Investment in Irrigation Systems under Weather Uncertainty

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Abstract

Irrigated agriculture will play a crucial role to meet future food demand, but a sustainable water resource management in agriculture is crucial as well. Therefore, the European Water Framework Directive promotes several measures, e.g., the adoption of adequate water pricing mechanisms or the promotion of water-saving irrigation techniques. Since production conditions such as weather and climate development are uncertain, farmers might be reluctant to invest in a water-saving but capital intensive irrigation system. We apply a stochastic dynamic programming approach to analyze a farmer's optimal investment strategy for either a water–saving drip irrigation system or sprinkler irrigation system under weather uncertainty and assess the probability of adopting either irrigation system until the year 2040. We design two policy scenarios: (i) irrigation water pricing and (ii) equipment subsidies for drip irrigation, and investigate how they affect the farmer's optimal investment strategy. Our case study analysis is performed for the region Marchfeld, a typical semi-arid agricultural production region in Austria. We use data from the bio-physical process simulation model EPIC (Environmental Policy Integrated Climate) which accounts for site and management related characteristics as well as weather parameters from a statistical climate change model. We find that investment in drip irrigation is unlikely unless subsidies for equipment cost are granted. Even water prices do not increase the probability to adopt a drip irrigation system, but rather decrease the probability to invest into either irrigation system.

Keywords: Irrigation investment, stochastic dynamic programming approach, water policies, weather uncertainty, EPIC.

1. Introduction

For Central and Southern Europe, it has been projected that areas under water stress can increase from 19% in 2007 to 35% in 2070 (IPCC 2007). Therefore, it is crucial to assess optimal irrigation management strategies in European agriculture. The European Water Framework Directive promotes a set of policy options focused on demand-side management such as appropriate water pricing and the implementation of metering to support volume-based charging. Such options shall ensure that agricultural subsidies are linked to more efficient water use as well as investing in technologies that increase water use efficiency (EEA 2009). In particular, drip irrigation systems have proven to increase crop water productivity i.e. increasing yields and decreasing the amount of water used (e.g. Cetin and Bilgel 2002, Fedaku and Teshome 1998 in Luquet et al 2005). However, Sauer et al. (2010) estimated that of the entire irrigated areas in Europe, drip irrigation systems only constitute a fraction of 18%, sprinkler systems of 48%, and basin and furrow irrigation of 34%. Currently, the most common obstacle to invest into drip irrigation systems is related to the investment costs, which are often not affordable for low or even medium income farmers (Vidal 2001, in Luquet et al 2005). Investment decisions in production equipment are additionally complicated, as farmers are confronted with uncertainty about production conditions, amongst others due to climatic or seasonal factors such as rainfall or frost events (Tozer 2009). With these problems in mind, we aim to model a farmer's decision to invest in a sprinkler irrigation system or an even more water-efficient drip irrigation system under uncertainty about the evolution of precipitation for two soil types in the Austrian Marchfeld region. Firstly, we assess the optimal timing to invest in the planning period 2009-2040. Secondly, we investigate how investment decisions are affected by policy measures, such as the introduction of water prices and equipment subsidies. Our case study focuses on the region Marchfeld in Austria, where intensive agriculture has expanded from the 1970s onwards, and has led to a decrease of the annual groundwater level from the 1970s to the 1990s (Stenitzer and Hoesch 2005). Currently, only sprinkler irrigation systems are used in Marchfeld, but as drip irrigation systems allow for a precise application of water, it might be viable to adopt drip irrigation systems in the Marchfeld in the future.[1]

We use agro-ecological data from the bio-physical process simulation model EPIC (Environmental Policy Integrated Climate) as well as weather parameters from a statistical climate change model for Austria (Strauss et al. 2010). We apply a stochastic dynamic programming approach, which provides a framework to analyze investment decisions under uncertainty about e.g. production conditions, irreversibility of capital investment and the possibility to wait and postpone investment to a later point in time into one model framework (e.g. Dixit and Pindyck 1994, Pindyck 1980).

The manuscript is structured as follows. In section 2, we introduce the EPIC model, data and case study area. This is followed by a brief introduction of the analysis method. In section 4, we provide results indicating the optimal timing to invest in either a drip or sprinkler irrigation system in case of no policies, water prices, and equipment subsidies. In section 5, we derive conclusions from our analysis.

