The Driving Forces and Barriers of Golf Course Superintendents' Adoption of Precision Irrigation Technology[1]

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Abstract

With the water scarcity crisis, how to use water more efficiently has become an issue that needs to be addressed. The US golf industry, which is known for its high irrigation water consumption, is seeking water-saving strategies. One possible solution is the adoption of precision irrigation technology. The technology is often regarded as an effective water-saving strategy in agricultural production, but the technology's adoption rate in US golf courses remains low. This paper aims to identify the driving forces and barriers to adoption of precision irrigation technologies among US golf course superintendents, as well as strategies to promote the adoption. Over one hundred golf course superintendents completed questions about precision irrigation technology adoption, golf course operation and demographics in our online survey. The results show the three main driving forces of precision irrigation technology adoption are reducing water use, increasing playability, and better turfgrass aesthetics, and the three main barriers are high initial adoption cost, approval by higher level administrators needed, and lack of information about the effectiveness of the technology. The main information sources used by golf course superintendents are industry association and peer referral. The results have important implications on how to improve the adoption rate of the precision irrigation technology on golf courses.

Index words: water saving, irrigation, new technology adoption, environmental benefits.

Significance to the Horticulture Industry

Based on our findings, there are several ways that turfgrass industry leaders can promote precision irrigation technology adoption on golf courses. First, researchers and manufacturers can improve the technologies so that they can meet superintendents demands better. For example, manufacturers may want to find an effective way to reduce the production costs and thus the prices of the technologies, which can make the high initial cost barrier lower. Second, according to our finding, superintendents may be unclear about precision irrigation's improvement on fertilizer use efficiency and how to use the technologies appropriately to improve the efficiency. Therefore, improving the understanding of precision irrigation's improvement on fertilizer use efficiency may be a potential feasible way to promote the adoption. Third, our findings suggest that industry associations or public agencies can generate promotion strategies, and that these promotional efforts should target decision makers, which for some superintendents is a higher level administrator. Fourth, new technologies often involve uncertainties in the outcomes, which increases the perceived risks of the technology. Information about the exact probability of success and concrete cost savings by the technology will be effective to increase superintendents' interests and willingness to pay (WTP) for the technology.

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Introduction

According to the United Nations (2020), by as early as 2025, half of the global population could be living in areas facing water scarcity. Since food production highly depends on water, water scarcity worsens food insecurity (Kehl 2020, Mancosu et al. 2015, Ungureanu et al. 2020). Water shortages also threaten industrial production and residents' benefits (e.g., access to clean drinking water and enough water for private lawn irrigation) (Schoengold and Sunding 2014). Such extensive negative socio-economic effects have made water scarcity a global crisis. In the United States (US), people are concerned about the increasingly serious water scarcity problem. Forty out of fifty state water managers expect water shortages in some areas of their jurisdictions by 2023 (United States Government Accountability Office 2014).

With the water scarcity crisis, how to use water more efficiently has become an issue that needs to be addressed (Kehl 2020, Zhang et al. 2020). The US golf industry, which is known for its high irrigation water consumption, is a possible target for improving water management (Bauer 2022, Gammon 2015). The golf industry across the US consumes about 8 million cubic meter of water (about 2.1 billion gallons of water) per day for turfgrass irrigation, accounting for approximately 0.5 percent of the total daily water consumption in the country (Lyman 2012). Many studies provide valuable information about golf course water management issues. For example, using the data from 129 golf courses in Canada, Scott et al. (2018) examined how golf course characteristics (e.g., dominant soil type, ownership type, and age of course) influence water use variability. They found that a potential water saving of 35% can be achieved by establishing "best in class" water use efficiency among courses with the same characteristics. Devitt et al. (2004) surveyed golf course superintendents in the southwestern US and concluded that superintendents do not oppose reusing water (tertiary-treated sewage effluent) for golf course irrigation, but using such water will bring some negative effects on golf course operation (e.g., pond maintenance and irrigation maintenance). Using data from the Golf Course Superintendents Association of America (GCSAA), several studies explained changes in US golf course water management in recent years (e.g., Gelernter et al. 2015, Shaddox et al. 2022). According to Gelernter et al. (2015), US golf courses reduced their water use by 21.8% from 2006 to 2014, but the water use reduction was largely attributed to the reductions in irrigated acres and the total number of golf facilities, rather than higher water use efficiency.

