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Adoption of Precision Agriculture in Alberta Irrigation Districts with Implications For Sustainability

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Abstract

To fulfill worldwide food requirements in the future, agriculture production will need to increase significantly. However, given the stress agriculture places on the environment, production must also be sustainable. A new suite of agricultural technologies commonly referred to as precision agriculture (PA) has been found to improve farming efficiency and environmental sustainability. This study focuses on the adoption of PA on irrigated farms in southern Alberta. Through irrigation, southern Alberta has become amongst the most fertile and productive agricultural regions in Canada. Alberta is also recognized for its entrepreneurial and progressive farm culture and practices. This economic and cultural environment may provide fertile ground for the adoption of PA technologies. In a survey of farmers in three irrigation districts in Alberta, we explore whether we see high rates of PA adoption. In exploring farmer and farm characteristics, we expect to find: (a) adoption leaning towards more advanced PA technologies; (b) the use of PA technologies leaning towards specialty crop production; (c) PA technology adoption to be negatively related to age; and (d) PA technology adoption to be positively related to both farm size and education. Finally, we expect there to be significant differences in farmer and farm characteristics across the three irrigation districts, owing to differences in cropping patterns and climatic variables. Our findings show no district embodies all the farm and farmer characteristics we expected. But, as expected, within districts and across districts, there are statistically significant differences in many of the characteristics studied. Consolidating and comparing the results leads to interesting profiles of the districts, where one district is relatively distinct and the two others are relatively similar; and consistent across all districts are the positive indicators for agricultural sustainability relative to farmers' estimates of reduced inputs of irrigation water, fertilizer, herbicides, and pesticides, as a result of the use of PA technologies.

Keywords: precision agriculture, irrigation, agriculture, technology, Alberta

1.0 Introduction

It has been estimated that agricultural production will need to increase by 70% to 100% to meet food requirements for the projected worldwide population of 9.2 billion by 2050 (Food and Agriculture Organization [FAO], 2011). But increased food production is juxtaposed alongside an over-arching environmental imperative—agriculture is a major cause of habitat loss and biodiversity decline, significant freshwater withdrawals, and greenhouse gas emissions (Capmourteres et al., 2018). Hence, approaches to enhance food production need to simultaneously consider sustainability.

Precision agriculture (PA) is a concept that holds promise (Cambouris, et al., 2014). PA consists of data collection and diagnostic tools, followed by applicative tools, which are used to more precisely allocate the required inputs on the field (Aubert et al., 2012). These technologies are recognized as a major contributor to farming efficiency and environmental sustainability (Aubert et al., 2012).

PA has been deemed one of the top ten developments in agriculture in the past 50 years and represents a paradigm shift in farming practices (Aubert et al., 2012; Crookston, 2006). Until the advent of PA, inputs were applied in a uniform pattern across an entire field. Such a practice overlooked field variability (Tye & Brindal, 2012). PA technologies allow fields to be deconstructed into smaller, more precise sections based on their variability. With such plot variability, allocations of inputs can be more precisely determined than those applied under earlier agricultural practices. Ultimately, PA involves applying the correct amount of inputs, at the correct time, in the correct location in the field, hence the term *precision agriculture*.

PA technologies lead to a much larger emphasis on the analytical aspect of the farming operation (Aubert et al., 2012). As such, it has the potential to reduce farming inputs, reduce costs, and increase farming profits. Further, collateral damage to the environment can be mitigated. A reduced use of nitrogen and phosphorus fertilizer, for example, can help reduce run-off on the landscape, and less irrigation water use can leave more water in the rivers. PA technologies have therefore received significant investment due to their effect on reducing inputs and resultant sustainability benefits.

There are three objectives of this study. The first objective is to determine individual and farm characteristics of adopters of PA technologies across three irrigation districts in southern Alberta. The individual characteristics are the farmers' age and education, and the farm characteristics are farm size, technology type, crop type, and land type. The study will analyze whether there are significant differences within and across the three districts with respect to the factors identified in this objective. Second, the study will review the rate of adoption of PA technologies across the three districts and compare those rates with other studies of PA adoption of Canadian crop farmers. Third, the study will assess whether farm inputs of fertilizer, pesticides, herbicides, and irrigation water are decreasing under PA technologies in order to contemplate the environmental implications of the adoption of PA technologies in the region.

The paper is structured as follows. The first section provides a literature review of the adoption of PA technologies on farms, including economic and social implications. This is followed by a description of irrigation farming in southern Alberta, as well as a description of the region studies and the study methodology. Survey results and statistical analyses are subsequently presented. The final section draws together the main results and situates these results within some of the broader themes identified in the literature before drawing some final conclusions and suggested future research topics.

2.0 Literature Review

PA technologies became commercially available in the early 1990's (Daberkow & McBride, 2003). Examples of such technologies include global positioning systems (GPS) that instruct machines to apply inputs such as fertilizer, seed, water, pesticides, and irrigation water by location, eliminating both under-application that can hold down yields and over-application that wastes money and pollutes the environment (Paarlberg, 2012). GPS positioning and remote-sensing technologies also allow irrigation-using farmers to conserve water by instructing machines to deliver water only where the seeds have been or will be planted and in response to actual soil moisture conditions at the depth of the plant roots (Paarlberg, 2012). Other PA technologies include soil mapping, yield mapping, and soil moisture monitoring. A full list of technologies considered in this study is outlined in the Study Area and Methodology section.

Given the potential benefits of PA, numerous aspects of the subject have been examined. Some of the early studies focussed on the rate of adoption of the technologies and found uptake to be slow. For example, a nationwide survey in the United States estimated that by 1998, only four percent of all farms used one or more PA technology for crop production (Daberkow & McBride, 2000). Additional surveys in Germany, Denmark, and Great Britain concluded that adoption of PA was less than expected (Fountas et al. 2005; Pedersen, 2003; Reichardt & Jürgens, 2007; Swinton & Lowenberg-Deboer, 2001).

However, more recent studies have found more encouraging results. The United States is one of the leading countries for adopting many innovative agricultural technologies (Say et al., 2018). For example, over 25% of peanut farms adopted GPS soil mapping, and over 40% used auto-steering (United States Department of Agriculture [USDA], 2015a). Sixty percent of rice farms adopted yield monitoring technology and about 55% used auto-guidance systems (USDA, 2015b). A survey of farmers in Kansas found 66% used automatic guidance and 47% used automated section control (Miller et al., 2017). In Europe, guidance adoption is slightly lower than in the Americas but variable rate technology fertiliser adoption is lagging almost everywhere (Lowenberg-DeBoer & Erickson, 2019).