2. Data

Our study area is the Marchfeld region in Austria, which is one of the most important field crop production areas as well as driest areas in Austria. We use the bio-physical process simulation model EPIC (Environment Policy Integrated Climate; Williams 1995, Izaurralde et al. 2006), which simulates important bio-physical processes in agricultural land use management providing model outputs on, inter alia, dry matter crop and straw yields, nitrogen emissions, soil organic carbon contents, evapotranspirations, and soil sediment losses. The EPIC simulations for the Marchfeld region have been validated in Schmid et al. (2004), and Schmid et al. (2007). The simulation outputs are mainly based on five thematic datasets addressing bio-physical modeling aspects: (i) land use data, (ii) topographical data, (iii) soil data, (iv) crop management data, and (v) climate data. We simulate biophysical impacts of five crops (winter wheat - included in two different crop rotations -, sugar beets, potatoes, corn, and carrots) which cover more than 50% of the agricultural land in the Marchfeld. We assume conventional tillage practices i.e. ploughing. The production inputs of nitrogen fertilizer and irrigation water are automatically determined by the EPIC model with respect to levels of nitrogen and water stress free days in the growing season and thus regarded as simulation outputs. In particular, 90% of the crop growth period is water and nitrogen stress-free; total annual nitrogen application rates are limited to 170 kg/ha; and the maximum annual irrigation volume allowed for each crop amounts to 500 mm. Crop production is simulated for two distinct soil types in Marchfeld. Soil 1 is a Chernozem with fine sediment and loess formation with available soil water capacity of 196 mm and topsoil humus contents of 2.6%. It covers 49% of the Marchfeld region. Soil 2 is a Para-Chernozem with 59 mm available soil water capacity and 1.4% topsoil humus content, representing 14% of the region (Schmid et al. 2004). Precipitation data is taken from a statistical climate model for Austria, which is based on in-situ weather observations from the period 1975 to 2007, provided by the Central Institute for Meteorology and Geodynamics (ZAMG; Strauss et al. 2010). To generate weather parameters for the future period, a temperature trend has been derived from a homogenized dataset for the period 1975-2007 and has been extrapolated for the period 2008-2040. In the period 1975-2007, the average annual maximum/minimum temperature was 14.8°C / 6.1°C. Over the period 2009-2040, the average annual maximum/minimum temperature is predicted to increase to 16.7°C / 8.0°C. In the period 1975-2007, the average annual precipitation sum was 522 mm, but no trend in precipitation was detected. To generate

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[1] www.marchfeldkanal.at; accessed in February 2011

a climate spectrum for the period 2008-2040, temperature residuals as well as observations of the weather parameters precipitation, solar radiation, relative humidity and wind have been bootstrapped 300 times on a daily base. Even though in the historical data no trend in precipitation was detected, in the following analysis, we assume a decrease in annual precipitation sums of - 5% until 2016, - 10% until 2024, -15% until and 2032, and - 20% until 2040 (Strauss et al. 2010). These values have been verified by the literature. For instance, Christensen et al. (2007) employ various General Circulation Models (GCMs) and Regional Climate Models (RCMs) by using different emission scenarios (A2 and B2; IPCC 2007) as well as different resolutions resulting in seasonal precipitation sums of +/-60% until 2100 depending on the assumptions made. In our study, the bootstrapping resulted in 300 'weather scenarios', which depict the uncertainty of annual precipitation sums in the stochastic dynamic programming model. As the weather data are a direct input to the EPIC model, we obtain for each year and each EPIC output parameter 300 realizations. In Table 1, we provide the mean and standard deviation of annual dry matter crop yield and irrigation quantities as well as profits (for details on profit calculation cp Section 3) over the period 2009-2040 and the 300 realizations. Variable production costs (BMLFUW, 2008) and mean commodity prices from 2005-2009 are used to calculate annual profits. Capital costs of irrigation systems were surveyed from producers (personal communication with Fa. Bauer, Fa. Parga).

Table 1. Summary statistic of crop yields, irrigation water, and profits for each crop and irrigation system.

