (GNSS), yield monitoring, soil mapping, variable rate application for

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seeding and variable rate fertilizer application. Such diversity needs to be taken into account when assessing the spread of precision agriculture technologies.

The main goal of this review is to assess the adoption rate of precision agriculture technologies by farmers, from the introduction of these technologies in the 1990's to the present. It focuses on field crops farms in developed countries. These farms are among the most likely to adopt precision agriculture technologies because of their capacity to invest in relatively expensive tools (compared to farms in developing countries), and because of their large field size which increases the probability of intra-field variability and allows for an economy of scale to pay for the investment in precision agriculture technologies. Special attention has been paid to the characterization of the various practices of precision agriculture, to identify the fastest-spreading and the slowest-spreading technologies.

Materials and Methods

Sample and Definition of Observations

For this review, after removing papers that relied on the same datasets, such as the National Resource Management Survey of the US Department of Agriculture or the Southern Cotton Farm Survey, 17 papers that studied the adoption rate of precision agriculture technologies by field crops farms in developed countries have been found. In order to compare similar figures, only adoption rates expressed as a percentage of farms have been retained for this study, whereas adoption rates expressed as a percentage of farm area have been rejected. When necessary, the original dataset has been consulted to obtain the data expressed in the right unit, as it was the case for the Agricultural Resource Management Survey [35] used by Schimmelpfennig and Ebel [29]. The characteristics of the 17 papers are given in Table 1. The data used in these studies came mainly from surveys which ask farmers (1) if they use precision agriculture technologies on their farms, (2) if yes, which technologies do they use?

The 17 papers provided numbers for the adoption rate of one or more precision agriculture technologies for 73 observations, each observation being defined by two parameters: country and year. For instance, Tickner studied the adoption rate of several precision agriculture technologies (GNSS use, yield mapping, soil mapping, and variable rate application) for two observations: {England, 2009} and {England, 2012} [34].

The 73 observations cover a period of 25 years, from 1992 to 2016. They refer to seven countries, and there are 42 observations for USA (57%), 23 for Australia (32%), 2 for Germany (3%), 2 for England (3%), 2 for Canada (3%), 1 for Finland (1%), and 1 for Denmark (1%).

Typology of Precision Agriculture Technologies

Figure 1 shows the typology proposed in this paper to define the most commonly precision agriculture technologies reviewed in the literature. These technologies can be divided into three main categories: GNSS use, use of intra-field diagnosis tools and application of variable rate treatment. Each of these categories may be further subdivided into several sub-categories. For instance, GNSS use may refer to use of GNSS for automatic section control or to use of GNSS for guidance assistance, which in turn may refer to visual guidance (such as the use of a light bar guidance system) or to auto-guidance (sometimes referred to as automated steering system). The goal of the typology of Fig. 1 is to reflect the interest of the previous studies into precision farming adoption, not to provide a comprehensive overview of all precision farming technologies. There may be some technologies, such as automatic section control for solid fertilizer spreader, which were not included in the reviewed papers.

No paper provided an estimation of the adoption rate of all the technologies mentioned in Fig. 1, and no technology was studied by all of the reviewed papers. The technology which was most frequently studied is the use of GNSS for autoguidance, with 51 of the 73 observations providing data about its adoption. The adoption rate of GNSS for autoguidance has been more frequently studied than the broader question of the use of GNSS for guidance, for which only 14 observations were found (Fig. 1). Since there is substantial heterogeneity in the practices surveyed by the 17 studies in the sample, a simple aggregation method was used to homogenize their results, and to show the dynamic of precision farming adoption.

Aggregation of the Results

To assess the development of precision farming, focus has been placed on the adoption of six important precision agriculture technologies: use of GNSS guidance system, use of automatic section control, yield monitoring, soil mapping, variable rate for fertilizing, and variable rate for seeding. To maximize the number of observations taken into account in the analysis, a simple aggregation method was implemented. For each technology and for each observation, when the adoption rate of a given category was not available, this value was replaced by the maximum adoption rate of the sub-categories related to this category, if the result of at least of one these sub-categories was available. For instance, for the observation {Germany, 2009}, Lawson et al. [17] did not report any estimation for