Precision irrigation is often regarded as an effective water-saving strategy in agricultural production (e.g., Evans and Sadler 2008, Schoengold and Sunding 2014). It is defined as reducing water consumption by making targeted or variable-rate irrigation applications only where, when, and in the amount needed (Straw et al. 2022). Using case studies, Sadler et al. (2005) found that, compared to traditional irrigation, precision irrigation can save about 8% to 20% of water annually on average. Similarly, Hedley, Yule, and Bradbury (2010) conducted an experiment of the cultivation of pasture, maize grain (*Zea mays* L.) and potato (*Solanum tuberosum* L.) in New Zealand and concluded that, compared to uniform rate irrigation, variable rate irrigation (a type of precision irrigation) can save water by 8% to 21%. Besides, precision irrigation has been proven to reduce soil nutrients loss, conserve soil moisture, and reduce agricultural production costs (Evans et al. 1996, Sadler et al., Smith et al. 2010). Specific to golf course, precision irrigation can achieve possible water use reductions, energy reductions, and improved playability (Straw et al. 2022). Many studies imply the need for precision irrigation application in golf courses, especially in fairways, because of the large-scale and extent of documented variability of turfgrass growth conditions (e.g., soil moisture, turfgrass quality, etc.). From a field experiment, Hejl et al. (2022) concluded that turfgrass and soil characteristics can influence soil moisture and turfgrass quality (measured by normalized difference vegetation index) variability within sand-capped golf course fairways (i.e., fairways with the addition of a sand layer above existing native soil). Using a mapping protocol, Straw et al. (2022) evaluated soil moisture variability on fairways at nine US golf courses, and found that, regardless of climatic region and course characteristics, soil moisture variability is inevitable on golf course fairways.

However, precision irrigation technologies are still not well adopted by US golf courses (Gelernter et al. 2015). For example, the percentage of golf courses in which in-ground soil moisture sensors have been adopted has hardly changed from 2005 to 2020, which is only about 3% (Shaddox et al. 2022). Straw et al. (2020) concluded that the current use of mapping technologies for precision irrigation in golf course management is sparse. Horgan and Straw (2019) introduced a simple soil moisture mapping protocol for precision irrigation at golf courses. However, according to Straw et al. (2022), although the protocol is widely downloaded, only less than 20 known golf courses have completed it.

Given the low adoption rate of precision irrigation technologies in US golf courses, this paper aims to identify the driving forces and barriers to adoption of precision irrigation technologies among US golf course superintendents, as well as strategies to promote adoption. This research enriches the literature on water management of green spaces, with a particular focus on golf courses (e.g., Devitt et al. 2004, Gelernter et al. 2015, Hejl et al. 2022, Scott et al. 2018, Shaddox et al. 2022). Our research adds to this literature by investigating precision irrigation technology adoption from a new perspective that links superintendents' beliefs (the driving forces and barriers of the adoption) and water management decisions (adoption decision and willingness to pay (WTP)). Such a new perspective provides important implications for decision-makers on how to promote precision irrigation technology adoption. In addition, this paper contributes to the literature on understanding people's technology adoption behaviors. Such studies aim to figure out which factors affect, and how they affect, peoples' technology adoption decisions. For instance, Liu (2013) tested the effects of risk attitudes on Chinese farmers' adoption decisions for genetically modified Bt cotton (*Gossypium hirsutum* L.) and found that farmers who are more risk averse or loss averse are more likely to adopt Bt cotton later, while farmers who overweight small probabilities (e.g., 1%, 5%) tend to adopt it earlier. Magnan et al. (2015) examined how social networks affect Indian farmers' demand for a resource-conserving technology with heterogeneous benefits and concluded that the effect of social networks depends on the benefit level of technology. Our study is unique in that it considers the relationship between people's subjective beliefs and technology adoption, enriching the literature on technology adoption behavior.

Materials and Methods

Survey design. A survey of US golf courses was conducted to determine the potential driving forces and barriers impacting their adoption of precision irrigation technologies. We made our online survey using Qualtrics^{TM} (Provo, UT), and the survey link was posted on the websites of United States Golf Association and state golf course associations. We also publicized the survey at industry conferences. In the survey, we asked questions related to adoption behaviors of precision irrigation technologies, golf course operation characteristics, and superintendents' demographics and WTP for technologies with different water-saving probabilities.

For precision irrigation technologies adoption behaviors, we asked respondents whether they have adopted specific precision irrigation technologies on their golf courses. The technologies include individual head irrigation control systems, handheld soil moisture sensors equipped with Global Position System (GPS), handheld soil moisture sensors without GPS, in-ground soil moisture sensors, unmanned aerial vehicles (UAVs) or drones, a weather station for evapotranspiration, and other technologies. For superintendents who have adopted at least one of the above-mentioned technologies, we asked them what were the driving forces and barriers for their adoption decisions. For superintendents who have not adopted any technology, we asked them what the potential driving forces and barriers would be if and when they decided to adopt a technology. We also asked every superintendent how they learned about precision irrigation technologies.

For golf course operation characteristics, superintendents were asked to report their zip codes, golf course turfgrass acreage, management budgets, and types of managed turfgrasses on four sections (greens, tees, fairways and roughs) of their golf courses. They also answered questions about whether they own shares in their golf courses, and whether they get performance pay. Demographics include gender, age, race, education, years of experience as a superintendent, membership in a local or national golf course superintendent's association, whether they are Certified Golf Course Superintendents and how much they earn as a superintendent.