		Soil 1						**Soil 2**					
		No irrigation		Sprinkler		Drip		No irrigation		Sprinkler		Drip	
		Mean	St.D.	Mean	St.D.	Mean	St.D.	Mean	St.D.	Mean	St.D.	Mean	St.D.
Corn		6.2	1.2	7.9	0.5	7.9	0.5	4.6	1.3	7.5	0.5	7.5	0.5
Carrots	crop yields t/ha/a	5.4	0.6	5.5	0.4	5.5	0.4	3.5	0.8	5.2	0.5	5.3	0.4
Potatoes		7.0	0.8	7.1	0.8	7.1	0.8	5.3	0.9	6.6	0.8	6.7	0.8
Sugar beets		7.8	1.2	10.1	0.6	10.3	0.5	6.2	1.2	9.8	0.7	10.0	0.6
Winter wheat 1		4.7	0.8	4.8	0.8	4.8	0.8	3.0	1.1	4.7	0.7	4.7	0.7
Winter wheat 2		4.9	0.8	5.1	0.7	5.1	0.8	3.0	1.1	4.9	0.7	5.0	0.7
Corn				127	51	113	45			254.6	45	229.1	42.4
Carrots				39	36	34	32			147.9	43	132.0	36.1
Potatoes	irrig. mm/a			53	37	47	32			162.9	38	144.5	32.3
Sugar beets				162	56	143	49			279.9	35	262.4	39.8
Winter wheat 1				35	35	32	31			141.4	40	126.0	34.8
Winter wheat 2				36	35	32	31			141.7	40	126.3	34.9
Corn		130	163	9.4	84.8	-249	70.2	-81.9	163	-115.2	789	-319.4	64.5
Carrots		8321	1100	8351	843	7909	825	4712	1648	7590.5	920	7357.5	863.2
Potatoes	profits €/ha/a	2347	515	2112	512	1815	514	1233	577	1748.3	501	1530.8	501.0
Sugar beets		48	198	60.0	104	-167	86.1	-216	194	-57.9	111	-229.7	88.8
Winter wheat 1		460	175	204.2	168	-100	169	107	221	120.1	145	-132.2	144.2
Winter wheat 2		516	160	281	141	-22	142	127	221	186.2	135	-65.0	133.9

Note: The mean is calculated over the period 2009-2040 and 300 weather scenarios. Crop yields in t/ha/a and irrigation rates in mm/a come from EPIC outputs, profits are calculated by our own.

The crop yields are declining compared to the past period 1975-2007. The summary statistics in Table 1 shows that irrigation in the period 2009-2040 leads to a decrease in crop yield variability, except for potatoes. Irrigation results in higher average dry matter crop yields compared to the case of no irrigation. Sprinkler irrigation systems require more irrigation water inputs, but drip irrigation yields the lowest average profits. Only for the production of carrots and sugar beets, sprinkler irrigation yields higher average profits than the scenario without irrigation. Notably, the annual capital cost of a drip irrigation system, which are assumed to operate for 15 years, is 400 €/ha/a for carrots and 233 €/ha/a for all other crops, whereas the annual capital cost for sprinkler irrigation is 213 €/ha/a for all crops. Notable differences in labor hour requirements per ha occur to install and run the respective irrigation system (drip irrigation: 30 h/ha/a; sprinkler irrigation: depending on irrigation amounts applied to the crops can vary between 1 h/ha/a for winter wheat and 6 h/ha/a for sugar beets).

3. Method

In the stochastic dynamic programming model, the farmer decides in each year of the planning period whether to invest into a drip or sprinkler irrigation system and whether to operate the installed system. Investment in irrigation systems is a long-term investment. We assume that a farmer bases his investment decision on his expectation about how annual precipitation will develop over the years 2009-2040. We further assume that in each year 300 possible annual precipitation sums, $P_t \sim U(\rho_t^1, \ldots, \rho_t^{300})$, can occur with equal probability. Once the system has been installed, the farmer can decide whether to operate the irrigation system or not from the following year onwards depending on his annual information about rainfall. To formulate the decision problem we denote x_t the state of the system in year t. x_t can take the values from the set $X_t = \{0, 1, 2\}$, where 0 implies that until period t no irrigation system has been built; 1 that drip irrigation has been built; and 2 that sprinkler irrigation has been built prior to period t. The investment decision in year t is denoted as a_t, chosen from the set $A_t = \{0,1,2\}$, where 0 means that no investment is made in the respective period; 1 that drip irrigation is adopted; and 2 that sprinkler irrigation is adopted. The set of feasible actions depends on the state of the system: in case a system has already been installed no further investment is possible. This constraint is expressed by $x_t a_t = 0$. The state of the system in the next year is determined by the current state and the investment decision in the current year, $x_{t+1} = x_t + a_t$. In the first period of the model no irrigation system is built, $x_1 = 0$. The operational decision, $u_t \in \{0, x_t\}$, can take the values $\{0,1,2\}$, with 1 representing that the drip system is switched on, 2 that sprinkler irrigation is switched on and 0 meaning that the previously installed irrigation system is not in use. The constraint $u_t \in \{0, x_t\}$ indicates that the system has been built before period t, but can only be operated from period t onwards.