Table 1 Characteristics of the 17 reviewed papers

References	Sample	Number of observations for the review
Adrian et al. [1]	85 US farms in 2004	1
Jochinke et al. [13]	146 Australian farms in 2006	1
Isgin et al. [11]	491 Ohio farms (USA) in 2003	1
Winstead et al. [37]	42 US farms in 2009	1
Reichardt et al. [25]	2058 German farms in 2007, with a subset of 23 farms for the details of the different technologies adopted	1
Diekmann and Marvin [5]	1163 Ohio farms (USA) in 2010	1
Lawson et al. [17]	76 German farms, 184 Danish farms, and 78 Finish farms in 2009	3
Schimmelpfennig and Ebel [29]	1129 US corn farms in 2005	1
Haak [9]	14,000 Canadian farms in 2006	1
Robertson et al. [27]	1170 Australian farms in 2009	1
Tickner [34]	1392 British farms in 2009, 2371 British farms in 2012	2
Llewellyn and Ouzman [19]	573 Australian farms, from 1992 to 2012	21
Schimmelpfennig and Ebel [30]	1507 US corn farms in 2010	1
Schimmelpfennig [28]	2491 US soybean farms in 2012	1
Miller et al. [21]	348 Kansas farms from 1995 to 2016	22
Steele [32]	261 West Canadian farms in 2016	1
Zhou et al. [39]	1811 US cotton farms from 2000 to 2012	13

soil mapping, but mentioned the adoption rates of the three sub-categories: grid sampling (14.47%), conductivity (1.32%) and zone sampling (5.26%). Therefore, the aggregation method implemented predicted that at least 14.47% of the farmers of the observation {Germany, 2009} used soil mapping, regardless of the method used. In this particular case, such method did not allow to account for farmers using only conductivity or zone sampling. For a given year, the number of adopters of a given technology was calculated as the mean of the adoption rates for all observations. Data treatments were performed with R software [24].

Results

Figure 2 shows the adoption rate for six precision farming technologies on field crops farms in developed countries. According to these results, soil mapping was the first technology to emerge in 1996, followed by guidance systems (assisted guidance or autoguidance) and yield monitor (coupled or not to GNSS) in 1997. Variable rate application started around 2000 (1999 for variable rate fertilizing, 2002 for variable rate seeding). Automatic section control was the last technology to emerge, in 2005.

From their emergence, all of these technologies have experienced regular growth, but various growth rates. Two groups may be distinguished: fast-spreading technologies (guidance system, automatic section control, and yield monitor) and slow-spreading technologies (soil mapping, variable rate fertilizing, and variable rate seeding). The fast-spreading technology group increased the number of users by approximately + 4% each year, which is twice as much as the annual growth of the slow-spreading technologies group (around + 2% of users each year).

As a consequence, GNSS guidance system and yield monitor are now widespread on field crops farms in developed countries (between 70 and 80% of users in 2016). Automatic section control was the last technology to emerge, but since it is the one with the fastest annual growth (+ 5.5% of users per year), its rate of adoption is now close to guidance system or yield monitor (60% of users in 2016). As regards the slow-spreading technologies, approximately one out of three farms used soil mapping or variable rate fertilizing in 2016 and only one out of five farms used variable rate seeding.