We used a three-question scenario to investigate how superintendents' WTP for a precision irrigation technology changes as the technology's risk level changes. In each question, we gave two possible outcomes of adopting a hypothetical technology: (1) saving irrigation water and (2) no effect. For example, in one scenario, we provided information stating that when irrigation water is saved, the irrigation cost will be decreased by $500,000 (10% of the total operational cost) due to water usage reduction; when the technology has no effect, the operational cost will not be reduced. In this scenario, no matter which outcome happens, there would be a cost to adopt the technology. The risk level is represented by the probability of irrigation water saved, p, and the probability of no effect, $1\text{-}p$. In the three questions, the probability of irrigation water saved gradually increased, i.e., $p = 50\%$, 70% and 90% and the superintendents were asked how much they were willing to pay for adopting the technology at each probability. Table 1 provides an example of the scenario question when $p = 50\%$. In total, 202 golf course superintendents started the survey, and 105 superintendents completed questions about precision irrigation technology adoption, golf course operation and their demographics. Among them, 98 superintendents also answered the WTP questions.

Model. To understand how golf course superintendents' precision irrigation technology adoption behaviors are associated with their self-reported adoption driving forces and barriers, two groups of regressions were conducted. The first group included two regressions to check how superintendents' adoption decisions were associated with the adoption driving forces and barriers, respectively. Since the dependent variable is a dummy variable indicating if a superintendent had adopted a certain technology (= 1, if the technology is adopted, = 0, otherwise), we used Probit Model (Wikipedia Contributors 2019) to analyze the data. In the Probit Model, Equations (1) and (2) defines the probability that a certain technology j is adopted and the probability that it is NOT adopted by the superintendent's golf course.

$$\begin{aligned}\Pr(Adoption_{ij} &= 1|\boldsymbol{KeyVariables}_{\mathrm{i}},\ \boldsymbol{Controls}_{ij}) \\ &= \Phi(\boldsymbol{\alpha}'\boldsymbol{KeyVariables_i} + \boldsymbol{\beta}'\boldsymbol{Controls}_{ij})\end{aligned} \tag{1}$$

Table 1. An example of the willingness to pay (WTP) questions asked for US golf course superintendents in a survey evaluating superintendents' precision irrigation technology adoption behaviors (p = 50%).

Water Cost Saving	
50% Probability of saving water	**50% Probability of NOT saving water**
$500,000	$0

Please choose **the highest cost** you'd like to pay for this technology from the following list. (In other words, how much money would you be willing to spend today on an irrigation technology, if you knew that the change would have a 50% chance of resulting in a present value of $500,000 in water cost savings.)
○$490,000 ○$450,000 ○$400,000 ○$350,000 ○$300,000 ○$250,000 ○$230,000 ○$200,000 ○$170,000 ○$140,000 ○$110,000 ○$80,000 ○$50,000 ○$20,000 ○Lower than $20,000

$$\begin{aligned}\Pr(Adoption_{ij} &= 0|\boldsymbol{KeyVariable}\mathrm{s}_i,\ \boldsymbol{Controls}_{ij}) \\ &= 1 - \Phi(\boldsymbol{\alpha}'\boldsymbol{KeyVariables_i} + \boldsymbol{\beta}'\boldsymbol{Controls}_{ij})\end{aligned} \tag{2}$$

In Equations (1) and (2), $\Phi(.)$ is the cumulative distribution function for standard normal distribution. $Adoption_{ij}$ is the dependent variable, an indicator of whether superintendent i has adopted technology j (=1, if superintendent i has adopted technology j; =0, otherwise), where j can be a technology mentioned in the last section (individual head irrigation control systems, handheld soil moisture sensors equipped with Global Position System (GPS), handheld soil moisture sensors without GPS, in-ground soil moisture sensors, unmanned aerial vehicles (UAVs) or drones, weather station for evapotranspiration, or other technologies). $\boldsymbol{KeyVariables_i}$ is the vector of independent variables related to adoption driving forces and barriers, etc. The associations of dependent variable and these independent variables are of our interest. $\boldsymbol{Controls}_{ij}$ is the vector of control variables. The control variables are variables held constant in the regression. In other words, the associations of dependent variable and key independent variables are evaluated holding control variables constant.

The control variable vector, $\boldsymbol{Controls}_{ij}$, includes four groups of control variables. The first group is superintendent demographics. The second group consists of two variables measuring the different kinds of superintendent compensation, the indicator of performance pay and the ownership shares owned by the superintendent. Many empirical findings show that a manager's compensation may influence his or her executive behaviors (e.g., Harris et al. 2014, Larraza-Kintana et al. 2007). The third group captures the basic characteristics of the golf course operation, including the total acreage of the golf course, the management budget, and the estimated average yearly precipitation in the location of the golf course (see Table 2 for descriptive statistics of the first three groups of variables). The fourth group includes six indicators of certain precision irrigation technologies (see Table 3 for the definitions of the indicators); these indicators are added to control the effects of certain technologies' properties on the adoption decisions.