The annual profits consist of revenue from crop cultivation less the costs of crop production, which includes cost specific for each crop and specific for each irrigation system. More precisely, the operational profits in period t, $\pi(u, \rho_t^i)$, depend on the operational decision and the annual precipitation sums (equation 1), and the annualized capital cost, $c(x_t + a_t)$, depend on the state in period t after the investment decision has been made (equation 2):

$$\begin{aligned}\pi(u,\rho_t^i) = y(u,\rho_t^i) \cdot p^c - \ (c\_Lh \cdot c + \ Varc) \\ - q^e(u,\rho_t^i) \cdot p^e - \ i\ Lh(u,\rho_t^i) \cdot \ c) - q^n(u,\rho_t^i) \cdot \ p^n) \qquad i = 1, \ldots, 300\end{aligned} \tag{1}$$

$$c(x_t + a_t) = aCapc(x_t + a_t) + \ a\_well(x_t + a_t) \tag{2}$$

The components of the operational profit include parameters assumed constant over time: p_i^c, the constant commodity price; c, the hourly wage; p^e, cost of electricity per kWh; p^n, the price of fertilizer; and $Varc_i$, the variable cost accrued per crop including reparation cost, fuel cost, liming cost, baron cost, cost of herbicide, fungicide, pest management and sowing cost. The remaining components vary by operational decision and the respective annual precipitation sum, determining amongst other the required quantity of irrigation water and nitrogen fertilizer. This includes the yield revenue, $y(u, \rho_t^i)$; and the labor requirement per crop, c_Lh_i. The variable cost of using the irrigation system include energy cost, determined by the quantity of energy used by the irrigation system, $q_i^e(u_t, \rho_t^i)$. The annual labor requirement for irrigation activity is given by $i\_Lh_i(u_t, \rho_t^i)$ and the annual amount of nitrogen fertilizer used, $q_i^n(u_t, \rho_t^i)$. As annual operational profits depend on changes in precipitation, any deviations in investment behavior must be due to changes in precipitation. The annualized fixed cost of the respective irrigation systems is the sum of the annualized capital cost, $aCapc(x_t + \ a_t)$, and the annualized cost of building a well, $a\_well(x_t + a_t)$.

The problem of the agent can be formulated as an optimization problem of timing his investment decisions, a_t, and choosing operational action, u_t, so that the expected sum of profits over the planning period is maximized (equation 3). The discount rate is given by r and $e^{-r\cdot t}$ is the discount factor, by which future profits received in time t must be multiplied to obtain the present value.

$$\max_{a_t,\, u_t}\left\{E\left[\sum_{t=1}^{31} e^{-r\cdot t}\cdot\left(\pi(u_t, P_t) - c(x_t + a_t)\right)\right]\right\} \tag{3}$$

$$\begin{aligned}
&s.t. \\
x_{t+1} &= x_t + a_t & t &= 1,\dots,31 \\
x_1 &= 0 \\
a_t &\in \{0,1,2\} & t &= 1,\dots,31 \\
x_t a_t &= 0 & t &= 1,\dots,31 \\
u_t &\in \{0, x_t\} & t &= 1,\dots,31 \\
P_t &\sim U(\rho_t^1, \dots, \rho_t^{300}) & t &= 1,\dots,31
\end{aligned}$$