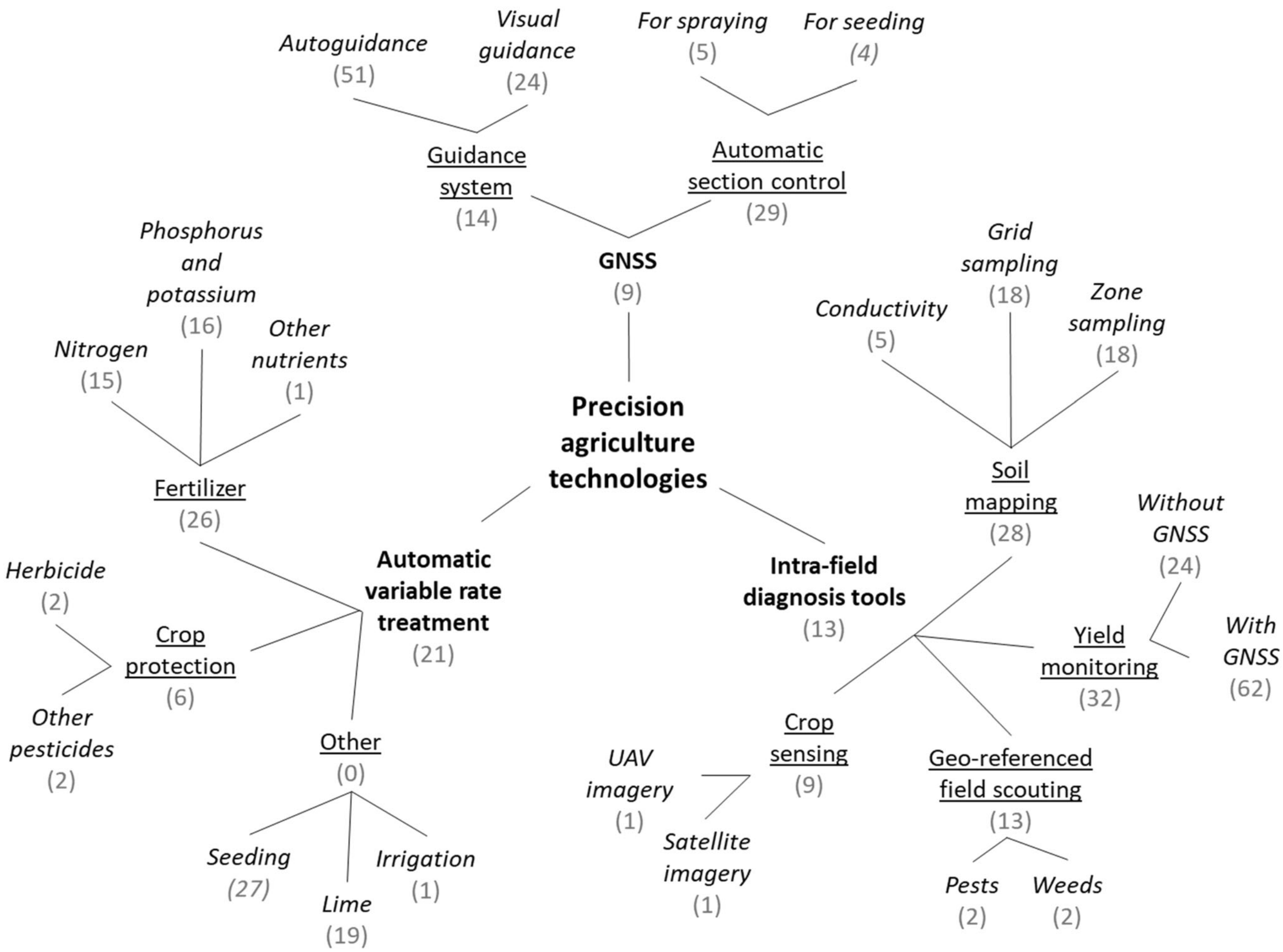

Fig. 1 Typology of precision agriculture technologies surveyed in the literature. The numbers in gray (in brackets), correspond to the number of observations which provide data for the adoption of each precision agriculture technology

When comparing the adoption rates of different geographical zones for a given year, North American countries (USA and Canada) showed a higher percentage of adopters than European countries (Denmark, England, Finland, and Germany). The difference was big for fast-spreading technologies, with an average of 17% more adopters in North America than in Europe. For instance, we found that, on average, 18% more North American farmers adopted guidance system on their farms, than European farmers. This difference was much smaller for the slow-spreading technologies (only 2% more adopters in North America).

Discussion

Difference in Adoption Rates Between Technologies

This review highlighted two different groups of precision agriculture technologies, based on their pace of adoption: fast-spreading technologies (such as guidance system, automatic section control, and yield monitor), and slow-spreading technologies (such as soil mapping, variable rate fertilizing, and variable rate seeding). A maximum of one out of three farms reported using one of these slow-spreading technologies (Fig. 2). Results are given here as a percentage of farm size and adoption rates are generally higher when expressed as a percentage of cropland area because large farms are among the first adopters [23]. Still, despite the expected economic and environmental gains of site-specific adaptation of agricultural practices [4, 26], adoption of variable rate treatments by farmers has been low and slow. Three hypothesis to explain this finding are discussed below.