We ran two models. In the first model, the independent variables (*KeyVariablesi*) were the indicators of driving forces of precision irrigation technology adoption (see column (0) in

Table 2. **Descriptive statistics of sampled US golf course superintendents in a survey evaluating superintendents' precision irrigation technology adoption behaviors (sample size=105).**

Variable	Definition	Mean (S.D.)
Age	**the age of the superintendent**: 22 = 18 to 25 years old 31 = 26 to 35 years old 41 = 36 to 45 years old 51 = 46 to 55 years old 61 = 56 to 65 years old 71 = Older than 65 years old	47.41 (11.30)
Education	**the education level of the superintendent**: 1 = High school diploma or equivalent 2 = Some college, but no degree 3 = College degree or higher	2.85 (.43)
Experience	**the experience working as a superintendent**: 2.5 = Less than or equal to 5 years 8 = 6 to 10 years 13 = 11 to 15 years 18 = 16 to 20 years 23 = 21 to 25 years 28 = 26 to 30 years 33 = More than 30 years	17.38 (11.02)
Membership	1 = the superintendent is a member of a local or national golf course superintendents association 0 = otherwise	.93 (.25)
Certified	1 = the superintendent is a Certified golf course superintendent 0 = otherwise	.2 (.40)
Income	**the superintendent's yearly income from golf course operation**: 12500 = Less than $25,000 37500 = $25,000 - $49,999 62500 = $50,000 - $74,999 87500 = $75,000 - $99,999 175000 = $100,000 - $249,999 375000 = $250,000 - $499,999 750000 = $500,000 - $999,999 1250000 = More than $1,000,000	174642.86 (227737.47)
Performance pay	1 = if the superintendent gets performance pay 0 = otherwise	.4 (.49)
Total area	**the total acreages of the golf course** (in acre (4046.86 square meters))	426801.98 (4372331.90)
Management budget	**the management budget of the golf course**: 125000 = Less than $250,000 375000 = $250,000 - $499,999 625000 = $500,000 - $749,999 875000 = $750,000 - $999,999 1750000 = $1,000,000 - $2,499,999 3750000 = $2,500,000 - $4,999,999 7500000 = $5,000,000 - $9,999,999 12500000 = More than $10,000,000	1534523.80 (1569742.40)
Average precipitation	**the average yearly precipitation** (in inch (0.0254 meters))	41.36 (15.43)

Table 4). In the second model, the independent variables were the indicators of adoption barriers (see column (0) in Table 5).

With Equation (1) and (2), the log-likelihood function of the Probit Model can be written as Equation (3).

$$logL(\boldsymbol{\alpha};\boldsymbol{\beta}) = \sum_{i=1}^{n}\sum_{j=1}^{7}\Big\{Adoption_{ij} * log\Phi\Big(\boldsymbol{\alpha KeyVariables_i} + \boldsymbol{\beta}'\boldsymbol{Controls_{ij}}\Big) + (1 - Adoption_{ij}) * \log\Big[1 - \Phi\Big(\boldsymbol{\alpha KeyVariables_i} + \boldsymbol{\beta}'\boldsymbol{Controls_{ij}}\Big)\Big]\Big\} \tag{3}$$

By the Maximum Likelihood Estimation, we can get the Probit estimates $\left(\hat{\boldsymbol{\alpha}};\hat{\boldsymbol{\beta}}\right)$ satisfying

$$\left(\hat{\boldsymbol{\alpha}};\hat{\boldsymbol{\beta}}\right) = argmax\left\{logL(\boldsymbol{\alpha};\boldsymbol{\beta})\right\} \tag{4}$$

We also examined how superintendents' WTP for adopting a technology are associated with the adoption driving forces and barriers. In the WTP model, the dependent variable was the WTP for adopting a technology with different water-saving probabilities (50%, 70%, and 90%). The independent variables were adoption driving forces or barriers. The control variables included the first three groups of control variables in Equation (1) and (2) and two indicators of the technology's water-saving probability (50% and 70%). Since the dependent variable was a continuous variable, we conducted the two linear regressions by Ordinary Least Squares (OLS). Hence, the regressions can be written as Equation (5).

$$WTP_i = \boldsymbol{\alpha}^{\boldsymbol{OLS}'}\boldsymbol{KeyVariables_i} + \boldsymbol{\beta}^{\boldsymbol{OLS}'}\boldsymbol{Controls_i^{OLS}} + \varepsilon_i \tag{5}$$

Results and Discussion

The current situation of precision irrigation technology adoption. The fourth column of Table 3 summarizes the current situation of technology adoption by golf courses. The

Table 3. **The current situation of precision irrigation technology adoption and corresponding indicator definitions.**

Technology	The indicator of technology (Variable name)	Definition of the indicator	Percentage of superintendents who have adopted the technology
Individual Head Irrigation Control Systems	ihics	= 1, the technology is individual head irrigation control systems; = 0, otherwise.	67.62
Handheld Soil Moisture Sensors Equipped with GPS	hsmswgps	= 1, the technology is handheld soil moisture sensors equipped with GPS; = 0, otherwise.	27.62
Handheld Soil Moisture Sensors Without GPS	hsmsngps	= 1, the technology is handheld soil moisture sensors without GPS; = 0, otherwise.	58.10
In-ground Soil Moisture Sensors	isms	= 1, the technology is in-ground soil moisture sensors; = 0, otherwise.	20.00
Unmanned Aerial Vehicles (UAVs) or Drones	uav	= 1, the technology is unmanned aerial vehicles (UAVs) or drones; = 0, otherwise.	9.52
Weather Station for Evapotranspiration	wse	= 1, the technology is weather station for evapotranspiration; = 0, otherwise.	40.95
Other Technologies	others	= 1, the technology is other technology not mentioned above; = 0, otherwise.	3.81

three most highly adopted precision irrigation technologies were individual head irrigation control systems (67.6%), handheld soil moisture sensors without GPS (58.1%), and a weather station for evapotranspiration (41.0%). The adoption rates of unmanned aerial vehicles and in-ground soil moisture sensors were low (9.5 and 20.0%, respectively).