The formulated problem is a standard stochastic optimal control problem in discrete time on a finite horizon and thus can be solved by the backward dynamic programming. The optimal investment and operational decision in each year are then obtained recursively by solving the Bellman equation, using the terminal condition that in the terminal period the value of the investment takes the value zero:

$$V_{32}(x,i) = 0 \qquad for\ \forall\, x \in \{0,1,2\} \quad \forall\, i \in \{1,\dots,300\} \tag{4}$$

$$V_t(x,i) = \max_{\substack{a,u:ax=0 \\ u\in\{0,x_t\}}}\left[\pi\left(u, \rho_t^i\right) - c(x+a) + e^{-r}\cdot\frac{\sum_{j=1}^{300} V_{t+1}(x+a,j)}{300}\right] \tag{5}$$

$$[a_t(x,i), u_t(x,i)] = \operatorname*{argmax}_{\substack{a,u:ax=0 \\ u\in\{0,x_t\}}}\left[\pi\left(u, \rho_t^i\right) - c(x+a) + e^{-r}\cdot\frac{\sum_{j=1}^{300} V_{t+1}(x+a,j)}{300}\right] \tag{6}$$

$$for\ \forall x \in \{0,1,2\} \quad \forall\, i \in \{1,\dots,300\} \quad t = 31,30,\dots,1$$

The right hand side of the Bellman equation can be decomposed into the sum of immediate profits, $\pi\left(u, \rho_t^i\right) - c(x+a)$, which the farmer receives upon investment in each precipitation scenario, and the expected discounted continuation value, $e^{-r}\cdot\frac{\sum_{j=1}^{300} V_{t+1}(x+a,j)}{300}$, which is assessed over the 300 possible precipitation scenarios occurring in each year. The expected discounted continuation value is evaluated for the state the farmer is in, which changes according to the investment actions the farmer undertakes. Thus, the farmer aims to find in each year and each precipitation scenario the combination of investment $a_t(x,i)$ and operational actions $u_t(x,i)$, which maximizes his immediate profit and discounted expected continuation value of his actions (equation 6).

The solution of the recursive optimization is a multidimensional matrix, which contains the optimal investment action, $a_t(x,i)$, and the optimal operational action , $u_t(x,i)$, for every state x, each precipitation scenario ρ_t^i and t. To analyze this outcome we calculate the cumulative probabilities of an action occurring in or prior to a specific year. The probability that an irrigation system is chosen is calculated separately for each crop.

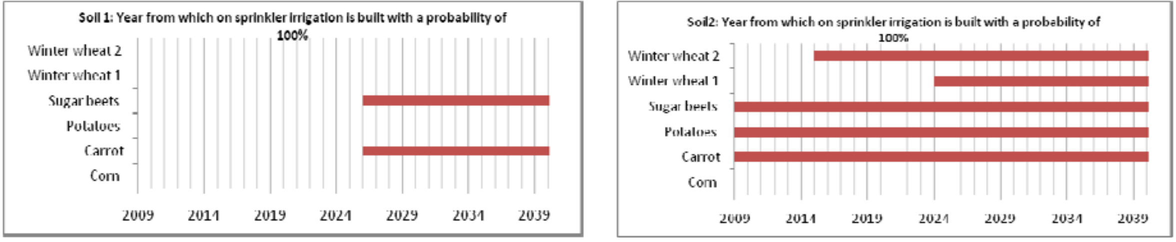
We use the software Matlab for all operations.

4. Results

4.1. Scenario 1 – No policies

For both soil types, we find that the probability to invest in a drip irrigation system at any point in time is zero for all crops. High capital cost or high operation cost respectively seem to render the adoption of drip irrigation unattractive. In contrast, the cumulative probability to invest into sprinkler irrigation is positive for sugar beets and carrots on soil 1, and for all crops, except corn, on soil 2 (Figure 1). On soil 1, the probability that sprinkler irrigation is adopted for production of carrots and sugar beets is 100% in year 2024. This result is not surprising as for both crops sprinkler irrigation yields higher profits than drip irrigation system or no irrigation. According to our climate scenarios, year 2025, marks a decrease in annual precipitation sums by 15% on all randomly drawn precipitation sums. On the less fertile soil type, our analysis reveals a 100% probability that sprinkler irrigation is adopted for the production of carrots, potatoes and sugar beets already in year 2009. We also find a 100% probability that sprinkler irrigation is adopted for the production of winter wheat of crop rotation system 1 in year 2023 and for winter wheat of crop rotation system 2 already in year 2015.The combination with sugar beets and carrots in crop rotation system 2 induces an earlier adoption of sprinkler irrigation for winter wheat. The results are not surprising, as the employment of sprinkler irrigation yields the highest average profits for the production of carrots, and minimizes average losses for the production of sugar beets, respectively.