Numerous studies have explored the characteristics of adopters and found a multitude of factors affecting adoption. The most notable factors include the personal traits of the adopter (age, education, etc.), characteristics of the farming operation, economic factors, and institutional support (Say et al., 2018). Adoption has consistently found to be: positively related to farm size, formal education, self-ownership, financial capability, computer literacy, full-time farming and field variability; and negatively related to age (Castle et al., 2016; Tey & Brindal, 2012; Daberkow & McBride, 2003; Paxton et al., 2010). Exploring the characteristics of adoption of PA technologies is one objective of this study. Findings in the literature lead to our first hypotheses: that adopting PA technologies by the three irrigation districts is negatively related to age and positively related to education and farm size.

For non-adopters, reasons for not adopting include high time requirements to learn the technologies, lack of technical knowledge, and incompatibility among different hardware devices (Reichart & Jürgens, 2009, Rotz et al., 2019). Studies found farmers experienced difficulties in managing large amounts of data, using data efficiently, and interpreting the data correctly (Reichart & Jürgens, 2009, Rotz et al., 2019). As emphasised in these studies, PA requires sophisticated knowledge with respect to mechanical operation for data collection, a high-level of competent data management, interpretation, and decision making in respect of agronomic solutions, knowledge and skill of operational staff, and commitment of the management in practice (Tey & Brindal, 2012; Lencsés & Takacs, 2014). Given the level of knowledge required to implement PA techniques, Weersink et al., (2018), note that "at present, our ability to generate data exceeds our ability to manage, analyse and use those data" (p. 32).

A further challenge to the adoption of PA technologies is a lack of compatibility among technologies produced by different machinery manufacturers, making incorporating PA technologies into existing farming practices and systems difficult (Higgins et al., 2017). The high cost of the technology is identified as another barrier to adoption (Reichart & Jürgens, 2009). Furthermore, the types of technologies being developed seem to be aimed at the needs of large-scale farmers (Rotz et al., 2019). These developments may be contributing to the economic polarization between small and medium-size farms towards large-scale farms (Kirschenmann et al.; 2004, Fraser; 2019, Rotz et al., 2019). A lack of ability to adapt is likely marginalizing small farmers who are unable to adapt (Weersink et al., 2018).

The large amounts of data generated by precision agriculture technologies, otherwise known as *big data*, has far-reaching societal impacts according to some studies. For example, Comi (2020) argues that "assemblages of actors" (p. 403) are now involved in making farm decisions as opposed to an individual farmer. Agricultural technology providers who collect farm data can aggregate that data and create value for seed and chemical firms, agronomists, co-operatives, farm insurance providers, and machinery firms (Fraser, 2019). Such companies are better able to create profitable products and services, which they then advise farmers to employ rather than develop them alongside farmers (Rotz et al., 2019). Further, according to Carolan (2020), some farm implement companies require farmers to sign licensing agreements with every purchase, which then commits them to only use approved service providers for future repairs (Carolan, 2020). Some studies raise privacy concerns when data are gathered by farm equipment that is fitted with sensors that stream data about soil and crop conditions (Bronson & Knezevic, 2016).

However, input and other cost savings derived from PA technologies are driving adoption. One study estimated up to 30% savings in fertilizer use (Lencés & Takacs, 2015). Schimmelpfennig and Ebel (2016) have argued that cost savings are better realized by adopting complementary packages of technologies that are used sequentially. In their study, various adoption scenarios ranging from entry-level to intermediate to advanced levels of the technologies resulted in the growth of cost savings from $13.45 per acre to $20.56 per acre to $25.01 per acre, respectively (Schimmelpfennig & Ebel, 2016). GPS guidance systems were found in one study to reduce fuel use by 6.3% for the average farmer in the study's sample. That study also estimated that the use of autosteering systems could save an average of 5.33% of fuel in the farm operation. Producers using these systems also report saving time. Furthermore, if producers use hired labor, their correspondingly reduced machine operating hours reduced the need to hire labour (Bora et al., 2012).

Studies specific to the adoption of PA technologies by Canadian crop farmers include the study by Steele (2017), which focussed on western Canada crop farms. That study found that 84% of farmers were using PA technologies on their farms, including 84% having combine harvester yield-monitoring capability, 79% using GPS auto-steer equipment guidance, and 75% using farm management software on a computer. Higher adoption rates were also found on farms with larger acreage and higher revenue. Reasons for not adopting PA technologies included: the high price of the technology, internet speeds and/or cellular data coverage, lack of knowledgeable people, continuously evolving technology, and incompatible older farm equipment (Steele, 2017). A 2018 study by Nicol and Nicol (2018) focussed specifically on the adoption of PA technologies on southern Alberta crop farms (irrigated and dryland). The study found that 86% of farmers in the region adopted some form of PA technology. Additional details of this study are included in the Study Area and Methodology section, which describes the study region.