Driving forces for precision irrigation technology adoption. We tried to identify the driving forces for adopting precision irrigation technologies. For superintendents who have adopted some technology(ies), we asked them what the driving forces are for adoption; for superintendents who have not adopted any technology, we asked them what the driving forces would be, if they decided to adopt a technology. Table 4 shows the driving forces and percentages of superintendent responses.

Column 1 in Table 4 shows the results of the whole sample with 105 superintendents. Overall, the three main driving forces of precision irrigation technology adoption are reducing water use (86.7%), increasing playability (67.6%), and achieving better turfgrass aesthetics (67.6%). Column 2 shows the percentages for the superintendents who have adopted at least one precision irrigation technology (the "adopted" group) and column (3) shows the results for those who have never adopted any of these technologies (the "unadopted" group). There are clear differences between columns (2) and (3). For example, for the "adopted" group, the most significant driving force is reducing water use (88.5%), while, for the "un-adopted" group, the most important driving force is to have better turfgrass aesthetics (88.9%). In the "adopted" group, 67.8% superintendents believe that easier decision making is a driving force, while, in the "un-adopted" group, only 33.3% superintendents believe so. In addition, although only 19.5% superintendents in the "adopted" group regard efficient use of fertilizer as a driving force, 61.1% superintendents in the "un-adopted" group do so. Although there exist such differences, for both groups, the three main driving forces mentioned above, reducing water use, increasing playability, and better turfgrass aesthetics, are very important.

Table 4. **The distribution of driving forces for precision irrigation technology adoption: whole sample, "adopted" group, "un-adopted" groups and corresponding indicator names[z].**

Driving Forces	(0) Indicators of the Driving Forces (Variable Name)	(1) Percent (%) (Whole Sample)	(2) Percent (%) ("Adopted")	(3) Percent (%) ("Un-adopted")
Reducing water use	df_wateruse	86.67	88.51	77.78
Energy savings	df_energy	42.86	41.38	50.00
Efficient use of fertilizer	df_fertilizer	26.67	19.54	61.11
Less dependency on weather	df_weather	28.57	26.44	38.89
Operational cost savings	df_cost	42.86	41.38	50.00
Easier decision making	df_decision	61.90	67.82	33.33
Environmental protection	df_envir	26.67	24.14	38.89
Increasing playability	df_playability	67.62	67.82	66.67
Better turfgrass aesthetics	df_aesthetics	67.62	63.22	88.89
Peer pressure	df_peer	1.90	1.15	5.56
Local restrictions on water use	df_lackwater	17.14	14.94	27.78
Curiosity	df_curiosity	10.48	12.64	0.00
Others	df_other	2.86	3.45	0.00
Observations		105	87	18

[z]The definitions of the indicators in column (0) are similar to the indicator definitions in Table 3. For example, df_wateruse is the indicator of reducing water use as a driving force. If the superintendent believe that reducing water use is a driving force for her or him to adopt a precision irrigation technology, then df_wateruse equals 1; otherwise, df_wateruse equals 0.

Table 5. **The distribution of barriers to precision irrigation technology adoption: whole sample, "adopted" group, "un-adopted" groups and corresponding indicator names[z].**

Barriers	(0) Indicators of the Barriers (Variable Name)	(1) Percent (%) (Whole Sample)	(2) Percent (%) ("Adopted")	(3) Percent (%) ("Un-adopted")
Potential risks of new technology	b_risk	10.48	11.49	5.56
Lack of information about the technology's effectiveness	b_noinfo	27.62	28.74	22.22
High initial cost of the adoption	b_cost	77.14	73.56	94.44
Resource or cost saving is limited.	b_limsaving	23.81	24.14	22.22
Requirement of highly skilled labor	b_skill	24.76	27.59	11.11
Golf course is not suitable for installation of relevant equipment.	b_notsuit	13.33	11.49	22.22
The decision needs to be approved by higher level administrators.	b_manage	36.19	26.44	83.33
Lack of technical knowledge about the technology	b_knowledge	16.19	17.24	11.11
Other	b_other	6.67	8.05	0.00
Observations		105	87	18

[z]The definitions of the indicators in column (0) are similar to the indicator definitions in Table 3. For example, b_risk is the indicator of potential risks of new technology as a barrier. If the superintendent believe that potential risks of new technology is a barrier for her or him to adopt a precision irrigation technology, then b_risk equals 1; otherwise, b_risk equals 0.