Figure 1: Year from which on sprinkler irrigation is adopted with a probability of 100% on soil 1 (left side), and on soil 2 (right side)



Note: own calculation.

4.2. Scenario 2 – Water Pricing Policies

We introduce water prices from 0.2€ to 2€ per mm of irrigation water used to reflect increasing levels of water scarcity. We test whether these increased operational costs have a positive impact on the adoption of drip irrigation systems. Our results reveal that drip irrigation is never adopted. At the same time we observe that increasing water prices either delay the adoption of sprinkler irrigation for some crops, or make the adoption not profitable at all (Table 2). On the more fertile soil type, already water prices of 20 cent/mm decrease the probability to adopt sprinkler irrigation for the production of sugar beets to zero. For carrot production, even with water prices of 1 €/mm the optimal timing to adopt sprinkler irrigation systems remains unchanged until the year 2024. Only water prices of 2 €/mm delay the optimal timing of investment to the year 2028 instead of 2025. On the less fertile soil type, the probability to adopt sprinkler irrigation in year 2009 for production of carrots and potatoes remains unchanged for all water pricing scenarios. In contrast, the optimal timing to adopt sprinkler irrigation for the production of sugar beets with a probability of 100% is delayed to the year 2023 with water prices of 50 cent/mm. For the production of winter wheat in both crop rotations systems, the introduction of water prices reveals that sprinkler irrigation is adopted in year 2039 with 43% for winter wheat in crop rotation system 1, and 39% in year 2039 for winter wheat of crop rotation system 2. From a water resource point-of-view, the decreasing probability of adopting an irrigation system could imply a favorable development as groundwater resources can recover from exploitation; on the other hand, without irrigation, less crop outputs per hectare are produced.

Table 2: Year in which sprinkler irrigation systems is adopted with a probability of 100%, for the scenario without policies and 4 alternative water pricing policy scenarios.

	Soil 1						**Soil 2**					
	Corn	Carrot	Potatoes	Sugar beets	Winter w. 1	Winter w. 2	Corn	Carrot	Potatoes	Sugar beets	Winter w. 1	Winter w. 2
No policy	-	2024	-	2024	-	-	-	2009	2009	2009	2023	2015
0.20 €	-	2024	-	-	-	-	-	2009	2009	2009	-	-
0.50 €	-	2024	-	-	-	-	-	2009	2009	2023	-	-
1 €	-	2024	-	-	-	-	-	2009	2009	-	-	-
2 €	-	2028	-	-	-	-	-	2009	2009	-	-	-

Note: own calculation.

4.3. Scenario 3 – Equipment subsidies for drip irrigation systems

We introduce a range of subsidies – as proportion of 10% to 90% of drip irrigation capital cost – to analyze how the investment decision is affected. The results are provided in Table 3. We find that on Soil 1, subsidies of 10% to 60% do not change the optimal investment plan. The optimal timing to invest into sprinkler irrigation for the production of carrots and sugar beets remains 100% in year 2024. For the production of carrots, subsidies of 70% of drip capital cost lead to a 100% probability to adopt drip irrigation in year 2020. Subsidies of 80% also lead to an adoption of drip irrigation for sugar beets in year 2024 and in 2011 for the production of carrots. With subsidies of 90% of capital costs, the year 2009 becomes the optimal timing to invest in drip irrigation for the production of carrots and sugar beets. At the same time the probability to adopt sprinkler irrigation decreases to zero for both crops. For the less fertile soil type 2, we find that subsidies from 10% to 50% of capital cost do not affect the optimal investment strategy for all crops. With subsidies of 60%, there is a 100% probability to adopt drip irrigation in year 2009 for the production of carrots; and with subsidies of 70%, there is a 100% probability to adopt drip irrigation for the production of sugar beets in year 2009. A subsidy of 80% also makes the investment in drip irrigation optimal for production of winter wheat of crop rotation system 1 in year 2022. With a subsidy of 90%, the probability to adopt drip irrigation for the production of carrots, potatoes, sugar beets, and winter wheat from the second crop rotation system is 100% already in year 2009. For the production of corn, the investment probability is 100% in year 2029 and for winter wheat of crop rotation system 1 in year 2015.