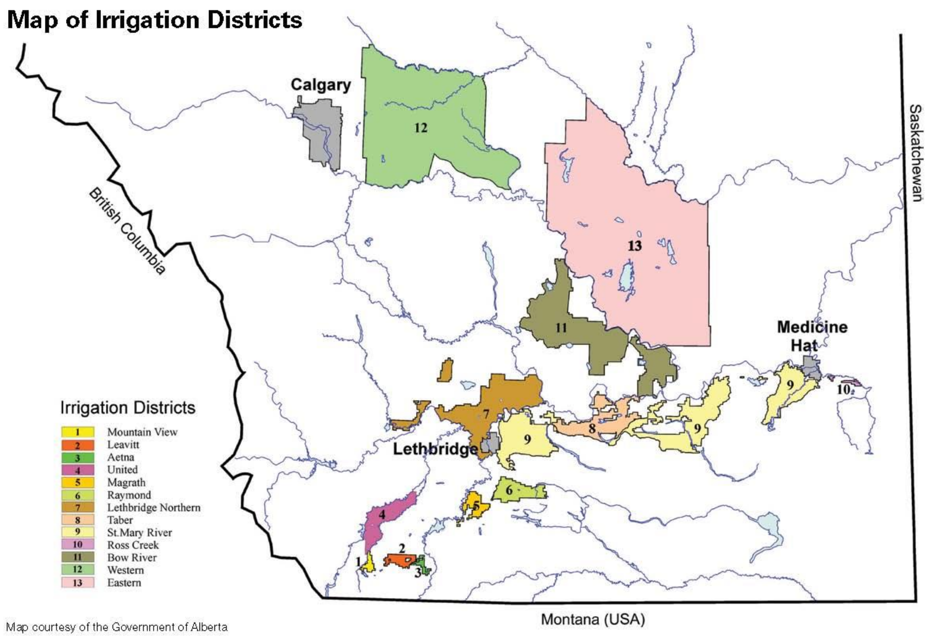
No study has explored the adoption of PA on *irrigation* farms in southern Alberta. As explained below, there are extensive benefits of Alberta's irrigation agriculture to the region. Therefore, gauging the industry's adoption of such advancements is important in order to maintain those benefits as well as contribute to environmental sustainability. The intent of this study is to fill this knowledge gap by exploring the adoption of PA technologies in the Taber, Bow River, and St. Mary River irrigation districts.

3.0 Irrigation Farming in Southern Alberta

Southern Alberta has the largest irrigation farming system in Canada, representing 68% of irrigated acreage in the country (Statistics Canada, 2019). It is within this region that the most extensive irrigation farming activity in the country takes place, representing one of the most fertile and productive agricultural regions in Canada.

There are 13 irrigation districts in Alberta, irrigating approximately 1.5 million acres of farm land, through 6,000 agricultural producers. An additional 312,384 acres of irrigation takes place on about 3,000 private projects (Paterson Earth and Water Consulting [Paterson], 2015; Alberta Agriculture and Forestry [AAF], 2020). The irrigation districts are depicted in Figure 1 below.

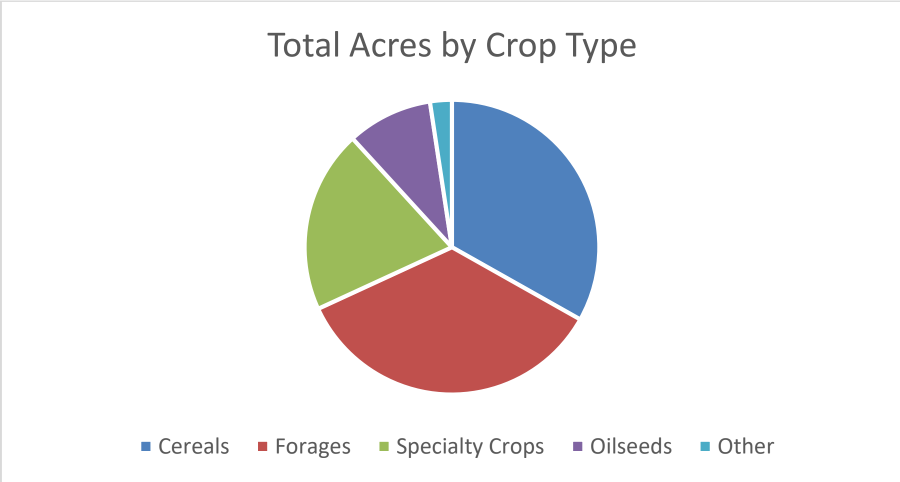
Figure 1. Map of Irrigation Districts in Alberta.



Source: Government of Alberta, 2020.

More than 60 crop varieties are grown under irrigation in Alberta, consisting of forages, cereals, specialty crops, and oilseeds. As a percentage of irrigated acreage, the amounts in each category are: 35 % forages, 33.2% cereals, 21.1% specialty crops, 9.4% oilseeds, 2.4 % 'other' (AAF, 2020). These percentages are depicted in Figure 2 below.

Figure 2. Irrigated Acres by Crop Type, Percentage of Total



Source: Alberta Agriculture and Forestry, 2020.

The presence of irrigation practices distinguishes agriculture in southern Alberta from other regions of the province. Under dryland practices, crops are generally restricted to cereals and oilseeds. Irrigation practices ensure a consistent supply of forage and silage, critical inputs to support the country's largest cattle feeding and processing industry (Paterson, 2015). Second, the combination of irrigation water, high heat units, and suitable soil quality make this a unique region for the production of a broad range of specialty crops. Amongst the most prominent speciality crops, in terms of irrigated acres, are dry beans, potatoes, sugar beets, canola seed, and alfalfa seed (AAF, 2020). These locally grown crops, in turn, provide the inputs for major processing industries in southern Alberta. These include, for example Viterra (processing of dry beans, dry peas, chickpeas, and lentils), Lantic (processing of sugar beets), McCain Foods (processing of potatoes), and Cavendish Farms (processing of potatoes).

The productivity of irrigation farming on crops is considerably higher than dryland farming crop productivity. For example, in 2018, the weighted average yield for wheat under irrigation was 93 bushels per acre versus 50 bushels per acre under dryland; canola: 64 bushels versus 30 bushels; barley: 112 bushels versus 66 bushels; peas: 67 bushels versus 41 bushels; lentils: 2,257 pounds per acre versus 947 pounds per acre (AFSC, 2019).

The benefits of irrigation agriculture in the southern Alberta economy are widespread given the significant amount of economic activity that is linked to irrigation agriculture. A study of the economic value of irrigation found: (a) the irrigation industry contributed about $3.6 billion to the provincial gross domestic product (GDP), (b) the irrigation industry generated $2.4 billion in labour income and 56,000 full-time equivalent jobs, (c) the irrigation agri-food sector contributed about 20% of the total agri-food sector GDP on 4.7% of the province's cultivated land base, and (d) almost 90% of irrigation-related benefits accrued to the region and the province and 10% to irrigation producers (Paterson, 2015).

4.0 Study Area and Methodology

The southern Alberta region is recognized for its entrepreneurial and progressive farm culture and practices, affording the potential for the adoption of PA technologies. As a recent study noted, "(t)raditional perceptions of agriculture that view the industry as simple farming or ranching do not consider the innovation occurring in agriculture, the ag-tech industry, agricultural sciences, or a host of other sciences behind the industry" (Calgary Economic Development, 2020, p. 40). New speciality crops, agriculture technology, and land management practices have emerged where the business of agriculture is shifting from food production to agri-business (Nicol & Nicol, 2019). Further, high-value speciality crops, such as those grown in the region, are recognized as good candidates for the adoption of new agricultural technologies because of the potential to reduce the high input costs involved (Cambouris et al., 2014).