Barriers to precision irrigation technology adoption. We also asked the superintendents what prevented them from adopting precision irrigation technology. Table 5 shows the potential barrier options and the corresponding percentages of superintendents who selected the options for the whole sample, the "adopted" group, and the "un-adopted" group. For all respondents (column 1) the three main barriers to precision irrigation technology adoption are high initial cost of the adoption (77.1%), approval by higher level administrators needed (36.2%), and lack of information about the effectiveness of irrigation technology (27.6%). When dividing the sample into two groups by technology adoption status we can find that high initial cost is a main barrier for both groups (73.6% and 94.4%, for adopted and un-adopted, respectively). For the "un-adopted" superintendents, the fact that the adoption decision needs to be approved by higher level administrators is also a major barrier (83.3%), which implies that, unwillingness to adopt by the superintendent is not always the primary barrier.

Information sources for precision irrigation technology adoption. To better understand how to promote the adoption of the precision irrigation technologies, we also asked the superintendents how they learned about precision irrigation technologies. Table 6 shows the information sources and the corresponding percentages of superintendents who used these sources. The three main sources to learn about precision irrigation technologies were industry associations (67.6%), peer referral (61.9%), and sales and manufacturer representatives (50.5%). Besides, employer or coworker (23.81%) and university extension (17.14%) are also considered as information sources by some superintendents. However, some widely used public information platforms are less chosen (e.g., social media (16.2%) and search engines (9.5%)). Accordingly, the main information sources are within the industry rather than public information platforms.

The driving forces, barriers and adoption decisions. We used Probit Model to examine how golf course superintendents' precision irrigation technology adoption decisions are associated with their self-reported adoption driving forces and barriers. The results are shown in Table 7. Column 1 lists the estimation results for driving forces. The indicator of reducing water use is not statistically significant, which is counterintuitive. However, the statistical insignificance is due to the lack of variation in the indicator. As shown in Table 4, most superintendents (about 87%) indicated reducing water use is the main driving force for adoption and very few superintendents did not see it as a driving force; therefore, the low variation of the indicator of reducing water use makes it statistically insignificant, which does not mean reducing water use is not an important driving force for the adoption of precision irrigation technology. The indicators of energy savings and easier decision making have positive significant coefficients, implying that superintendents who believe energy savings or easier decision making can be driving force(s) of their adoptions tend to adopt a technology, which may reflect that the current precision irrigation technologies can effectively save energy and help superintendents make operational decisions. According to Souza and Rodrigues (2022), compared to traditional irrigation methods, precision irrigation can save electricity by less pumping of irrigation, which is consistent with the above finding. However, according to the coefficient of efficient fertilizer use indicator, there is a significantly negative association between the indicator of efficient use of fertilizer and adoption decision, which means superintendents

Table 6. **The distribution of information sources from which US golf course superintendents learned about precision irrigation technologies.**

Information Source	Percent (%)
Industry association	67.62
Peer referral	61.90
Employer or coworker	23.81
University extension	17.14
Television	0.00
Newspaper	0.00
Podcast	6.67
Search engines	9.52
Social media	16.19
Internet advertisement	7.62
Academic journals	14.29
Sales and manufacturer representatives	50.48
Others	2.86
Observations	105

Table 7. Probit Model: how US golf course superintendents' precision irrigation technology adoption decisions are associated with their self-reported adoption driving forces and barriers (dependent variable: the indicator of whether a superintendent have adopted a certain technology)[z].

Variables	(1) Driving forces	(2) Barriers
df_wateruse	0.149 (0.191)	
df_energy	0.549*** (0.157)	
df_fertilizer	−0.304* (0.164)	
df_weather	−0.033 (0.149)	
df_cost	0.032 (0.142)	
df_decision	0.526*** (0.132)	
df_envir	−0.183 (0.160)	
df_playability	−0.083 (0.143)	
df_aesthetics	−0.002 (0.133)	
df_peer	−0.120 (0.481)	
df_lackwater	−0.158 (0.181)	
df_curiosity	−0.099 (0.192)	
df_other	0.079 (0.373)	
b_risk		0.344 (0.212)
b_noinfo		0.073 (0.148)
b_cost		−0.327** (0.153)
b_limsaving		−0.047 (0.146)
b_skill		0.055 (0.147)
b_notsuit		−0.507*** (0.196)
b_manage		−0.554*** (0.141)
b_knowledge		0.253 (0.166)
b_other		0.243 (0.263)
Age	0.011 (0.009)	0.009 (0.009)
Education	0.098 (0.147)	−0.036 (0.143)
Experience	−0.016* (0.010)	−0.014 (0.009)
Membership	0.417 (0.287)	0.566* (0.293)
Certified	0.331** (0.159)	0.311** (0.155)
Income	0.000 (0.000)	0.000 (0.000)
Performance pay	0.289** (0.122)	0.267** (0.122)
Total area	0.000 (0.000)	−0.000 (0.000)
Management budget	0.000*** (0.000)	0.000* (0.000)
Average Precipitation	0.001 (0.004)	−0.005 (0.004)
ihics	2.466*** (0.277)	2.467*** (0.277)
hsmswgps	1.291*** (0.274)	1.295*** (0.274)
hsmsngps	2.183*** (0.274)	2.179*** (0.273)
isms	0.989*** (0.281)	0.992*** (0.281)
uav	0.469 (0.300)	0.471 (0.300)
wse	1.688*** (0.272)	1.691*** (0.273)
Constant	−3.840*** (0.688)	−2.327*** (0.681)
Observations	735	735