Reasons for non-adoption of a technology by farmers can be divided into two broad categories: They are either unable (first and second hypothesis) or unwilling (third hypothesis) to adopt [22]. First, since site-specific adaptation of agricultural practices generally requires the adoption of other technologies such as GNSS and diagnostic tools for soil or crop mapping, variable rate application is

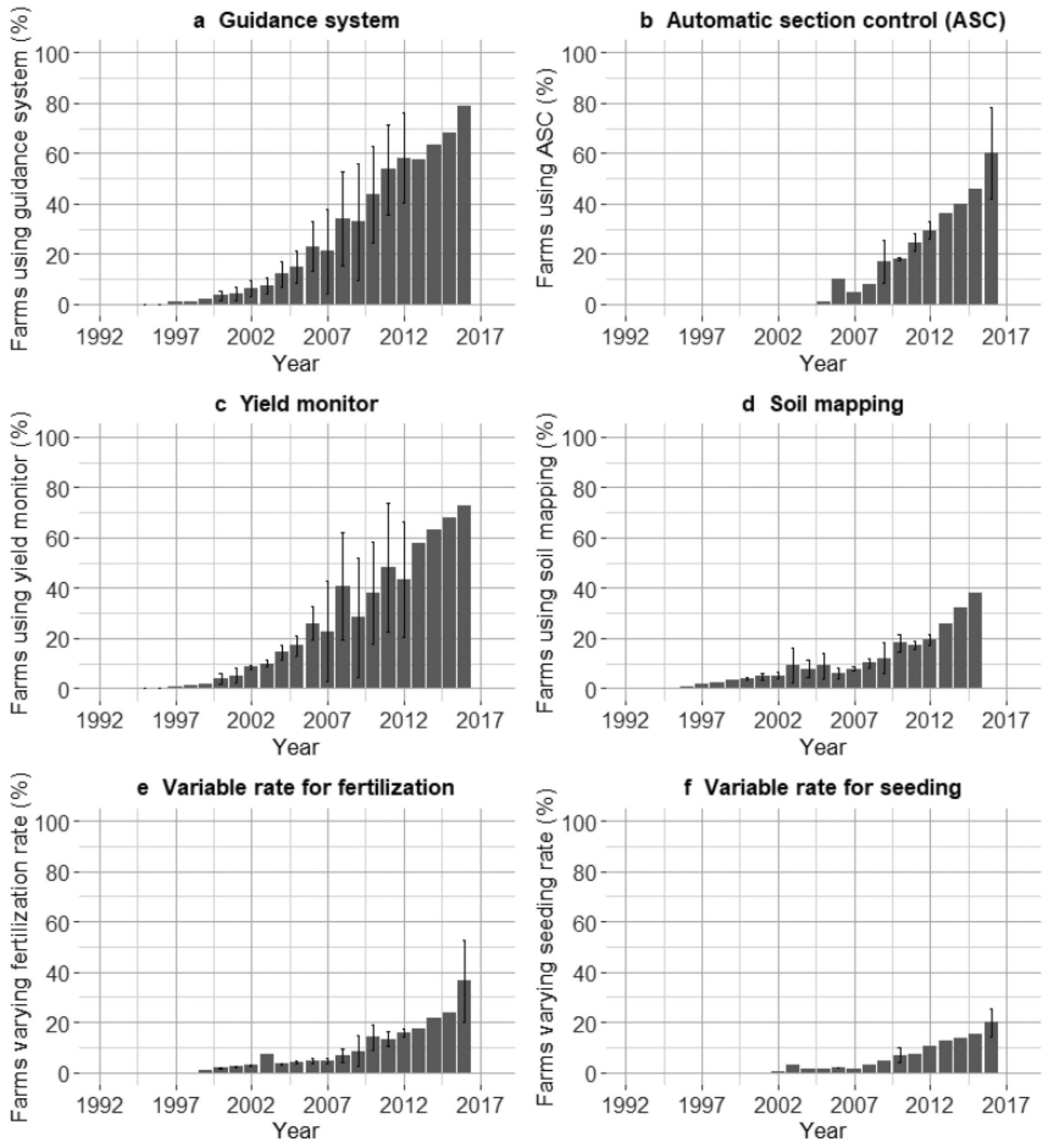

Fig. 2 Adoption rate of six precision farming technologies for field crops farms in developed countries. The barplots show the average percentage of farms using each technology, based on a review of the literature. The error bars represent the standard deviations

expected to be the technology last adopted by farmers. Such explanation may be consistent with the observations presented in Fig. 2. The adoption rate of fast-spreading technologies, and especially the adoption rate of guidance system, seems to follow the classical pattern of diffusion of innovations [20]. Rogers idea is that at the introduction of an innovation, relatively few people are aware of it and most people are not likely to adopt it, but when the adoption rate reaches a critical point (usually between 10 and 20% of users), its rate of growth accelerates. Based on these theoretical arguments, precision agriculture might appear to have been adopted by field crops farms in developed countries. The fast-spreading technologies are already being widely used. The slow-spreading technologies seem to be reaching their tipping point, and their adoption might be expected to accelerate.