Nicol & Nicol (2018) describe how digital technologies are being utilized in the region. That study found that between 63% and 86% of southern Alberta farmers implemented PA technologies. The rate of adoption depended on the degree of sophistication of the technology—the most basic forms of the technology had a higher adoption rate than more advanced technologies. That study concluded the region is actively advancing PA technologies with technologies spread across all land and crop types; the technologies are being applied to both dryland and irrigated farms and across cereals, oilseed, and specialty crops. Further, farmers are highly satisfied with PA technologies and intend to continue their adoption. Finally, consistent with findings enumerated in the literature review, limits to adoption relate to small farm size and high investment costs of some PA technologies (Nicol & Nicol, 2018).

This economic and cultural environment provides the justification to focus on southern Alberta and, within it, three of the 13 irrigation districts to study the adoption of PA. The study focussed on the Taber irrigation district (TID), Bow River irrigation district (BRID), and St. Mary River irrigation district (SMRID) because of the high concentration of specialty crop production in those districts, compared to other districts. Together these three districts account for 78% of total specialty crop acreage—225,843 acres out of a total 291,219 acres in 2019. And together, the three districts account for 53% of total irrigation district acreage—764,007 of a total of 1,449,894 acres (AAF, 2020). Pertinent to this study is that not all farmland within irrigation districts is irrigated. It is common for irrigation district irrigators to concurrently farm dryland. However, not all irrigators farm dryland, some farm only irrigated land.

Because of the high input costs involved in speciality crop production, and the potential for cost savings through the adoption of precision agriculture (Camboursis et al.; 2014, Schimmelpfennig & Ebel, 2016; Bora et al., 2012), it is therefore hypothesized that these three districts will have relatively high adoption rates of precision agriculture technologies compared to crop farmers in general, as reported in other Canadian studies (namely Steele, 2017 and Nicol & Nicol, 2018).

The breakdown in acreages devoted to cereals, forages, oilseeds, and speciality crops across the three irrigation districts is outlined in Table1 below. The table consists of census data contained in the document *Alberta Irrigation Information, 2020,* which provides comprehensive irrigation district data related to a host of factors, including on-farm irrigation methods, gross annual water diversions, and irrigation district reservoirs, for example (AAF, 2020).

Table 1. *Crop Types Grown by Irrigation District, 2019, Percentage of Total Acreage*

Crop type	**Taber** **%**	**Bow River** **%**	**St. Mary** **%**
Cereals	31.0	41.8	36.0
Forages	28.8	16.6	27.0
Oil seeds	2.8	8.0	9.0
Specialty crops	36.9	33.2	26.8
Other	0.4	0.4	1.1

Source: AAF, 2020.

The census nature of the crop data outlined above identifies actual differences in cropping patterns across these three districts. This alone indicates the appropriateness of viewing these irrigation districts' uniqueness in terms of PA technology adoption considerations. For example, for the TID approximately 37 percent of irrigated acreage in 2019 was dedicated to speciality crop production while only approximately 27 percent of acreage was dedicated to speciality crop production in the SMRID. And in the BRID, for example, approximately 42 percent of acreage was dedicated to cereals while in the Taber irrigation district, the acreage was 31%.

Across the geography of the three irrigation districts, producers farm brown chernozemic soil. Thus the differences in cropping pattern are unlikely to be due to soil type but may be due to differences in heat units (a measurement of cumulative heat over the growing season) and the number of frost-free days across the districts, critical factors for the growth of specialty crops. Indeed, for instance, between Lethbridge (on the western edge of the SMRID) and Bow Island (located within the TID), there are noticeable differences in heat units and the number of frost-free days (>0 degrees centigrade) over a five-year period. The average number of heat units from 2015 to 2019 was 10.5% higher in Bow Island than Lethbridge, and the number of frost-free days was 33.6% higher in Bow Island than Lethbridge (AAF, 2020-2016).

Finally, although there are no data that would allow for comparison of farm size across the districts, data on irrigated acres and the number of irrigators in each district allows us to estimate the average number of irrigated acres per farm across districts. The average acreages show considerable variation: 701 acres in TID, 387 acres in BRID, and 260 acres in SMRID. This suggests TID irrigators irrigate more acres per farm compared to BRID irrigators and especially compared to SMRID irrigators.

Given the characteristics of each region, we hypothesize that PA technologies will be primarily applied to *specialty crops* on *irrigated* land using *advanced* PA technologies.

And given the differences in characteristics of the three irrigation districts enumerated above, we hypothesize that the adoption of PA technologies will be significantly different across the three irrigation districts.

There are many PA technologies available. This study identified and surveyed a comprehensive list of 20 technologies. The technologies were grouped into three categories, as listed in Table 2.

Table 2. *Precision Agriculture Technologies*

Basic	**Soil Mapping Techniques**	**Data Management**
Auto-steer technology	Terrain mapping/analysis	Study/analyze yield data
Yield mapping	Spatial variability of available water-hold capacity	Use hydrological modeling and forecasting to predict soil moisture status
Soil moisture monitoring	Electric conductivity mapping	Develop dynamic water management zones
Weather monitoring	Satellite imagery	Use precision agriculture data management software or services
Variable rate fertilizer application	Unmanned aerial vehicle mapping	Use precision agriculture technology for records and analysis
Variable rate irrigation application	Establish field boundaries/low spots/unfarmable land	Use precision agriculture for on-farm research
GPS soil sampling		
Develop management zones		

This study was survey-based and carried out in two stages. The first survey was administered to the TID in the fall of 2018, and the second, identical survey, was administered to the SMRID and BRID in the fall of 2019.

The survey questions drew on previously published studies tailored to conditions in the southern Alberta farm irrigation region and the study's objectives. Given the TID was the first district surveyed, a draft of the survey questionnaire was provided to the TID manager and the TID's board of directors. Recommended changes were then incorporated into the final version of the questionnaire. Ethics approval to conduct the study was received from the University of Lethbridge Research Ethics Committee on July 31, 2018. The survey questionnaire was then uploaded on a Qualtrics online survey platform (Qualtrics, 2018).