[z]Standard errors in parentheses ** p<0.01, ** p<0.05, * p<0.1.

who regard efficient use of fertilizer as a driving force of their adoptions are less likely to adopt a technology. A possible reason is that, although precision irrigation can improve fertilizer use efficiency, superintendents are not knowledgeable, so superintendents who want to use fertilizer more efficiently are not willing to adopt precision irrigation technologies.

The regression results for the adoption barriers are shown in column (2) of Table 7. The indicators of high initial adoption cost, unsuitability for the installation, and approval by higher level administrators needed have significantly negative coefficients, implying negative associations between these barriers and deciding to adopt a technology. This indicates that high initial adoption cost, unsuitability for the installation, and a requirement approval by higher level administrators are important barriers for the adoption of precision irrigation technology. For both regressions, the coefficients of the Certified Golf Course Superintendents indicator, performance pay indicator, and management budget are significantly positive, indicating that a certified golf course superintendent is more likely to adopt precision irrigation technology, and a superintendent with performance pay or higher management budget is also more willing to adopt a technology.

The driving forces, barriers and WTPs. We applied two OLS regressions to explore how superintendents' WTP for adopting a hypothetical technology with a certain water-saving probability are associated with their self-reported adoption driving forces and barriers. Table 8 shows the results. Column 1 provides the results for the adoption driving forces. The positive significant coefficient of energy savings indicator implies that the superintendent who regards energy savings as an adoption driving force is willing to pay about $42,864 more for adopting the technology than an identical superintendent who does not think that energy savings is a driving force. Similarly, superintendents who regard less dependency on weather as a driving force tend to pay about $51,197 more compared to those who do not think less dependency on weather is a driving force. The technology can reduce irrigation water usage, so that the irrigation will be affected less by the weather, especially by the precipitation, which may make irrigation easier to manage and save operational costs; hence, "less dependency on weather" drives superintendents to pay more for the technology. The indicator of curiosity also has a significantly positive coefficient, implying that, superintendents who believe that curiosity is their adoption driving force are willing to pay an extra $129,702 dollars compared to those who do not think curiosity as their driving force. The more curious a superintendent is, the more willing he or she is to spend extra money on new technologies. However, the significant negative coefficient of increasing playability indicator implies that a superintendent who expects to improve golf course playability through precision irrigation technologies tends to pay about $44,706.24 less for adopting the technology. A plausible explanation is that our experiment only focused on the risk levels (i.e., the different water-saving probabilities) and saved operational cost of the technology but said nothing about playability. As a result, superintendents who pay attention to playability may not be willing to pay that much. From another perspective, this also implies that playability is a significant factor for superintendents when adopting a technology. In the experiment, we also did not provide information regarding how precision irrigation technology might impact turfgrass aesthetics, but the indicator of better turfgrass aesthetics does not have a significant association with the WTPs. This may mean that the concern about how the technology will influence turfgrass aesthetics is not important enough to affect the WTPs, but the significant association between playability and WTPs implies that playability is important.

Column 2 of Table 8 shows the results for the adoption barriers. The indicators of new technology's potential risks have a significant positive coefficient. In other words, if superintendents believe that the risks brought by adopting new technology can hinder their adoptions, they will pay an extra $80,554 for the adoption. This counterintuitive result can be attributed to the specified risk levels in our

Table 8. Ordinary Least Squares (OLS) regression: how US golf course superintendents' WTP are associated with their self-reported adoption driving forces and barriers (dependent variable: WTP for a hypothetical technology with a certain risk level)[z].