Second, the complexity and the technical issues associated with some precision agriculture technologies may slow down their adoption. Yield monitoring may be considered to be a tool for evaluating intra-field heterogeneity (Fig. 1), but it may have other applications, such as monitoring crop moisture during harvest [37]. Yield monitors need to be connected to a GNSS receiver, and the data produced need to be extracted from the monitor and treated with a specific software in order to produce yield maps. In a study of 573 Australian farmers in 2012, Llewellyn and Ouzman found that only one out of two farmers who had a yield monitor produced yield maps [19]. According to Lindblom et al. “many farmers have the necessary technology to operate site-specifically” [18]. Therefore, the restricted use of precision agriculture technologies may be due to the complexity of the decision support systems associated with them, and to their non-adaptation to the present needs of farmers. Such hypothesis is consistent with the work of Barnes et al., who proposed a classification of precision agriculture technologies according to the required degree of involvement [2]. ‘Embodied knowledge technologies’ which require no additional skills for their operation and ‘information intensive technologies’ which require further investment in terms of knowledge, software or data analysis are very similar to the fast- and slow-spreading technologies identified in this review, respectively. Complexity of certain precision-farming technologies is indeed a restraint to the adoption of these technologies. One way forward may be the expected automation of precision agriculture, with further development of on-board sensors able to perform simultaneous diagnosis and variable rate application [38].

Third, improving the efficiency and productivity of agricultural productions may not be the main driver for the adoption of precision agriculture technologies. Farmers also tend to adopt innovations that provide opportunities for significant improvements in their quality of life and working conditions. The desire to reduce the drudgery of repetitive tasks is a factor contributing to the adoption of precision livestock farming technologies [10, 15]. For field crops farms, one of the advantages of GNSS-based technologies, such as guidance system and automatic section control, is to eliminate overlaps and therefore to reduce inputs consumption, but the use of these technologies also reduce fatigue, while variable rate treatments mainly aimed at increasing the efficiency of agricultural practices. Furthermore, as described above, the complexity of some technologies may even be perceived as a factor that can worsen working conditions.

Limits and Perspectives

The main limit of the literature review is that it mixes data from various sources such as data from internet surveys, interviews conducted during farm shows or national surveys. To counterbalance this variability due to a wide variety of sources that is difficult to avoid in a review, it has been decided to focus the study on field crops farms from developed countries, thus limiting the variability due to the type of production or investment capacity. Still, these farms may experiment different dynamics of adoption due to their type of field crops, the structure of the farm or the local context. Kutter et al. stressed the importance of the proximity of agricultural contractors or service providers in precision agriculture technologies adoption [16]. Such factors may explain some variability observed between studies (Fig. 2). It remains that, for the USA, the main results of this review show similar trends to those reported in the “Precision Agricultural Services Dealership Survey” regularly conducted by Purdue University to monitor the precision agriculture technology services provided by agricultural input suppliers [6].

It is more difficult to assess the adoption rate of European farms. Overall, the adoption rate of precision agriculture was higher for North American farms than for European farms. Bigger field crops farms and bigger fields in the USA and Canada may partly explain this difference, since the sizes of farms and fields have already been identified as major drivers of precision agriculture adoption [23]. For instance, in 2010 the median size of field crops farms was 486 ha in USA, compared to 239 ha in Germany [14]. However, this comparison between North America and Europe is to be taken cautiously, because most of the studies reviewed in this article referred to American or Canadian farms, whereas studies for Europe are relatively scarce. More studies will be required to precisely assess the development of precision agriculture in Europe.

Finally, as explained above, it has been decided to focus this review on field crops farms from developed countries. The cost of precision farming technologies is likely to limit their adoption in less developed countries but it would be interesting to compare the results of this study with data from field crops farms from other countries with advanced mechanized agriculture, such as Brazil [31]. It would also be relevant to investigate if the same dynamic of adoption is true for other type of production, in particular, high-value crops such as arboriculture or grapevine.

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