Table 3: Year in which drip and sprinkler irrigation systems are adopted with a probability of 100% for the scenario without policies and 5 alternative irrigation subsidy policy scenarios.

	Soil 1											
	Corn		Carrots		Potatoes		Sugar beets		Winter w. 1		Winter w. 2	
	Drip	Spri.	Drip	Spri.	Drip	Spri.	Drip	Spri.	Drip	Spri.	Drip	Spri.
No policy	-	-	-	2024	-	-	-	2024	-	-	-	-
10%	-	-	-	2024	-	-	-	2024	-	-	-	-
30%	-	-	-	2024	-	-	-	2024	-	-	-	-
50%	-	-	-	2024	-	-	-	2024	-	-	-	-
60%	-	-	-	2024	-	-	-	2024	-	-	-	-
70%	-	-	2020	-	-	-	-	2024	-	-	-	-
80%	-	-	2011	-	-	-	2024	-	-	-	-	-
90%	-	-	2009	-	-	-	2009	-	-	-	-	-
	Soil 2											
	Corn		Carrots		Potatoes		Sugar beets		Winter w. 1		Winter w. 2	
	Drip	Spri.	Drip	Spri.	Drip	Spri.	Drip	Spri.	Drip	Spri.	Drip	Spri.
No policy	-	-	-	2009	-	2009	-	2009	-	2023	-	2015

10%	-	-	-	2009	-	2009	-	2009	-	2023	-	2015
30%	-	-	-	2009	-	2009	-	2009	-	2023	-	2015
50%	-	-	-	2009	-	2009	-	2009	-	2023	-	2015
60%	-	-	2009	-	-	2009	-	2009	-	2023	-	2015
70%	-	-	2009	-	-	2009	2009	-	-	2023	-	2015
80%	-	-	2009	-	-	2009	2009	-	2022	-	-	2015
90%	2019	-	2009	-	2009	-	2009	-	2015	-	2009	-

5. Summary and conclusion

A more sustainable water management in agriculture can be achieved by employing irrigation systems which minimize irrigation water inputs per unit of output. We employ a stochastic dynamic programming model to investigate a farmer's investment decision to adopt either a sprinkler, or a more water-efficient drip irrigation system under uncertainty about future precipitation patterns. Until 2040, a downward trend in annual precipitation sums of up to 20% until 2040 is assumed, 300 possible annual precipitation sums can materialize with equal probability. We investigate how farmers' investment decisions are influenced by the introduction of water pricing policies and the provision of subsidies on capital cost of drip irrigation systems. The analysis is performed separately for the production of five typical crops found in the agricultural region Marchfeld in Austria on two alternative soil types. We use simulation outputs from the bio-physical process model EPIC and precipitation data from a statistical climate model (Strauss et al. 2010). There are notable differences in production between both soil types. Average annual crop yields are always higher on the more fertile soil type. On the more fertile soil type, production under sprinkler irrigation achieves the highest average annual profits for carrots and sugar beets and for both crops we find that investment in sprinkler irrigation takes place in year 2025. In contrast, on the less fertile soil type sprinkler irrigation yields the highest average annual profits for all crops, except corn. Investment in sprinkler irrigation is optimal for the production of carrots, sugar beets and potatoes in year 2009 and for winter wheat of crop rotation system 1 and 2, in year 2023 and 2015, respectively. For production on both soil types, we find that drip irrigation seems not to be an investment option when no policies are considered. Introducing water prices, the probability to adopt drip irrigation remains zero and the probability to adopt the sprinkler irrigation system decreases for many crops on both soil types. From a resource point-of-view, less irrigation allows groundwater resources to recover from over extraction. On the other hand, rain-fed crops produce less crop output than irrigated production, which is undesirable as well. Considering the introduction of subsidies around 70% to 90% of drip irrigation's capital costs results in an earlier adoption of drip irrigation systems for carrots and sugar beets on the more fertile soil type and all crops on the less fertile soil types. As subsidies in this extent can weigh heavily on the national budget, it should be determined whether a shift to drip irrigation is sufficiently productive for all crops and soil types. Also, water-efficient irrigation technologies must be appropriate for agricultural needs as well as the capacities of the operating systems and farmers.

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