Survey participants were recruited through the TID's head office via an invitation from the manager of the TID. The invitation was sent via e-mail and text messaging, which included a link to the survey. A link to the survey was also posted on the TID website home page. TID irrigators were given from October 9, 2018, to November 13, 2018, to participate in the survey.

Approximately one year later, SMRID and BRID irrigators were similarly invited to participate in the same form of survey. Ethics approval to conduct the survey was received from the University of Lethbridge Research Ethics Committee on May 6, 2019. An invitation and link to the survey were sent to district irrigators via e-mail. The link was also posted on the irrigation districts' home pages. That survey was available from October 15, 2019, to November 30, 2019.

Drawing the hypotheses together, they include:

- Adopting PA technologies is negatively related to age and positively related to education and farm size.
- The districts have high adoption rates of PA technologies.
- PA technologies will be primarily applied to specialty crops on irrigated land using advanced PA technologies.

As related to individual and farm characteristics of adopters specified in the hypotheses above, we will test the hypothesis that findings will vary significantly across irrigation districts.

Finally, the study explores whether farm inputs of irrigation water, fertilizer, pesticides, and herbicides are decreasing under PA technologies in order to contemplate the effect on agricultural sustainability.

For analytical purposes, descriptive statistics are supplemented by Hypergeometric Distribution probabilities to determine the extent of differences of characteristics *within* districts. The principle is to show that the samples we observe are based on the hypothesis that the outcomes are equally likely, within a district, relative to two alternatives to a characteristic. Data within districts are collapsed into two categories, with the null hypothesis being that the outcomes are equally likely relative to the observed data at a significance level of <.05. We also provide prob. values with respect to these statistics.

In addition to within-district tests of characteristic differences, we consider whether the proportions of various characteristics are significantly different *across* districts, using population proportion estimates, and calculating Z-statistics to determine statistically significant differences in these proportions, at a 0.05 level of significance, given our observed samples.[1] For ease of analysis, except for adoption rates and environmental effects, the across-district differences are consolidated into one table in the Significance Across District section near the end of the Survey Results.

5.0 Survey Results

5.1 Survey Response Rate

The overall response rate to the survey was 14.0% of the total number of irrigators in the three districts combined, and who received an invitation to participate (2,270). On a district-by-district basis, this included: TID – 26.7% of irrigators (32 of 120 irrigators); BRID – 15.5% of irrigators (101 of 650

[1] Note: t-statistics are used to determine statistically significant differences in the average number of technologies adopted, in Table 3, because we are evaluating sample means, not sample proportions.

irrigators); and SMRID – 12.3% of irrigators (184 of 1,500 irrigators). The sample sizes in the survey being relatively large compared to their respective within-district populations, we use the Hypergeometric Distribution to assess within-district characteristics differences.

5.2 Current Adoption Rates

The survey results indicate that the vast majority of irrigators have adopted at least one PA technology. As Table 3 shows, the TID and BRID have comparable rates of adoption of approximately 82% (sample proportion, p = 0.82) and the SMRID with a somewhat lower 72% (sample proportion, p = 0.72) rate of adoption. In terms of the average *number* of technologies adopted, the TID and BRID have close to an equal average number of technologies, approximately five, and the SMRID a lower rate of approximately three.

Table 3. *Adoption Rate and Average Number of Technologies, Percent of Adopters*

Factor	**Taber**	**Bow River**	**St. Mary**
Adopted rate	81.3%	81.5%	72.3%
Average # of technologies	5.1	4.7	3.3

Turning to our hypothesis regarding adoption, these three districts would be expected to have relatively high adoption rates of at least one PA technology. Compared to the Steele (2017) and Nicol and Nicol (2018), studies of western Canada and southern Alberta farmers, respectively, the rates of adoption across the three irrigation districts are marginally lower, but in similar neighbourhoods. The two previous studies found 84% and 86% rates of adoption, respectively, compared to the approximate 81% adoption rates for the TID and BRID and 72% adoption rate for the SMRID. However, we do not have a means of comparing these statistically, owing to the difference in the respective survey methodologies, and also the fact that the former studies were relative to irrigated and dryland farms together, whereas the current study is in relation to irrigated farms alone.

Using the data in Table 3, we can compare the adoption rate across irrigation districts to determine whether we observe statistically significant differences in the respective proportions. Z-statistics are used for this purpose. For the adoption rate the results indicate there is no statistically significant difference in adoption rates between districts (TID-BRID Z = 0.0078, p = .99202; BRID-SMRID Z = 1.6706, p = .09492; TID-SMRID Z = 1.0623, p = .28914). These Z statistics do not reject the null hypothesis that adoption rates do not differ across the three regions at a significance level of 0.05. In other words, our hypothesis that there is a significant difference in adoption rates across districts is disproven.

Second, using the data in Table 3, we then consider the average number of technologies across districts. The results indicate there is no statistically significant difference between the TID and BRID, but there is a statistically significant difference between the TID and SMRID; and between the BRID and SMRID, in terms of the average number of technologies adopted (TID-BRID t = 0.460246, p = 0.323299; TID-SMRID t = 2.224217, p = 0.013736, BRID-SMRID t = 3.314887, p = 0.000579). These t-statistics indicate the average number of technologies adopted by the SMRID is statistically significantly different (lower), than the average number of technologies adopted by the TID and SMRID. We expect this is due to the relatively higher percentage of irrigated acreage devoted to specialty crop production within the TID and BRID relative to the SMRID.

5.3 Characteristics of Technology Application

Next, we explore the application of PA technologies by crop type by irrigation district. The data presented in Table 4 show relatively high adoption rates for specialty crop production by the TID, 86% (sample proportion, p = 0.86), compared to the BRID and SMRID of between 48% (sample proportion, p = .48) and 54% (sample proportion, p = 0.54), respectively.