Variables	(1) Driving Forces	(2) Barriers
df_wateruse	−36,957.32 (24,436.38)	
df_energy	42,864.02** (21,448.65)	
df_fertilizer	−8,587.24 (22,381.84)	
df_weather	51,197.11** (21,574.65)	
df_cost	20,531.91 (19,456.55)	
df_decision	646.74 (17,357.29)	
df_envir	1,033.90 (22,019.57)	
df_playability	−44,706.24** (19,844.85)	
df_aesthetics	−9,076.68 (18,026.01)	
df_peer	−81,348.77 (60,191.33)	
df_lackwater	−26,021.38 (26,263.14)	
df_curiosity	129,701.51*** (25,662.02)	
df_other	47,607.64 (48,386.92)	
b_risk		80,553.93*** (29,128.86)
b_noinfo		5,440.55 (20,695.72)
b_cost		−29,361.27 (21,939.96)
b_limsaving		51,395.02** (20,060.29)
b_skill		−9,041.74 (21,229.61)
b_notsuit		30,029.89 (25,339.05)
b_manage		26,717.45 (18,562.69)
b_knowledge		−5,777.43 (22,782.12)
b_other		65,648.06* (37,725.67)
Age	2,400.007* (1,249.043)	1,438.13 (1,244.86)
Education	−4,269.154 (20,574.560)	-43,899.62** (19,812.41)
Experience	−3,771.883*** (1,259.859)	−2,737.11** (1,210.11)
Membership	−26,193.098 (34,483.090)	−14,260.23 (35,403.38)
Certified	68,806.264*** (22,627.430)	48,980.38** (22,231.49)
Income	0.046 (0.043)	0.06 (0.04)
Performance pay	16,721.487 (17,407.458)	30,672.27* (17,348.26)
Total area	−0.004** (0.002)	−0.003* (0.002)
Management budget	0.012** (0.006)	0.002 (0.006)
Average Precipitation	692.844 (574.797)	989.83* (541.24)
i50	−124,923.523*** (18,426.764)	−125,440.26*** (18,901.13)
i70	−67,340.206*** (18,469.474)	−67,340.21*** (18,947.20)
Constant	182,196.431** (88,184.165)	278,111.10*** (90,346.18)

[z]Standard errors in parentheses *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

experiment. When making adoption decisions, superintendents often do not know the technology's exact risk level (i.e., the distribution of possible outcomes of the adoption), so the potential risks of the technology may hinder the adoption in two ways: (1) the uncertainty of the outcome, and (2) the unknown distribution of possible outcomes. In our experiment, we told superintendents what the exact distribution of possible outcomes is, which reduced the perceived potential risks brought by unknown probabilities and outcomes. As a result, superintendents who regard new technology's potential risks as an adoption barrier were willing to pay more. Similarly, superintendents who consider limited resource or cost savings to be an adoption barrier were willing to pay $51,395.02 more, because in our experiment we explicitly specified that the technology can reduce 10% of operational cost, which may be a high cost saving from the view of the superintendents regarding limited cost saving as an adoption barrier; therefore, they have higher WTP for the technology. According to both regressions, superintendents with more experience or who manage golf courses with greater acreage are more likely to have lower WTPs, while certified golf course superintendents tend to pay more for adopting the technology.

In conclusion, to investigate the driving forces and barriers of precision irrigation technology adoption in golf courses, we surveyed a group of US golf course superintendents. In the survey, 105 superintendents completed questions about precision irrigation technology adoption, golf course operation and their demographics. Among them, 98 superintendents also answered questions about their WTP for a given precision irrigation technology with different water-saving probabilities. Our analysis resulted in several key findings. First, the three main driving forces of precision irrigation technology adoption are reducing water use (86.7%), increasing playability (67.6%), and better turfgrass aesthetics (67.6%), and the three main barriers are high initial adoption cost (77.1%), approval by higher level administrators needed (36.2%), and lack of information about the effectiveness of the technology (27.6%). Second, superintendents who regard energy savings or easier decision making as adoption driving forces are more likely to adopt a precision irrigation technology, while superintendents whose driving force is efficient use of fertilizer are more unwilling to adopt. Superintendents who believe that high initial cost, unsuitability for the installation, and approval by higher level administrators needed can be their adoption barriers are less likely to adopt a technology. Third, for a precision irrigation technology with different risk levels, superintendents whose driving forces include energy savings, less dependency on weather, or curiosity tend to have higher WTP, and superintendents with adoption barriers including potential risks of new technology or limited resource/cost savings are also willing to pay more for the technology when the probability of success is concrete and the cost saving is high enough.

Based on our findings, there are several ways that turfgrass industry leaders can promote precision irrigation technology adoption on golf courses. First, researchers and manufacturers can improve the technologies so that they can meet superintendents demands better. For example, manufacturers may want to find an effective way to reduce the production costs and thus the prices of the technologies, which can make the high initial cost barrier lower. Second, according to our finding, superintendents may be unclear about precision irrigation's improvement on fertilizer use efficiency and how to use the technologies appropriately to improve the efficiency. Therefore, improving the understanding of precision irrigation's improvement on fertilizer use efficiency may be a potential feasible way to promote the adoption. Third, our findings suggest that industry associations or public agencies can generate promotion strategies, and that these promotional efforts should target decision makers, which for some superintendents is a higher level administrator. Fourth, new technologies often involve uncertainties in the outcomes, which increases the perceived risks of the technology. Information about the exact probability of success and concrete cost savings by the technology will be effective to increase superintendents' interests and WTP for the technology. According to our findings about how superintendents learn about the technologies, public information platforms are not fully utilized when promoting the technology. Within industry promotions, using public information platforms such as social media and search engines may make the promotion more effective. An example is precisely pushing the information about the technologies to superintendents by social media. Public research programs can help fill important gaps by conducting research that quantifies the benefits of precision irrigation technologies in multiple golf course management contexts. Communicating research-based results should improve adoption, which can spur innovation leading to lower cost solutions in the future.

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