Table 4. *Adoption of Precision Agriculture Technologies by Crop Type by Irrigation District, Percent of Total Adopters*

Crop type	**Taber**	**Bow River**	**St. Mary**
Specialty crops	86.0	47.7	54.2
Cereals	7.0	6.8	17.0
Oilseeds	7.0	43.2	13.6
Forages	0	2.3	15.1

To determine if adoption by crop type within each district is statistically significantly different, cereals, oilseeds and forages were collapsed into one category and then compared to specialty crops. Hypergeometric Distribution tests of a null hypothesis at a 0.05 significance level that there is no difference in adoption for speciality crop production versus other crop production given our observed samples, show a significant difference in adoption within the TID (p = 0.00004) and within the SMRID (p = 0.0440) towards specialty crop production. There is no statistically significant difference in adoption by crop type in the BRID (p = 0.0841). Thus, these results emphasize the relative greater weight given to speciality crop production in the TID and SMRID compared to the BRID. Our hypothesis that adoption of technologies will be weighted towards specialty crops is therefore true for the TID and SMRID but not for the BRID. In fact, within the BRID the raw data suggests PA technologies are concentrated almost equally amongst speciality crop and oilseed crop production, as distinct from the TID and SMRID.

In Table 5, data on the total number of technologies adopted by irrigation district was allocated across three categories: (1) basic, (2) soil mapping techniques, and (3) data management. By far the greatest percentage of technologies adopted across irrigation districts was in the ‘basic’ category. Slightly over 50% of the technologies adopted were in this category. As the data show, comparatively speaking, the number of technologies in the ‘soil mapping techniques’ and ‘data management’ categories accounted for approximately 25% each of the remaining allocation.

Table 5. *Adoption by Category and Irrigation District, Percent of Total Adopters*

Category	**Taber**	**Bow River**	**St. Mary**
Basic	52.3	51.7	53.8
Soil Mapping Techniques	25.0	24.0	22.6
Data Management	22.7	24.4	23.7

To test for statistically significant of differences of adoption *within* the irrigation district by category of technologies, soil mapping techniques and data management categories were collapsed into an 'advanced technology' category in order to compare adoption of that category relative to the 'basic' category. We again use the Hypergeometric Distribution with a null hypothesis that there is no difference in adoption of 'basic' versus 'advanced' PA technologies within districts. These results indicate that there are no statistically significant differences within the TID ($p = 0.159$) or BRID ($p = 0.091$) at a significance level of 0.05. However, there was a statistically significant difference within the SMRID ($p = 0.044$) at a significance level of 0.05, with greater emphasis on the adoption of basic PA technologies. This suggests that, for the TID and BRID, adoption is more evenly weighted towards adoption of both basic and advanced technologies, relative to being more heavily weighted towards basic technologies in the SMRID. Therefore, the hypothesis that adoption will tend towards advanced technologies within the districts is not true for any district, given TID and BRID adoptions are not significantly different between basic and advanced technologies and SMRID irrigators are weighted towards adoption of basic technologies. When combined with earlier results, SMRID irrigators are somewhat distinct from the TID and BRID in that the district is applying a statistically significantly *lower number* of *basic* PA technologies relative to the other two districts.

As noted earlier, some irrigation farmers also farm dryland. Therefore, it is useful to understand which land types PA technologies are applied to. Adopters were asked to allocate the total percentage of PA technologies between irrigated land and dryland acreage that they farmed. Results are shown in Table 6. TID adopters indicated 92% of their PA technologies are applied to irrigated acreage, leaving 8% to dryland acreage. This was followed by SMRID, with approximately 80/20 irrigated acreage versus dryland split. The BRID had the lowest percentage applied to the irrigated area – an approximate 70/30 split.

Table 6. *Adoption of Precision Agriculture Technologies by Land Type by Irrigation District, Percent of Total Acreage*

Land Type	**Taber**	**Bow River**	**St. Mary**
Irrigated	92.0	69.6	80.2
Dryland	8.0	30.1	19.8

With respect to irrigated versus dryland adoption within irrigation districts, there is a statistically significant difference in adoption by land type in all irrigation districts (TID $p = 0$, BRID $p = 0$, SMRID $p = 0$). Therefore, statistically significant adoption of PA technologies in all districts is weighted towards irrigated land, confirming our hypothesis.

5.4 Characteristics of Adopters

Based on studies outlined in the literature review, it is hypothesized that adoption of PA technologies is negatively related to age. Adoption should, therefore, be relatively high amongst 'younger' farmers compared to 'older' farmers. Data in Table 7 below enumerate the percentage of adopters by four age groups across the three districts.

Table 7. *Adopters by Age and Irrigation District, Percent of Total Adopters*

Age Range	**Taber**	**Bow River**	**St Mary**
<20	0	0	0
20-34	7.7	13.3	15.8
35-55	46.2	35.6	40.4
>55	46.2	40.4	43.9

The average age of farmers in Alberta is 55.7 years. Just over half of the farmers (56.4%) in Alberta are 55 years of age and older (Statistics Canada, 2016). In this study, therefore, significance tests within districts were conducted on adopters 'over 55' versus '55 and under' age categories in order to determine if there is a statistically significant difference in adoption between older (older than 55) and younger (55 and younger) age groups.

Within irrigation districts our statistical tests show that, within the BRID and SMRID, there are statistically significant differences in adoption between these two age categories at a 0.05 significance level. For the BRID ($p = 0$) and the SMRID ($p = 0$) adoption is weighted towards 'younger' farmers. For the TID, there was no statistically significant difference, with adoption equally weighted towards 'older' and 'younger' farmers ($p = 0.159$) at a 0.05 significance level. Thus, for the BRID and the SMRID the hypothesis that adoption is negatively related to age is upheld.

We next test the hypothesis that PA technology adoption is positively related to farm size. Table 8 shows that there are distinctive differences by farm size in adoption across the irrigation districts. Adopters in the BRID were spread almost equally across the four farm sizes – about 25% across each range. For TID and SMRID adopters, the allocation was more variable across farm size. The adoption rates by farm size were opposite at the two extremes - for TID adopters, about a third of adopters were of the smallest farm size (less than 499 acres) and just 15% for the large farm size (greater than 5,000 acres). For the SMRID, only 13% of adopters were of the smallest farm size and almost one-third were the largest farm size.

To analyse whether there is a statistically significant difference in adoption by farm size *within* districts, farm sizes were collapsed within each district into 'small' (less than 2,000 acres) and 'large' (2,000 acres and greater). Within irrigation districts, the adoption between small and large farms is not statistically significantly different for TID and BRID districts, but the rate adoption is statistically significantly different for SMRID adopters, weighted towards large farms, based on Hypergeometric Distribution probabilities, at a 0.05 significance level (TID p = .1591, BRID p = .0914, SMRID p = .0249).

Table 8. *Adopters by Farm Size, Percent of Total Adopters*

Farm Size	**Taber**	**Bow River**	**St. Mary**
<499 acres	30.8	24.1	13.3
500-1,999 acres	23.0	25.9	22.2
2,000-5,000 acres	30.8	25.9	33.3
>5,000 acres	15.4	24.1	31.1

These data demonstrate that for SMRID adopters, adoption is more prevalent for large farms while in the TID and BRID there is no statistically significant difference in adoption between small and large farms. Our hypothesis that PA adoption is positively related to farm size is not therefore upheld, except for one of the three irrigation districts where PA technology adoption rates are weighted towards large farm sizes. The rationale for this finding may be that the SMRID has more large-sized farms than the other two districts. However, data on the distribution of farm size by irrigation districts are not available and warrants further research.

Regarding PA adoption by education level, our hypothesis predicts that PA technology adoption will be positively related to educational attainment level. Data in Table 9 show the majority of adopters across the three irrigation districts had more than a high school education. This was especially the case for the TID, with close to 70% of adopters having a college diploma or higher, followed by the SMRID with 66.7% and the BRID with 56.1%. Further, the TID had the highest percentage of adopters with a 'university degree,' almost 40%, followed by the SMRID with approximately 24%, and the BRID with approximately 18%.

Table 9. *Adopters by Highest Level of Education, Percent of Total*

Education Level	**Taber**	**Bow River**	**St. Mary**
High School	30.7	43.9	33.3
College Diploma	30.6	35.1	37.8
University Degree	38.5	17.5	24.4
Graduate Degree	0	3.5	4.4

To analyse whether there is a statistically significant difference *within* irrigation districts, the percentage with a high school education was compared against the percentage of 'greater than high school' education by combining college, university, and graduate degree numbers. Hypergeometric Distribution probabilities show a statistically significant difference between these two categories within each irrigation district at a 0.05 significance level, where adoption rates are statistically significantly higher for irrigation farmers with greater than high school education (TID p = .0155, BRID p = .047, SMRID p = 0).

Thus, the hypothesis that adoption is positively related to education level is confirmed by these findings.

5.5 Significance Across Irrigation Districts

Recall that we hypothesize that farmer and farm characteristics of adopters of PA technologies will vary statistically significantly *across* irrigation districts, and several results in this regard were reported in Table 3 above, with a discussion. In addition, we also consider whether the proportions of various other characteristics are statistically significantly different *across* districts, using population proportion estimates, and calculating Z-statistics for differences in population proportions, to determine whether there are statistically significant differences in these proportions, at a 0.05 level of significance. These test results are presented in Table 10 below.

Table 10. *Significant Difference Between Districts*

Factor	**TID-BRID**	**BRID-SMRID**	**TID-SMRID**
Specialty Crop type Differences (Table 4)	**Yes** (Z = 5.7144, p = .00001)	No (Z = 0.8487, p = .39532)	**Yes** (Z = 4.9377, p = .00001)
Basic PA Adoption Differences (Table 5)	No (Z = 0.2336, p = .8181)	No (Z = -0.4161, p = .67448)	No (Z = -0.0271, p = .97606)
Irrigated Land Differences (Table 6)	**Yes** (Z = 3.9654, p = .00008)	No (Z = 1.633, p = .1031, p = .1031)	**Yes** (Z = -- 2.4454, p = .01428)
< 55 Age Differences (Table 7)	No (Z = 0.5326, p = .59612)	No (Z = 0.4851, p = .62414)	No (Z = -0.2391, p = .81034)
Small Farm Size Differences (Table 8)	No (Z = - 0.2336, p = .8181)	**Yes** (Z = 2.2964, p = .02144)	**Yes** (Z = 1.9936, p = -.0406)
Post-Secondary Educational Differences (Table 9)	No (Z = - 1.1876, p = .23404)	No (Z = 1.5943, p = .11184)	No (Z = -0.23, p = .8181)

The Z-tests indicate the three districts are statistically significantly different from each other across half—three of the six—characteristics considered. Table 10 shows that, by district, the TID differs from either the BRID or SMRID five times; the BRID differs from either the TID or SMRID three times; and the SMRID differs from either the TID or BRID four times. Across six characteristics, there are statistically significant differences in three characteristics across two of the three combinations of districts. These characteristics include: the average number of technologies adopted (as reported in Table 3 earlier) and adoption by crop type, land type, and farm size. There are no statistically significant differences in the remaining four characteristics: adoption rate (reported in Table 3), adoption by technology type, age, and education level. The hypothesis that farmers and the farm characteristics of adopters of PA technologies vary statistically significantly across irrigation districts is supported by these data, for half of the characteristics considered in this study.

5.6 Environmental Effects

The survey explored the annual effects of PA technological adoption on inputs of irrigation water, fertilizer, herbicides, and pesticides in order to gain insights into the effects of PA adoption on agricultural sustainability. The results, based on estimates by PA adoption irrigators, are contained in Table 11 below.

Decreases in farm inputs were reported across four types of inputs. Within the irrigation districts, the greatest percentage decrease reported was in irrigation water use, ranging between 21% by the BRID to 26% by the SMRID. Decreases in fertilizer use ranged from 15% (BRID) to 22% (SMRID); in herbicide use from 14% (TID) to 17% (SMRID); and in pesticide use from 13% (BRID) to 20% (SMRID). There were no statistically significant differences in the percentages of reductions *across* the districts at a 0.05 significance level (Irrigation water: TID-BRID $Z = 0.508$, $p = .61006$; BRID-SMRID $Z = -0.8339$, $p = .40654$; TID-SMRID $Z = -0.3266$, $p = .7413$; fertilizer: TID-BRID $Z = 1.1043$, $p = .27134$; BRID-SMRID $Z = 1.2747$, $p = .20408$; TID-SMRID $Z = 0.1721$, $p = .86502$; herbicide: TID-BRID $Z = 0.3858$, $p = .69654$; BRID-SMRID $Z = 0.3858$, $p = .69654$; TID-SMRID $Z = 0$, $p = 1$; pesticide: TID-BRID $Z = 1.1573$, $p = .24604$; BRID-SMRID $Z = 1.3335$, $p = .18352$; TID-SMRID Z – 0.1785, $p = .85716$). By any measure, the reductions are notable and should have positive implications for sustainability.

Table 11. *Annual Input Effects by Irrigation District, Annual Percentage Change*

Reduction	**Taber**	**Bow River**	**St. Mary**
	%	**%**	**%**
Irrigation water	23.8	21.0	25.5
Fertilizer	20.5	15.3	21.5
Herbicides	13.6	15.4	17.4
Pesticides	19.0	13.1	20.2

6.0 Discussion and Conclusion

In exploring PA technology adoption by individual farmers' and farms' characteristics, we find that PA technologies are applied to irrigated land and that PA technology adoption is positively related to age. Other results are mixed. However, PA technology adoption is weighted towards specialty crops in the TID and SMRID, but not in the BRID. We also find that adoption is not weighted towards advanced technologies as expected, and, in fact, for the SMRID, adoption is more prevalent with respect to basic technologies. PA technology adoption is negatively related to age for the BRID and SMRID but not for the TID. With respect to farm size, the SMRID sees adoption as more prevalent for large farms. In summary, with respect to these three irrigation districts, none align exactly with published literature to date. However, in that earlier literature, none of those studies were focused purely on the adoption of PA technology with respect to irrigated farms. Our results indicate that there is no 'one-size-fits-all' when it comes to PA adoption by irrigation farms, an interesting result in itself. This suggests that other irrigation district characteristics play a role in the outcomes seen here, warranting further study of these irrigation districts and others in Alberta.

With respect to a more nuanced viewing of the results, statistical tests confirm our hypothesis that farmers' and farms' characteristics of PA technology adopters vary significantly across these three irrigation districts. These characteristics are significantly different in half, four of eight, characteristics studied. However, as discussed below, when farmer and farm characteristics *within* irrigation districts are consolidated and compared, the SMRID is somewhat distinct from the other two districts, whereas the TID and BRID are more similar to each other.

The features distinguishing the SMRID from the TID and the BRID are first that adopters are acquiring a significantly *lower* number of technologies. Second, within the district itself adoption is uniquely concentrated on *basic* technologies adopted on *large* farmers. This is not the case for the TID and BRID. And while it is the case that adoption within the SMRID is greater with respect to specialty crops (like the TID) on irrigated land (like the TID and BRID), a factor that may drive other differences is that within the SMRID the percentage of acreage devoted to specialty crops is lower relative to the TID and BRID. Further, the SMRID farms may have less intensive irrigated farming. Recall that we estimated the average number of irrigated acres by irrigator in the TID is 701 acres, the BRID 387 acres, and SMRID 260 acres.

Several results from this study suggest the TID and BRID are somewhat similar. First, there is no significant difference between the two districts in terms of the *adoption rate* or the *average number* of technologies adopted. Further, within the districts, for the TID and BRID, there is no statistically significant difference in adoption of PA technologies by *type of technology* ('basic' versus 'advanced), or by *farm size* ('small' versus 'large'). Within both districts, adoption is similarly weighted towards irrigated land by adopters with higher educational attainment levels (greater than high school). Within the three districts, there are only two results that differ between the TID and BRID, and that is adoption in the TID is weighed towards 'specialty' crops versus 'other' crops while in the BRID there is no statistical difference between adoption for 'speciality' and 'other' crop production. And within the BRID adoption is weighted towards 'younger' farmers, whereas in the TID there is no significant difference in adoption between 'younger' and 'older' farmers' adoption. One underlying factor which may explain some of the similarities is the almost equal percentage of acreage in the TID and BRID devoted to speciality crop production.

In relation to other studies, given the emphasis on specialty crop production in the three irrigation districts, it was expected that they would have relatively high adoption rates than other Canadian crop farm studies. Compared to the Steele (2017) and Nicol and Nicol (2018) studies of western Canada and southern Alberta farmers, respectively, the rates of adoption across the three irrigation districts are marginally lower but still at very high overall levels. As noted, owing to difference in the respective survey methodologies, and also the fact that the former studies were relative to irrigated and non-irrigated farms together, whereas the current study is in relation to irrigated farms alone, we did not have a means of comparing these results statistically.

In exploring the environmental implications of PA technology adoption by the three irrigation districts, farm inputs of irrigation water, fertilizer, pesticides, and herbicides are reported to be decreasing under PA technologies, in notable amounts as estimated by adopters. The implications of PA technology adoption for agricultural sustainability are therefore positive.

Finally, the findings of the study can be used as evidence in relation to certain issues with PA technologies identified in the literature review. Recall that it is argued that PA technologies require sophisticated knowledge and that at present, the ability to generate PA data can exceed the ability to manage, analyse and use those data. While our results show SMRID adopters lean towards the adoption of less knowledge-intensive, ‘basic’ technologies, for the TID and BRID there is no statistically significant difference between the adoption of ‘basic’ versus adoption of the more sophisticated ‘advanced’ PA technologies identified in the study. Therefore, except for the SMRID, it does not appear as if irrigation districts are being inhibited from adopting more ‘advanced’ PA technologies which require sophisticated knowledge.

Studies in the literature review also imply that the high cost of some PA technologies, being affordable by only large farms, may be contributing to the economic polarization of smaller and larger-scale farms. Our results show that SMRID adopters are more likely to be in the large farm category, but for the TID and BRID, adopters are equally likely to be in the large or the small size farm category. Thus, the results in this study do not unequivocally point to PA technologies contributing to economic polarization based on farm size.

Suggestions for future research include further exploration into the adoption of PA technologies by farm size to include data on the distribution of farms by farm size. This will provide for more explanatory capability of the farm size characteristic. Future research could also explore the characteristics of non-adopters to investigate whether factors such as high time requirements, lack of technical knowledge, incompatibility between different hardware devices, and the high cost of some technologies are driving non-adoption. Some issues of concern raised in the literature also warrant further study including, for example, privacy concerns regarding data gathering and use, as well as licensing concerns. Finally, while we attempt to compare our findings to other studies of crop farms in Canada, future research could explore comparisons of our findings to PA technology adoption in the United States and Europe. Such work could be instructive, given the relatively larger average farm sizes in the United States versus those in Europe.

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